FOURTH EDITION

BUILDING SOILS FOR BETTER CROPS

ECOLOGICAL MANAGEMENT FOR HEALTHY SOILS

FRED MAGDOFF
and HAROLD VAN ES

SARE
Sustainable Agriculture
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HANDBOOK 10

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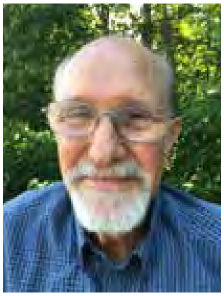
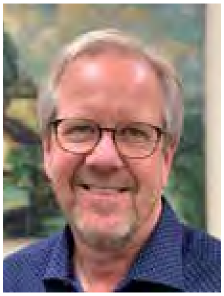


Fred Magdoff is emeritus professor of plant and soil science at the University of Vermont. He was Plant and Soil Science Department chair for eight years and for two decades was the coordinator of the 12-state Northeast Region for the U.S. Department of Agriculture's Sustainable Agriculture Research and Education (SARE) program. He is also a fellow of the American Society of Agronomy and the 2016 recipient of the Presidential Award of the Soil Science Society of America "for outstanding influence on soil science and enduring impact on the future of our science and profession." He has worked on soil testing for nitrogen and phosphorus, the effects of manures on soil properties and crop yields, buffering of soil pH, and many other issues related to soil health. He lives in Burlington and Fletcher, Vt., with his wife, two dogs, a large garden, an occasional flock of chickens and a small herd of beef cows.



Harold van Es is professor of soil science at Cornell University and served as chair of the Department of Crop and Soil Sciences. Born in Amsterdam, Netherlands, he moved to the United States for graduate studies and eventually a life and career in science. His current research, teaching and Extension efforts focus on soil health, digital agriculture and environmental statistics. He co-developed the widely used CASH soil health test and was the lead inventor of the Adapt-N technology, which was successfully commercialized and received the $1 million prize for the Tulane Nitrogen Reduction Challenge. He was the 2016 president of the Soil Science Society of America and is also a fellow of that society, as well as a fellow of the American Society of Agronomy. He and his wife live in Lansing, N.Y., where they raised three children.

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ABOUT SARE

Sustainable Agriculture Research and Education (SARE) is a grant-making and outreach program. Its mission is to advance—to the whole of American agriculture—innovations that improve profitability, stewardship and quality of life by investing in groundbreaking research and education. Since it began in 1988, SARE has funded more than 7,500 projects around the nation that explore innovations—from rotational grazing to direct marketing to cover crops—and many other best practices. Administering SARE grants are four regional councils composed of farmers, ranchers, researchers, educators and other local experts. SARE-funded Extension professionals in every state and island protectorate serve as sustainable agriculture coordinators who run education programs for agricultural professionals. SARE is funded by the National Institute of Food and Agriculture, U.S. Department of Agriculture.

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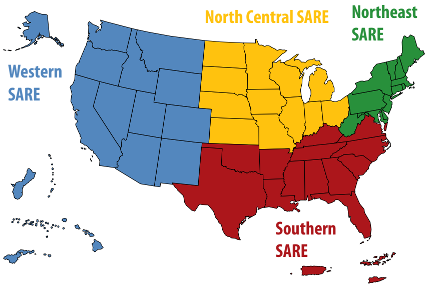

SARE's four regional offices and outreach office work to advance sustainable innovations to the whole of American agriculture.

PREFACE

Used to be anybody could farm. All you needed was a strong back … but nowadays you need a good education to understand all the advice you get so you can pick out what'll do you the least harm.

—VERMONT SAYING, MID-1900s

We have written this book with farmers, farm advisors, students and gardeners in mind, although we have also found copies of earlier editions on the bookshelves of many of our colleagues in science. *Building Soils for Better Crops* is a practical guide to ecological soil management that provides background information as well as details of soil-improving practices. This book is meant to give the reader a holistic appreciation of the importance of soil health and to suggest ecologically sound practices that help to develop and maintain healthy soils.

Building Soils for Better Crops has evolved over time. The first edition focused exclusively on the management of soil organic matter. It is *the* central component of healthy soils, and if you follow practices that build and maintain good levels of soil organic matter, you will find it easier to grow healthy and high-yielding crops. Plants can better withstand droughty conditions and won't be as bothered by insects and diseases. By maintaining adequate levels of organic matter in soil, you have less reason to use as much commercial fertilizer, lime and pesticides as many farmers now purchase. Soil organic matter is that important. The second edition expanded the scope to other aspects of soil management and became recognized as a highly influential book that inspired many towards holistic soil health management.

The third edition was rewritten, expanded with new chapters, and had broader geographical scope; it evolved into a more comprehensive treatise of sustainable soil management for a global audience. Since its publication in 2009, the understanding and promotion of soil health and more holistic approaches to managing crops and soils has truly taken off. We now have numerous major soil health initiatives by governments and NGOs in the United States and around the world.

The fourth edition provides critical updates to reflect the new science and many new exciting developments in soil health. It still has a primary perspective on farming and soils in the United States, but we further expanded the global scope and included a new chapter on growing plants in urban environments.

A book like this one cannot give exact answers to problems on specific farms. In fact, we purposely stay away from prescriptive approaches. There are just too many differences from one field to another, one farm to another, and one region to another, to warrant blanket recommendations. To make specific suggestions, it is necessary to know the details of the soil, crop, climate, machinery, human considerations and other variable factors. Good soil management is knowledge intensive and needs to be adaptive. It is better achieved through education and understanding than with simple recommendations.

Over many millennia, people have struggled with the same issues of maintaining soil productivity as we struggle with today. We quote some of these people in many of the epigraphs at the beginning of each chapter in appreciation for those who have come before. *Vermont Agricultural Experiment Station Bulletin No. 135,* published in 1908, is especially fascinating; it contains an article by three scientists about the importance of soil organic matter that is strikingly modern in many ways. The message of Edward Faulkner's *Plowman's Folly*—that reduced tillage and increased use of organic residues are essential to improving soil—is as valid today as it was in 1943 when it was first published. And let's not forget the first textbook of soil management, Jethro Tull's *A Horse-Hoeing Husbandry, or an Essay on the Principles of Tillage and Vegetation,* first published in 1731. Although it discusses now-refuted concepts, like the need for intensive tillage, it also contains the blueprints for modern seed drills and crop rotations. The saying is right: what goes around comes around. Sources are cited at the end of each chapter and at the end of the book, although what's provided is not a comprehensive list of references on the subject.

Many people reviewed individual chapters for this edition or the entire manuscript at one stage or another and made very useful suggestions. We would like to thank Anthony Bly, Tom Bruulsema, Dennis Chessman, Doug Collins, Willie Durham, Alan Franzluebbers, Julia Gaskin, Vern Grubinger, Joel Gruver, Ganga Hettiarachchi, Jim Hoorman, Tom Jensen, Zahangir Kabir, Doug Karlen, Carl Koch, Peter Kyveryga, Doug Landblom, Matt Leibman, Kate MacFarland, Teresa Matteson, Tai McClellan Maaz, Justin Morris, Rob Myers, Doug Peterson, Heidi Peterson, Sarah Pethybridge, Steve Phillips, Matt Ryan, Paul Salon, Brandon Smith, John Spargo, Diane Stott, Candy Thomas, Sharon Weyers, Charlie White and Marlon Winger.

We recognize colleagues who provided photos in the figure captions, and we are grateful for their contributions. All other photos are our own or are in the public domain. We also acknowledge some of our colleagues—Bob Schindelbeck, Joseph Amsili, Jean Bonhotal, George Abawi, David Wolfe, Omololu (John) Idowu, Bianca and Dan Moebius-Clune, Ray Weil, Nina Bassuk, and Rich Bartlett (deceased)—as well as many of our former students and postdocs, who have made contributions or whose ideas, insights and research have helped shape our understanding of the subject. And we thank our wives, Amy Demarest and Cindy van Es, for their patience and encouragement during the writing of this book. Any mistakes are, of course, ours alone.

A final note about units of measure. Agricultural practitioners are notorious for using different units around the world, like bushels, quintals, hectares, acres, manzanas, and imperial or metric tons. This book has an expanding global audience, and many readers outside North America, and scientists like us, would perhaps prefer the use of metric units. But we decided to maintain the use of imperial units in the book for the convenience of our original target audience. We trust that it does not excessively distract from your reading experience and that readers will make the conversions when the numbers really matter.

Fred Magdoff, University of Vermont
Harold van Es, Cornell University

January 2021

INTRODUCTION

... it is our work with living soil that provides sustainable alternatives to the triple crises of climate, energy, and food. No matter how many songs on your [smartphone], cars in your garage, or books on your shelf, it is plants' ability to capture solar energy that is at the root of it all. Without fertile soil, what is life?

—VANDANA SHIVA, 2008

Throughout history, humans have worked the fields, and land degradation has been a common occurrence. Many civilizations have disintegrated from unsustainable land use, including the cultures of the Fertile Crescent in the Middle East, where the agricultural revolution first began about 10,000 years ago. The 2015 *Status of the World's Soil Resources* report produced by FAO's Intergovernmental Technical Panel on Soils raised global awareness on soil's fundamental role for life on earth but estimated that 33 percent of land is moderately to highly degraded, and it is getting worse. The report identified 10 main threats to soil's ability to function: soil erosion, soil organic matter loss, nutrient imbalance, soil acidification, soil contamination, waterlogging, soil compaction, soil sealing, salinization and loss of soil biodiversity. The current trajectories have potentially catastrophic consequences and millions of people are at risk, especially in some of the most vulnerable regions. Moreover, this has become much more relevant as soils are critical environmental buffers in a world that sees its climate rapidly changing.

In the past, humankind survived because people developed new lands for growing food. But a few decades ago the total amount of agricultural land actually began to decline because new land could no longer compensate for the loss of old land retired from agriculture due to degradation or due to its use for urban, suburban and commercial development. The loss of agricultural land combined with three current trends—increasing populations; greater consumption of animal products produced in large-scale facilities, which creates less-efficient use of crop nutrients; and expanding acreages for biofuel crops—strains our ability to produce sufficient food for the people of the world. We have now reached a point where we are expanding into marginal lands like shallow hillsides and arid areas, which are very fragile and can degrade rapidly (Figure I.1). Another area of agricultural expansion is virgin savannah and tropical rainforest, which are the last remnants of unspoiled and biologically rich land and help moderate climate change. The rate of deforestation at this time is very disconcerting: if continued at this level, there will be little virgin forest left by the middle of the century. We must face the reality that we are running

Figure I.1. Reaching the limits: Marginal rocky land is put into production in Africa.

out of land and need to use the agricultural land we have more productively. We have already seen hunger and civil strife over limited land resources and productivity, and global food crises are a regular occurrence. Some countries with limited water or arable land are purchasing or leasing land in other countries to produce food for the "home" market, and investors are obtaining land in Africa, Southeast Asia and Latin America.

Nevertheless, human ingenuity has helped us overcome many agricultural challenges, and one of the truly modern miracles is our agricultural system, which produces abundant food. High yields often come from the use of improved crop varieties, fertilizers, pest control products and irrigation. These yields have resulted in food security for much of the developed world. At the same time, mechanization and the ever-improving capacity of field equipment allow farmers to work an increasing amount of acreage. But we have also spectacularly altered the flows of organic matter and nutrients in an era when agricultural commodities are shipped across continents and oceans. Despite the high productivity per acre and per person, many farmers, agricultural scientists and Extension specialists see severe problems associated with our intensive agricultural production systems. Examples abound:

- With conventional agricultural practices heavily dependent on fossil fuels, unpredictable swings in their prices affect farmers' net income.
- Prices farmers receive and food prices in retail stores fluctuate in response to both supply and demand, as well as to speculation in the futures markets.
- Increasing specialization of agriculture and geographical separation of grain and livestock production areas—even the diversion of food and animal feed crops to ethanol and biodiesel production—have reduced the natural cycling of carbon and nutrients with severe consequences for soil health and water and air quality.
- Too much nitrogen fertilizer or animal manure often causes elevated nitrate concentrations in streams and groundwater. These concentrations can become high enough to pose a human health hazard. Many of the biologically rich estuaries and where rivers flow into seas around the world—the Gulf of Mexico, Baltic Sea and increasingly other areas—are hypoxic (have low oxygen levels) during late summer months due to nitrogen enrichment from agricultural sources.
- Phosphate and nitrate in runoff and drainage water enter freshwater bodies and degrade their quality by stimulating algae growth.
- Antibiotics used to fight diseases in confined, concentrated farm animals, or used just to promote growth, can enter the food chain and may be found in the meat we eat. Perhaps even more important: their overuse on farms where large numbers of animals are crowded together has resulted in outbreaks of human illness from strains of disease-causing bacteria that have become resistant to many antibiotics.
- Erosion associated with conventional tillage and lack of good rotations degrades our precious soil and, at the same time, causes reservoirs, ponds and lakes to silt up.
- Soil compaction by large equipment reduces water infiltration and increases runoff, thereby increasing flooding while at the same time making soils more drought prone.
- Agriculture, as it expanded into desert regions, has become by far the largest consumer of fresh water. In many parts of the world groundwater is being used for agriculture faster than nature can replenish it. This is a global phenomenon, with over half of the largest aquifers and rivers in the world being exploited at rates exceeding recharge.

The whole modern system of agriculture and food is based on extensive fossil fuel use: to make and power large field equipment, produce fertilizers and pesticides, dry grains, process food products, and transport them over long distances. With the declining production from easily extractable oil and gas, there has been a greater dependence on sources that are more difficult to extract, such as deep wells in the oceans, the tar sands of Canada and a number of shale deposits (accessed by hydraulic fracturing of the rock). All of these sources have significant negative effects on soil, water, air and climate. With the price of crude oil fluctuating but tending to be much greater than in the 20th century, and with the current relatively low price of natural gas dependent on a polluting industry (water pollution and methane emissions with hydraulic fracturing), the economics of the "modern" agricultural system need to be reevaluated.

The food we eat and our surface and groundwaters are sometimes contaminated with disease-causing organisms and chemicals used in agriculture. Pesticides used to control insects, weeds and plant diseases can be found in foods, animal feeds, groundwater and surface water running off agricultural fields. Farmers and farmworkers are at special risk. Studies have shown higher cancer rates among those who work with or near certain pesticides. Children in areas where pesticides are used extensively are also at risk of having developmental problems. When considered together, the costs from these inadvertent byproducts of agriculture are huge. More than a decade ago, the negative effects on wildlife, natural resources, human health and biodiversity in the United States were estimated to cost between $6 billion and $17 billion per year. The general public is increasingly demanding safe, high-quality food that is produced without excessive damage to the environment—and many are willing to pay a premium to obtain it.

To add to the problems, farmers are in a perpetual struggle to maintain a decent standard of living. The farmer's bargaining position has weakened as corporate consolidations and other changes occur with the agricultural input (seeds, fertilizers, pesticides, equipment, etc.), food processing and marketing sectors. For many years the high cost of purchased inputs and the low prices of many agricultural commodities, such as wheat, corn, cotton and milk, caught farmers in a cost-price squeeze that made it hard to run a profitable farm. As some farms go out of business, this dynamic has favored the expansion of production among remaining farmers seeking physical and economic advantages of scale.

Given these problems, you might wonder if we should continue to farm in the same way. A major effort is under way by farmers, Extension educators and researchers to develop and implement practices that are both more environmentally sound than conventional practices and, at the same time, more economically rewarding for farmers. As farmers use management skills and better knowledge to work more closely with the biological world and with the consumer, they frequently find that there are ways to increase profitability by decreasing the use of inputs purchased off the farm and by selling directly to the end user.

Governments have played an ambiguous role in promoting sustainability in agriculture. Many promoted certain types of farming and production practices that worsened the problems, for example through fertilizer subsidies, crop insurance schemes and price guarantees. But governments also pour funds into conservation programs (especially in the United States), require good farming practices for receiving subsidies (especially Europe) and establish farming standards (e.g., for organic production and for fertilizer and pesticide use). A new bright spot is that private-sector sustainability initiatives in agriculture are gaining ground. The general public is increasingly aware of the aforementioned issues and is demanding change. Several large consumer-facing retail and food companies (many that are international) therefore see a benefit from projecting an image of corporate sustainability. They are using supply chain management approaches to work with agricultural businesses and farmers to promote environmentally compatible farming. Indeed, the entire agriculture and food sector benefits when it becomes more sustainable, and there are numerous win-win opportunities to reduce waste and inefficiencies while helping farmers become more profitable over the long run.

SOIL HEALTH INTEGRAL TO SUSTAINABLE AGRICULTURE

You might wonder how soil health fits into all this. It turns out that it is a key aspect of agricultural sustainability because soils are foundational to the food production system while also providing other critical services related to water, air and climate. With the new emphasis on sustainable agriculture comes a reawakening of interest in soil health. Early scientists, farmers and gardeners were well aware of the importance of soil quality and organic matter to the productivity of soil after they saw fertile lands become unproductive. The significance of soil organic matter, including living organisms in the soil, was understood by scientists at least as far back as the 17th century. John Evelyn, writing in England during the 1670s, described the importance of topsoil and explained that the productivity of soils tended to be lost with time. He noted that their fertility could be maintained by adding organic residues. Charles Darwin, the great natural scientist of the 19th century who developed the modern theory of evolution, studied and wrote about the importance of earthworms to nutrient cycling and the general fertility of the soil.

Around the turn of the 20th century, there was again an appreciation of the importance of soil health. Scientists realized that "worn-out" soils, whose productivity had drastically declined, resulted mainly from the depletion of soil organic matter. At the same time, they could see a transformation coming: Although organic matter was "once extolled as the essential soil ingredient, the bright particular star in the firmament of the plant grower, it fell like Lucifer" under the weight of "modern" agricultural ideas (Hills, Jones, and Cutler, 1908). With the availability of inexpensive fertilizers and larger farm equipment after World War II, and with the availability of cheap water for irrigation in dry regions, many people forgot or ignored the importance of organic matter in promoting high-quality soils. In fact, the trading of agricultural commodities in a global economy created a serious imbalance, with some production regions experiencing severe organic matter losses while others had too much. For example, in specialized grain production, most of the organic matter and nutrients—basic ingredients for soil health—are harvested and routinely shipped off the farm to feed livestock or to be industrially processed many miles away, sometimes across continents or oceans. They are never returned to the same production fields, and moreover the carbon and nutrients pose problems at their destinations because the soils became overloaded.

As farmers and scientists were placing less emphasis on soil organic matter during the last half of the 20th century, farm machinery was also getting larger. More horsepower for tractors allowed more land to be worked by fewer people. Large four-wheel-drive tractors allowed farmers to do field work when the soil was wet, creating severe compaction and sometimes leaving the soil in a cloddy condition, requiring more harrowing than otherwise would be needed. The moldboard plow was regarded as a beneficial tool in 19th and early 20th century agriculture that helped break virgin sod and controlled perennial weeds, but with repeated use it became a source of soil degradation by breaking down soil structure and leaving no residues on the surface. Soils were left bare and very susceptible to wind and water erosion. As farm sizes increased, farmers needed heavier manure and fertilizer spreaders as well as more passes through the field to prepare a seedbed, plant,

> *"[Organic matter was] once extolled as the essential soil ingredient, the bright particular star in the firmament of the plant grower. …"*

spray pesticides and harvest, both of which created more soil compaction.

A new logic developed that most soil-related problems could be dealt with by increasing external inputs. This is a reactive way of dealing with soil issues—you respond after seeing a "problem" in the field. If a soil is deficient in some nutrient, you buy fertilizer and spread it on the soil. If a soil doesn't store enough rainfall, all you need is irrigation. If a soil becomes too compacted and water or roots can't easily penetrate, you use a big implement to tear it open. If a plant disease or insect infestation occurs, you apply a pesticide. But are these really individual and unrelated problems? Perhaps they are better viewed as symptoms of a deeper, underlying problem. The ability to tell the difference between what is the underlying problem and what is only a symptom of a problem is essential to deciding on the best course of action. For example, if you are hitting your head against a wall and you get a headache, is the problem the headache and is aspirin the best remedy? Clearly, the real problem is your behavior, not the headache, and the best solution is to stop banging your head against the wall!

What many people think are individual problems may just be symptoms of a degraded, poor-quality soil, which in turn is often related to the general way it is farmed. These symptoms are usually directly related to soil organic matter depletion, lack of a thriving and diverse population of soil organisms, chemical pollution or compaction caused by heavy field equipment. Farmers have been encouraged to react to individual symptoms instead of focusing their attention on general soil health management. A different approach—agroecology—is gaining wider acceptance, implementing farming practices that take advantage of the inherent strengths of natural systems and aiming to create healthy soils. In this way, farmers prevent many symptoms of unhealthy soils from developing, instead of reacting after they develop and trying to overcome them through expensive inputs. If we are to work together with nature rather than attempt to overwhelm and dominate it, then building and maintaining good levels of organic matter in our soils are as critical as managing physical conditions, pH and nutrient levels. Interestingly, the public's concern about climate change has generated a renewed interest in soil organic matter management through so-called carbon farming. Indeed, putting more carbon into the soil can also help reduce global warming.

> *What many people think are individual problems may just be symptoms of a degraded, poor-quality soil.*

The use of inputs such as fertilizers, pesticides and fuels—aided by their relatively low cost—was needed for agricultural development and for feeding a rapidly expanding global population. Let's not ignore that. But it overlooked the important role of soil health and helped push the food production system towards practices where environmental consequences and long-term impacts are not internalized into the economic equation. It could then be argued that matters will not improve unless these structural problems are recognized and economic incentives are changed. Many farming regions have become economically dependent on a global system of export and import of commodities that are not compatible with long-term soil health management. Also, the sector that sells farm machinery and inputs has become highly consolidated and powerful, and these corporations generally have an interest in maintaining the status quo. Input prices have increased markedly over the last decades while prices for those commodities, with the exception of short-term price spikes, have tended to remain low. It is believed that this drives farming towards greater efficiencies, but not necessarily in a sustainable manner. In this context, we argue that sustainable soil management is profitable, and that such management will cause profitability to increase with greater scarcity of resources and higher prices of crop inputs. Even the interests of corporations in the agricultural and food industries can be served in this paradigm.

This book has four parts. Part 1 provides background information about soil health and organic matter: what it is, why it is so important, why we have problems, the importance of soil organisms, and why some soils are of higher quality than others. Part 2 includes discussions of soil physical properties, soil water storage, and carbon and nutrient cycles and flows. Part 3 deals with the ecological principles behind, and the practices that promote, building healthy soil. It begins with chapters that place a lot of emphasis on promoting organic matter buildup and maintenance. Following practices that build and maintain organic matter may be the key to soil fertility and may help solve many problems. Practices for enhancing soil quality include the use of animal manures and cover crops; good residue management; appropriate selection of rotation crops; use of composts; reduced tillage; minimizing soil compaction and enhancing aeration; better nutrient and amendment management; good irrigation and drainage; and adopting specific conservation practices for erosion control. Part 4 discusses how you can evaluate soil health and combine soil-building management strategies that actually work on the farm, and how to tell whether the health of your soils is improving.

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PART 1

ORGANIC MATTER—THE KEY TO HEALTHY SOILS

Photo by Dennis Nolan

Chapter 1

HEALTHY SOILS

All over the country [some soils are] worn out, depleted, exhausted, almost dead. But here is comfort: These soils possess possibilities and may be restored to high productive power, provided you do a few simple things.

—C.W. BURKETT, 1907

It should come as no surprise that many cultures have considered soil central to their lives. After all, people were aware that the food they ate grew from the soil. Our ancestors who first practiced agriculture must have been amazed to see life reborn each year when seeds placed in the ground germinated and then grew to maturity. In the Hebrew Bible, the name given to the first man, Adam, is the masculine version of the word "earth" or "soil" (*adama*). The name for the first woman, Eve (or Hava in Hebrew), comes from the word for "living." Soil and human life were considered to be intertwined. A particular reverence for the soil has been an important part of the cultures of many civilizations, including Native American tribes. In reality, soil *is* the basis of all terrestrial life. We humans are derived from soil. Aside from when we eat fish and other aquatic organisms, we obtain the essential elements in our bodies, such as the calcium and phosphorus in our bones and teeth, the nitrogen in our proteins, the iron in our red blood cells, and so on, all by directly or indirectly consuming plants that took these from the soil.

Although we focus on the critical role soils play in growing crops, it's important to keep in mind that soils also provide other important services. Soils govern whether rainfall runs off the field or enters the ground and eventually helps recharge underground aquifers. When a soil is stripped of vegetation and starts to degrade, excessive runoff and flooding are more common. Soils also absorb, release and transform many different chemical compounds. For example, they help to purify wastes flowing from the septic system drain fields in your backyard. Soils also provide habitats for a diverse group of organisms, many of which are very important, such as those bacteria that produce antibiotics and fungi that help plants obtain nutrients and water and improve soil structure. Soil organic matter stores a huge amount of atmospheric carbon. Carbon, in the form of carbon dioxide, is a greenhouse gas associated

Photo by Dan Anderson

with global warming. So, by increasing soil organic matter, more carbon can be stored in soils, reducing the potential for climate change. We also use soils as a foundation for roads, industry and our communities.

HOW IS SOIL MADE?

Before we consider what makes a soil rich or poor, we should learn how it comes into existence. Soil consists of four parts: solid mineral particles, water, air and organic matter. The particles are generally of sand, silt and clay size (and sometimes also larger fragments) and were derived from weathering of rocks or deposition of sediments. They mainly consist of silicon, oxygen, aluminum, potassium, calcium, magnesium, phosphorus, potassium and other minor chemical elements. But these elements are generally locked up in the crystalline particles and are not directly available to plants. However, unlike solid rock, soil particles have pore spaces in between them that allow them to hold water through *capillary action*: the soil can act like a sponge. This is an important process because it allows the soil water, with the help of carbon dioxide in the air, to very slowly dissolve the mineral particles and release nutrients—we call this *chemical weathering*. The soil water and dissolved nutrients, together referred to as the *soil solution*, are now available for plants. The air in the soil, which is in contact with the air above ground, provides roots with oxygen and helps remove excess carbon dioxide from respiring root cells.

What role do plants and soil organisms play? They facilitate the cycling of organic matter and of the nutrients, which allows soil to continue supporting life. Plants' leaves capture solar energy and atmospheric carbon from carbon dioxide (CO_2) through photosynthesis. The plant uses this carbon to build the sugars, starches and all the other organic chemicals it needs to live and reproduce. At the same time, plant roots absorb both soil water and the dissolved nutrients (nitrogen is added to soils or directly to plants through associated biological processes). Now, the mineral nutrients that were derived from the soil are stored in the plant biomass *in organic form* in combination with the carbon from the atmosphere. The seeds tend to be especially high in nutrients, but the stems and leaves also contain important elements. Eventually plants die and their leaves and stems return to the soil surface. Sometimes plants don't return directly to the soil surface, but rather are eaten by animals. These animals extract nutrients and energy for themselves and then defecate what remains. Soil organisms help to incorporate both manure and plant residues into the soil, while the roots that die, of course, are already in the soil. This dead plant material and manure become a feast for a wide variety of organisms—beetles, spiders, worms, fungi, bacteria, etc.—that in turn benefit from the energy and nutrients the plants had previously stored in their biomass. At the same time, the decomposition of organic material makes nutrients available again to plants, now completing the cycle.

But is it a perfect cycle? Not quite, because it has not evolved to function under intensive agricultural production. The chemical weathering process that adds new nutrients into the cycle continues at a very slow pace. On the other end of the cycle the soil captures some of the organic matter and puts it "in storage." This happens because soil mineral particles, especially clays, form bonds with the organic molecules and thereby protect them from further decomposition by soil organisms. In addition, organic matter particles inside soil aggregates are protected from decomposition. Over a long time, the soil builds up a considerable reservoir of nutrients from slowly decomposing minerals and carbon, and of energy from plant residue in the form of organic matter—similar to putting a small amount of money into a retirement account each month. This organic matter storage system is especially impressive with prairie and steppe soils in temperate regions (places like the central United States, Argentina and Ukraine) because natural grasslands have deep roots and high organic matter turnover (Figure 1.1).

In a natural system this process is quite efficient and has little nutrient leakage. It maximizes the use of mineral nutrients and solar energy until the soil has reached its maximum capacity to store organic matter (more about this in Chapter 3). But when lands were first developed for agriculture, plowing was used to suppress weeds and to prepare the soil for planting grain crops. Plowing was also beneficial because it accelerated organic matter decomposition and released more nutrients than unplowed land. This was a major rift in organic matter cycling, because it caused more organic matter to be lost each year than was returned to the soil. In addition, a related rift occurred in nutrient cycling as some of the nutrients were harvested as part of the crop, removed from the fields and never returned. Other nutrients were washed out of the soil. Over time, the organic matter bank account that had slowly built up under natural vegetation was being drawn down.

However, until organic matter became seriously depleted, its increased decomposition through tillage helped to supply crops with released nutrients and these rifts did not cause widespread concern. On sloping lands these losses went much faster because the organic matter near the surface also eroded away after the soil was exposed to rain and wind. Only in the past century did we find effective ways to replenish the lost nutrients by applying fertilizers that are derived from geologic deposits or the Haber-Bosch process for producing nitrogen fertilizers. But the need to replace the organic matter (carbon) was mostly ignored until recently.

Figure 1.1. Soils build a storage reservoir of carbon and nutrients in organic matter, and can also hold water and air. The organic matter builds up from decayed plant material and accumulates mostly in the dark root zone under the surface. Photo by USDA-NRCS.

The organic matter in the soil is more complex and plays many important roles in soils that we will discuss in Chapter 2. Not only does it store and supply nutrients and energy for organisms, it also helps form aggregates when mineral and organic particles clump together. When it is made up of large amounts of different-sized aggregates, the soil contains more spaces for storing water and allowing gas exchange, as oxygen enters for use by plant roots and by soil organisms and the carbon dioxide produced by organisms leaves the soil. So in summary, the mineral particles and pore spaces form the basic structure of the soil, but the organic matter is mostly what makes it *fertile*.

WHAT KIND OF SOIL DO YOU WANT?

Farmers sometimes use the term *soil health* to describe the condition of the soil. Scientists usually use the term *soil quality*, but both refer to the same idea: how well the soil is functioning for whatever use is being considered. The concept of *soil health* focuses on the human factor—the *anthropogenic* influence—that is increasingly significant due to many years of intensive management. This is different from the inherent differences in soils that are the result of the natural factors that formed the soil, such as the parent material, climate, etc. Thereby, an analogy with humans is apt: We may have some natural differences from our genetic backgrounds (taller or shorter, fairer or darker, etc.), but our health still strongly affects the way we can function and is greatly influenced by how we treat our bodies.

In agriculture, soil health becomes a question of how good the soil is at supporting the growth of high-yielding, high-quality and healthy crops. Given this, how then would you know a high-quality soil from a lower-quality soil? Most farmers and gardeners would say they know one when they see one. Farmers can certainly tell you which of the soils on their farms are of low, medium or high quality, and oftentimes they refer to how dark and crumbly it is. They know high-quality soil because it generates higher yields with less effort. Less rainwater runs off and fewer signs of erosion are seen on the better-quality soils. Less power is needed to operate machinery on a healthy soil than on poor, compacted soils. But there are other characteristics that we'd like a soil to have. These can be condensed into seven desirable attributes of healthy soils:

1. **Fertility**. A soil should have a sufficient supply of nutrients throughout the growing season.
2. **Structure**. We want a soil with good tilth so that plant roots can fully develop with the least amount of effort. A soil with good tilth is more spongy and less compact than one with poor tilth. A soil that has a favorable and stable soil structure also promotes rainfall infiltration and water storage for plants to use later.
3. **Depth**. For good root growth and drainage, we want a soil with sufficient depth before a compact soil layer or bedrock is reached.
4. **Drainage and aeration**. We want a soil to be well drained so that it dries enough in the spring and during the following rains to permit timely field operations. Also, it's essential that oxygen is able to enter the root zone and just as important that carbon dioxide leaves it (it also enriches the air near the leaves as it diffuses out of the soil, allowing plants to have higher rates of photosynthesis). Keep in mind that these general characteristics do not necessarily hold for all crops. For example, flooded soils are desirable for cranberry and paddy rice production.
5. **Minimal pests**. A soil should have low populations of plant disease and parasitic organisms. Certainly, there should also be low weed pressure, especially of aggressive and hard-to-control weeds. Most soil organisms are beneficial, and we certainly want high amounts of organisms that help plant growth, such

THINK LIKE A ROOT!

If you were a root, what would you like from an ideal soil? Surely you'd want the soil to provide adequate nutrients and to be porous with good tilth, so that you could easily grow and explore the soil and so that the soil could store large quantities of water for you to use when needed. But you'd also like a very biologically active soil, with many beneficial organisms nearby to provide you with nutrients and growth-promoting chemicals, as well as to keep potential disease organism populations as low as possible. You would not want the soil to have any chemicals, such as soluble aluminum or heavy metals, that might harm you; therefore, you'd like the pH to be in a proper range for you to grow, and you wouldn't want to be in a soil that somehow became contaminated with toxic chemicals. You would also not want any subsurface layers that would restrict your growth deep into the soil.

as earthworms and many bacteria and fungi.

6. **Free of toxins**. We want a soil that is free of chemicals that might harm the plant. These can occur naturally, such as soluble aluminum in very acid soils or excess salts and sodium in arid soils. Potentially harmful chemicals also are introduced by human activity, such as fuel oil spills or when sewage sludge with high concentrations of toxic elements is applied.
7. **Resilience**. Finally, a high-quality soil should resist being degraded. It should also be resilient, recovering quickly after unfavorable changes like compaction.

THE NATURE AND NURTURE OF SOILS

Some soils are exceptionally good for growing crops and others are inherently unsuitable, but most are in between. Many soils also have limitations, such as low organic matter content, texture extremes (coarse sand or heavy clay), poor drainage or layers that restrict root growth. Midwestern loess-derived prairie soils are naturally blessed with a combination of a silt loam texture and high organic matter content. By every standard for assessing soil health, these soils, in their virgin state, would rate very high. But even many of these prairie soils required drainage in order for them to be highly productive.

The way we care for, or *nurture*, a soil modifies its inherent nature. A good soil can be abused through years of poor management and can turn into one with poor health, although it generally takes a lot of mistreat ment to reach that point. On the other hand, an innately challenging soil may be very “unforgiving” of poor management and quickly become even worse. For example, a heavy clay loam soil can be easily compacted and turned into a dense mass. Naturally good and poor soils will probably never reach parity through good farming practices because some limitations simply cannot be completely overcome, but both can be productive if they are managed well.

HOW DO SOILS BECOME DEGRADED?

Although we want to emphasize healthy, high-quality soils because of their ability to produce high yields of crops, it is also crucial to recognize that many soils in the United States and around the world have become degraded: they have become “worn out.” Degradation most commonly begins with tillage—plowing and harrowing the soil—causing soil aggregates to break apart, which then causes more rapid loss of soil organic matter as organisms have greater access to residues. This accelerates erosion, because soils with lower organic matter content and less aggregation are more prone to accelerated erosion. And erosion, which takes away topsoil enriched with organic matter, initiates a downward spiral resulting in poor crop production. Soils become compact, making it hard for water to infiltrate and for roots to develop properly. Erosion continues and nutrients decline to levels too low for good crop growth. The development of saline (too salty) soils under irrigation in arid regions is another cause of reduced soil health. (Salts added in the irrigation water need to be leached beneath the root zone to avoid the problem.)

Soil degradation caused significant harm to many early civilizations, including the drastic loss of productivity resulting from soil erosion in many locations in the Middle East (such as present day Israel, Jordan, Iraq and Lebanon) and southern Europe. This led either to colonial ventures to help feed the citizenry—like the Romans invading the Egyptian breadbasket—or to the decline of the civilization. The only exceptions were the convergence zones in the landscapes, valleys and deltas where the nutrients and sediments flow together and fertility can be maintained for many centuries (more about this in Chapter 7).

Tropical rainforest conditions (high temperature and rainfall, with most of the organic matter near the soil surface) may lead to significant soil degradation within two or three years of conversion to cropland. This is the reason the “slash and burn” system, with

Figure 1.2. Agricultural soil (left) and natural soil (grassland; right) from adjacent sites in the U.S. Great Plains. Agricultural soil has lower soil organic matter and higher density. Photos by Kirsten Kurtz.

people moving to a new patch of forest every few years, developed in the tropics. After farmers depleted the soils (the readily decomposed organic matter) in a field, they would cut down and burn the trees in the new patch, allowing the forest and soil to regenerate in previously cropped areas.

The westward push of U.S. agriculture was stimulated by rapid soil degradation in the East, originally a zone of temperate forest. Under the environmental conditions of the Great Plains (moderate rainfall and temperature, with organic matter distributed deeper in the soil), it took many decades for the effects of soil degradation to become evident (Figure 1.2).

The extent of deteriorating soil on a worldwide basis is staggering: Soil degradation has progressed so far as to decrease yields on about 20% of all the world's cropland and on 19–27% of the grasslands and rangelands. The majority of agricultural soils are in only fair, poor or very poor condition. Erosion remains a major global problem, robbing people of food and each year continuing to reduce the productivity of the land. Each year some 30–40 billion tons of topsoil are eroded from the croplands of the world.

HOW DO YOU BUILD A HEALTHY, HIGH-QUALITY SOIL?

Some characteristics of healthy soils are relatively easy to achieve. For example, an application of ground limestone will make a soil less acid and will increase the availability of many nutrients to plants. But what if the soil is only a few inches deep? In that case, there is little that can be done within economic reason, except on a very small, garden-size plot. If the soil is poorly drained because of a restricting subsoil layer of clay, tile drainage can be installed, but at a significant cost economically and environmentally.

We use the term *building soils* to emphasize that the nurturing process of converting a degraded or low-quality soil into a truly high-quality one requires understanding, thought and significant actions. It is a process that mirrors the building of soil through natural processes where plants and organic matter are key elements. This is also true for maintaining or

> … What now remains of the formerly rich land is like the skeleton of a sick man, with all the fat and soft earth having wasted away and only the bare framework remaining. Formerly, many of the mountains were arable. The plains that were full of rich soil are now marshes. Hills that were once covered with forests and produced abundant pasture now produce only food for bees. Once the land was enriched by yearly rains, which were not lost, as they are now, by flowing from the bare land into the sea. The soil was deep, it absorbed and kept the water in the loamy soil, and the water that soaked into the hills fed springs and running streams everywhere. Now the abandoned shrines at spots where formerly there were springs attest that our description of the land is true.
>
> —PLATO, 4TH CENTURY B.C.

EVALUATING YOUR SOILS

Score cards and laboratory tests have been developed to help farmers assess their soils, using scales to rate the health of soils. In the field, you can evaluate the presence of earthworms, severity of erosion, ease of tillage, soil structure and color, extent of compaction, water infiltration rate and drainage status. Doing some digging can be especially enlightening! Then you rate crops growing on the soils by such characteristics as their general appearance, growth rates, root health, degree of resistance to drought and yield. It's a good idea for all farmers to fill out such a scorecard for every major field or soil type on your farm every few years, or, alternatively, to send in soil to a lab that offers soil health analyses. But even without doing that, you probably already know what a really high-quality and healthy soil—one that would consistently produce good yields of high-quality crops with minimal negative environmental impact—would be like. You can read more on evaluating soil health in Chapter 23.

improving already healthy soils. Soil organic matter has a positive influence on almost all of the characteristics we've just discussed. As we will see in chapters 2 and 8, soil organic matter is even critical for managing pests. Appropriate organic matter management is, therefore, the foundation for high-quality soil and for a more sustainable and thriving agriculture. It is for this reason that so much space is devoted to organic matter in this book. However, we cannot forget other critical aspects of management, such as trying to lessen soil compaction and good nutrient management.

Although the details of how best to create high-quality soils differ from farm to farm and even field to field, the general approaches are the same. For example:

- **Minimize tillage** and other soil disturbances to maintain soil structure and decrease losses of native soil organic matter.
- **Implement a number of practices** that add diverse sources of organic materials to the soil.
- **Maximize live roots** in the soil and use **rotations and cover crops** that include a diverse mix of crops with different types of root systems.
- **Provide plenty of soil cover** through cover crops and/or surface residue even when economic crops aren't present in order to protect the soil from raindrops and temperature extremes.
- Whenever traveling on the soil with field equipment, use practices that help **develop and maintain good soil structure**.
- Manage **soil fertility** status to maintain optimal pH levels for your crops and a sufficient supply of nutrients for plants without contributing to water pollution.
- In arid regions, reduce the amount of **sodium or salt** in the soil.

There are also large-scale considerations related to the structure of agriculture and associated nutrient and carbon flows that tie into this. Later in the book we will return to these and other practices for developing and maintaining healthy soils.

SOIL HEALTH, PLANT HEALTH AND HUMAN HEALTH

Of the literally tens of thousands of species of soil organism, relatively few cause plant diseases. And the same is true for human diseases, with examples such as tetanus (a toxin produced by a bacterium), hookworm (a nematode), and ringworm (a fungus). But the physical condition of soil can also affect human health. For example, people in the path of dust storms, which pick up fine particles from bare soils, may have significant respiratory problems and damaged lung tissue. In general, soils with a high degree of biological diversity, good soil structure and continual cover with living plants will be healthier for people as well as the plants growing in them. In fact, frequent contact with soil and farm animals early in life results in fewer allergies and stimulates the immune system, helping it to better respond to infections as one grows older.

We discuss soil degradation in this chapter because protecting soil's productivity and limiting environmental impacts are important objectives in and of themselves. However, there are ongoing debates around the world about whether improved soil health also translates into better-quality food and human health outcomes. Soils are the primary source of minerals for humans and animals, but can soil degradation eventually lead to nutrition and health problems? Also, is organically produced food healthier than conventional foods?

To answer these questions we need to understand the two main components of the food chain: how soil health affects plant health and how plant health subsequently affects human health. Together, this is the soil-plant-human health connection. For our discussion we'll ignore the impacts of intermediate steps of food processing, diets and food sourcing, although these can also have significant impacts.

Soils provide plants with nutrients and water, but this doesn't always happen in an optimal way. Healthy plants require *essential* nutrients like nitrogen, phosphorus, potassium and other major and minor elements discussed in Chapter 18. Other elements are not essential but are considered *beneficial* because they have a positive effect on plant growth or help the uptake of other elements. These are typically taken up by plants in trace amounts. A third category is *toxic* elements that are detrimental to plants at certain concentrations. Sometimes, elements are essential or beneficial at low concentrations and may become toxic at high concentrations, like copper and iron.

Nutrient Deficiencies

When crops are grown over many years, nutrients in soil are steadily absorbed by plants. In natural ecosystems the nutrients in plant material are mostly cycled back to the soil, but agricultural systems generally remove many of these nutrients from the farm when the harvested crops are sold, with variable amounts of nutrients remaining on the farm in residues, depending on the crop. (We discuss cycles and flows in Chapter 7). With the use of synthetic fertilizers some nutrients, notably nitrogen, phosphorus, potassium and calcium, are being replenished, but the minerals needed in small or trace amounts generally don't get replaced. This is especially the case in developing countries where farmers often don't analyze their soils and they apply standard fertilizer blends. Sometimes this is aggravated by compaction problems, when the minerals may be present in deeper soil layers but are not root accessible. In some cases soils are naturally deficient in essential elements that may affect plants, animals or humans. For example, selenium is naturally low in the northeastern and northwestern United States. It does not affect plants much but can cause problems with animals and humans.

Toxicities

Many elements in soil can become toxic to plants, animals or humans. The most egregious cases tend to be associated with some type of pollution from human activities. For example, heavy metals may have accumulated from atmospheric deposition of industrial smokestack emissions or from acid deposition from coal-fired power plants. In other cases agricultural activities themselves cause problems, like the long-term use of fertilizers containing high levels of cadmium. An unusual case involved the introduction of tube wells in Bangladesh to irrigate rice. The groundwater source contains naturally high levels of arsenic, which accumulates in the rice grains, causing serious health concerns with local populations. (A common occurrence in regions of grain crop production is the over application of nitrogen fertilizer, which can lead to high concentrations of nitrate in drinking water, which adversely affects the health of rural residents. Although this problem is not a result of direct consumption of plants, it is directly related to how we grow crops.)

Another issue is that crops growing on soils low in biodiversity, in which plant disease organisms flourish, are generally treated with pesticides (fungicides, insecticides, nematicides). These chemicals, as well as herbicides, may find their way into the foods we eat, sometimes into the groundwater we drink. There has been a link established between a number of pesticides in the environment and human diseases.

Human Health Effects

It is difficult to scientifically prove effects of soil health on human health, in part due to the complexity of diets and ethical considerations around clinical trials involving humans. The most significant effect of soil degradation relates to the reduced ability to produce sufficient nutritious foodstuffs to meet peoples' basic caloric and protein needs. Especially in isolated rural areas in developing countries people depend on crops and animals raised on their own farms with little opportunity to buy additional food. Degraded soils and weather extremes can cause crop losses and significantly impact the food supply, with especially high concerns for the long-term impacts to children.

A secondary problem associated with soil degradation is deficiencies of essential minerals, especially in soils that are naturally of low fertility. Again, this may be a problem in regions with mineral mining and heavy dependence on local grain-dominated diets. In developed societies nutritional deficiencies are rare because people obtain food from diverse sources. For example, regional soil selenium deficiency does not impact people when they also eat nuts from other regions. (In developed societies, the concern is increasingly about unhealthy diet choices and the affordability of healthy food.)

Humans also benefit from organic plant compounds that may be indirectly linked to soil health, like the protein content in grains (related to nitrogen in soil), or so-called *secondary metabolites* that have beneficial health effects, like antioxidant activity (for example, phenolics and anthocyanins). A question is whether we can link the benefits of better soil management to actual higher human health outcomes. For example, organic management requires certain practices that enhance soil health because it involves integrated nutrient and organic matter management through better use of rotations and organic amendments. But will it also improve food quality and human health? Many people choose organic foods due to concerns about pesticides (which is a real potential health issue that we should be aware of) or because they believe it tastes better. Or they feel strongly about supporting farmer livelihoods and reducing environmental impacts. There is no evidence that nutrients from organic sources affect human health differently than those from synthetic or processed sources, because either way plants take up the nutrients almost exclusively as inorganic forms. Some studies have shown that organically produced food can positively impact some indicators such as increased levels of antioxidants. But due to many other confounding factors (people who eat organic food typically have better diets, healthier lifestyles, and are wealthier), no study has been able to definitively correlate those with positive human health outcomes.

A LARGER VIEW

In this book we discuss the ecological management of soils. And although the same basic principles discussed here apply to all soils around the world, the problems may differ in specifics and intensity, and different mixes of solutions may be needed on any particular farm or in any ecological zone. It is estimated that close to half the people in the world are deficient in nutrients and vitamins and that half the premature deaths that occur globally are associated with malnutrition. Part of the problem is the low amount of nutrient-rich foods such as vegetables and fruits in diets. When grains form too large a part of the diet, even if people obtain sufficient calories and some protein, the lack of other nutrients results in health problems. Although iron, selenium, cobalt and iodine deficiencies in humans are rare in the United States, they may occur in developing countries whose soils are depleted and nutrient poor. It frequently is an easier and healthier solution to get these nutrients into peoples' diets by increasing plant content by adding these essential elements to the soil (or through irrigation water for iodine) rather than to try to provide everyone with supplements. Enhancing soil health—in all its aspects, not just nutrient levels—is probably one of the most essential strategies for providing nutritious food to all the people in the world and ending the scourge of hunger and malnutrition.

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Chapter 2

ORGANIC MATTER: WHAT IT IS AND WHY IT'S SO IMPORTANT

Follow the appropriateness of the season, consider well the nature and conditions of the soil, then and only then least labor will bring best success. Rely on one's own idea and not on the orders of nature, then every effort will be futile.

—JIA SIXIE, 6TH CENTURY, CHINA

As we will discuss at the end of this chapter, organic matter has an overwhelming effect on almost all soil properties, although it is generally present in relatively small amounts. A typical agricultural soil has 1–6% organic matter by weight. It consists of three distinctly different parts: living organisms, fresh residues and molecules derived from well-decomposed residues. These three parts of soil organic matter have been described as the *living*, the *dead* and the *very dead*. This three-way classification may seem simple and unscientific, but it is very useful in understanding soil organic matter.

The living. This part of soil organic matter includes a wide variety of microorganisms, such as bacteria, viruses, fungi, protozoa and algae. It even includes plant roots and the insects, earthworms and larger animals, such as moles, woodchucks and rabbits that spend some of their time in the soil. The living portion represents about 15% of the total soil organic matter. The range of organisms in soil is so great that it is estimated that they represent about 25% of the world's total biodiversity. Microorganisms, earthworms and insects feed on plant residues and manures for energy and nutrition, and in the process they mix organic matter into the mineral soil. In addition, they recycle plant nutrients. Sticky substances on the skin of earthworms and other materials produced by fungi help bind particles together. This helps to stabilize the soil aggregates, which are clumps of particles that make up good soil structure. Sticky substances on plant roots as well as the proliferation of fine roots and their associated mycorrhizae help promote development of stable soil aggregates. Organisms such as earthworms and some fungi also help to stabilize the soil's structure (for example, by producing channels that allow water to infiltrate) and, thereby, improve soil water status and aeration. Plant roots also interact in significant ways with the various microorganisms and

Photo by Christine Markoe

animals living in the soil. Another important aspect of soil organisms is that they are in a constant struggle with each other (Figure 2.1). Further discussion of the interactions between soil organisms and roots, and among the various soil organisms, is provided in Chapter 4.

A multitude of microorganisms, earthworms and insects get their energy and nutrients by breaking down organic residues in soils. At the same time, much of the energy stored in residues is used by organisms to make new chemicals as well as new cells. How does energy get stored inside organic residues in the first place? Green plants use the energy of sunlight to link carbon atoms together into larger molecules. This process, known as *photosynthesis*, is used by plants to store energy for respiration and growth, and much of this energy ends up as residues in the soil after the plant dies.

The dead. The fresh residues, or "dead" organic matter, consist of recently deceased microorganisms, insects, earthworms, old plant roots, crop residues and recently added manures. In some cases, just looking at them is enough to identify the origin of the fresh residues (Figure 2.2). This part of soil organic matter is the active, or easily decomposed, fraction. This active fraction of soil organic matter is the main supply of food for various organisms—microorganisms, insects and earthworms—living in the soil. As organic materials are decomposed by the "living," they release many of the nutrients needed by plants. Organic chemical compounds produced during the decomposition of fresh residues also help to bind soil particles together and give the soil good structure.

Some organic molecules directly released from cells of fresh residues, such as proteins, amino acids, sugars and starches, are also considered part of this fresh organic matter. These molecules generally do not last long in the soil. Their structure makes them easy to decompose because so many microorganisms use them as food. Some cellular molecules such as lignin are decomposed, but it takes longer for organisms to do so. This can make up a large fraction of the soil organic matter in poorly drained soils, like peats and mucks, as well as wetlands that have been taken into agricultural production. These hold large amounts of organic matter that was not decomposed due to waterlogging, but they don't provide the same benefits as the fresh residues.

The very dead. This includes other organic substances in soils that are difficult for organisms to decompose. Some use the term *humus* to describe all soil organic matter. We'll use the term to refer only to that relatively stable portion of soil organic matter that

Figure 2.1. A nematode feeds on a fungus, part of a living system of checks and balances. Photo by Harold Jensen.

Figure 2.2. Partially decomposed fresh residues removed from soil. Fragments of stems, roots, and fungal hyphae are all readily used by soil organisms.

resists decomposition. Humus is protected from decomposition mainly because its chemical structure makes it hard for soil organisms to utilize.

Identifiable fragments of undecomposed or partially decomposed residue, including remains of microorganisms, can be held inside aggregates in spaces too small for organisms to access. In a sense they behave as if they were "very dead" because of being inaccessible to organisms. As long as organic residue is physically protected from attack by microorganisms it will behave as part of the "very dead." When these aggregates are broken up by freezing and thawing, drying and rewetting, or by tillage, entrapped organic fragments and simple organic substances adsorbed on clays can be made accessible to microorganisms and are readily decomposed. Because much of soil organic matter is so well protected from decomposition, physically and chemically, its age in soils can be as high as hundreds of years.

But even though humus is protected from decomposition, its chemical and physical properties make it an important part of the soil. Humus holds on to some essential nutrients and stores them for slow release to plants. Some medium-size molecules also can surround certain potentially harmful chemicals, like heavy metals and pesticides, and prevent them from causing damage to plants and the environment. The same types of molecules can also make certain essential nutrients more available to plants. Good amounts of soil humus and fragments of crop residues can lessen drainage and compaction problems that occur in clay soils. They also improve water retention in sandy soils by enhancing aggregation, which reduces soil density, and by holding on to and releasing water.

Char. Another type of organic matter, one that has gained a lot of attention lately, is usually referred to as *black carbon* or *char*. Many soils contain some small pieces of charcoal, the result of past fires of natural or human origin. Some, such as the black soils of Saskatchewan, Canada, may have relatively high amounts of char, presumably from naturally occurring prairie fires. However, an increased interest in charcoal in soils has come about mainly through the study of the soils called dark earths, the *terra preta de indio* that are on sites of long-occupied villages in the Amazon region of South America that were depopulated during the colonial era. These dark earths contain 10–20% black carbon in the surface foot of soil, which gives them a much darker color than the surrounding soils. The soil charcoal was the result of centuries of cooking fires and in-field burning of crop residues and other organic materials. The manner in which the burning occurred—slow burns, perhaps because of the wet conditions common in the Amazon—produced a lot of char material and not as much ash as occurs with more complete burning at higher temperatures. These soils were intensively used in the past but have been abandoned for centuries. Still, they remain much more fertile than the surrounding soils, partially due to the high inputs of nutrients in animal and plant residue that were initially derived from the nearby forest, and they yield better crops than surrounding soils typical of the tropical forest. Part of this higher fertility—the ability to supply plants with nutrients with very low amounts of leaching loss—has been attributed to the large amount of black carbon and the high amount of biological activity in the soils (even centuries after abandonment). Charcoal is a very stable form of carbon that helps maintain relatively high cation exchange capacity and supports biological activity by providing suitable habitat. However, char does not provide soil organisms with readily available food sources as do fresh residues and compost. People are experimenting with adding biochar to soils, but this is likely not economical at large scales. The quantity needed to make a major difference to a soil is apparently huge— many tons per acre—and may limit the usefulness of this practice to small plots of land, gardens and container plants, or as a targeted additive coating seeds. Also, benefits from adding biochar should be considered

BIOCHAR AS A SOIL AMENDMENT

It is believed that the unusually productive "dark earth" soils of the Brazilian Amazon region and other places in the world were produced and stabilized by long-term incorporation of charcoal. Black carbon, produced by wildfires as well as by human activity and found in many soils around the world, is a result of burning biomass at around 600–900 degrees Fahrenheit under low oxygen conditions. This incomplete combustion results in about half or more of the carbon in the original material being retained as char. The char, also containing ash, tends to have high amounts of negative charge (cation exchange capacity), has a liming effect on soil, retains some nutrients from the wood or other residue that was burned, stimulates microorganism populations, and is very stable in soils. Although many times increases in yield have been reported following biochar application—probably partially a result of increased nutrient availability or increased pH—sometimes yields suffer. Legumes do particularly well with biochar additions, while grasses frequently become nitrogen deficient, indicating that nitrogen may be deficient for a period following application.

Biochar is a variable material because a variety of organic materials and burn methods can be used to produce it, perhaps contributing to its inconsistent effects on soil and plants. The economic and environmental effects of making and using biochar depend on the source of organic material being converted to biochar, whether heat and gases produced in the process are utilized or just allowed to dissipate, the amount of available oxygen during biochar production, and the distance from where it is produced to the field where it is applied. On the other hand, when used as a seed coating, much less biochar is needed per acre, and it may still stimulate seedling growth and development.

Note: The effects of biochar on raising soil pH and immediately increasing calcium, potassium, magnesium, etc., are probably mostly a result of the ash rather than the black carbon itself. These effects can also be obtained by using more completely burned material, which contains more ash and little black carbon.

in comparison to what might be gained when using the same source materials like wood chips, crop residues or food waste added directly to the soil, after composting or even after complete combustion as ash.

Carbon and organic matter. *Soil carbon* is sometimes used as a synonym for *organic matter*, although the latter also includes nutrients and other chemical elements. Because carbon is the main building block of all organic molecules, the amount in a soil is strongly related to the total amount of all the organic matter: the living organisms plus fresh residues plus well-decomposed residues. When people talk about soil carbon instead of organic matter, they are usually referring to organic carbon, or the amount of carbon in organic molecules in the soil. The amount of organic matter in soils is about twice the organic carbon level. However, in many soils in glaciated areas and semiarid regions it is common to have another form of carbon in soils—limestone, either as round concretions or dispersed evenly throughout the soil. Lime is calcium carbonate, which contains calcium, carbon and oxygen. This is an *inorganic* (mineral) form of carbon. Even in humid climates, when limestone is found very close to the surface, some may be present in the soil. In those cases the *total amount of soil carbon* includes both inorganic and organic carbon, and the organic matter content could not be estimated simply by doubling the total carbon percent.

Normal organic matter decomposition that takes place in soil is a process that is similar to the burning of wood in a stove. When burning wood reaches a certain temperature, the carbon in the wood combines with oxygen from the air and forms carbon dioxide. As this occurs, the energy stored in the carbon-containing chemicals in the wood is released as heat in a process called oxidation. The biological world, including humans, animals and microorganisms, also makes use of the energy inside carbon-containing molecules. This process of converting sugars, starches and other compounds into a directly usable form of energy is also a type of oxidation. We usually call it *respiration*. Oxygen is used, and carbon dioxide and heat are given off in the process.

WHY SOIL ORGANIC MATTER IS SO IMPORTANT

A fertile and healthy soil is the basis for healthy plants, animals and humans. And soil organic matter is the very foundation for healthy and productive soils. Understanding the role of organic matter in maintaining a healthy soil is essential for developing ecologically sound agricultural practices. But how can organic matter, which only makes up a small percentage of most soils, be so important that we devote the three chapters in this section to discuss it? The reason is that organic matter positively influences, or modifies the effect of, essentially all soil properties, and it is what makes the soil fertile. That is the reason it's so important to our understanding of soil health and of how to manage soils better. Organic matter is essentially the heart of the story, but, as we will discuss later, certainly not the only part. In addition to functioning in a large number of key roles that promote soil processes and crop growth, soil organic matter is a critical part of a number of global and regional cycles.

It's true that you can grow plants on soils with little organic matter. In fact, you don't need to have any soil at all. Although gravel and sand hydroponic systems, and even aeroponics (where a nutrient solution is sprayed directly on plant roots) without soil, can grow excellent crops, large-scale systems of this type may have ecological problems and make sense economically only for a limited number of high-value crops grown close to their markets. It's also true that there are other important issues aside from organic matter when considering the health of a soil. However, as soil organic matter decreases, it becomes increasingly difficult to grow plants, because problems with fertility, water availability, compaction, erosion, parasites, diseases and insects become more common. Ever higher levels of inputs—fertilizers, irrigation water, pesticides and machinery—are required to maintain yields in the face of organic matter depletion. But if attention is paid to proper organic matter management, the soil can support a good crop with less need for expensive fixes.

The organic matter content of agricultural topsoil is usually in the range of 1–6%. A study of soils in Michigan demonstrated potential crop-yield increases of about 12% for every 1% increase in organic matter. In a Maryland experiment, researchers saw an increase of approximately 80 bushels of corn per acre when organic matter increased from 0.8% to 2%. The enormous influence of organic matter on so many of the soil's properties—biological, chemical and physical—makes it of critical importance to healthy soils (Figure 2.3). Part of the explanation for this influence is the small particle size of the well-decomposed portion of organic matter, the humus. Its large surface area–to–volume ratio means that humus is in contact with a considerable portion of the soil. The intimate contact of humus with the rest of the soil allows many reactions, such as the release of available nutrients into the soil water, to occur rapidly. However, the many roles of living organisms make soil life an essential part of the organic matter story.

Plant Nutrition

Plants need 17 chemical elements for their growth: carbon (C), hydrogen (H), oxygen (O), nitrogen (N),

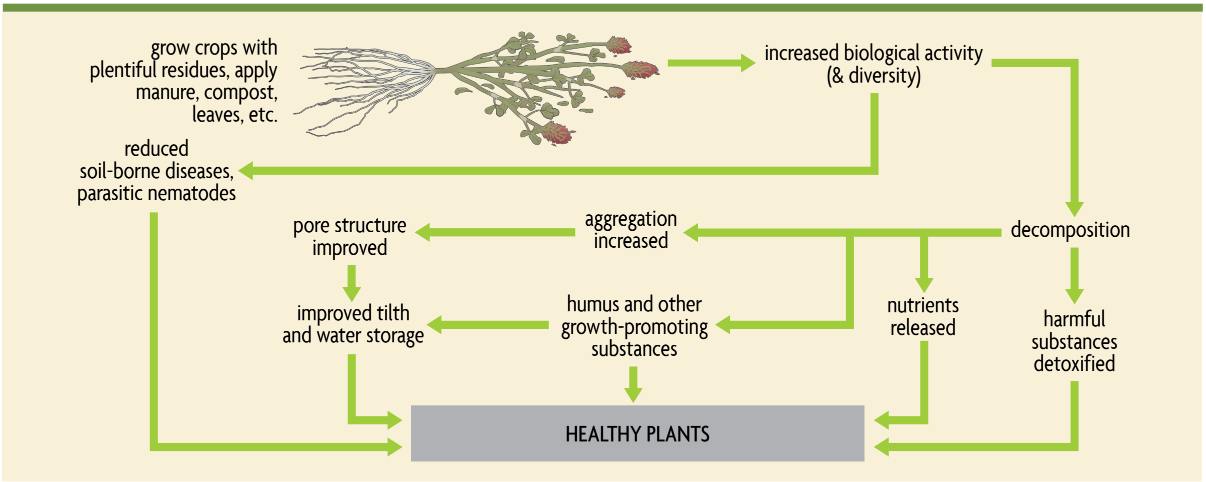


Figure 2.3. Adding organic matter results in many changes. Modified from Oshins and Drinkwater (1999).

phosphorus (P), potassium (K), sulfur (S), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), boron (B), zinc (Zn), molybdenum (Mo), nickel (Ni), copper (Cu), cobalt (Co), and chlorine (Cl). Plants obtain carbon as carbon dioxide (CO_2) from the atmosphere (with some of that diffusing up from the soil underneath as organisms decompose organic substances). Oxygen is also mostly taken from the air as oxygen gas (O_2). The remaining essential elements are obtained mainly from the soil. The availability of these nutrients is influenced either directly or indirectly by the presence of organic matter. The elements needed in large amounts—carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium and sulfur—are called macronutrients. The other elements, called micronutrients, are essential elements needed in small amounts. Sodium (Na) and silica (Si) help many plants grow better but are not considered essential to plant growth and reproduction.

Nutrients from decomposing organic matter. Most of the nutrients in soil organic matter can't be used by plants as long as those nutrients exist as part of large organic molecules. As soil organisms decompose organic matter, nutrients are converted into simpler, inorganic (mineral) forms that plants can easily use. This process, called mineralization, provides much of the nitrogen that plants need by converting it from organic forms. For example, proteins are converted to ammonium (NH_4^+) and then to nitrate (NO_3^-). Most plants will take up the majority of their nitrogen from soils in the form of nitrate. The mineralization of organic matter is also an important mechanism for supplying plants with such nutrients as phosphorus and sulfur, and most of the

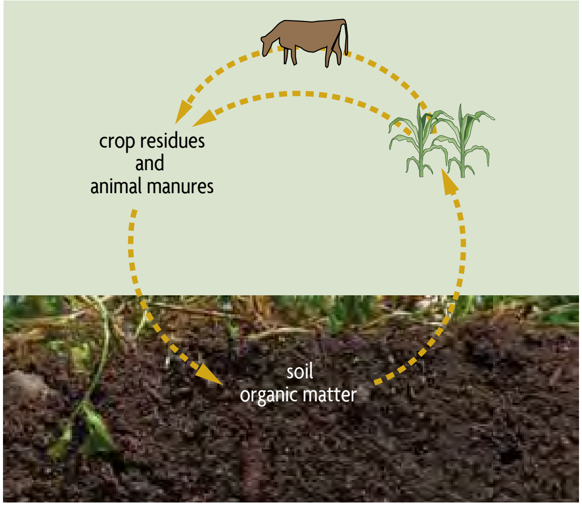


Figure 2.4. The cycle of plant nutrients.

WHAT MAKES TOPSOIL?

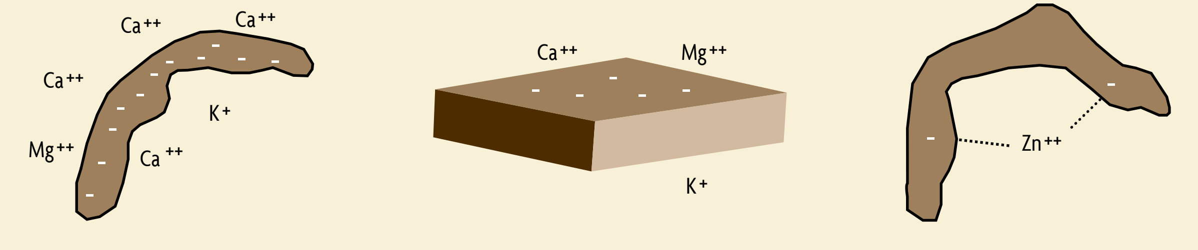
Having a good amount of topsoil is important. But what gives topsoil its beneficial characteristics? Is it because it's on TOP? If we bring in a bulldozer and scrape off one foot of soil, will the exposed subsoil now be topsoil because it's on the surface? Of course, everyone knows that there's more to topsoil than its location on the soil surface. Most of the properties we associate with topsoil—good nutrient supply, tilth, drainage, aeration, water storage, etc.—are there because topsoil is rich in organic matter and contains a huge diversity of life. These characteristics diminish the farther down you dig, making topsoil a unique and indispensable part of the soil profile.

micronutrients. This release of nutrients from organic matter by mineralization is part of a larger agricultural nutrient cycle (see Figure 2.4 and Chapter 7).

Addition of nitrogen. Bacteria living in nodules on legume roots convert nitrogen from atmospheric gas (N_2) to forms that the plant can use directly. A number of free-living bacteria also fix nitrogen.

Storage of nutrients on soil organic matter. Decomposing organic matter can feed plants directly, but it also can indirectly benefit the nutrition of the plant. A number of essential nutrients occur in soils as positively charged molecules called cations (pronounced cat-eye-ons). The ability of organic matter to hold on to cations in a way that keeps them available to plants is known as cation exchange capacity (CEC). Humus has many negative charges, and because opposite charges attract, it is able to hold on to positively charged nutrients, such as calcium (Ca^{++}), potassium (K^{+}), and magnesium (Mg^{++}) (see Figure 2.5a). This keeps them from leaching (washing through the soil) deep into the lower soil. Nutrients held in this way can be gradually released into the soil solution and made available to plants throughout the growing season. However, keep in mind that not all plant nutrients occur as cations. For example, the nitrate form of nitrogen is negatively charged (NO_3^{-}) and is actually repelled by the negatively charged CEC. Therefore, nitrate leaches easily as water moves down through the soil and beyond the root zone.

Clay particles also have negative charges on their surfaces (Figure 2.5b), but organic matter may be the major source of negative charges for coarse and medium-textured soils. Some types of clays, such as those found in the southeastern United States and in the



a) cations held on humus

b) cations held on clay particle

c) cations held by organic chelate

Figure 2.5. Cations held on negatively charged organic matter and clay.

tropics, tend to have low amounts of negative charge. When those clays are present, organic matter is even more critical as it is the main source of negative charges that bind nutrients.

Protection of nutrients by chelation. Organic molecules in the soil may also hold on to and protect certain nutrients. These particles, called *chelates* (pronounced key-lates) are byproducts of the active decomposition of organic materials or are secreted from plant roots. In general, elements are held more strongly by chelates than by binding of positive and negative charges. Chelates work well because they bind the nutrients at more than one location on the organic molecule (Figure 2.5c). In some soils, trace elements, such as iron, zinc and manganese, would be converted to unavailable forms if they were not bound by chelates. It is not uncommon to find low-organic-matter soils or exposed subsoils deficient in these micronutrients.

Other ways of maintaining available nutrients. There is some evidence that organic matter in the soil can inhibit the conversion of available phosphorus to forms that are unavailable to plants. One explanation is that organic matter coats the surfaces of minerals that can bond tightly to phosphorus. Once these surfaces are covered, available forms of phosphorus are less likely to react with them. In addition, some organic molecules may form chelates with aluminum and iron, both of which can react with phosphorus in the soil solution. When they are held as chelates, these metals are unable to form an insoluble mineral with phosphorus.

Beneficial Effects of Soil Organisms

Soil organisms are essential for keeping plants well supplied with nutrients because they break down organic matter, including other dead organisms. These organisms make nutrients available by freeing them from organic molecules. Some bacteria fix nitrogen gas from the atmosphere, making it available to plants. Other organisms dissolve minerals and make phosphorus more available. Without sufficient food sources, soil organisms aren't plentiful and active, and consequently more fertilizers will be needed to supply plant nutrients.

ORGANIC MATTER INCREASES THE AVAILABILITY OF NUTRIENTS ...

Directly

- As organic matter is decomposed, nutrients are converted into forms that plants can use directly.
- CEC is produced during the decomposition process, increasing the soil's ability to retain calcium, potassium, magnesium and ammonium.
- Organic molecules are produced that hold and protect a number of micronutrients, such as zinc and iron.
- Some organisms make mineral forms of phosphorus more soluble while others fix nitrogen, which converts it into forms that other organisms or plants may use.

Indirectly

- Substances produced by microorganisms promote better root growth and healthier roots. With a larger and healthier root system, plants are able to take up nutrients more easily.
- Organic matter improves soil structure, which results in increased water infiltration following rains and increased water-holding capacity of the soil; it also enhances root growth into more permeable soil. This results in better plant health and allows more movement of mobile nutrients (such as nitrates) to the root.

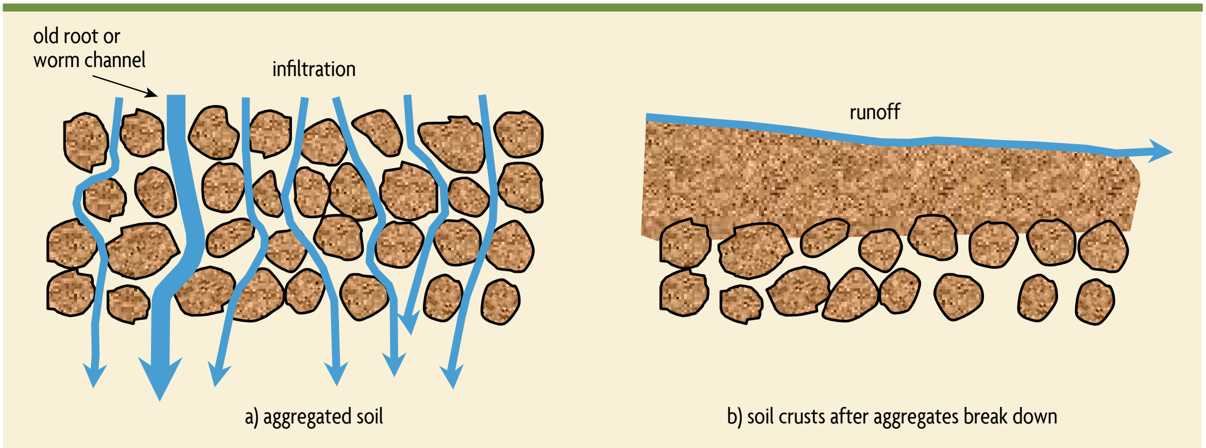


Figure 2.6. Changes in soil surface and water-flow pattern when seals and crusts develop.

A varied community of organisms is your best protection against major pest outbreaks and soil fertility problems. A soil rich in organic matter and continually supplied with different types of fresh residues, through the use of cover crops, complex rotations and applied organic materials such as compost or animal manure, is home to a much more diverse group of organisms than soil depleted of organic matter. The residues provide sufficient food sources to maintain high populations of soil organisms. There are two aspects to biological diversity, both aboveground and belowground: 1) the range of different organisms present and 2) their relative populations (referred to as evenness). It's good to have diverse species of organisms, but it is a richer environment when there are also similar population sizes. For example, if there is a moderate population of disease organisms, we don't just want a small population of beneficial organisms present; the soil is biologically richer if there is also a moderate population of beneficials. Good populations of diverse organisms help ensure that fewer potentially harmful organisms will be able to develop sufficient numbers to reduce crop yields.

Soil Tilth

When soil has a favorable physical condition for growing plants, it is said to have good *tilth*. Such a soil is porous and allows water to enter easily, instead of running off the surface (Figure 2.6). More water is stored in the soil for plants to use between rains, and less erosion occurs. Good tilth also means that the soil is well aerated. Roots can easily obtain oxygen and get rid of carbon dioxide. A porous soil does not restrict root development and exploration. When a soil has poor tilth, its deteriorates and soil aggregates break down, causing increased compaction and decreased aeration and water storage. A soil layer can become so compacted that roots can't grow. A soil with excellent physical properties will have numerous channels and pores of many different sizes.

Studies on both undisturbed and agricultural soils show that as organic matter increases, soils tend to be less compact and have more space for air passage, helping to conduct water into the soil and storing it for plants to use. Sticky substances are produced during the decomposition of plant residues. Along with plant roots and fungal hyphae, they bind mineral particles together into clumps, or aggregates. In addition, the sticky secretions of mycorrhizal fungi—beneficial fungi that enter roots while growing thin filaments into the soil that help plants get more water and nutrients—are important binding material in soils. The arrangement and collection of individual particles as aggregates and the degree of soil compaction have huge effects on plant growth (see chapters 5 and 6). The development of aggregates is desirable in all types of soils because it promotes better drainage, aeration and water storage. The one exception is for some wetland crops, such as rice, where you want a dense soil that keeps fields flooded. (Although newer rice-growing systems show that high yields can be obtained with less flooding, thereby saving water.)

Organic matter, as residue on the soil surface or as a binding agent for aggregates near the surface, plays an important role in decreasing soil erosion. As with leaves and stems of living plants, surface residues intercept raindrops and decrease their potential to detach soil particles. These surface residues also slow water as it flows across the field, giving it a better chance to infiltrate into the soil. Aggregates and large channels greatly enhance the ability of soil to conduct water from the surface into the subsoil. Larger pores are formed in a number of ways. Old root channels may remain open for some time after the root decomposes. Larger soil organisms, such as insects and earthworms, create channels as they move through the soil. The mucus that earthworms secrete to keep their skin from drying out also helps to keep their channels open for a long time.

Most farmers can tell that one soil is better than another by looking at them, seeing how they work up when tilled, or even by sensing how they feel when walked on or touched. What they are seeing or sensing is really good tilth. And digging a bit into the soil can give a sense of its porosity and extent of aggregation.

Since erosion tends to remove the most fertile part of the soil, it can cause a significant reduction in crop yields. In some soils, the loss of just a few inches of topsoil may result in a yield reduction of 50%. The surface of some soils low in organic matter may seal over, or crust, as rainfall breaks down aggregates and as pores near the surface fill with solids. When this happens, water that can't infiltrate into the soil runs off the field, carrying away valuable topsoil (Figure 2.6).

Protection of the Soil Against Rapid Changes in Acidity

Acids and bases are released as minerals dissolve and organisms go about their normal functions of decomposing organic materials or fixing nitrogen. Acids or bases are excreted by the roots of plants, and acids form in the soil from the use of nitrogen fertilizers. It is best for plants if the soil acidity status, referred to as pH, does not swing too wildly during the season. The pH scale is a way of expressing the amount of free hydrogen (H^+) in the soil water, but in soils it is strongly related to the availability of plant nutrients and toxicity of certain elements like aluminum. It is a log scale, so a soil at pH 4 is very acidic and its solution is 10 times more acidic than a soil at pH 5. A soil at pH 7 is neutral: there is just as much base in the water as there is acid. Most crops do best when the soil is slightly acid and the pH is around 6 to 7, although there are acid-loving crops like blueberries. Essential nutrients are more available to plants in this pH range than when soils are either more acidic or more basic. Soil organic matter is able to slow down, or buffer, changes in pH by taking free hydrogen

Figure 2.7. In an experiment by Rich Bartlett, adding humic acids to a nutrient solution increased the growth of tomatoes and corn as well as the amount and branching of roots. Corn grown in nutrient solution with (right) and without (left) chelating agents (extracted from soil). Photo by R. Bartlett.

out of solution as acids are produced or by giving off hydrogen as bases are produced. (For discussion about management of acidic soils, see Chapter 20.)

Stimulation of Root Development

Humic substances in soil may stimulate root growth and development by both increasing availability of micronutrients and by changing the expression of a number of genes (Figure 2.7). Microorganisms in soils produce numerous substances that stimulate plant growth. These include a variety of plant hormones and chelating agents. The stimulation by chelating substances (siderophores) is mainly due to making micronutrients more available to plants, which causes roots to grow longer and to have more branches. In addition, free-living nitrogen fixing bacteria provide the plant with additional sources of that essential nutrient while some bacteria help dissolve phosphorus from minerals, which makes it more available to plants.

Darkening of the Soil

Organic matter tends to darken soils. You can easily see this in coarse-textured sandy soils containing light-colored quartz minerals. Under well-drained conditions, a darker soil surface allows a soil to warm up a little faster in the spring. This provides a slight advantage for seed germination and the early stages of seedling development, which is often beneficial in cold regions.

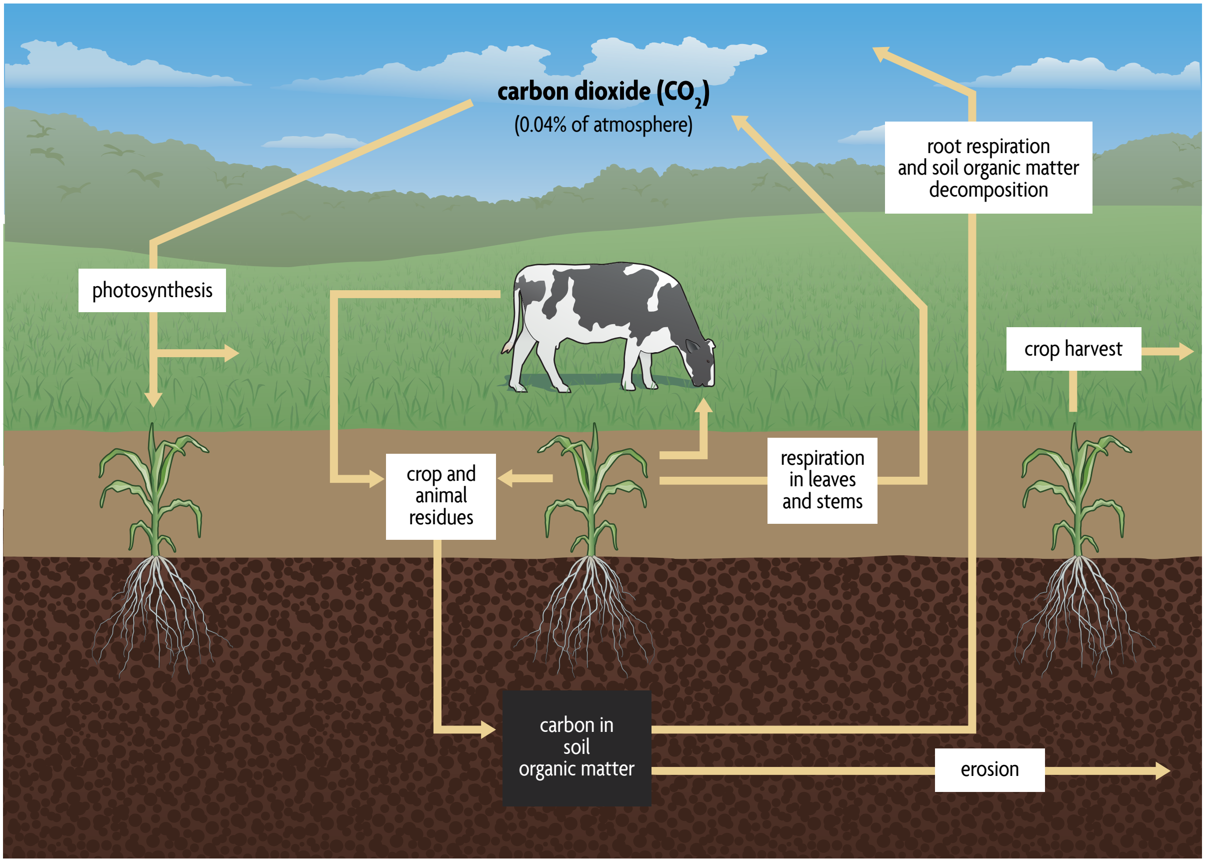


Figure 2.8. The role of soil organic matter in the carbon cycle. Illustration by Vic Kulihin.

Protection Against Harmful Chemicals

Some naturally occurring chemicals in soils can harm plants. For example, aluminum is an important part of many soil minerals and, as such, poses no threat to plants. As soils become more acidic, especially at pH levels below 5.5, aluminum becomes soluble. Some soluble forms of aluminum, if present in the soil solution, are toxic to plant roots. However, in the presence of significant quantities of soil organic matter, the aluminum is bound tightly and will not do as much damage.

Organic matter is the single most important soil property that reduces pesticide leaching. It holds tightly on to a number of pesticides. This prevents or reduces leaching of these chemicals into groundwater and allows time for detoxification by microbes. Microorganisms can change the chemical structure of some pesticides, industrial oils, many petroleum products (gas and oils), and other potentially toxic chemicals, rendering them harmless.

ORGANIC MATTER AND NATURAL CYCLES

The Carbon Cycle

Soil organic matter plays a significant role in a number of global cycles. People have become more interested in the carbon cycle because the buildup of carbon dioxide in the atmosphere is the primary cause of climate destabilization.

A simple version of the natural carbon cycle that leaves out industrial sources, showing the role of soil organic matter, is given in Figure 2.8. Carbon dioxide is removed from the atmosphere by plants and used to make all the organic molecules necessary for life. Sunlight provides plants with the energy they need to carry out this process. Plants, as well as the animals feeding on plants, release carbon dioxide back into the atmosphere as they use organic molecules for energy. Carbon dioxide is also released to the atmosphere when fuels, such as gas, oil, coal and wood are burned.

Soils are amassing the cumulative carbon and nutrient capture from plant production, and the largest amount of carbon present on the land is not in the living plants but is instead stored in soil organic matter. It has taken a while, but that understanding is now finding its way into discussions of the carbon cycle. More carbon is stored in soils than in all plants, all animals and the atmosphere combined. Soil organic matter contains an estimated four times as much carbon as living plants, and in fact carbon stored in all the world's soils is two to three times the amount in the atmosphere. As soil organic matter is depleted, it becomes a source of carbon dioxide for the atmosphere. Also, when forests are cleared and burned, a large amount of carbon dioxide is released. A secondary, often larger flush of carbon dioxide is emitted from soil through the rapid depletion of soil organic matter following conversion of forests to agricultural practices. There is as much carbon in seven inches of a soil with 1% organic matter as there is in the atmosphere above a field. If organic matter

COLOR AND ORGANIC MATTER

In Illinois, a handheld chart has been developed to allow people to estimate percent of soil organic matter. Their darkest soils, almost black, indicate 3.5–7% organic matter. A dark brown soil indicates 2–3%, and a yellowish brown soil indicates 1.5–2.5% organic matter. (Color may not be as clearly related to organic matter in all regions because the amount of clay and the types of minerals also influence soil color.) Recently, mobile apps have been developed that use smartphone cameras to estimate soil organic matter content and have proven to work quite well for rough estimates.

CLIMATE CHANGE AND SOILS

Climate change is already having profound effects on the planet by warming seas, melting glaciers and sea ice, thawing frozen soil (permafrost), and increasing weather extremes: more heat waves, increasing intensity of rainfall in many places and more frequent dry conditions in other locations. As we write this, the last five years (2015, 2016, 2017, 2018 and 2019) have been the warmest since record keeping began in the 1880s. The 2018 and 2019 heat waves in North America, Europe, and southeast and eastern Asia, as well as during the following Australian summer (beginning in December 2018 and then again in their 2019–2020 summer, accompanied this time by historic wildfires), have been especially severe. July 2019 was the warmest month ever recorded. Farming has already been affected in many parts of the world, with increasing night temperatures lowering grain yields as more energy that plants produce during the day is used up by greater nighttime respiration, and with regional droughts causing crop failures.

Gases such as carbon dioxide (CO_2), methane (CH_3) and nitrous oxide (N_2O) trap heat in the atmosphere, resulting in a warming Earth, the so-called greenhouse effect. Atmospheric carbon dioxide concentrations increased from around 320 parts per million (ppm) in the mid 1960s to 415 ppm as we write these words, and it is increasing at the rate of about 2 to 3 ppm per year. The historical conversion of forests and grasslands to farming was responsible for a large transfer of carbon (from accelerated soil organic matter decomposition) into the atmosphere as CO_2. This agricultural conversion is second to the burning of fossil fuels as the largest contributor to increasing atmospheric CO_2 concentrations (remember, fossil fuels are derived from carbon stored in ancient plants). As forests are burned and soils are plowed in order to grow crops (enhancing the use of organic matter by soil organisms), CO_2 is emitted into the atmosphere.

But soils managed in ways that build up organic matter can become net sinks for carbon storage and can enhance their health at the same time. Increasing soil organic matter is no silver bullet for combating climate change, but it can help to slow the increase in CO_2 for a while if done on a massive scale all over the world. A number of non-governmental organizations in the United States, along with a number of international efforts, are encouraging farmers to increase soil organic matter levels in the form of payments for sequestering carbon. (Large-scale "geoengineering" schemes have been proposed to take CO_2 out of the atmosphere or to shoot particles into the atmosphere to reflect some of the incoming radiation from the sun. The costs and potentially negative side effects of such proposals have not been established. Thus, at present, drastically reducing fossil fuel use through switching to renewable energy sources and reducing total energy use is the only sure way we know to stop or reverse climate change.)

Ecologically sound management of agricultural soils using practices that promote the buildup of organic matter certainly has a part to play in combating climate change. It offers win-win outcomes because higher levels of organic matter also increase resilience of soils that are being confronted with the more intense storms and dry periods resulting from a warming planet with increasingly destabilized weather patterns. Read further about the role of soil health in climate resilience in the SARE bulletin *Cultivating Climate Resilience on Farms and Ranches* (www.sare.org/climate-resilience).

decreases from 3% to 2%, the amount of carbon dioxide in the atmosphere could double. (Of course, wind and diffusion move the carbon dioxide to other parts of the globe, and it can be absorbed by the oceans and taken up by plants downwind during photosynthesis.)

The Nitrogen Cycle

Gains. Another important global process in which organic matter plays a major role is the *nitrogen cycle*. It is of direct importance in agriculture because there is frequently not enough available nitrogen in soils for plants to grow their best. Both nitrate and ammonium can be used by plants, but most nitrogen used by plants is taken up in the nitrate form, with a small amount as ammonium. Small quantities of some sources of amino acids and small proteins can be absorbed. Figure 2.9 shows the nitrogen cycle and how soil organic matter enters into the cycle. Almost all of the nitrogen in soils exists as part of the organic matter, in forms that plants are not able to use as their main nitrogen source. Every

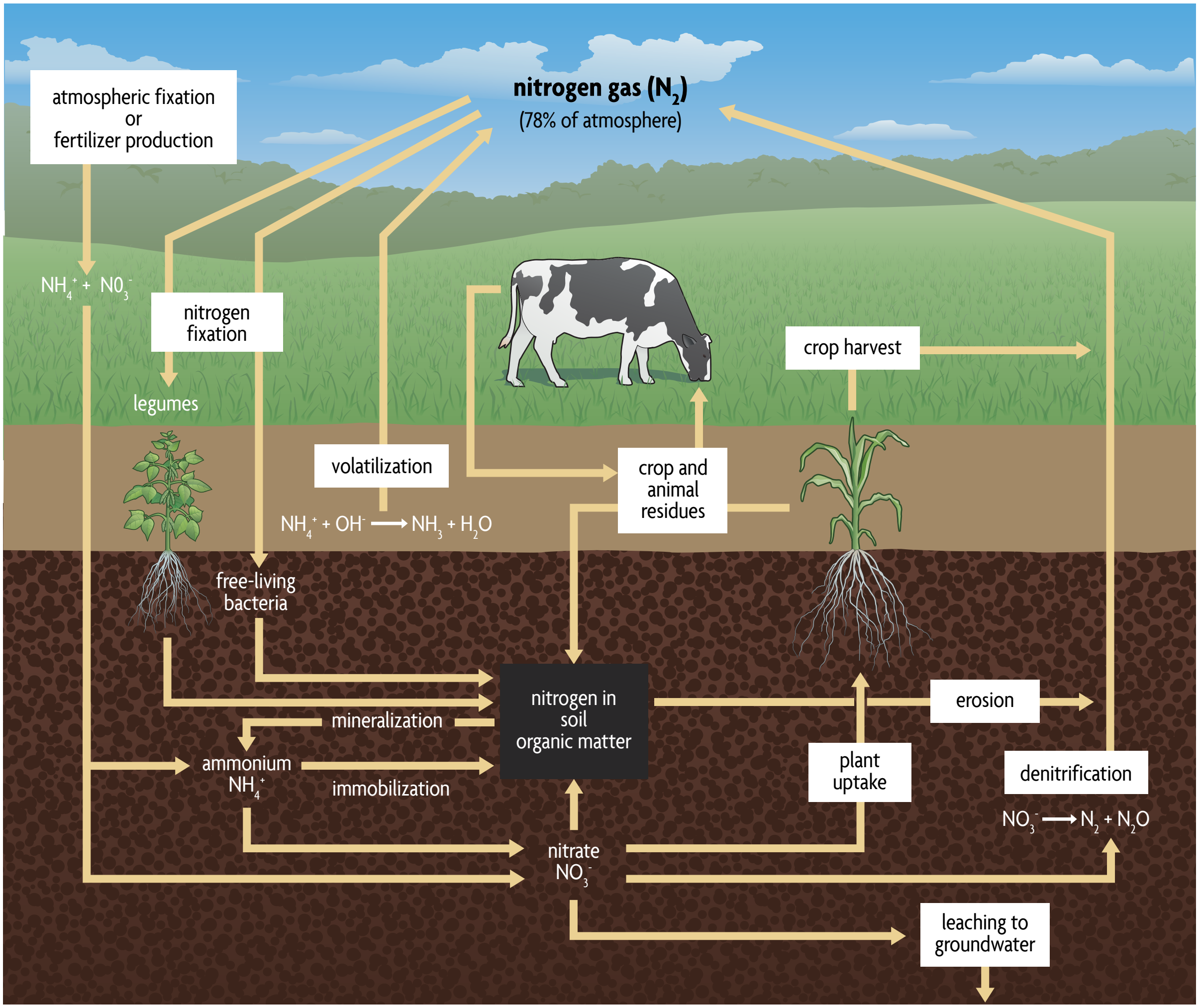


Figure 2.9. The role of organic matter in the nitrogen cycle. Illustration by Vic Kulihin.

percent organic matter in a surface soil (to 6 inches deep) contains approximately 1,000 pounds of nitrogen. Each year bacteria and fungi convert some portion of the organic forms of nitrogen into ammonium, and different bacteria convert ammonium into nitrate. Depending on the soil organic matter levels, a typical crop may derive 20–50% of its nitrogen from mineralized organic matter.

Animal manures can also make large contributions to the plant-available nitrogen pool in the soil. They typically have high organic nitrogen contents that are made readily available when microorganisms convert organic forms to ammonium and nitrate. Most of the crop's nitrogen demand can be met with manure on livestock farms where large amounts of it are generated.

In addition to decomposing organic matter and manure, nitrogen is also derived from some bacteria living in soils that can "fix" nitrogen, converting nitrogen gas to forms that other organisms, including crop plants, can use. These can be modest amounts of nitrogen in typical cereal crop systems but large quantities when growing a legume. Also, inorganic forms of nitrogen, like ammonium and nitrate, exist in the atmosphere naturally and are sometimes enhanced by air pollution. Rainfall and snow deposit these inorganic nitrogen forms on the soil, but generally in modest amounts relative to the needs of a typical crop. Inorganic nitrogen also may be added in the form of commercial nitrogen fertilizers, which for most cash grain crops (except legumes like soybeans) is generally the largest nitrogen addition. These fertilizers are derived from nitrogen gas in the atmosphere through an industrial fixation process that requires quite a lot of energy.

Losses. Nitrogen can be lost from a soil in a number of ways. Soil conditions and agricultural practices govern the extent of loss and the way in which nitrogen is lost. When crops are removed from fields, nitrogen and other nutrients also are removed. When uncomposted manure or certain forms of nitrogen fertilizer are placed on the soil surface, gaseous losses (volatilization) may occur, which may cause losses of up to 30%. The nitrate (NO_3^-) form of nitrogen leaches readily from soils and may end up in groundwater at levels unsafe for drinking or may enter surface waters where it causes low-oxygen "dead zones." Leaching losses are greatest in sandy soils and in soils with tile drainage. Organic forms of nitrate, as well as nitrate and ammonium (NH_4^+), may be lost by runoff water and erosion.

Once freed from soil organic matter, nitrogen may be converted to forms that end up back in the atmosphere. Bacteria convert nitrate to nitrogen (N_2) and to nitrous oxide (N_2O) gases in a process called denitrification, which can be a significant pathway of loss from soils that are saturated. Nitrous oxide (also a potent greenhouse gas) contributes strongly to climate change, and in fact is estimated to be the largest agricultural contribution to greenhouse gas emissions (more than carbon dioxide and methane). In addition, when it reaches the upper atmosphere, it decreases ozone levels that protect the earth's surface from the harmful effects of ultraviolet (UV) radiation. So if you needed another reason to use nitrogen fertilizers and manures efficiently—in addition to the economic costs and the pollution of ground and surface waters—the possible formation of nitrous oxide should make you cautious.

The Water Cycle

Organic matter plays an important part in local, regional and global water cycles due to its role in promoting water infiltration into soils and storage within the soil. The water cycle is also referred to as the *hydrologic* cycle. Water evaporates from the soil surface and from living plant leaves as well as from oceans and lakes. Water then returns to the earth, usually far from where it evaporated, as rain and snow. Soils high in organic matter, with excellent tilth, enhance the rapid infiltration of rainwater into the soil *and* increase storage of water in soil. When we look at the increasing

VALUE OF SOIL ORGANIC MATTER

It is very difficult, if not impossible, to come up with a meaningful monetary value for the worth of organic matter in our soils. It positively affects so many different properties that taking them all into account and figuring out their dollar value is an enormous task. One percent organic matter in the top 6 inches of an acre of soil contains about 1,000 pounds of nitrogen. At about 45 cents per pound, this alone is worth about $450 for every percent organic matter in your soil. Adding in the value of 100 pounds each of phosphorus, sulfur and potassium, the total comes to $500 per acre for every percent of organic matter. But we also need to consider other nutrients that are present and the beneficial effects that organic matter has on reducing other inputs and increasing yields. And what are the monetary benefits of reduced flooding, water pollution and climate change? We know it truly is an invaluable resource, but it is difficult to put an exact price on it.

occurrence of major flooding in parts of the world, especially in the U.S. grain belt, we point to climate change. But surely this is worsened by the gradual degradation of regional soils that are mostly used for intensive crop production.

The water that has entered the soil may be available for plants to use or it may percolate deep into the subsoil and help to recharge the groundwater supply. Since groundwater is commonly used as a drinking water source for homes and for irrigation, recharging groundwater is important. When the soil's organic matter level is depleted, it is less able to accept and store water, and high levels of runoff and erosion result. This means less water for plants and decreased groundwater recharge.

SUMMARY

Soil organic matter is the key to building and maintaining healthy soils because it has such great positive influences on essentially all soil properties—aggregation, nutrient availability, soil tilth and water availability, biological diversity and so on—helping to grow healthier plants. Organic matter consists mainly of the living organisms in the soil ("the living"), the fresh residue ("the dead"), and the well-decomposed (or burned) material physically or chemically protected from decomposition ("the very dead"). Residue trapped inside aggregates (a portion of "the dead" organic matter), especially small ones, is protected also from decomposition because organisms are unable to access the material. Each of these types of organic matter plays an important role in maintaining healthy soils. Soil organic matter transformations are a key part of plant nutrition and the ability to achieve good crop yields. Soil organic matter is also an integral part of local and global cycles of carbon, nitrogen and water, impacting many aspects that define the sustainability and future survival of life on earth.

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Chapter 3

AMOUNT OF ORGANIC MATTER IN SOILS

The depletion of the soil humus supply is apt to be a fundamental cause of lowered crop yields.

—J.L. HILLS, C.H. JONES AND C. CUTLER, 1908

The amount of organic matter in any particular soil is the result of a wide variety of environmental, soil and agronomic influences. Some of these, such as climate and soil texture, are naturally occurring. Hans Jenny carried out pioneering work on the effect of natural influences on soil organic matter levels in the United States more than 70 years ago. But agricultural practices also influence soil organic matter levels. Tillage, crop rotation and manuring practices all can have profound effects on the amount of soil organic matter.

The amount of organic matter in a soil is the result of all the additions and losses of organic materials that have occurred over the years (Figure 3.1). In this chapter, we will look at why different soils have varying levels of organic matter. While we will be looking mainly at the total amount of organic matter, keep in mind that all three “types” of organic matter—the living, dead and very dead—serve critical roles, and the amount of each may be affected differently by natural factors and agricultural practices.

Anything that adds large amounts of organic residues to a soil may increase organic matter. On the other hand, anything that causes soil organic matter to decompose more rapidly or to be lost through erosion may deplete organic matter.

If additions are greater than losses, organic matter increases, which happens naturally when soils are formed over many years. When additions are less than

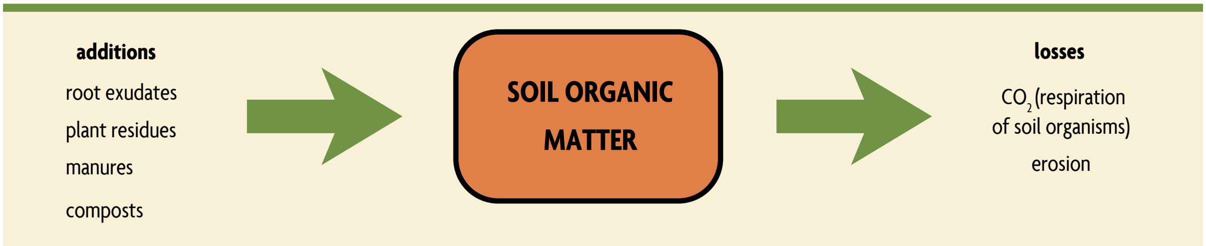


Figure 3.1. Additions and losses of organic matter from soils.

Photo by Jerry DeWitt

STORAGE OF ORGANIC MATTER IN SOIL

Organic matter is protected in soils by:

- Formation of strong chemical bonds between organic matter and clay particles (and fine silt)
- Being inside small aggregates (physically protected)
- Conversion into stable substances such as humic materials that are resistant to biological decomposition
- Restricted drainage that reduces the activity of the decomposing organisms that need oxygen to function
- Stable char chemistry that is produced by incomplete burning

Large aggregates are made up of many smaller ones that are held together by sticky substances from roots, bacterial colonies and fungal hyphae. Organic matter in large aggregates—but outside of the small aggregates that make up the larger ones—and freely occurring particulate organic matter (the "dead") are available for soil organisms to use. However, poor aeration resulting from restricted drainage because of a dense subsurface layer, compaction or being at the bottom of a slope or wetland area may cause a low rate of use of the organic matter. So the organic matter needs to be in a favorable chemical form and physical location for organisms to use it; plus, the environmental conditions in the soil—adequate moisture and aeration—need to be sufficient for most soil organisms to use the residues and thrive.

losses, there is a depletion of soil organic matter, which generally happens when soils are put into crop production. When the system is in balance and additions equal losses, the quantity of soil organic matter doesn't change over the years.

NATURAL FACTORS

Temperature

In the United States, it is easy to see how temperature affects soil organic matter levels. Traveling from north to south, higher average temperatures lead to less soil organic matter. As the climate gets warmer, two things tend to happen (as long as rainfall is sufficient): More vegetation is produced because the growing season is longer, and the rate of decomposition of organic materials in soils increases because soil organisms work more rapidly and are active for longer periods of the year at higher temperatures. Faster decomposition with warmer temperatures becomes the dominant influence determining soil organic matter levels.

In the arctic and alpine regions there is not a lot of organic matter added to soils each year because of the very short season during which plants can grow. But arctic soils have high levels of organic matter because of the extremely slow decomposition rate caused by cold (and freezing) temperatures. However, with the Arctic's temperature increasing and with the thawing of frozen soils, organic matter can be rapidly lost as microorganisms use it to live and give off CO_2 during their respiration. Another greenhouse gas trapped in these soils, methane (CH_4), is also being lost to the atmosphere. Thereby, the warming of the arctic and alpine regions is especially worrisome.

Rainfall

Soils in arid climates usually have low amounts of organic matter. In a very dry climate, such as a desert, there is little growth of vegetation. Decomposition is also low because of low amounts of organic inputs and low microorganism activity when the soil is dry. When it finally rains, a very rapid burst of decomposition of soil organic matter occurs. Soil organic matter levels generally increase as average annual precipitation increases. With more rainfall, more water is available to plants, and more plant growth results. As rainfall increases, more residues return to the soil from grasses or trees. At the same time, soils in high rainfall areas may have less organic matter decomposition than well-aerated soils. Decomposition is slowed by restricted aeration.

Soil Texture

Fine-textured soils, containing high percentages of clay and silt, tend to have naturally higher amounts of soil organic matter than coarse-textured sands or sandy loams. The organic matter content of sands may be less than 1%; loams may have 2% to 3%, and clays from 4% to more than 5%. The strong chemical bonds that develop between organic matter and clay and fine silt protect organic molecules from attack and decomposition by microorganisms and their enzymes. Also, clay and fine silt combine with organic matter to form very small aggregates that in turn protect the organic matter inside from organisms and their enzymes. In addition, fine-textured soils tend to have smaller pores and less oxygen than coarser soils. This also limits decomposition rates, one of the reasons that organic matter levels in fine-textured soils are higher than in sands and loams.

Soil Drainage and Position in the Landscape

Decomposition of organic matter occurs more slowly in poorly aerated soils. In addition, some major plant compounds such as lignin will not decompose at all in anaerobic environments. For this reason, organic matter tends to accumulate in wet soil environments. When conditions are extremely wet or swampy for a very long period of time, organic (peat or muck) soils develop, with organic matter contents of more than 20%. When these soils are artificially drained for agricultural or other uses, the soil organic matter will decompose rapidly. When this happens, the elevation of the soil surface actually decreases. Homeowners on organic soils in Florida normally sink the corner posts of their houses below the organic level to provide stability. Originally level with the ground, some of those homes now perch on posts atop a soil surface that has decreased so dramatically that the owners can park their cars under their homes!

Soils in depressions at the bottom of hills or in floodplains receive runoff, sediments (including organic matter) and seepage from upslope, and tend to accumulate more organic matter than drier soils farther upslope. In contrast, soils on a steep slope or knoll will tend to have low amounts of organic matter because the topsoil is continually eroded.

Type of Vegetation

The type of plants that grow on the soil as it forms can be an important source of natural variation in soil organic matter levels. Soils that form under grassland vegetation generally contain more and a deeper distribution of organic matter than soils that form under forest vegetation. This is probably a result of the deep and extensive root systems of grassland species (Figure 3.2). Their roots have high “turnover” rates as root die-off and decomposition constantly occur and as new roots are formed. Dry natural grasslands also frequently experience slow-burning fires from lightning strikes, which contribute biochar that is very resistant to degradation. The high levels of organic matter in soils that were once in grassland partly explain why these are now some of the most productive agricultural soils in the world. By contrast, in forests, litter accumulates on top of the soil, and surface organic layers commonly contain over 50% organic matter. However, the mineral layers immediate below typically contain less than 2% organic matter.

Figure 3.2. Root systems of annual wheat (at left in each panel) and wheatgrass, a perennial, at four times of the year. Approximately 25–40% of the wheatgrass root system dies back each year, adding considerable amounts of organic matter, and then grows back again. Compared to annual wheat, it has a longer growing season and has much more growth both above ground and below ground. Wheatgrass was 12 and 21 months old when the first and last photos were taken. Photo by the Land Institute.

Acidic Soil Conditions

In general, soil organic matter decomposition is slower under acidic soil conditions than at a more neutral pH. In addition, acidic conditions, by inhibiting earthworm activity, encourage organic matter to accumulate at the soil surface, rather than to distribute throughout the soil layers.

HUMAN INFLUENCES

Erosion loss of topsoil that is rich in organic matter has dramatically reduced the total amount of organic matter stored in many soils after they were developed for agriculture. Crop production obviously suffers when part of the most fertile layer of the soil is removed. Erosion is a natural process and occurs on almost all soils. Some soils naturally erode more easily than others, and the problem is greater in some regions (like dry sparsely vegetated areas) than others. However, agricultural practices greatly accelerate erosion whether by water, wind or even tillage practices themselves (see Chapter 16). It is estimated that erosion in the United States is responsible for annual losses of about $1 billion in available nutrients and many times more in total soil nutrients.

Unless erosion is severe, a farmer may not even realize a problem exists. But that doesn't mean that crop yields are unaffected. In fact, yields may decrease by 5–10% when only moderate erosion occurs. Yields may suffer a decrease of 10–20% or more with severe erosion. The results of a study of three Midwestern soils (referred to as Corwin, Miami and Morley), shown in Table 3.1, indicate that erosion greatly affects both organic matter levels and water-holding ability. Greater amounts of erosion decreased the organic matter content of these

ROOT VERSUS ABOVEGROUND RESIDUE CONTRIBUTION TO SOIL ORGANIC MATTER

Roots, already being well distributed and in intimate contact with the soil, tend to contribute a higher percentage of their weight to the more persistent organic matter ("dead" and "very dead") than to aboveground residues. In addition, compared to aboveground plant parts, many crop roots have higher amounts of materials such as lignin that decompose relatively slowly. One experiment with oats found that only one-third of the surface residue remained after one year, while 42% of the root organic matter remained in the soil and was the main contributor to particulate organic matter. In another experiment, five months after spring incorporation of hairy vetch, 13% of the aboveground carbon remained in the soil, while close to 50% of the root-derived carbon was still present. Both experiments found that the root residue contributed much more to particulate organic matter (active, or "dead") than did aboveground residue.

loamy and clayey soils. In addition, eroded soils stored less available water than minimally eroded soils.

Organic matter also is lost from soils when organisms decompose more organic materials during the year than are added. This occurs as a result of practices that accelerate decomposition, such as intensive tillage and crop production systems that return low amounts of plant biomass, directly as crop residues or indirectly as manure. Even with residue retention, cash grain production systems export 55–60% of the organic matter off the farm. Therefore, much of the rapid loss of organic matter following the conversion of grasslands to agriculture has been attributed to large reductions in plant residue annually returned to soil, accelerated mineralization of organic matter because of plowing, and erosion.

Table 3.1
Effects of Erosion on Soil Organic Matter and Water

Soil	Erosion	Organic Matter (%)	Available Water Capacity (%)
Corwin	slight	3.03	12.9
	moderate	2.51	9.8
	severe	1.86	6.6
Miami	slight	1.89	16.6
	moderate	1.64	11.5
	severe	1.51	4.8
Morley	slight	1.91	7.4
	moderate	1.76	6.2
	severe	1.6	3.6

Source: Schertz et al. (1985).

Tillage Practices

Tillage practices influence both the amount of topsoil erosion and the rate of decomposition of organic matter. Conventional plowing and disking provide multiple short-term benefits: creating a smooth seedbed, stimulating nutrient release by enhancing organic matter decomposition, and helping control weeds. But by breaking down natural soil aggregates, intensive tillage destroys large, water-conducting channels and the soil is left in a physical condition that is highly susceptible to wind and water erosion.

The more a soil is disturbed by tillage practices, the greater the potential breakdown of organic matter by soil organisms. This happens because organic matter held within aggregates becomes readily available to soil organisms when aggregates are broken down during tillage. Incorporating residues with a moldboard plow, breaking aggregates open and fluffing up the soil also allow microorganisms to work more rapidly. It's something like opening up the air intake on a wood stove, which lets in more oxygen and causes the fire to burn hotter. Rapid loss of soil organic matter (and a burst of CO_2 pumped into the atmosphere) occurs in the early years because of the high initial amount of active ("dead") organic matter available to microorganisms. In Vermont, we found a 20% decrease in organic matter after five years of growing silage corn on a clay soil that had previously been in sod for decades. During the early years of agriculture in the United States, when colonists cleared the forests and planted crops in the East, and farmers later moved to the Midwest to plow the grasslands, soil organic matter decreased rapidly as the soils were literally mined of this valuable resource. In the Midwest, many soils lost 50% of their organic matter within 40 years of the onset of cropping. It was quickly recognized in the Northeast and Southeast that fertilizers and soil amendments were needed to maintain soil productivity. In the Midwest, the deep, rich soils of the tall-grass prairies were able to maintain their productivity for a long time despite accelerated loss of soil organic matter and significant amounts of erosion. The reason for this was their unusually high reserves of soil organic matter and nutrients at the time of conversion to cropland.

After much of the biologically active portion is lost, the rate of organic matter loss slows and what remains is mainly the already well-decomposed "passive" or "very dead" materials. With the current interest in reduced ("conservation") tillage, growing row crops in the future should not have such a detrimental effect on soil organic matter. Conservation tillage practices leave more residues on the surface and cause less soil disturbance than conventional moldboard plows and disks. In fact, soil organic matter levels usually increase when no-till planters place seeds in a narrow band of disturbed soil, leaving the soil between planting rows undisturbed. Residues accumulate on the surface because the soil is not inverted by plowing. Earthworm populations increase because they are naturally adapted to feeding on plant residues left at the soil surface. They take some of the residues deeper into the soil and create channels that also help water infiltrate into the soil. The beneficial effects on soil organic matter levels from minimizing tillage are often observed quickly at the soil surface, but deeper changes are much slower to develop. In the upper Midwest there is conflicting evidence as to whether a long-term no-till approach results in greater accumulation of soil organic matter than a conventional tillage system when the full profile is considered. In contrast, significant increases in profile soil organic matter have been routinely observed under no-till in warmer locations.

Crop Rotations and Cover Crops

Levels of soil organic matter may fluctuate during the different stages of a crop rotation. Soil organic matter may decrease, then increase, then decrease, and so forth. While annual row crops under conventional moldboard-plow cultivation usually result in decreased soil organic matter, perennial legumes, grasses and legume-grass forage crops tend to increase soil organic matter. The high amount of root production by hay and pasture crops, plus the lack of soil disturbance, causes organic matter to accumulate in the soil. This effect is seen in the comparison of organic matter increases when growing alfalfa compared to corn silage (Figure 3.3). In addition, different types of crops result in different quantities of residues being returned to the soil. When corn grain is harvested, more residues are left in the field than after soybean, wheat, potato or lettuce harvests. Harvesting the same crop in different ways leaves different amounts of residues. When corn grain is harvested, more residues remain in the field than when the entire plant is harvested for silage or when stover is used for purposes like bioenergy (Figure 3.4). You can therefore imagine a worst case scenario when a field has continuous annual row crop production, with grain and residue harvested from the field, and is combined with intensive tillage and no other organic additions like manure, compost or cover crops.

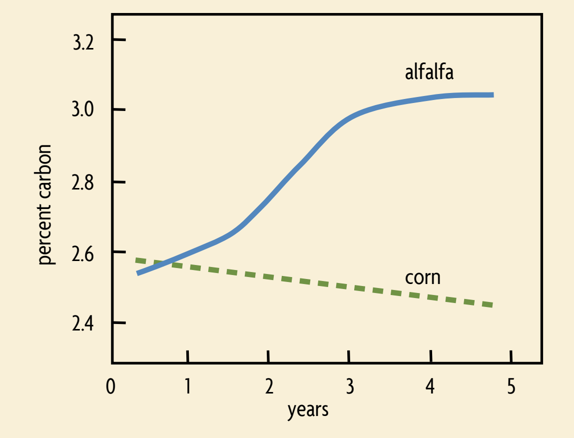


Figure 3.3. Organic carbon changes when growing corn silage or alfalfa. Redrawn from Angers (1992).

Soil erosion is greatly reduced and topsoil rich in organic matter is conserved when rotation crops, such as grass or legume hay, are grown year round. The permanent soil cover and extensive root systems of sod crops account for much of the reduction in erosion. Having sod crops as part of a rotation reduces the loss of topsoil, decreases decomposition of residues, and builds up organic matter by the extensive residue addition of plant roots.

Cover crops help protect soils from erosion during the part of the year between commercial crops when soils would otherwise be bare. In addition to protecting organic-matter-rich topsoil from erosion, cover crops may add significant amounts of organic materials to soil. But the actual amount added is determined by the type of cover crop (grass species versus legumes versus brassicas, etc.) and how much biomass accumulates before it is suppressed/killed in order to plant the following commercial crop.

Use of Synthetic Nitrogen Fertilizer

Fertilizing nutrient-deficient soils usually results in greater crop yields. A significant additional benefit is that it also achieves greater amounts of crop residue—roots, stems and leaves—resulting from larger and healthier plants. Most crop nutrients are applied in reasonable balance with crop uptake if the soil is regularly tested. However, nitrogen management is more challenging and includes more risk to farmers. Therefore, N fertilizer is commonly applied at much higher rates than needed by plants, sometimes by as much as 50%, which is costly and also creates environmental problems. (See Chapter 19 for a detailed discussion of nitrogen management.)

Use of Organic Amendments

An old practice that helps maintain or increase soil organic matter is to apply manures or other organic residues generated off the field. This happened naturally in older farming systems where crops and livestock were raised on the same farm, and much of the crop organic matter and nutrients was recycled as manure. A study in Vermont found that between 20 and 30 tons (wet weight, including straw or sawdust bedding) of dairy manure per acre were needed to maintain soil organic matter levels when silage corn was grown each year. This is equivalent to one or one and a half times the amount produced by a large Holstein cow over the whole year. Varying types of manure—bedded, liquid stored, digested, etc.—can produce very different effects on soil organic matter and nutrient availability. Manures differ in their initial composition and are affected by how they are stored and handled in the field, for example, surface applied or incorporated, which we discuss in Chapter 12.

ORGANIC MATTER DISTRIBUTION WITHIN SOIL

With Depth

In general, more organic matter is present near the surface than deeper in the soil (see Figure 3.5). This is one of the main reasons that topsoils are more productive than subsoils that become exposed by erosion or mechanical removal of surface soil layers.

a) corn silage

b) corn grain

Figure 3.4. Soil surface after harvest of corn silage or corn grain. Photos by Bill Jokela and Doug Karlen.

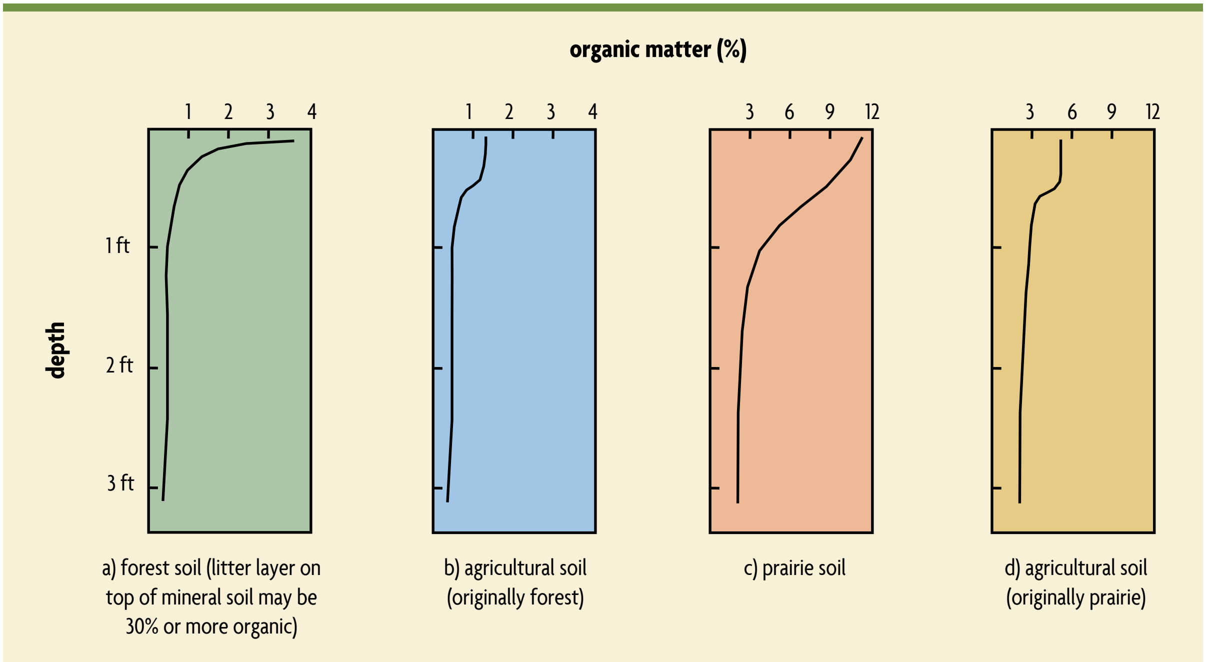


Figure 3.5. Examples of soil organic matter content with depth (note different scales for forest and prairie soils). Modified from Brady and Weil (2008).

Some of the plant residues that eventually become part of the soil organic matter are from the aboveground portion of plants. In most cases, plant roots are believed to contribute more to a soil's organic matter than do the crop's shoots and leaves. But when the plant dies or sheds leaves or branches, thus depositing residues on the surface, earthworms and insects help incorporate the residues on the surface deeper into the soil. The highest concentrations of organic matter, however, remain within 1 foot of the surface.

Litter layers that commonly develop on the surface of forest soils may have very high organic matter contents (Figure 3.5a). Plowing forest soils after removal of the trees incorporates the litter layers into the mineral soil. The incorporated litter decomposes rapidly, and an agricultural soil derived from a sandy forest soil in the North or a silt loam in the South would likely have a distribution of organic matter similar to that indicated in Figure 3.5b. Soils of the tall-grass prairies have a deeper distribution of organic matter (see Figure 3.5c). After cultivation of these soils for 50 years, far less organic matter remains (Figure 3.5d). In addition to accelerated organic matter loss caused by soil disturbance and aggregate breakdown, there is much less input of organic matter from crops that grow for three or four months during the year when compared to prairie vegetation.

Inside and Outside Aggregates

Organic matter occurs outside of aggregates as living roots, larger organisms or pieces of residue from a past harvest. Some organic matter is even more intimately associated with soil. Humic materials may be adsorbed onto clay and small silt particles, and small- to medium-size aggregates usually contain particles of organic matter. The organic matter inside very small aggregates is physically protected from decomposition because microorganisms and their enzymes can't reach inside.

This organic matter also attaches to mineral particles and thereby makes the small particles stick together better. The larger soil aggregates, composed of many smaller ones, are held together primarily by the hyphae of fungi with their sticky secretions, by sticky substances produced by other microorganisms, and by roots and their secretions. Microorganisms are also found in very small pores within larger aggregates, which can sometimes protect them from their larger predators: paramecium, amoeba and nematodes.

There is an interrelationship between the amount of fines (silt and clay) in a soil and the amount of organic matter needed to produce stable aggregates. The higher the clay and silt content, the more organic matter is needed to produce stable aggregates, because more is needed to occupy the surface sites on the minerals during the process of organic matter accumulation. In order to have more than half of the soil composed of water-stable aggregates, a soil with 50% clay may need twice as much organic matter as a soil with 10% clay.

ACTIVE VERSUS *PASSIVE* ORGANIC MATTER

Most of the discussion in this chapter so far has been about the factors that control the quantity and location of total organic matter in soils. However, we should keep in mind that we are also interested in balancing the different types of organic matter in soils: the living, the dead (active) and the very dead (humus). As discussed earlier, a portion of soil organic matter is protected from decomposition because of its chemical composition, by being adsorbed on clay particles, or by being inside small aggregates that organisms can't access (Table 3.2). We don't want just a lot of passive organic matter (humus) in soil, we also want a lot of active organic matter to provide nutrients and aggregating glues when it decomposes. It supplies food to keep a diverse population of organisms present. When forest or grassland soils were first cultivated, rapid organic matter decreases were almost entirely due to a loss of the unprotected and therefore biologically active ("dead") component. But although it *decreases* fastest when intensive tillage is used, the active portion also *increases* fastest when soil building practices such as reduced tillage, improved rotations, cover crops, and applying manures and composts are used to increase soil organic matter.

Table 3.2
Location and Type of Soil Organic Matter

Type	Location
Living	Roots and soil organisms live in spaces between medium to large aggregates and inside large aggregates
Active (dead)	Fresh and partially decomposed residue in spaces between medium to large aggregates and inside large aggregates
Passive (very dead)	a) Molecules and fragments of dead microorganisms tightly held on clay and silt particles; b) particles of organic residue inside very small (micro) aggregates; c) organic compounds that by their composition are difficult for organisms to use.

AMOUNTS OF *LIVING* ORGANIC MATTER

In Chapter 4, we discuss the various types of organisms that live in soils. The weight of fungi present in forest soils is much greater than the weight of bacteria. In grasslands, however, there are about equal weights of the two. In agricultural soils that are routinely tilled, the weight of fungi is less than the weight of bacteria. The loss of surface residues with tillage lowers the number of surface-feeding organisms. And as soils become more compact, larger pores are eliminated first. To give some perspective, a soil pore that is 1/25 of an inch (1 millimeter) is considered large. These are the pores in which soil animals, such as earthworms and beetles, live and function, so the number of such organisms in compacted soils decreases. Plant root tips are generally about 0.1 millimeter (1/250 of an inch) in diameter. Very compacted soils that lost pores greater than that size have serious rooting problems. The elimination of smaller pores and the loss of some of the network of small pores with even more compaction is a problem for even small soil organisms.

The total amounts (weights) of living organisms vary in different cropping systems. In general, soil organisms are more abundant and diverse in systems with complex rotations that return more diverse crop residues and that use other organic materials such as cover crops, animal manures and composts. Leaves and grass clippings may be an important source of organic residues for gardeners. When crops are rotated regularly, fewer parasite, disease, weed and insect problems occur than when the same crop is grown year after year.

On the other hand, frequent cultivation reduces the populations of many soil organisms because their food supplies are depleted by decomposition of organic matter. Compaction from heavy equipment also causes harmful biological effects in soils. It decreases the number of medium to large pores, which reduces the volume of soil available for air, water and populations of organisms, such as mites and springtails, which need the large spaces in which to live.

HOW MUCH ORGANIC MATTER IS ENOUGH?

We already mentioned that soils with higher levels of fine silt and clay usually have higher levels of organic matter than those with a sandier texture. However, unlike plant nutrients or pH levels, there are few accepted guidelines for adequate organic matter content in particular agricultural soils. We do know some general guidelines. For example, 2% organic matter in a sandy soil is very good and difficult to reach, but in a clay soil 2% indicates a greatly depleted situation. The complexity of soil organic matter composition, including biological diversity of organisms, as well as the actual organic chemicals present, means that there is no simple interpretation for total soil organic matter tests. We also know that soils higher in silt and clay need more organic matter to produce sufficient water-stable aggregates to protect soil from erosion and compaction.

Some research has been conducted to determine the levels of organic matter where the fine soil mineral particles become *saturated*, having adsorbed as many organic compounds as possible. This provides some guidance where the soil is in terms of the current versus the potential organic matter level and whether or not the soil is at an upper equilibrium level. It also tells us whether the soil has the potential to store more organic matter as part of a carbon farming effort (carbon is 58% of organic matter). In this calculation, a soil with 20% silt and clay, for example, can store a maximum of 3.6% organic matter, while a soil with 80% silt and clay can hold 6.1% organic matter. This does not include the additional particulate organic matter that may be either subject to rapid decomposition (active) or protected from decomposition by soil organisms inside small (micro) aggregates (part of the passive organic matter). However, the clay content and type of clays present influence the amount of organic matter particles "stored" inside micro-aggregates.

Organic matter accumulation takes place slowly and is difficult to detect in the short term by measurements of total soil organic matter. However, even if you do not greatly increase soil organic matter (and it might take years to know how much of an effect is occurring), improved management practices such as adding organic materials, creating better rotations and reducing tillage will help maintain the levels currently in the soil. And, perhaps more important, continuously adding a variety of residues results in plentiful supplies of "dead" organic matter—the relatively fresh particulate organic matter—that helps maintain soil health by providing food for soil organisms and promoting the formation of soil aggregates. We now have a soil test that tells you early on whether you are moving your organic matter levels in the right direction. It determines the amount of organic matter thought to be the *active* portion, is more sensitive to soil management than total organic matter and is an early indicator for soil health improvement (see Chapter 23).

> *The question will be raised, "How much organic matter should be assigned to the soil?" No general formula can be given. Soils vary widely in character and quality. Some can endure a measure of organic deprivation … others cannot. On slopes, strongly erodible soils, or soils that have been eroded already, require more input than soils on level lands.*
>
> —HANS JENNY, 1980

ORGANIC MATTER AND CROPPING SYSTEMS

Natural (virgin) soils generally have much higher organic matter levels than agricultural soils. But there are also considerable differences among cropping systems that can be generalized as follows: In a cash grain operation, about 55–60% of the aboveground plant biomass is harvested as grain and sold off the farm, thereby returning less than half of the mass of the aboveground plant to the soil. The nutrients removed in the crops are replaced through fertilizers, but the carbon is not. On dairy farms, on the other hand, the crops are commonly fully harvested as a forage and fed to the animals, and then most of the plant biomass, including nutrients and carbon, is returned to the field as manure. While most dairy farms also grow their own feed grain, some import grain from other places, thereby accumulating additional organic matter and nutrients. When considering a typical conventional vegetable operation, as with cash grain, much of the plant biomass is harvested and sold off the farm, with limited return to the land. But a typical organic vegetable system imports a lot of compost or manure to maintain soil fertility and thereby applies quite a lot of organic matter to the soil. They are also more likely to grow a green manure crop to build fertility for the cash crop.

A recent New York study analyzed soil organic matter levels and soil health for such distinctive cropping systems and found considerable differences (Table 3.3). Soils that were used to grow annual grain crops (corn, soybeans, wheat) averaged 2.9% organic matter and conventional processing vegetables averaged 2.7%. Dairy fields averaged somewhat higher levels (3.4%) and mixed vegetables (mainly small organic farms) averaged 3.9% organic matter. The highest organic matter levels, however, were measured for pastures (4.5%), where much of the plant is recycled as manure and the soil is not tilled. As a result of the soil management and organic matter dynamics, the physical condition of the soil is also impacted. Aggregate stability, which is a good indicator of the physical health of the soil, is greater when the organic matter content is higher *and* the soil is not tilled (Table 3.3).

THE DYNAMICS OF RAISING AND MAINTAINING SOIL ORGANIC MATTER LEVELS

It is not easy to dramatically increase the organic matter content of soils or to maintain elevated levels once they are reached. In addition to using cropping systems that promote organic matter accumulation, it requires a sustained effort that includes a number of approaches that add organic materials to soils and minimize losses. It is especially difficult to raise the organic matter content of soils that are very well aerated, such as coarse sands, because of low potential for aggregation (which shelters organic matter from microbial attack) and limited protective bonds with fine minerals. Soil organic matter levels can be maintained with lower additions of organic residues in high-clay-content soils with restricted aeration than in coarse-textured soils because of the slower decomposition. Organic matter can be increased much more readily in soils that have become depleted of organic matter than in soils that already have a good amount of organic matter given their texture and drainage condition.

Table 3.3
Organic Matter Levels and Percent Soil in Water-Stable Aggregates Associated with Different Cropping Systems in New York

Cropping System	Description	Organic Matter (%)	Aggregate Stability (%)
Conventional vegetable	Intensive tillage; mostly inorganic fertilizer; crop biomass removed	2.7	27
Annual grain	Range of tillage; mostly inorganic fertilizer; crop biomass mostly removed	2.9	30
Dairy	Rotation with perennial forage crops; mostly intensive tillage with corn silage; crop biomass removed but mostly recycled through manure	3.4	36
Mixed vegetable (mostly organic)	Intensive tillage; green manure and cover crops; mostly organic fertilizer like compost	3.9	44
Pasture	No-till; perennial forage crop; crop biomass mostly recycled through manure	4.5	70

Starting Point

It is good to consider the soil's current status when you build up organic matter in a soil. A useful analogy is the three glasses of water in Figure 3.6 that represent organic matter levels in different cropping systems. We are generalizing here, but some soils that are severely degraded (case 1, say from severe erosion or intensive tillage, etc.) have low organic matter levels (empty glass) and have the potential to increase and store much more. Another soil (case 3) may be in a cropping system that has for a long time been cycling much of the organic matter or has received a lot of external organic inputs as we discussed previously. Here the glass is nearly full and not much additional organic matter can be stored. In such cases we should focus on protecting the existing organic matter levels by minimizing losses. The in-between scenario (case 2) may be a conventional grain or vegetable farm where organic matter levels are suboptimal and can still be increased. In the context of carbon farming and raising overall soil organic matter levels, benefits will accrue more in cases 1 and 2 than in case 3, where the soil is already close to being saturated with organic matter. Moreover, if farms that fit case 3 are located near those that fit cases 1 or 2, there are potential gains from transferring the excess organic residues, like manure from a livestock farm to a farm growing only grain crops. Note: The amount of stored organic matter also depends on the soil type, especially clay content, and you may imagine a larger glass for a fine soil than a coarse soil, and the fullness of the glass is similarly proportional.

Adding Organic Matter

When you change practices on a soil depleted in organic matter, perhaps one that has been intensively

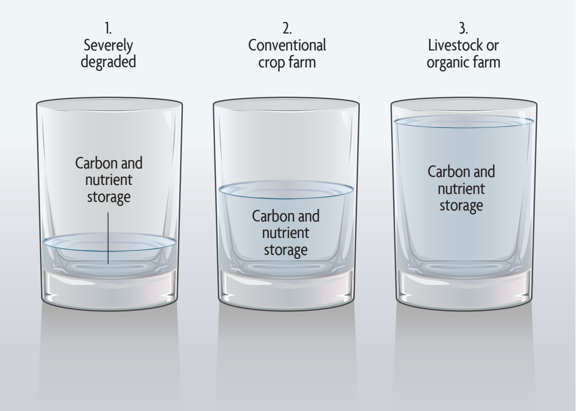


Figure 3.6. Soil organic matter (carbon) levels vary in different soils and cropping systems, analogous to glasses filled with variable amounts of water.

row-cropped for years and has lost a lot of its original aggregation, organic matter will increase slowly, as diagrammed in Figure 3.7. At first, any free mineral surfaces that are available for forming bonds with organic matter will form organic-mineral bonds. Small aggregates will also form around particles of organic matter, such as the outer layer of dead soil microorganisms or fragments of relatively fresh residue. Then larger aggregates will form, made up of the smaller aggregates and held by a variety of means: frequently by mycorrhizal fungi and small roots. Once all possible mineral sites have been occupied by organic molecules and all of the small aggregates have been formed around organic matter particles, organic matter accumulates mainly as free particles, within the larger aggregates or completely unaffiliated with minerals. This is referred to as *free particulate organic matter*. After you have followed similar soil-building practices (for example, cover cropping or applying manures) for some years, the soil will come into equilibrium with your management and the total amount of soil organic matter will not change from year to year. In a sense, the soil is "saturated" with organic matter as long as your practices don't change. All the sites that protect organic matter (chemical bonding sites on clays and physically protected sites inside small aggregates) are occupied, and only free particles of organic matter can accumulate. But because there is little protection for the

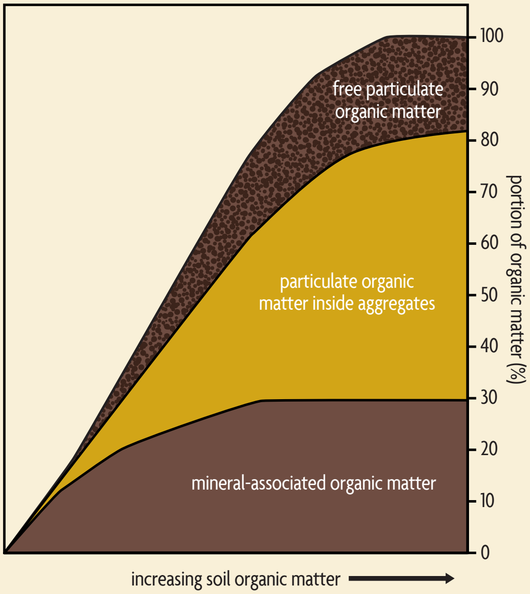


Figure 3.7. Organic matter changes in soil as practices favoring buildup are implemented. Redrawn and modified from Angers (1992).

HOW MUCH ORGANIC MATERIAL IS NEEDED TO INCREASE SOIL ORGANIC MATTER BY 1%?

To increase organic matter in your soil by 1%, let's say from 2% to 3%, requires a lot of organic material to be added. This usually takes the form of plant roots, aboveground plant residues, manures and composts. But to give an idea of how much needs to be added for such a seemingly small increase (and is actually a LARGE increase), let's do some calculations. A surface soil to 6 inches weighs about 2 million pounds. One percent organic matter in this soil would then weigh 20,000 pounds. But when organic material is added to soil, a large percentage is used as food by soil organisms, so a lot is lost during decomposition. If we assume that 80% is lost as soil organisms go about their lives and 20% eventually ends up as relatively stable soil organic matter, some 100,000 pounds (50 tons!) of organic materials (dry weight) would be needed. Because smaller amounts of residue are usually added to soils, large soil organic matter increases usually take time. In addition, soils with different amounts of clay and with different degrees of drainage have different abilities to protect organic materials from decomposition (see Table 3.4).

Table 3.4
Estimated Levels of Soil Organic Matter after Many Years with Various Rates of Decomposition (Mineralization) and Residue Additions*

		Fine texture, poorly aerated ↔ Coarse texture, well aerated				
		Annual rate of organic matter decomposition				
Annual organic material additions**	Added to soil if 20% remains after one year	1%	2%	3%	4%	5%
-----pounds per acre per year-----		-----equilibrium % organic matter in soil-----				
2,500	500	2.5	1.3	0.8	0.6	0.5
5,000	1,000	5	2.5	1.7	1.3	1
7,500	1,500	7.5	3.8	2.5	1.9	1.5
10,000	2,000	10	5	3.3	2.5	2

*Assumes the upper 6 inches (15 centimeters) of soil weighs 2 million pounds.
**10,000 pounds per acre addition is equivalent to 11,200 kilograms per hectare.

free particles of organic matter, they tend to decompose relatively rapidly under normal (oxidized) conditions.

The reverse of what is depicted in Figure 3.7 occurs when management practices that deplete organic matter are used. First, free particles of organic matter are depleted, and then physically protected organic matter becomes available to decomposers as aggregates are broken down. What usually remains after many years of soil-depleting practices is organic matter that is tightly held by clay mineral particles and trapped inside very small (micro) aggregates.

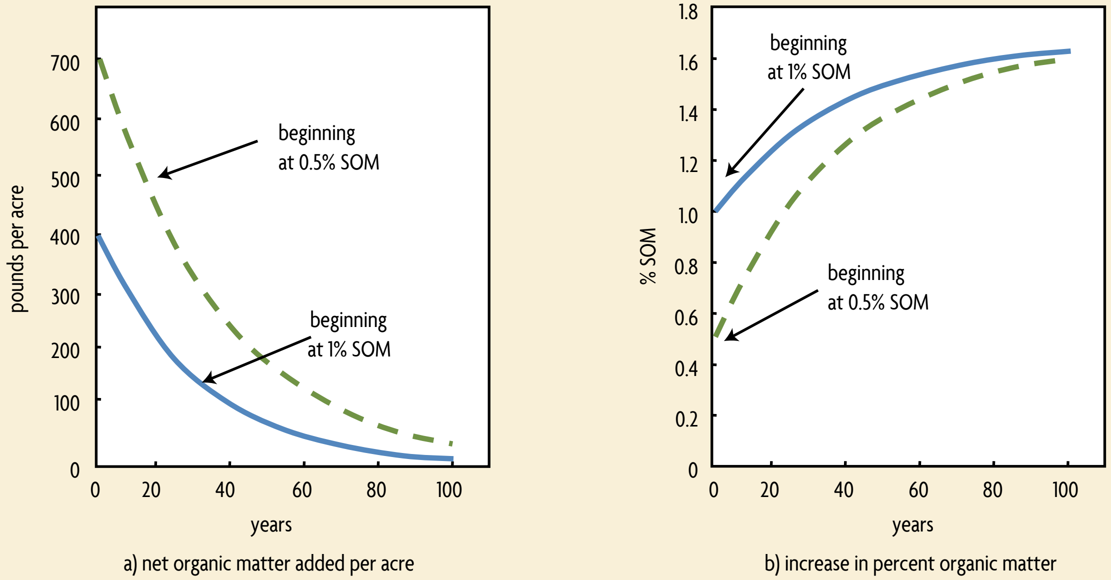
Equilibrium Levels of Organic Matter

Assuming that the same management pattern has occurred for many years, a fairly simple model can be used to estimate the percent of organic matter in a soil when it reaches an equilibrium of gains and losses. This model allows us to see interesting trends that reflect the real world. To use the model you need to assume reasonable values for rates of addition of organic material and for soil organic matter decomposition rates in the soil. Without going through the details (see the appendix to this chapter for sample calculations), the estimated percent of organic matter in soils for various combinations of addition and decomposition rates indicates some dramatic differences (Table 3.4). It takes about 5,000 pounds of organic residues added annually to a sandy loam soil (with an estimated decomposition rate of 3% per year) to result eventually in a soil with 1.7% organic matter. On the other hand, 7,500 pounds of residues added annually to a well-drained, coarse-textured soil (with a soil organic matter mineralization, or decomposition, rate of 5% per year) are estimated to result after many years in only 1.5% soil organic matter.

Normally when organic matter is accumulating in soil it will increase at the rate of tens to hundreds of pounds per acre per year, but keep in mind that the weight of organic material in 6 inches of soil that contains 1% organic matter is 20,000 pounds. Thus, the small annual changes, along with the great variation you can find in a single field, means that it usually takes years to detect changes in the total amount of organic matter in a soil.

In addition to the final amount of organic matter in a soil, the same simple equation used to calculate the information in Table 3.4 can be used to estimate organic matter changes as they occur over a period of years or decades. Let's take a more detailed look at the case where 5,000 pounds of residue is added per year with only 1,000 pounds remaining after one year. We assume that the residue remaining from the previous year behaves the same as the rest of the soil's organic matter—in this case, decomposing at a rate of 3% per year. As we mentioned previously, with these assumptions, after many years a soil will end up having 1.7% organic matter at equilibrium. If a soil starts at 1% organic matter content, it will have an annual net gain of around 350 pounds of organic matter per acre in the first decade, decreasing to very small net gains after decades of following the same practices (Figure 3.8a). Thus, even though 5,000 pounds per acre are added each year, the net yearly gain decreases as the soil organic matter content reaches a *steady state*. If the soil was very depleted and the additions started when it was only at 0.5% organic matter content, a lot of organic material can accumulate in the early stages as it is bound to clay mineral surfaces and inside very small- to medium-size aggregates that form—preserving organic matter in forms that are not accessible to organisms to use. In this case, it is estimated that the net annual gain in the first decade might be over 600 pounds per acre (Figure 3.8a).

The soil organic matter content rises more quickly for the very depleted soil (starting at 0.5% organic matter) than for the soil with 1% organic matter content (Figure 3.8b), because so much more organic matter can be stored in organo-mineral complexes and inside very small and medium-size aggregates. This might be a scenario where a very degraded soil on a grain crop farm for the first time receives manure or compost, or starts to incorporate a cover or perennial crop. Once all the possible sites that can physically or chemically protect organic matter have done so, organic matter accumulates more slowly, mainly as free particulate (active) material.



a) net organic matter added per acre

b) increase in percent organic matter

Figure 3.8. Net organic matter additions and changes in % organic matter content for soils. Estimated for soil starting at 0.5% or 1% organic matter, receiving a total of 5,000 pounds of residue per acre per year; 20% remains after one year, and soil organic matter decomposes at the rate of 3% a year.

INCREASING ORGANIC MATTER VERSUS MANAGING ORGANIC MATTER TURNOVER

Increasing soil organic matter on depleted soils is important, but so is continually supplying new organic matter even on soils with good levels. It's important to feed a diversity of soil organisms and provide replacement for older organic matter that is lost during the year. Organic matter decomposes in all soils, and we want it to do so. But that means we must continually manage the turnover. Practices to increase *and maintain* soil organic matter can be summarized as follows:

- Minimize soil disturbance to maintain soil structure with plentiful aggregation (reducing erosion, maintaining organic matter within aggregates);
- Keep the soil surface covered 1) with living plants if possible, planting cover crops when commercial crops are not growing, or 2) with a mulch consisting of crop residue (reducing erosion, adding organic matter);
- Use rotations with perennials and cover crops that increase biodiversity and add organic matter, including some crops with extensive root systems and plentiful aboveground residue after harvest;
- Add other organic materials from off the field when possible, such as composts, manures or other types of organic materials (uncontaminated with industrial or household chemicals).

APPENDIX

Calculations for Table 3.3 and Figure 3.7 Using a Simple Equilibrium Model

The amount of organic matter in soils is a result of the balance between the gains and losses of organic materials. Let's use the abbreviation SOM as shorthand for soil organic matter. Then the change in soil organic matter during one year (the SOM change) can be represented as follows:

SOM change = (gains) – (losses)
[equation 1]

If gains are greater than losses, organic matter accumulates and the SOM change is positive. When gains are less than losses, organic matter decreases and SOM change is negative. Remember that gains refer not to the amount of residues added to the soil each year but rather to the amount of residue added to the more resistant pool that remains at the end of the year. This is the fraction (F) of the fresh residues added that do not decompose during the year multiplied by the amount of fresh residues added (A), or gains = (F) x (A). For purposes of calculating the SOM percentage estimates in Table 3.3 we have assumed that 20% of annual residue additions remain at the end of the year in the form of slowly decomposing residue.

If you follow the same cropping and residue or manure addition pattern for a long time, a steady-state situation usually develops in which gains and losses are the same and SOM change = 0. Losses consist of the percentage of organic matter that's mineralized, or decomposed, in a given year (let's call that K) multiplied by the *amount* of organic matter (SOM) in the surface 6 inches of soil. Another way of writing that is losses = (K) x (SOM). The amount of organic matter that will remain in a soil under steady-state conditions can then be estimated as follows:

SOM change = 0 = (gains) – (K) x (SOM)
[equation 2]

Because in steady-state situations gains = losses, then gains = (K) x (SOM), or

SOM = (gains) / (K)
[equation 3]

A large increase in soil organic matter can occur when you supply very high rates of crop residues, manures and composts or grow cover crops on soils in which organic matter has a very low rate of decomposition (K). Under steady-state conditions, the effects of residue addition and the rate of mineralization can be calculated using equation 3 as follows.

If K = 3% and 2.5 tons of fresh residue are added annually, 20% of which remains as slowly degradable following one year, then the gains at the end of one year = (5,000 pounds per acre) x 0.2 = 1,000 pounds per acre.

Assuming that gains and losses are happening only in the surface 6 inches of soil, then the amount of SOM after many years when the soil is at equilibrium = (gains) / (K) = 1,000 pounds / 0.03 = 33,333 pounds of organic matter in an acre to 6 inches. The percent SOM = 100 (33,000 pounds of organic matter / 2,000,000 pounds of soil). The percent SOM = 1.7%.

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Chapter 4

THE LIVING SOIL

... long before [humans] existed the land was in fact regularly ploughed, and continues to be thus ploughed by earthworms.

—CHARLES DARWIN, 1881

Soils are alive and the organisms living in them, both large and small, play a critical role in maintaining a healthy soil system and healthy plants. A handful of soil contains billions of bacteria and fungi, plus other organisms, and soils are a major reservoir of life on Earth. Living organisms in the top 6 inches of an acre of soil with 3% organic matter will weigh about 1.5 tons, the equivalent weight of two Holstein milk cows.

When soil organisms go about their normal functions of getting energy for growth from organic molecules, they "respire," just as plant roots do, by using oxygen and releasing carbon dioxide to the atmosphere. (Of course, as we take our essential breaths of air, we do the same.) An entire field can be viewed as breathing as if it is one large organism, with oxygen diffusing into the soil and carbon dioxide diffusing out into the atmosphere. The soil is like a living being in another way, too; it may get "sick" in the sense that it has difficulty supporting healthy plants.

Although soil organisms are involved in many different types of activities with a variety of outcomes, one of the reasons for our interest in these organisms is their role in breaking down organic residues and incorporating them into the soil. Soil organisms influence every aspect of decomposition and nutrient availability, and they have profound effects on promoting good structure. As organic materials decompose, nutrients become available to plants, humus is produced, soil aggregates are formed, channels are created for water infiltration and better aeration, and those residues originally on the surface are brought deeper into the soil. And while we are interested in maintaining good amounts of organic matter in soil, we also want to maintain active populations of diverse organisms.

We can discuss soil organisms in several different ways. Each can be considered separately or all organisms that do the same types of things can be discussed as a group. We can also look at soil organisms according to their role in the decomposition of organic materials. For example, organisms that use residues as their source of food are called primary (1°), or first-level, consumers of organic materials (see Figure 4.1). Many of these break

Photo by Jerry DeWitt

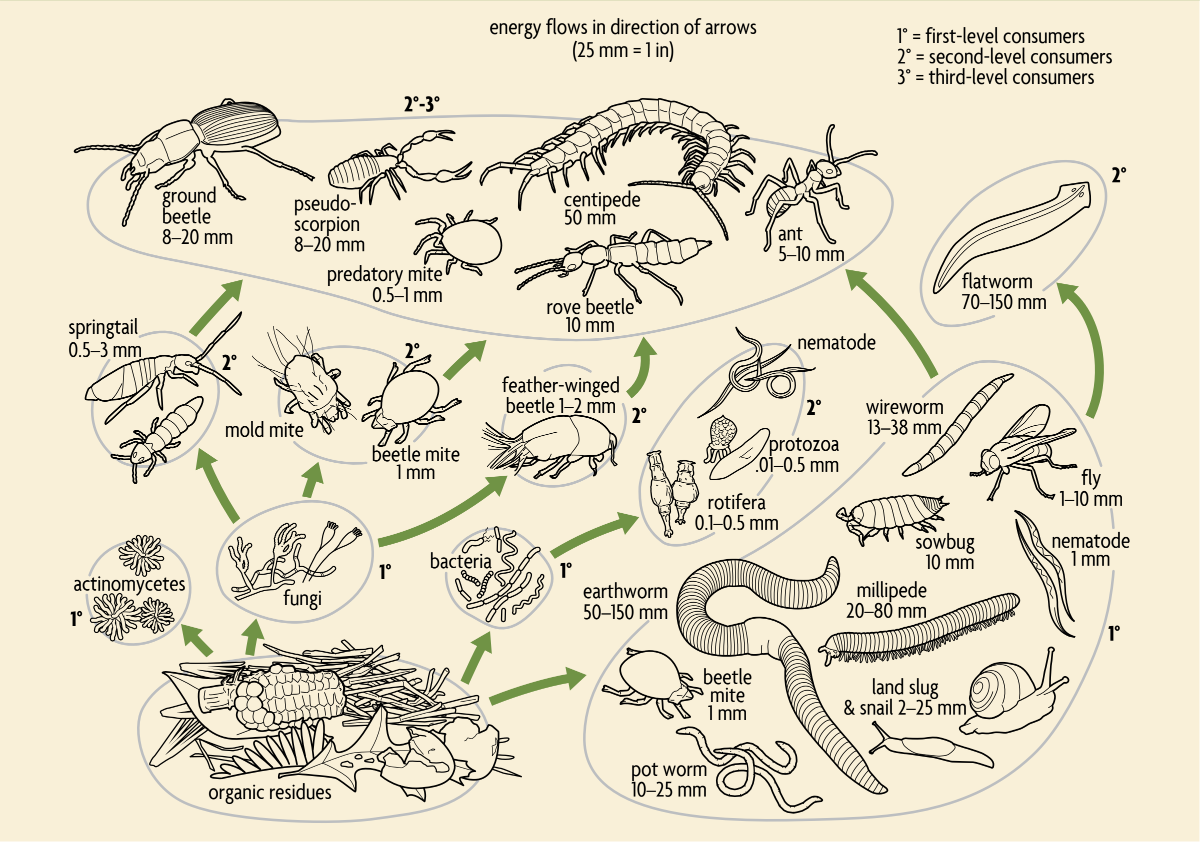

Figure 4.1. The soil food web. Modified from D.L. Dindal (1972). Illustration by Vic Kulihin.

down large pieces of residues into smaller fragments. Secondary (2°) consumers are organisms that feed on the primary consumers themselves or their waste products. Tertiary (3°) consumers then feed on the secondary consumers. Another way to treat organisms is by general size, such as very small, small, medium, large and very large. This is how we will discuss soil organisms in this chapter.

There is constant interaction among the organisms living in the soil. Some organisms help others, as when bacteria that live inside the earthworm's digestive system help decompose organic matter. Although there are many examples of such mutually beneficial, or *symbiotic*, relationships, an intense competition occurs among most of the diverse organisms in healthy soils. Organisms may directly compete with each other for the same food. Some organisms naturally feed on others: Nematodes may feed on fungi, bacteria or other nematodes, and some fungi trap and kill nematodes. There are also fungi and bacteria that parasitize nematodes and completely digest their content. The many types of soil organisms participate in a complex multi-path food system (Figure 4.1), usually called a food *web* (compared to a food *chain*, which involves only one direction).

Some soil organisms can harm plants either by causing disease or by being parasites. In other words, there are "good" as well as "bad" bacteria, fungi, nematodes and insects. One of the goals of agricultural production systems should be to create conditions that enhance the growth of beneficial organisms, which are the vast majority, while decreasing populations of those few that are potentially harmful.

SOIL MICROORGANISMS

Microorganisms are very small forms of life that can sometimes live as single cells, although many also form colonies of cells. A microscope is usually needed to see individual cells of these organisms. Many more microorganisms exist in topsoil, where food sources are more plentiful, than in subsoil. They are especially abundant in the area immediately next to plant roots (called the rhizosphere), where sloughed-off cells and chemicals released by living roots provide ready food sources. Rhizosphere soil may have 1,000 times or greater the number of organisms than the soil just a fraction of an inch further away from the root. These organisms are primary decomposers of organic matter, but they do other things, such as provide nitrogen through fixation to help growing plants, detoxify harmful chemicals (toxins), suppress disease organisms and produce products that might stimulate plant growth. Soil microorganisms have had another direct importance for humans: they are the source of most of the antibiotic medicines we use to fight diseases.

Bacteria

Bacteria live in almost any habitat. They are found inside the digestive systems of animals, in the ocean and freshwater, in air, and certainly in compost piles (even at temperatures over 130 degrees Fahrenheit) and in soils. Bacteria are an extremely diverse group of organisms; a gram of soil (about 0.035 ounce) may contain many thousand different species. Although some kinds of bacteria live in flooded soils without oxygen, most require well-aerated soils. In general, bacteria tend to do better in neutral or alkaline pH soils than in acid soils. When colonies of bacteria develop they frequently produce a sticky material that, together with remnant cell walls of dead bacteria, help to form soil aggregates. In addition to being among the first organisms to begin decomposing residues in the soil, bacteria benefit plants by increasing nutrient availability. For example, many bacteria dissolve phosphorus, making it more available for plants to use.

Bacteria and nitrogen. Bacteria are very instrumental in providing nitrogen to plants, which they need in large amounts but is often deficient in agricultural soils. They do it in multiple ways. First, bacteria themselves tend to be rich in nitrogen (that is, they have a low carbon to nitrogen level) and when decomposed (or eaten) by other organisms, like protozoa, nitrogen is released to the soil in forms that plants can use.

You may also wonder how soils can be deficient in nitrogen when we are surrounded by it: 78% of the air we breathe is composed of nitrogen gas. And each percent soil organic matter in the topsoil contains about 1,000 pounds of nitrogen per acre. Yet plants as well as animals face a dilemma similar to that of the Ancient Mariner, who was adrift at sea without fresh water: "Water, water, everywhere nor any drop to drink." Unfortunately, neither animals nor plants can use nitrogen gas (N_2) for their nutrition. Nor can plants use the nitrogen tied up as part of an organic molecule. It needs to be converted to the *in*organic forms of ammonium and nitrate to become available for plants to use. This process involves bacteria and is called *nitrogen mineralization*.

Another important conversion process is known as *nitrogen fixation*. Some types of free-living bacteria are able to take nitrogen gas from the atmosphere and convert it into a form that plants can use to make amino acids and proteins. Azospirillum and Azotobacter are two groups of free-living, nitrogen-fixing bacteria. Along with supplying N, Azospirillum attaches to the root surfaces and promotes plant growth by producing a number of substances that help plants better tolerate various kinds of stress. While these types of bacteria provide only a modest amount of nitrogen to the soil, this N addition is quite important to natural systems where nutrient cycling is efficient. Some innovative companies are now trying to enhance nitrogen fixation by free-living bacteria through soil additives and seed coatings.

Another type of nitrogen-fixing bacteria forms mutually beneficial associations with plants. One such symbiotic relationship that is very important to agriculture involves the nitrogen-fixing rhizobia group of bacteria that live inside nodules formed on the roots of legumes. People eat some legumes or their products, such as peas, dry beans, lentils and soybeans in the form of tofu or edamame. Soybeans, alfalfa and clover are used for animal feed. The symbiotic bacteria provide nitrogen in a form that leguminous plants can use, while the legume provides the bacteria with sugars for energy. It is common to apply rhizobia inoculant to seeds if the legume (or one with which it shares a strain of nitrogen-fixing bacteria) has not been grown in the field recently. Nodulation is enhanced in cool soils with lots of biological activity and plentiful growth-promoting bacteria. Clovers and hairy vetch are legumes grown as cover crops that enrich the soil with organic matter as well as nitrogen for the following crop. In an alfalfa field, the bacteria in the plant root nodules may fix hundreds of pounds of nitrogen per acre each year. With peas, the amount of nitrogen fixed is much lower, around 30–50 pounds per acre.

The actinomycetes, another group of bacteria, break large lignin molecules into smaller sizes. Lignin is a large and complex molecule found in plant tissue, especially stems, that is difficult for most organisms to break down. Lignin also frequently protects other molecules

RELATIVE AMOUNTS OF BACTERIA AND FUNGI

All soils contain both bacteria and fungi, but they may have different amounts depending on soil conditions. Relative to their carbon contents, bacteria are higher in nitrogen than fungi. Bacteria also have short life cycles, and when they die or are consumed by another organism such as a nematode, plant-available nitrogen is released. But in the off season when no commercial crop is present in the field (fall through early spring) this nitrogen may be lost. Fungi live longer and less nitrogen is released when they are decomposed.

The ways in which you manage your soil—the amount of disturbance, the degree of acidity permitted and the types of residues added—will determine the relative abundance of these two major groups of soil organisms. Soils that are disturbed regularly by intensive tillage tend to have more bacteria than fungi. So do flooded rice soils, because fungi can't live without oxygen, while many species of bacteria can. Tillage destroys the network of mycorrhizal hyphae, and in the absence of living plants (fall, winter, spring), viable spore numbers decrease, causing lower inoculation of spring-planted crops. Soils that are not tilled tend to have more of their fresh organic matter at the surface and to have higher levels of fungi than bacteria. Because fungi are less sensitive to acidity, higher levels of fungi than bacteria may occur in very acid soils.

Despite many claims, relatively little is known about the agricultural significance of bacteria versus fungal-dominated soil microbial communities. Therefore, it is difficult to state whether higher versus lower ratios are better or worse, just that soils that tend to have more bacteria relative to fungi are more characteristic of soils near or above neutral pH that are intensively tilled, enhancing rapid organic matter decomposition and temporary nutrient availability.

like cellulose from decomposition. Actinomycetes have some characteristics similar to those of fungi, but they are sometimes grouped by themselves and given equal billing with bacteria and fungi. That earthy scent you smell from healthy soils, especially after a rain, is produced by actinomycetes.

Another important soil organism is cyanobacteria, frequently called "blue-green algae" although they *are* bacteria. They are found near the soil surface, in field puddles and in flooded soils. They can fix atmospheric nitrogen *as well as* photosynthesize. Oxygen is released as a byproduct of photosynthesis and cyanobacteria are believed to be the organisms living in ancient seas that oxygenated the Earth's atmosphere, allowing plants and animals that need oxygen to evolve and survive. It was the oxygen pumped into the atmosphere by cyanobacteria that led to an incredibly wide proliferation of organisms, including all those you see around you on farms, in forests and prairies, in cities, and in lakes and oceans.

Soils contain a group of organisms that look like bacteria under the microscope but have very different biochemistry and are now classified in their own group (called a "domain" by biologists), the Archaea (pronounced ar-key-uh). These organisms can live under all types of conditions, including extreme temperatures and in very salty environments. They are also commonly found in soil, some playing a major role in the nitrogen cycle by carrying out nitrogen fixation or by converting ammonium to nitrate, producing nitrite (NO_2^-).

The tree of life is made up of three domains (or "superkingdoms"):

- Archaea
- Bacteria
- All other organisms (this includes all the rest of life, such as fungi, algae, plants, single-cell organisms such as amoeba, and animals)

Fungi

Fungi are another group of soil organisms. Many are small, some even single celled. Yeast, an example of a single-celled fungus, is used in baking and in the production of alcohol. Other fungi produce a number of antibiotics. Some form colonies that we can see, such as when you let a loaf of bread sit around too long only to find mold growing on it. We have seen or eaten mushrooms, the very visible fruiting structures of some fungi. Farmers know that there are fungi that cause many plant diseases, such as downy mildew, damping-off, various types of root rot and apple scab. Fungi also initiate the decomposition of fresh organic residues. They help get things going by softening organic debris and making it easier for other organisms to join in the decomposition process. Fungi are also the main decomposers of lignin and are less sensitive to acid soil conditions than bacteria. None are able to function without oxygen. The low amount of soil disturbance resulting from reduced tillage systems tends to promote organic residue accumulation at and near the surface, which in turn encourages fungal growth, as happens in many natural, undisturbed ecosystems.

Once classified as fungi because they form filaments and live on decaying organic materials, **oomycetes** have cell walls that are chemically different from fungi. This group includes water molds, one of which, *Phytophthora infestans* (causing late blight in potatoes and tomatoes), is the organism that decimated the Irish potato crop in the 1840s, causing nearly 1 million deaths and massive emigration. Another oomycete group causes the downy mildew plant diseases in a number of vegetables and in grapes.

Mycorrhizal fungi are of special interest, and it is hard to overemphasize their importance in relation to plants. Roots of most crop plants occupy only 1 percent or less of the topsoil (grasses may occupy a few percent), but many plants develop a beneficial relationship with fungi that increases the contact of roots with the soil. Fungi infect the roots and send out root-like structures called *hyphae* (see figures 4.2 and 4.3). The hyphae of these mycorrhizal fungi take up water and nutrients that can then feed the plant. The hyphae are very thin, about 1/60 the diameter of a plant root, and are able to exploit the water and nutrients in small spaces in the soil that might be inaccessible to roots. This is especially important for the phosphorus nutrition of plants growing in low-phosphorus soils. While the hyphae help the plant absorb water and nutrients, in return the fungi receive energy in the form of sugars, which the plant produces in its leaves and sends down to the roots. This symbiotic interdependence between fungi and roots is called a **mycorrhizal relationship**. Mycorrhizal associations also stimulate the free-living, nitrogen-fixing bacteria such as azospirillum and azotobacter, which in turn produce both nitrogen that plants can use and chemicals that stimulate plant growth. They also stabilize soil aggregates by producing sticky proteins.

Crop rotations select for more types of, and better performing, fungi than does mono cropping. Some studies indicate that cover crops, especially legumes, between main crops help maintain high levels of spores and promote good mycorrhizal development in the next crop. And if flooding or very wet soils prevent planting a cash crop, it is important to plant a cover crop if conditions permit so that there will be high levels of mycorrhizal colonization of the roots of next year's commercial crop. Roots that have lots of mycorrhizae are better able to resist fungal diseases, parasitic nematodes, drought, salinity and aluminum toxicity. All things considered it is a pretty good deal for both plant and fungus. But keep in mind that mycorrhizae do not associate with some crops, mainly those in the cabbage family, making it more important to follow these with cover crops that help build fungal spores for the next cash crop.

Algae

Algae, like crop plants, convert sunlight into complex molecules like sugars, which they can use for energy and to help build other molecules they need. Algae are found in abundance in the flooded soils of swamps and rice paddies, and they can be found on the surface of poorly drained soils and in wet depressions. Algae may also occur in relatively dry soils, and they form mutually

Figure 4.2. A soybean root heavily colonized with mycorrhizal fungi (*Rhiziphagus irregularis*). Photo by Yoshihiro Kobae.

Figure 4.3. A white fungal network called hyphae, not plant roots, is the principal structure for the uptake of many important nutrients by plants. Illustration by Michael Rothman, all rights reserved.

THE PLANT MICROBIOME

The human microbiome consists of the multitude of microorganisms living on our skin and inside us, especially in our gastrointestinal tract. It has become clear that these organisms that comprise roughly the same number of cells as the rest of our body play an important role in human health. Maintaining a diverse and healthy microbiome, especially among the bacteria in the gut, has multiple beneficial effects on our wellbeing.

Plants also have microbiomes, with organisms living on leaves and shoots, inside plant tissue, and on and immediately adjacent to root surfaces (the rhizosphere). As happened with animals, when plants evolved over the eons, they did so in tandem with microorganisms that depended on plants for their sustenance. In turn, many provide benefits to the plant: a truly symbiotic or mutualistic relationship. (The relationship of plants and mycorrhizae is thought to have begun hundreds of millions of years ago.) About half of the substances produced during photosynthesis are transported from the leaves to the roots, supporting root growth and maintenance. And about a third of what roots receive (approximately 15 percent of total production by the plant) is exuded (released) into the soil as a complex mixture of organic chemicals, which provides nutrition to the vast numbers of organisms in the rhizosphere. This large quantity of microbial food sources is the reason why there are such large quantities of organisms present in this zone immediately next to the root compared to the rest of the soil. As the numbers of bacteria and fungi increase, so do the populations of organisms that feed on microorganisms, such as springtails (collembola) and nematodes, thereby stimulating the reproduction of microbes. The type and amount of root exudates varies by plant species and variety, and shapes the composition of the microbiome. (By the way, mycorrhizae also have a microbiome living on their hyphae.) Clearly we want to grow plants in ways that favor a beneficial microbiome: more complex rotations, decreased compaction and soil disturbance, more use of cover crops, and so on.

beneficial relationships with other organisms. Lichens found on rocks are associations between fungi and algae.

Protozoa

Protozoa are single-celled animals that use a variety of means to move about in the soil. Like bacteria and many fungi, they can be seen only with the help of a microscope. They are mainly secondary consumers of organic materials, feeding on bacteria, fungi, other protozoa and organic molecules dissolved in the soil water. Protozoa—through their grazing on nitrogen-rich organisms (especially bacteria) and waste excretions—are believed to be responsible for mineralizing (releasing nutrients from organic molecules) much of the nitrogen in agricultural soils.

SMALL AND MEDIUM-SIZE SOIL ANIMALS

Nematodes

Nematodes are simple, multicellular soil animals that resemble tiny worms but are nonsegmented. They tend to live in the water films around soil aggregates. Some types of nematodes feed on plant roots and are well-known plant pests. Fungi such as *Pythium* and *Fusarium*, which may enter nematode-feeding wounds on the root, sometimes cause greater disease severity and more damage than the nematode itself. A number of plant-parasitic nematodes vector important and damaging plant viruses of various crops. However, there are also many beneficial nematodes that help in the breakdown of organic residues and feed on fungi, bacteria and protozoa as secondary or tertiary consumers. In fact, as with the protozoa, nematodes feeding on fungi and bacteria help convert nitrogen into forms for plants to use. As much as 50% or more of mineralized nitrogen comes from nematode feeding. A number of nematodes alone or with special bacteria parasitize and kill insects such as the larvae of the cabbage looper and the grubs of the Japanese beetle. Finally, several nematodes infect animals and humans, causing serious diseases such as river blindness and heartworm. Thankfully, these nematodes *do not* live in soil.

Earthworms

Earthworms are every bit as important as Charles Darwin believed they were more than a century ago. They are keepers and restorers of soil fertility. Different types of earthworms, including the night crawler, field (garden) worm and manure (red) worm used frequently in vermicomposting, have different feeding habits. Some feed on plant residues that remain on the soil surface, while other types tend to feed on organic matter that is already mixed with the soil.

The surface-feeding night crawlers fragment and mix fresh residues with soil mineral particles, bacteria and enzymes in their digestive system. The resulting material is given off as *worm casts*. They are produced by all earthworms and are generally higher in available plant nutrients, such as nitrogen, calcium, magnesium and phosphorus, than the surrounding soil and, therefore, contribute to the nutrient needs of plants. Night crawlers also bring food down into their burrows, thereby mixing organic matter deep into the soil. Earthworms feeding on debris that is already below the surface continue to decompose organic materials and mix them with the soil minerals.

A number of types of earthworms, including the surface-feeding night crawler, make burrows that allow rainfall to easily infiltrate the soil. Some worms burrow to 3 feet or more, unless the soil is saturated or very hard. Other types of worms that don't normally produce channels to the surface still help loosen the soil, creating channels and cracks below the surface that help aeration and root growth. The number of earthworms in the soil ranges from close to zero to over 1 million per acre. Just imagine, if you create the proper conditions for earthworms, you could have 800,000 small channels per acre that conduct water into your soil during downpours.

Earthworms do some unbelievable work. They move a lot of soil from below up to the surface, from about 1 to 100 tons per acre each year. One acre of soil 6 inches deep weighs about 2 million pounds, or 1,000 tons. So 1 to 100 tons is the equivalent of about .006 of an inch to about half an inch of soil. A healthy earthworm population may function as nature's plow and help replace the need for tillage by making channels and by bringing up subsoil and mixing it with organic residues. All for free!

Earthworms do best in well-aerated soils that are supplied with plentiful amounts of organic matter. A study in Georgia showed that soils with higher amounts of organic matter contained higher numbers of earthworms. Surface feeders, a type we would especially like to encourage, need residues left on the surface. They are harmed by plowing or disking, which disturbs their burrows and buries their food supplies. Worms are usually more plentiful under no-till practices than under conventional tillage systems. Although most pesticides have little effect on worms, some insecticides are very harmful to earthworms.

Diseases or insects that overwinter on leaves of crops can sometimes be partially controlled by high earthworm populations. The apple scab fungus, which is a major pest of apples in humid regions, and some leaf miner insects can be partly controlled when worms eat the leaves and incorporate the residues deeper into the soil.

Although the night crawler is certainly beneficial in farm fields, this invasive species from Europe has caused problems in some northern American forests.

As fishermen have discarded unused worms near forest lakes, night crawlers have become adapted to the forests. They have in some cases reduced the forest litter layer almost completely, accelerating nutrient cycling and changing species composition of the understory vegetation. So some forest managers view this organism, considered so positively by farmers, as a pest! There are also many other non-native earthworms that have been introduced from Europe and Asia. These introduced worms tend to predominate in areas of the northern United States that were covered by glaciers during the last ice age: New England, New York, a good part of the upper Midwest, and the very northern parts of Washington, Idaho and Montana. Species of a relatively recent invasive worm, "jumper worms," introduced from Japan and Korea, are becoming a problem in some locations, especially in gardens, forests and orchards, frequently displacing native earthworms as well as the introduced night crawlers. Jumper worms live in the upper layer of soil and convert both the soil and the surface residues to the consistency of ground coffee. In forest settings, their elimination of the mulch layer severely limits tree regeneration. They are commonly found in nursery stock, leaves and compost.

There is a group of organisms that are not considered earthworms, although they behave similarly and have similar effects on soils. Pot worms or white worms (the scientific name is Enchytraeidae) look like small white earthworms. They can be found in huge numbers in compost and in soil, and they help decompose organic matter, mix it with soil minerals, and leave behind fecal pellets, helping aggregations and making the soil more porous.

Insects and Other Small- to Medium-Size Soil Animals

Insects are another group of animals that inhabit soils. Common types of soil insects include termites, springtails, ants, fly larvae and beetles. Many insects are secondary and tertiary consumers. Springtails feed on fungi and animal remains, and in turn are food for predacious mites. Many beetles, in particular, eat other types of soil animals such as caterpillars, ants, aphids and slugs. Some surface-dwelling beetles feed on weed seeds in the soil, and the dung beetle famously dines on fresh manure, with some species laying eggs in balls they make from manure and then bury. Termites, well-known feeders of woody material, also consume decomposed organic residues in the soil.

Other medium-size soil animals include millipedes, centipedes, the larger species of mites, slugs, snails and spiders. Millipedes are primary consumers of plant residues, whereas centipedes tend to feed on other organisms. Mites may feed on food sources like fungi, other mites and insect eggs, although some feed directly on residues. Spiders feed mainly on insects and keep insect pests from developing into large populations.

LARGE SOIL ANIMALS

Very large soil animals, such as moles, rabbits, woodchucks, snakes, prairie dogs and badgers, burrow in the soil and spend at least some of their lives below ground. Moles are secondary consumers; their diet consists mainly of earthworms. Most of the other very large soil animals exist on vegetation. In many cases, their presence is considered a nuisance for agricultural production or lawns and gardens. Nevertheless, their burrows may help conduct water away from the surface during downpours and thus decrease erosion. In the southern United States, the burrowing action of crawfish, abundant in many poorly drained soils, can have a large effect on soil structure and can encourage water infiltration. (In Texas and Louisiana, some rice fields are "rotated" with crawfish production.)

PLANT ROOTS

Until now we discussed soil organisms in the animal kingdom, but soil life also includes plants. Healthy plant roots are essential for good crop yields. This is why plants evolved to expend so much energy on growing a sizable root system. During early to mid-season, corn plants send about 20 percent of the sugars produced during photosynthesis to the roots. These sugars are for root growth, and they provide material to excrete that nourishes mycorrhizal fungi and the wide variety of organisms in the rhizosphere. Roots are clearly influenced by the soil in which they live, and their extent and health are good indicators of soil health. Over eons, roots and their associated microorganisms (the root microbiome) have played an important role in capturing and storing nutrients such as calcium, magnesium and phosphorus from weathering of minerals in rocks and grains, and then making them available for plant growth. Plant roots will not grow well if the soil is compact, is low in nutrients or water, includes high populations of root pathogens, has high or low pH, or has other problems. Conversely, plant roots also influence the soil in which they grow. The physical pressure of roots growing through soil helps form aggregates by bringing particles closer together. Small roots also help bind particles together. In addition, many organic compounds are given off, or exuded, by plant roots and provide nourishment for soil organisms living on or near the roots. The zone surrounding roots is one of especially great numbers and activity of organisms that live off root exudates and sloughed-off cells. This increased activity by microorganisms, plus the slight disruption caused as roots grow through the soil, enhances the use of active ("dead") organic matter by organisms, which increases nutrient availability to the plant. A sticky layer surrounding roots, called the *mucigel*, provides close contact between microorganisms, soil minerals and the plant (Figure 4.4). Root hairs, those small protrusions that grow from the outermost root layer (the epidermis), enable better access to water and nutrients by providing more contact with soil, and help form aggregates. Plant roots also contribute to organic matter accumulation. They are usually well distributed in the soil and may be slower to decompose than surface residues, even if incorporated by plowing or harrowing.

For plants with extensive root systems, such as grasses, the amount of living tissue below ground may actually be greater than the amount of leaves and stems we see above ground.

> *The soil population must be considered from the point of view of a biological complex; it is not sufficient to separate it into different constituent groups.*
>
> —S.A. WAKSMAN, 1923

BIOLOGICAL DIVERSITY, ABUNDANCE, ACTIVITY AND BALANCE

A diverse biological community in soils is essential to maintaining a healthy environment for plant roots. There may be over 100,000 different types of organisms living in soils. Most are providing numerous functions that assist plants, such as making nutrients more available, producing growth-stimulating chemicals and helping form soil aggregates. In a teaspoon of agricultural soils it is estimated that there are from 100 million to 1 billion bacteria, several yards of fungi and several thousand protozoa. It may hold 10–20 bacterial-feeding nematodes and a few fungal-feeding and plant parasitic nematodes. Arthropods can number up to 100 per square foot, and earthworms from 5 to 30 per square foot.

Soil organisms are not evenly distributed through the soil, and even when present, organisms may be in a resting state. On the other hand, there are a number of zones of high amounts of active organisms in soil that are taking in food sources, interacting with other organisms, growing and reproducing. The zone immediately surrounding roots contains a very large population of diverse organisms (the root microbiome), stimulated by the continuous leakage (exuding) of energy sources

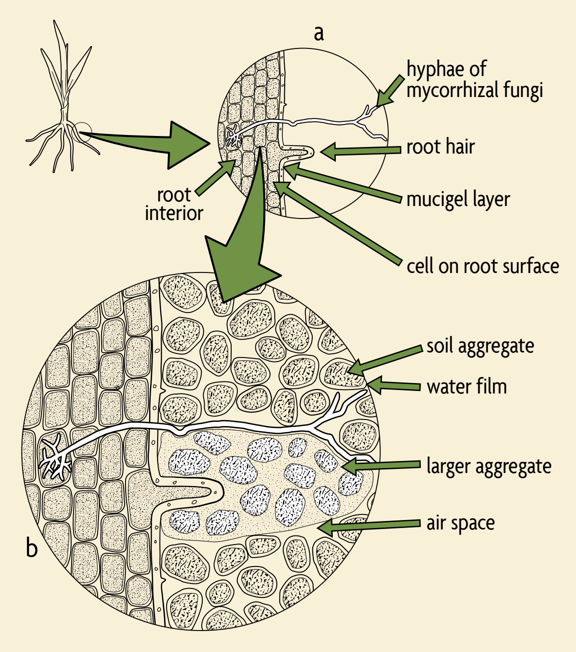

Figure 4.4. Close-up view of a plant root: (a) The mucigel layer is shown containing some bacteria and clay particles on the outside of the root. Also shown is a mycorrhizal fungus sending out its rootlike hyphae into the soil. (b) Soil aggregates are surrounded by thin films of water. Plant roots take water and nutrients from these films. Also shown is a larger aggregate made up of smaller aggregates pressed together and held in place by the root and hyphae. Illustration by Vic Kulihin.

from the roots as well as sloughed off root cells. Other locations of high activity of organisms are around particles of decaying organic matter, on or near aggregate surfaces, and inside earthworm channels and old root channels.

Of all the organisms in soils, only a small number of bacteria, fungi, insects and nematodes might harm plants in any given year. Their negative impact is reduced in a more diverse soil biome. Diverse populations of soil organisms maintain a system of checks and balances that can keep disease organisms or parasites from becoming major plant problems. Some fungi kill nematodes, and others kill insects. Still others produce antibiotics that kill bacteria. Protozoa feed on bacteria and may attack fungi. Some bacteria kill harmful insects. Many protozoa, springtails and mites feed on disease-causing fungi and bacteria.

Beneficial organisms, such as the fungus *Trichoderma* and the bacteria *Pseudomonas fluorescens*, colonize plant roots and protect them from attack by harmful organisms. Some of these organisms or their byproducts, such as the insect-attacking chemical produced by *Bacillus thuringiensis* (BT), are now sold commercially as biological control agents. (Plants have also been genetically engineered to produce the toxin that BT produces in order to control crop-eating insects.) The effects of bacteria and fungi that suppress plant disease organisms are thought to arise from competition for nutrients, production of antagonistic substances, and/or direct parasitism. In addition, a number of beneficial soil organisms induce the immune systems of plants to defend the plants (*systemic acquired resistance*; see discussion in Chapter 8). Also, roots of agronomic crops usually have their own characteristic microbial communities with numerous interactions.

Soil management can have dramatic effects on soil biological composition (see Figure 4.5 for management effects on organisms). For example, the less a soil is disturbed by tillage, the greater the importance of fungi relative to bacteria. Cropping practices that encourage abundance and diversity of soil organisms encourage a healthy soil. Crop rotations of plants from different families are recommended to keep microbial diversity at its maximum and to break up any potential damaging pest cycles such as the soybean cyst nematode. Crop rotations that include perennial crops, usually grass and legume forages, can also reduce annual weeds. Additional practices that promote the diversity and activity of soil organisms include low amounts of soil disturbance, use of cover crops, maintaining pH close to neutral and routine use of organic sources of slow-release fertility.

It is believed that more is unknown about soil life than what is known. New methodologies like microbial

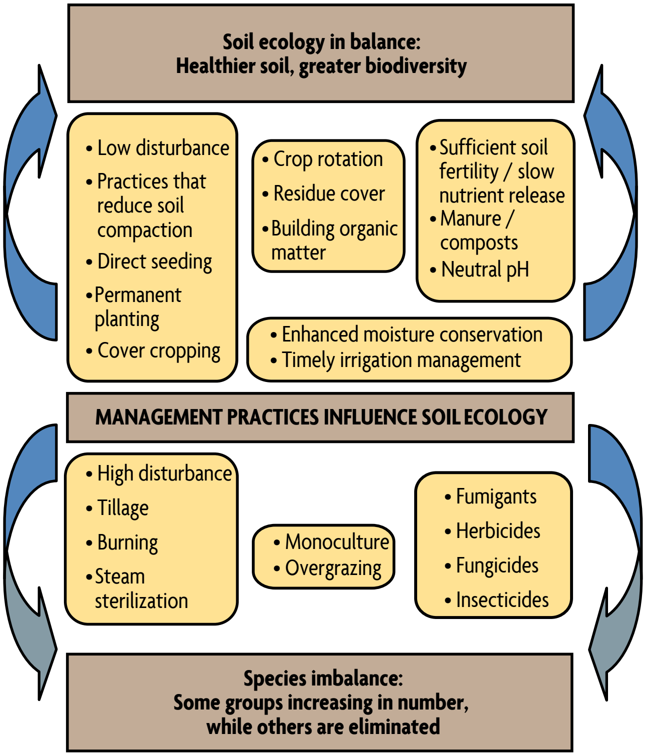

Figure 4.5. Management practices that influence soil life. Modified from Kennedy, Stubbs and Schiller (2004).

community analysis use DNA sequencing and advanced computational methods to help us understand the makeup of soil life. The next step is to use this technology to enhance the plant-soil microbiome and increase our capacity to grow more food, more sustainably.

SUMMARY

Soils are alive with a fantastic number of many types of organisms, most of which help grow healthy plants and protect them from pests. The food for all the soil's organisms originates with crop residues and organic materials added from off the field. These provide the fuel that powers the underground life that has such a positive effect on the soil's chemical and physical properties, as well as, of course, maintaining a system of equilibrium that helps regulate the populations of organisms. Soil organisms are associated with each other in a balance in which each type of organism performs specific roles and interacts with other organisms in complex ways. When there is an abundance of food and minimal soil disturbance, the complex food web that exists helps to maintain self-regulation of organisms, as bacteria and protozoa eat bacteria and some fungi, nematodes eat bacteria and fungi, fungi eat nematodes, and so on up the food web. We should be using management practices that promote a thriving and diverse population of soil organisms. New scientific research may offer additional opportunities to enhance the plant microbiome.

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PHYSICAL PROPERTIES AND NUTRIENT CYCLES AND FLOWS

PART 2

Photo by Dennis Nolan

Chapter 5

SOIL PARTICLES, WATER AND AIR

Moisture, warmth, and aeration; soil texture; soil fitness; soil organisms; its tillage, drainage, and irrigation; all these are quite as important factors in the makeup and maintenance of the fertility of the soil as are manures, fertilizers, and soil amendments.

—J.L. HILLS, C.H. JONES AND C. CUTLER, 1908

The physical condition of a soil has a lot to do with its ability to produce crops, mostly because it anchors their roots. A very fundamental aspect of soil is its ability to hold water between particles and act like a sponge in the landscape. This phenomenon, *capillarity* (or capillary action), helps store precipitation, thereby making it available to plants and other organisms or transmitting it slowly into groundwater or streams. Also, water in soil allows for the very slow but steady dissolving of soil minerals, which are absorbed by plants and cycled back onto the soil as organic matter. Over the course of many years these small amounts of minerals build up as a pool of stored organic nutrients available for agricultural production.

A degraded soil usually has reduced water infiltration and percolation (drainage into the deeper soil), aeration and root growth. These conditions lessen the ability of the soil to supply nutrients, render harmless many hazardous compounds (such as pesticides), and maintain a wide diversity of soil organisms. Small changes in a soil's physical conditions can have a large impact on these essential processes. Creating a good physical environment, which is a critical part of building and maintaining healthy soils, requires attention and care.

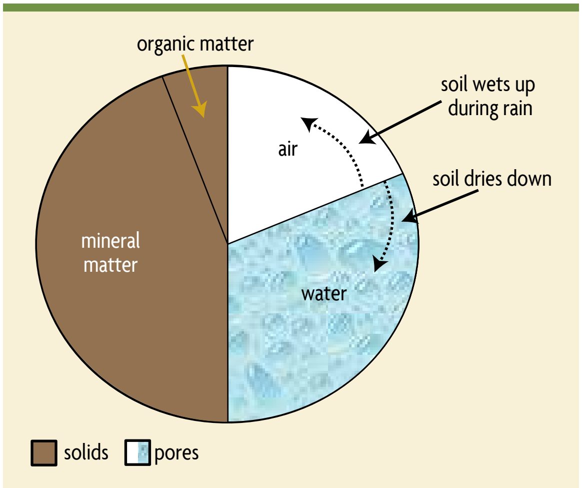

Figure 5.1. Distribution of solids and pores in soil.

Photo courtesy Ray Weil

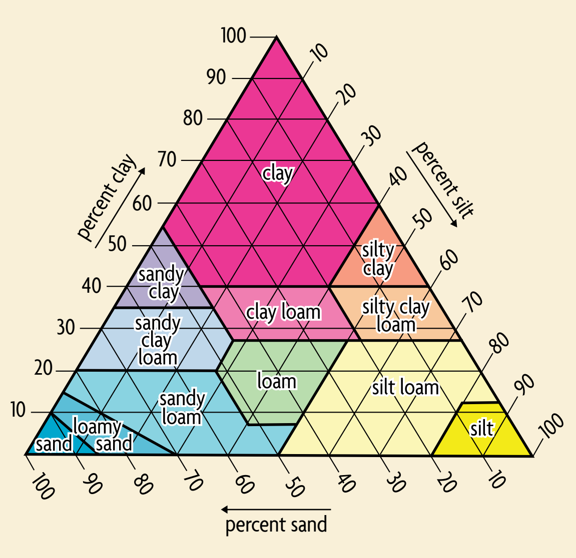

Figure 5.2. The percentages of sand, silt and clay in the soil textural classes.

Let's first consider the physical nature of a typical mineral soil. It usually contains about 50% solid particles on a volume basis (Figure 5.1), with the spaces in between, pores, accounting for the remaining volume. Most solid particles are minerals, and organic matter is a small, but a very important, component of the soil. The soil's mineral particles are a mixture of variously sized minerals that define its texture. A soil's textural class, such as a clay, clay loam, loam, sandy loam or sand, is perhaps its most fundamental inherent characteristic, as it affects many of the important physical, biological and chemical processes in a soil. Soil texture changes little over time, no matter how the soil is managed.

TEXTURE, A BASIC SOIL PROPERTY

The textural class of a soil (Figure 5.2) indicates the coarseness or fineness of a soil's particles. It is defined by the relative amounts of sand (.05–2 millimeters particle size), silt (.002–.05 millimeters) and clay (less than 0.002 millimeters). Particles that are larger than 2 millimeters are rock fragments (pebbles, cobbles, stones and boulders), which are not considered in the textural class because they are relatively inert.

Soil particles are the building blocks of the soil skeleton. But the spaces between the particles and between aggregates are just as important as the particles themselves, because that's where most physical and biological processes happen. The quantity of variously sized pores—large, medium, small and very small—govern the important processes of water and air movement. Also, soil organisms live and function in pores, which moreover is where plant roots grow. Most pores in clay are small (generally less than 0.002 millimeters), whereas most pores in sandy soil are large (but generally still smaller than 2 millimeters). The pore sizes are affected not only by the relative amounts of sand, silt and clay in a soil, but also by the amount of *aggregation*. On the one extreme, we see that beach sands have large particles (in relative terms, at least—they're visible) and no aggregation due to a lack of organic matter or clay to help bind the sand grains. A good loam or clay soil, on the other hand, has smaller particles, but they tend to be aggregated into crumbs that have larger pores between them and small pores within. Although soil texture doesn't change over time, the total amount of pore space and the relative amount of variously sized pores are strongly affected by management practices. Aggregation and structure may be destroyed or improved depending on, for example, how much tillage occurs, whether good rotations are followed, or if cover crops are used.

WATER AND AERATION

Soil pore spaces are generally filled with water, air and biota. Their relative amounts change as the soil wets and dries (figures 5.1, 5.3). On the wet extreme, when all pores are filled with water, the soil is water saturated and the exchange of gases between the soil and atmosphere is very slow. During these conditions, carbon dioxide produced by respiring roots and soil organisms can't escape from the soil and atmospheric

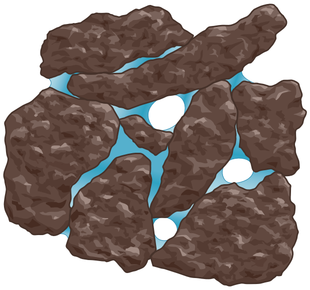

Figure 5.3. A moist sand with pores between grains that contain water and air. The larger pores have partially drained and allowed air entry, while the narrower ones are still filled with water. Illustration by Vic Kulihin.

oxygen can't enter, leading to undesirable anaerobic (no oxygen) conditions. On the other extreme, a soil with little water may have good gas exchange but may be unable to supply sufficient water to plants and soil organisms.

Water in soil is mostly affected by two opposing forces that basically perform a tug of war: Gravity pulls water down and makes it flow to deeper layers, but capillarity holds water in a soil pore because it is attracted to solid surfaces (adhesion) and has a strong affinity for other water molecules (cohesion). The latter are the same forces that keep water drops adhering to glass surfaces, and their effect is strongest in small pores (Figure 5.3) because of closer contact with solids. Soils are thus a lot like sponges in the way they hold and release water (Figure 5.4). When a sponge is fully saturated, it quickly loses water by gravity but will stop dripping after about 30 seconds. The largest pores drain rapidly because they are unable to retain water against the force of gravity. But when it stops dripping, the sponge still contains a lot of water in the smaller pores, which hold it more tightly. This water would, of course, come out if you squeezed the sponge. Its condition following free drainage is akin to a soil reaching its so-called *field capacity* water content, which in the field occurs after about two days of free drainage following saturation by a lot of rain or irrigation. If a soil contains mainly large pores, like a coarse sand, most pores empty out quickly and the soil loses a lot of water through quick gravitational drainage. Therefore the soil's field capacity water content is low. This drainage is good because the pores are now open for air exchange. On the other hand, little water remains for plants to use, resulting in more frequent periods of drought stress. Therefore, coarse sandy soils have very small amounts of water available to plants before they reach their wilting point (Figure 5.4a). Also, the rapidly draining sands more readily lose dissolved chemicals in the percolating water (pesticides, nitrate, etc.), but this is much less of a problem with fine loams and clays. A dense, fine-textured soil, such as a compacted clay loam, has mainly small pores that tightly retain water and don't release it. It therefore has a high field capacity water content, and the more common anaerobic conditions resulting from extended saturated conditions cause other problems, like gaseous nitrogen losses through denitrification, as we will discuss in Chapter 19.

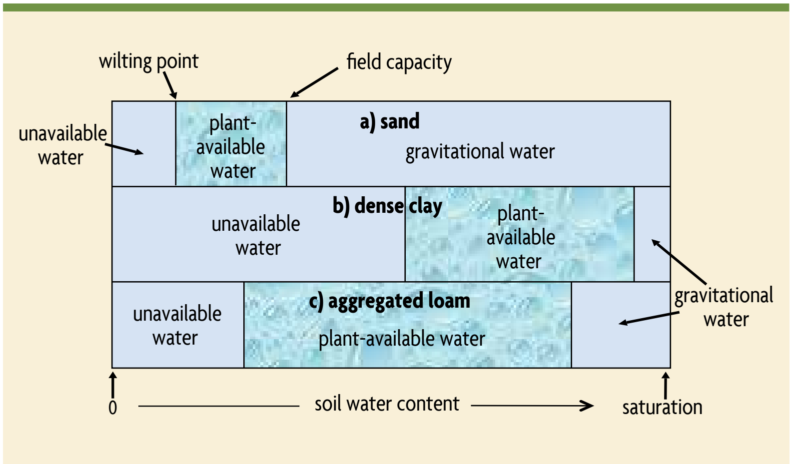

Figure 5.4. Water storage for three soils.

The ideal soil is somewhere between the two extremes, and its behavior is typical of that exhibited by a well-aggregated loam soil

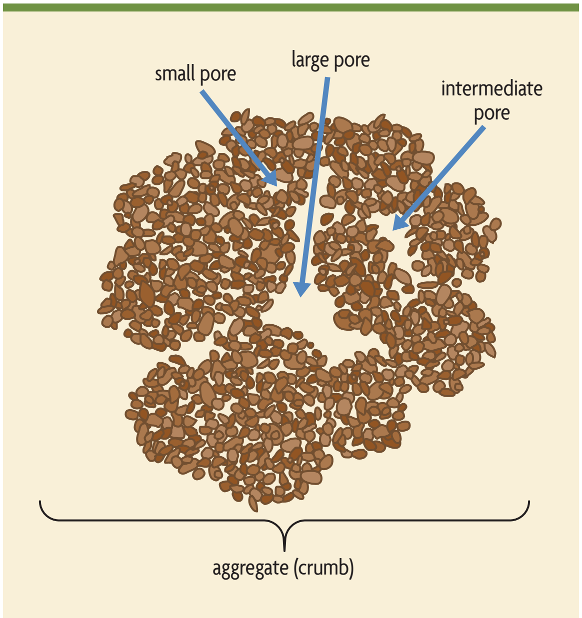

Figure 5.5. A well-aggregated soil has a range of pore sizes. This medium-size soil crumb is made up of many smaller ones. Very large pores occur between the medium-size aggregates.

(figures 5.4c, 5.5). Such a soil has a sufficient amount of large pore spaces between the aggregates to provide adequate drainage and aeration during wet periods, but also has enough small pores and waterholding capacity to provide water to plants and soil organisms between rainfall or irrigation events. Besides retaining and releasing water at near optimum quantities, such soils also allow for good water infiltration, thereby increasing plant water availability and reducing runoff and erosion. This ideal soil condition is therefore characterized by medium texture and crumb-like aggregates, which are common in good topsoil.

AVAILABLE WATER AND ROOTING

There is an additional dimension to plant-available water capacity of soils: The water and nutrients not only need to be stored and available in the soil pores, but roots also need to be able to access them. This may be a problem if the soil is compacted. Consider the soil from the compacted surface horizon in Figure 5.6 (left), which was penetrated only by a single corn root with few fine lateral rootlets. The soil volume holds sufficient water, which in principle would be available to the corn plant, but the roots are unable to penetrate most of the hard soil volume. The corn plant, therefore, could not obtain the moisture and nutrients it needed. Conversely, the corn roots on the right (Figure 5.6) are able to fully explore the soil volume with many roots, fine laterals,

Figure 5.6. Left: Corn root in a compacted soil cannot access water and nutrients from most of the soil volume. Right: Dense rooting allows for full exploration of soil water and nutrients.

Figure 5.7. Corn roots on the right were limited to the plow layer due to a severe compaction pan. Roots on the left penetrated into deeper soil following subsoiling and could access more water and nutrients.

root hairs and mycorrhizal fungi (not shown) allowing for better water and nutrient uptake.

Similarly, the depth of rooting can be limited by compaction. Figure 5.7 shows, on the right, corn roots from moldboard-plowed soil with a severe *plow pan* (a hard layer right below the depth of tillage). The roots cannot penetrate into the subsoil and are therefore limited to water and nutrients in the plow layer near the surface. The corn on the left is grown in soil that was subsoiled, and the roots are able to reach about twice the depth. Subsoiling opens up more soil for root growth and, therefore, more usable water and nutrients. Thus, plant water availability is a result of both the soil's water retention capacity (related to texture, aggregation and organic matter) and potential rooting volume, which is strongly influenced by compaction.

INFILTRATION VERSUS RUNOFF

An important function of soil is to absorb water at the land surface and either store it for use by plants or slowly release it to groundwater through gravitational flow (Figure 5.8). When rainfall hits the ground, most water will infiltrate the soil, but under certain conditions it may run off the surface or stand in ruts or depressions before infiltrating or evaporating. The maximum amount of rainwater that can enter a soil in a given time, called *infiltration capacity*, is influenced by the soil type (large pores result in higher capacity), structure and moisture content at the start of the rain.

If rain is very gentle, the infiltration capacity is generally not exceeded and all precipitation enters the soil. Even in an intense storm, water initially enters a soil readily as it is literally sucked into the dry ground. But as the soil wets up during a continuing intense storm, water entry into the soil is reduced and a portion of rainfall may begin to run downhill over the surface to a nearby stream or wetland. The ability of a soil to maintain high infiltration rates, even when saturated, is related to the sizes of its pores. Since sandy and gravelly soils have more large pores, they maintain better infiltration during a storm than fine loams and clays. But soil aggregation is also important in governing the number of pores and their sizes: When finer-textured soils have strong aggregates due to good management, they can also maintain high infiltration rates. But this

CROP WATER NEEDS

Different crops need different amounts of water, supplied by precipitation or by irrigation. For example, crops like alfalfa require a lot of water for maximum yields and the plant's long taproot helps it access water deep in the soil. On the other hand, vineyards and crops such as wheat need much smaller amounts of water. And many crops such as corn and potatoes are in between in their water needs. This may influence farmers' choice of crops to grow as some regions of the United States and other parts of the world are projected to become drier and warmer as the climate changes and water for irrigation becomes harder to obtain.

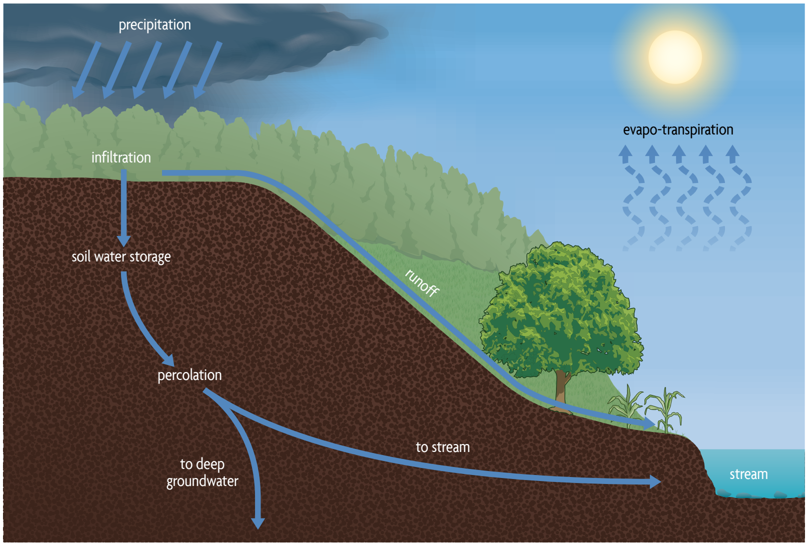

Figure 5.8. The infiltration capacity of the soil determines whether water infiltrates or runs off the surface. Illustration by Vic Kulihin.

is not the case when those aggregates fail and the soil becomes compacted.

Runoff is produced when rainfall exceeds a soil's infiltration capacity. Rainfall or snowmelt on frozen ground generally poses even greater runoff concerns, as pores are blocked with ice. Runoff happens more readily with poorly managed soils because they lack strong aggregates that hold together against the force of raindrops and moving water and, therefore, have few large pores open to the surface to quickly conduct water downward. Such runoff can initiate erosion, with losses of nutrients and agrochemicals as well as sediment.

SOIL WATER AND AGGREGATION

Processes like erosion, soil settling and compaction are affected by soil moisture conditions, and in turn affect soil hardness and the stability of aggregates. When soil is saturated and all pores are filled with water, the soil is very soft. (Fungal hyphae and small roots also serve to form and stabilize aggregates deeper in the soil.) Under these saturated conditions, the weaker aggregates may easily fall apart from the impact of raindrops and allow the scouring force of water moving over the surface to carry soil particles away (Figure 5.9). Supersaturated soil has no internal strength, and the positive water pressure in fact pushes particles apart (Figure 5.10, left). This makes soil very susceptible to erosion by water flowing over the surface or allows it to be pulled down by gravity as land (mud) slides.

As soil dries and becomes moist instead of wet, the pore water remaining in contact with solid surfaces becomes curved and pulls particles together, which makes the soil stronger and harder (Figure 5.10, middle). But when soils low in organic matter and aggregation, especially sands, are *very* dry, the bonding between particles decreases greatly because there is no pore water left to hold the particles together. The soil then becomes loose and the shear force of wind may cause particles to become airborne and cause wind erosion (Figure 5.10, right).

Strong aggregation is especially important during

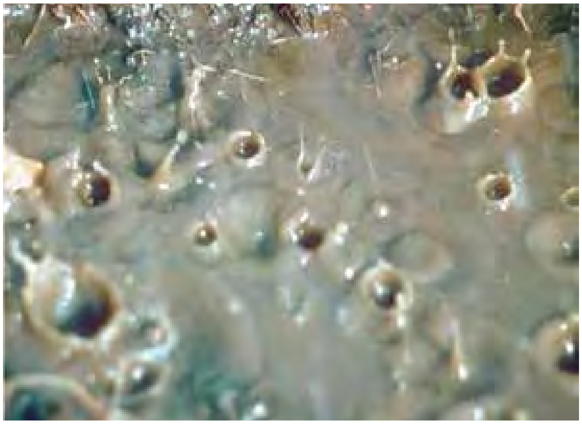

Figure 5.9. Saturated soil is soft, easily dispersed by raindrop impact and readily eroded. Photo by USDA-NRCS.

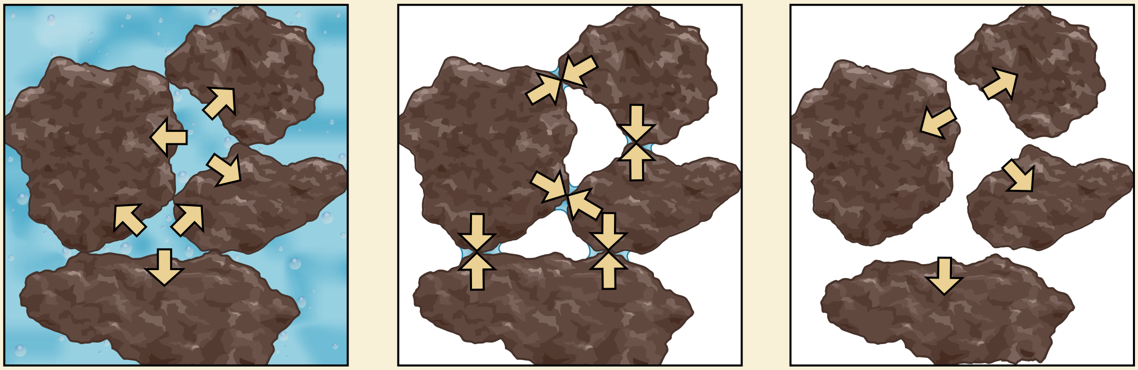

Figure 5.10. Pore water pushes soil particles apart in supersaturated soils (left). Moist soils are firm or hard because curved water-surface contacts of the pore water pull particles together (middle). Particles become loose in dry soil due to a lack of cohesion from pore water (right). Illustration by Vic Kulihin.

these moisture extremes, as it provides another source of cohesion that keeps the soil together. Good aggregation, or *structure*, helps to ensure a high-quality soil and prevents dispersion (Figure 5.11). A well-aggregated soil also results in good *soil tilth*, implying that it forms a good seedbed after soil preparation. Aggregation in the surface soil is enhanced by mulching or by leaving residue on the surface, and also by limiting or eliminating tillage. A continuous supply of organic materials, roots of living plants and mycorrhizal fungi hyphae are also needed to maintain good soil aggregation.

Figure 5.11. Well-aggregated soil from an organically managed field with a rye cover crop.

Surface residues and cover crops protect the soil from wind and raindrops and moderate the temperature and moisture extremes at the soil surface. Conversely, an unprotected soil may experience very high temperatures at the surface and become extremely dry. Worms and insects will then move deeper into the bare soil, which results in a surface zone that contains few active organisms. Many bacteria and fungi that live in thin films of water may die or become inactive, slowing the natural process of organic matter cycling. Large and small organisms promote aggregation in a soil that is protected by a surface layer of crop residue cover, mulch or sod and has continuous supplies of organic matter to maintain a healthy food chain. An absence of both erosion and compaction processes also helps maintain good surface aggregation.

The soil's chemistry also plays a role in aggregate formation and stability, especially in dry climates. Soils that have high sodium content (see chapters 6 and 20) pose particular challenges.

WHAT COMES FROM THE SKY: THE LIFEBLOOD OF ECOSYSTEMS

We need to take a short diversion from our focus on soils and briefly discuss climate. Various characteristics of precipitation affect the potential for crop production and the losses of water, sediment and contaminants to the environment. These include the annual amount of precipitation (for example, an arid versus humid climate); the seasonal distribution and relation to the growing season (wet seasons and dry seasons; can rainfall supply the crops or is irrigation routinely needed?); and the intensity, duration and frequency of rain (regular gentle showers are better than infrequent intense storms that may cause runoff and erosion).

Precipitation patterns are hardly ever ideal, and most agricultural systems have to deal with shortages of water at some time during the growing season, which remains the most significant yield-limiting factor worldwide. Water excess can also be a big problem, especially in humid regions or monsoonal tropics. In that case the main problem is not the excess water itself but the lack of air exchange and oxygen. Many management practices focus on limiting the effects of these climatic deficiencies. Subsurface drainage and raised beds remove excess water and facilitate aeration; irrigation overcomes inadequate rainfall; aquatic crops like rice allow for grain production in poorly drained soil; and so forth. (See Chapter 17 for a discussion of irrigation and drainage.)

So, climate affects how soils function and the processes occurring in soils. What is perhaps less understood is that good soil management and healthy

CLIMATE RISK AND RESILIENCE

The concept of risk integrates the cost of an adverse event with the chance of it occurring. With increasing frequency of weather extremes, the **risk** of costly or catastrophic events affecting farms and communities goes up. Their vulnerability is characterized by three aspects:

- **Exposure:** weather-related challenges you are likely to face
- **Sensitivity:** how and to what degree those events threaten your operation
- **Adaptive capacity:** how well you can minimize weather-related damage and take advantage of new opportunities

Generally, exposure to extreme weather events is a given, although farmers can help reduce overall greenhouse gas emissions through better cropping systems and nutrient management. Sensitivity to adverse weather events can be addressed through many of the practices we discuss in this book, as well as through other strategies, such as building soil health and thereby enhancing crop vigor while reducing runoff and crop drought stress; diversifying crop and livestock systems to spread risk from an extreme event; incorporating climate risk management into farm planning; building skills and experience with farm staff; installing physical infrastructure like irrigation or drainage; building social networks that allow you to respond better to adverse events; and managing finances and insurance to absorb setbacks.

By building an overall resilient farm operation you reduce potential damages and allow for faster recovery from weather-related disruptions. Still, after-the-fact adaptations still need to be anticipated, like growing an alternative crop when your initial crop was lost and using a weather-adaptive nitrogen management tool.

Adapted from Lengnick (2015)

soils are important to reducing susceptibility to climatic vagaries and making soils and crops more resilient to weather extremes. The Great Plains area of the United States learned this during the Dust Bowl era of the 1930s, when a decade of drought and unsustainable soil management practices resulted in excessive wind and water erosion, crop failures, the collapse of the agricultural industry, and massive human migrations out of the region. That devastating experience gave birth to the soil conservation movement, which has achieved much; but most soils, even in the United States, are still in need of protection from erosion, which requires good soil management practices.

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Chapter 6

SOIL DEGRADATION: EROSION, COMPACTION AND CONTAMINATION

Hard ground makes too great resistance, as air makes too little resistance, to the surfaces of roots.

—JETHRO TULL, 1733

Under natural conditions, soils are generally stable and effectively store water, nutrients and carbon, which are cycled efficiently with plants, animals and the atmosphere. With the onset of agricultural development—as early as 10,000 years ago in western Asia and continuing today in countries such as Brazil—this balance was disrupted and soils became degraded. On sloping lands tillage generated erosion and the topsoil was washed or blown away. In many irrigated areas salts would build up and make the land unsuitable for crops. Further stress was put onto soils with increasing mechanization, heavier equipment, more intensive tillage, the export of grains and contamination from industrial products.

Soil organic matter levels are directly impacted by tilling the soil and subsequent water runoff, and by erosion. As soils are disturbed and aggregates are broken down, more soil organic matter is lost by way of making particles of organic matter more available to soil organisms. This loss of organic matter then makes the soil more susceptible to erosion. Thus a downward spiral of soil degradation commonly occurs, with the end result being lower crop yields (Figure 6.1).

Now, with increasing awareness and understanding of the causes and consequences of soil degradation, there is a need to adopt practices that reverse these trends.

EROSION

Soil loss during agricultural production is mainly caused by water, wind and tillage. Additionally, landslides (gravitational erosion) may occur on very steep slopes. While water erosion and landslides occur under extremely wet soil conditions, wind erosion is a concern with very dry soil. Tillage erosion occurs on fields that are either steep or have undulating topography. Erosion is the result of the combination of an erosive force (water, wind or gravity), a susceptible soil and several management- or landscape-related factors. A soil's inherent susceptibility to erosion (its *erodibility*) is primarily a function of its texture (generally, silts more so than sands and clays), its aggregation (the strength

Photo by Jerry DeWitt

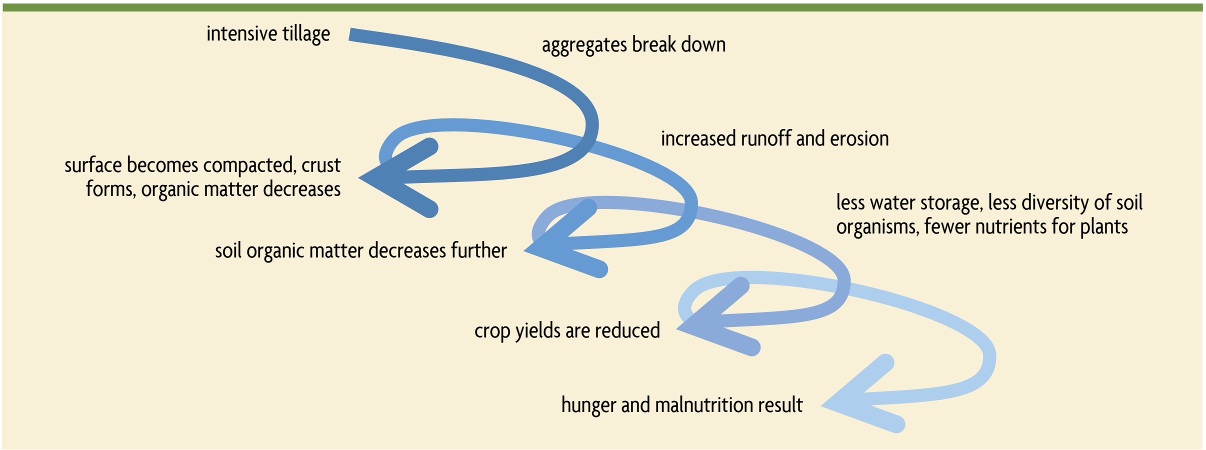

Figure 6.1. The downward spiral of soil degradation. Modified from Topp et al. (1995).

and size of aggregates, related to the amount of organic matter and clay), and soil water conditions. Many management practices can reduce soil erosion, although different types of erosion have different solutions.

Water Erosion

Water erosion is especially severe on bare, sloping land when intense rainfall rates cause runoff. The water flowing over the soil surface concentrates into tiny streamlets, which detach the saturated soil and transport the particles downhill. Runoff water gains more energy as it moves down the slope, scouring away more soil and also carrying more agricultural chemicals and nutrients, which end up in streams, lakes and estuaries (Figure 6.2). Erosion can involve broad areas in fields where small depths of soil are removed all the way to deep gullies that leave scars in the landscape.

Soil erosion is of greatest concern when the surface is unprotected and directly exposed to the destructive energy of raindrops and wind (Figure 6.2). The erosion process leads to a decrease in soil organic matter and aggregation, which in turn promotes further erosion.

Figure 6.2. Left: Water erosion on clean-tilled soil in Bulgaria. Topsoil has been lost in the background field. Right: A stream in Guarico, Venezuela, contaminated with dispersed sediment.

SOIL AND WATER CONSERVATION IN HISTORICAL TIMES

Some ancient farming civilizations recognized soil erosion as a problem and developed effective methods for runoff and erosion control. Ancient terracing practices are apparent in various parts of the world, notably in the Andean region of South America and in Southeast Asia. Other cultures, like in pre-Columbian America, did not till the fields and effectively controlled erosion using mulching and intercropping. Some ancient desert civilizations, such as the Anasazi in the southwestern United States (600–1200 A.D.), retained runoff water and eroded silt from upper parts of the landscape with check dams to grow crops in downhill depressions (see the picture of a now forested site). For most agricultural areas of the world today, erosion still causes extensive damage (including the spread of deserts) and remains the greatest threat to agricultural sustainability and water quality.

Thus, a vicious cycle begins. Soil is degraded because the most fertile part of the soil, the surface layer enriched in organic matter, is removed by erosion. Erosion also selectively removes the more easily transported finer soil mineral particles, clays, which help store nutrients and organic matter and stabilize soil aggregates. Severely eroded soils, therefore, have less favorable physical, chemical and biological characteristics, leading to a reduced ability to sustain crops and an increased potential for harmful environmental impacts.

The lower infiltration capacity of eroded soils reduces the amount of water that is available to plants and the amount that percolates through the soil into underground aquifers, while increasing the potential for flooding. This reduction in underground water recharge results in streams drying up during drought periods. Watersheds with degraded soils thus experience lower stream flow during dry seasons and increased flooding during times of high rainfall, undesirable in both cases. In fact, we surmise that the trend of increased flooding in many areas is not only the result of changed weather patterns but also compounded by gradual soil degradation.

Wind Erosion

The photograph of wind erosion from the Dust Bowl era (Figure 6.3) provides a graphic illustration of land degradation. Wind erosion can occur when soil is dry and loose, the surface is bare and smooth, and the landscape has few physical barriers to wind. The wind tends to roll and sweep larger soil particles along the soil surface, which will dislodge other soil particles and increase overall soil detachment. The smaller soil particles (very fine sand and silt) are lighter and will go into

Figure 6.3. Drought and poor soil health created wind and water erosion during the Dust Bowl. Photo by USDA.

Figure 6.4. Wind erosion damaged young wheat plants through abrasion. Photo by USDA Wind Erosion Research Unit.

Figure 6.5. Sustained rains from Hurricane Mitch in 1998 caused supersaturated soils and landslides in Central America. Photo by Benjamin Zaitchik.

suspension in the atmosphere. They can be transported over great distances, sometimes across continents and oceans. Wind erosion affects soil quality through the loss of topsoil rich in organic matter and can cause crop damage from abrasion (Figure 6.4). In addition, wind erosion affects air quality, which is a serious concern for nearby communities. During the Dust Bowl, soil was blown all the way from the central part of the continent to New York and Washington, making East Coast residents directly aware of the environmental disaster occurring in the middle of the continent.

The ability of wind to erode a soil depends on how that soil has been managed, because strong aggregation makes it less susceptible to dispersion and transportation. In addition, many soil-building practices like no-till, mulching and the use of cover crops protect the soil surface from both wind and water erosion.

Landslides

Landslides occur on steep slopes when the soils have become supersaturated from prolonged rains. They are especially of concern in mountainous countries where high population pressure resulted in farming on steep hillsides (Figure 6.5). The sustained rains saturate the soil, especially in landscape positions that concentrate water from upslope areas. This has two effects: It increases the weight of the soil mass (all pores are filled with water), and it decreases the cohesion of the soil (see the compaction of wet soil in Figure 6.12, right) and thereby its ability to resist the force of gravity. Agricultural areas are more susceptible than forests because they lack large, deep tree roots that can hold soil material together and may be without living vegetation for a portion of the year. Pastures on steep lands, common in many mountainous areas, typically have shallow-rooted grasses and may readily experience

Figure 6.6. Effects of tillage erosion on soils. Photo by Ron Nichols, USDA-NRCS.

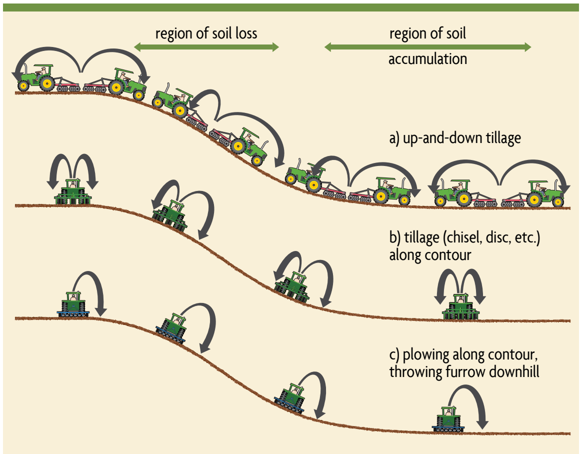

Figure 6.7. Three causes of erosion resulting from tilling soils on slopes. Illustration by Vic Kulihin.

slumping. With certain soil types, landslides can become liquefied and turn into mudslides.

Tillage Erosion

Tillage promotes water and wind erosion by breaking down aggregates and exposing soil to the elements. But it can also cause erosion by routinely moving soil down the slope to lower areas of the field, which becomes an increasing problem with more intensive mechanized tillage. In complex topographies—such as seen in Figure 6.6—tillage erosion ultimately removes surface soil from knolls and deposits it in depressions (swales) at the bottom of slopes. What causes tillage erosion? Basically, when soil is moved by a plow or harrow on sloping land it causes more soil to move into the downslope than the upslope direction, resulting in net downslope transport. As an analogy, when throwing a ball upwards or downwards on a hillside it will go a farther distance in the down direction. Soil is similarly thrown farther downslope when tilling in the downslope direction than is thrown uphill when tilling in the upslope direction (Figure 6.7a). Over many years this has the cumulative effect of moving a lot of soil down the slope. Also, downslope tillage (with gravity) typically occurs at greater speeds than when traveling uphill (against gravity), making the situation even worse.

Tillage along the contour also results in downslope soil movement. Soil lifted by a tillage tool comes to rest at a slightly lower position on the slope (Figure 6.7b). A more serious situation occurs when using a moldboard plow along the contour. Moldboard plowing is often performed by throwing the soil to the side and down the slope, as this inverts the soil better than by trying to turn the furrow up the slope (Figure 6.7c).

One unique feature of tillage erosion compared to wind, water and gravitational erosion is that it is unrelated to extreme weather events and occurs gradually with every tillage operation. Tillage erosion makes field management more challenging as it results in lower crop productivity on the knolls and hillsides, and higher productivity in the swales. However, it does not generally result in offsite damage because the soil is merely moved from higher to lower positions within a field. But it is another reason to reduce tillage on sloping fields.

SOIL TILTH AND COMPACTION

A soil becomes more compact, or dense, when aggregates or individual particles of soil are forced closer together. Soil compaction has various causes and different visible effects. It can occur either at or near the surface (shallow compaction, which includes surface crusting) or deeper down in the soil (subsoil compaction). See Figure 6.8.

Shallow Compaction

Shallow compaction, which is compaction of the surface layer or plow layer, occurs to some extent in all intensively worked agricultural soils. It is the result of a loss of soil aggregation that typically has three primary causes: erosion, reduced organic matter levels and forces exerted by the weight of field equipment. The first two result in reduced supplies of sticky binding materials and a subsequent loss of aggregation. Livestock can

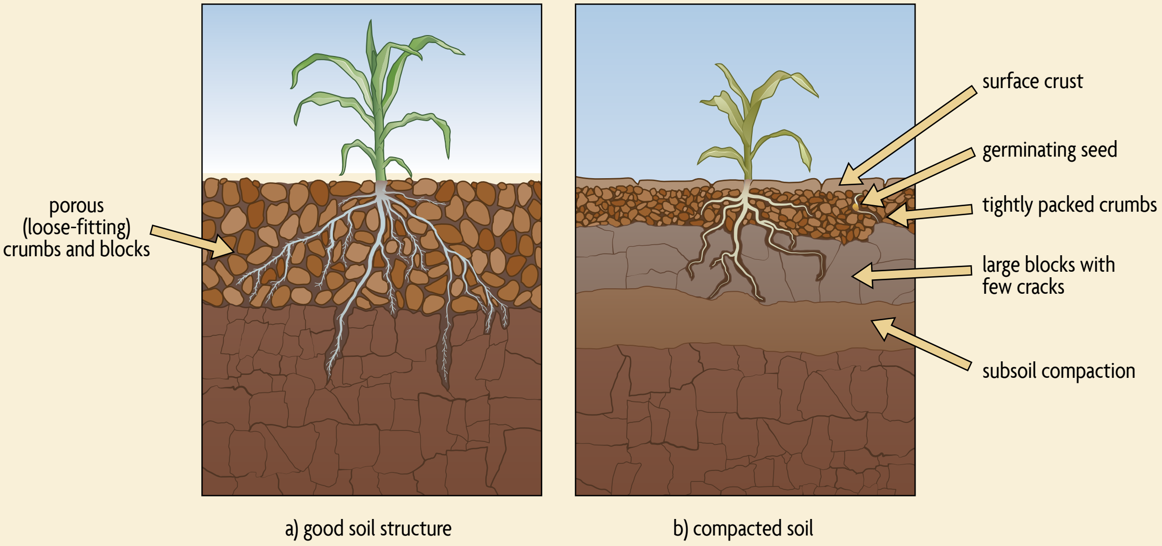

Figure 6.8. Plants growing in (a) soil with good tilth and (b) soil with all three types of compaction. Illustration by Vic Kulihin.

damage pastures through their hoof action during times when soils are susceptible to compaction.

Compaction of soils by heavy equipment and tillage tools is especially damaging when soils are wet. To understand this, we need to know a little about soil *consistence*, or how soil reacts to external forces. At very high water contents, a soil may behave like a liquid (Figure 6.9) because it has little internal cohesion (Figure 5.10, left). On a slope it can simply flow as a result of the force of gravity, as with mudslides during excessively wet periods. At slightly lower water contents, soil has somewhat more cohesion, but it can still be easily molded and is said to be *plastic* (Figure 6.9). Upon further drying, the soil will become *friable*: it will break apart rather than mold under pressure (Figure 6.9).

The point between plastic and friable soil, the *plastic limit*, has important agricultural implications. When a soil is wetter than the plastic limit, it may become seriously compacted if tilled or trafficked because soil aggregates are pushed together into a smeared, dense mass. This may be observed when you see shiny, cloddy furrows or deep tire ruts in a field (Figure 6.10). The soil is more resistant to deformation when the soil is friable (the water content is below the plastic limit). It crumbles when tilled and aggregates resist compaction by field traffic. Thus, the potential for compaction is strongly influenced by the timing of field operations, as it is much lower when the soil is adequately dry. A soil's

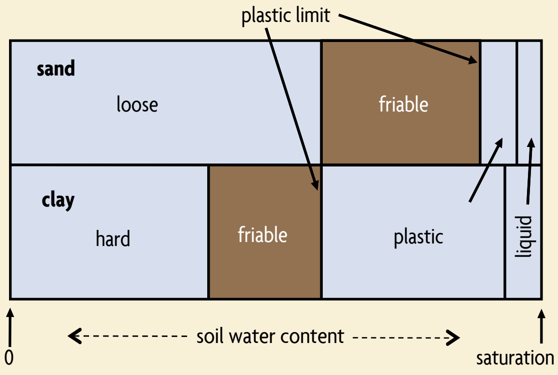

Figure 6.9. Soil consistency states for a sand soil and for a clay soil (friable soil is best for tillage).

Figure 6.10. Deep tire ruts in a hay field following harvest when soil was wet and plastic.

consistency is strongly affected by its texture (Figure 6.9). For example, as coarse-textured sandy soils drain, they rapidly change from being plastic to being friable. Fine-textured loams and clays need longer drying periods to lose enough water to become friable. This extra drying time may cause delays when scheduling field operations.

Soils are thus less susceptible to compaction when they are dry, which may be a better time to run heavier equipment. Similarly, when soils are frozen and the soil particles are fused by ice, the soil becomes solid and resistant to compaction.

Surface sealing and crusting. This problem is also caused by aggregate breakdown but specifically occurs when the soil surface is unprotected by crop residues or plant canopies. The energy of raindrops disperses wet aggregates, pounding them apart so that particles settle into a thin, dense layer. The sealing of the soil reduces water infiltration, and the surface forms a hard crust when dried. Crusting generally occurs after tillage and planting when the soil is unprotected, and it can delay or prevent seedling emergence. Even when the crust is not severe enough to limit germination, it can reduce water infiltration. Soils with surface crusts are prone to high rates of runoff and erosion. You can

a) Stage 1: Cloddy soil after tillage makes for a poor seedbed.

b) Stage 2: Soil is packed and pulverized to make a fine seedbed.

c) Stage 3: Raindrops disperse soil aggregates, forming a surface crust.

Figure 6.11. Three stages of tilth for a compacted soil that has become addicted to tillage.

CHECK BEFORE TILLING

To be sure that a soil is ready for equipment use, you can do the simple "ball test" by taking a handful of soil from the lower part of the plow layer and trying to make a ball out of it. If it molds easily and sticks together, the soil is too wet. If it crumbles readily, it is sufficiently dry for tillage or heavy traffic.

reduce surface crusting by leaving more residue on the surface and by maintaining strong soil aggregation. Sometimes, farmers break crusts with a harrow, but that only treats the symptom, not the cause.

Intensive tillage. Shallow compaction is especially common with repeated soil disturbance. Tillage operations often become part of a vicious cycle in which a compacted soil tills up very cloddy (Figure 6.11a) and then requires extensive secondary tillage and packing trips to create a satisfactory seedbed (Figure 6.11b). Natural aggregates break down, and organic matter decomposes in the process—contributing to more compaction in the future. Although the final seedbed may be ideal at the time of planting, rainfall shortly after planting may cause surface sealing and further settling (Figure 6.11c) because few sturdy aggregates are present to prevent the soil from dispersing. The result may be a dense soil with a crust at the surface. Some soils may hard-set like cement, even after the slightest drying, thereby slowing plant growth. Although the soil becomes softer when it re-wets, that moisture provides only temporary relief to plants.

Subsoil Compaction

Subsoil compaction occurs deeper in the soil and is sometimes referred to as a *plow pan*, although it is commonly caused by more than just plowing. Subsoil is prone to compaction because it is usually wetter, denser, higher in clay content, lower in organic matter, and less aggregated than topsoil. Also, subsoil is not loosened by regular tillage and cannot easily be amended with

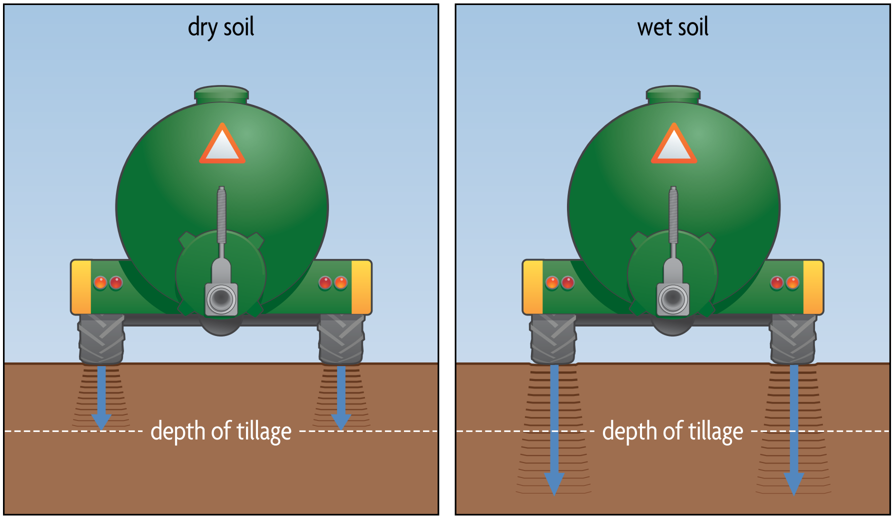

Figure 6.12. Forces of heavy tillage loads are transferred deep into the soil, especially when the soil is wet. Illustration by Vic Kulihin.

additions of organic materials. Another challenge is that the subsoil is by definition buried and therefore compaction is invisible unless you dig down or push a rod into the soil.

Subsoil compaction occurs when farmers run heavy vehicles, especially those with poor weight distribution. The load exerted on the surface is transferred into the soil along a cone-shaped pattern (Figure 6.12). With increasing depth, the compaction force is distributed over a larger area, thereby reducing the pressure in deeper layers. When the loading force at the surface is small, say through foot or hoof traffic or a light tractor, the pressure exerted deep in the soil is minimal. But when the load is high from heavy equipment, like with a heavy manure spreader or combine, the pressures at depth are sufficient to cause considerable soil compaction. When the soil is wet, the force causing compaction near the surface is more easily transferred to the subsoil, which causes even more compaction damage. Clearly, the most severe compaction in subsoils occurs with the combination of heavy vehicle traffic and wet soil conditions.

Another major cause of subsoil compaction is the pressure of a tillage implement, especially a plow or disk, pressing on the soil below (hence the term plow pan). Plows cause compaction because the weight of the plow plus the lifting of the furrow slices results in high downward forces from the plow share (bottom) onto the soil layer immediately underneath. Disks also have much of their weight concentrated at the bottom of the disk and can cause shallow pans. Subsoil compaction may also occur during moldboard plowing when a set of tractor wheels is placed in the open furrow, thereby applying wheel pressure directly to the soil below the plow layer. Overall, these pans are very common in soil that has been plowed, sometimes even many years after the field was converted to no-till.

CONSEQUENCES OF COMPACTION

As compaction pushes particles closer together, the soil becomes dense and pore space is lost. Notably, the large pores are lost as they are compressed into smaller ones (Figure 6.13). Loss of large pores between aggregates is particularly harmful for fine- and medium-textured soils that depend on those pores for good infiltration and percolation of water, as well as air exchange with the atmosphere. Although compaction can also damage coarse-textured soils, the impact is less severe. They depend less on aggregation because the pores between individual particles are sufficiently large to allow good water and air movement.

Figure 6.13. Compacted soil (left) lacks large pores for water and air transmission and root growth, and it becomes hard when it dries. Aggregated soil (right) has large pores and remains crumbly when it dries.

Compacted soil becomes hard when it dries, as it has many small pores that can hold water under high suction and pull particles tightly together. This can restrict root growth and the activity of soil organisms. Compacted soils typically have greater resistance to penetration at a given soil moisture level than a well-structured soil (Figure 6.14), which has large pores between aggregates that therefore easily pull apart. The resistance to penetration for a moist, high-quality soil is usually well below the critical level where root growth ceases for most crops: 300 pounds per square inch (psi, or 2 megapascals). As the soil dries, its strength increases, but a high-quality soil may not exceed the critical level for most (or all) of the moisture range. A compacted soil, on the other hand, has a very narrow water content range for good root growth. The soil has increased resistance to penetration even in the wet range (the soil is hard). When it dries, a compacted soil hardens quicker than a well-structured soil, rapidly becoming so hard that it is well above the critical 300-psi level that restricts root growth.

SOME CROPS ARE MORE SENSITIVE THAN OTHERS

Compaction doesn't affect all crops to the same extent. An experiment in New York found that direct-seeded cabbage and snap beans were more harmed by compaction than were cucumbers, table beets, sweet corn and transplanted cabbage. Much of the plant damage was caused by the secondary effects of compaction, such as prolonged soil saturation after rain, reduced nutrient availability or uptake, and greater pest susceptibility. Some crops also grow more roots when the soil is soft. For example, cool-season crops that grow well in the early season can take advantage of moister, softer soil conditions, while summer crops may experience dryer, harder soils.

Restricted Rooting

Actively growing roots need large pores with diameters greater than about 0.1 millimeter, the size of most root tips. Roots must enter the pore and anchor themselves before continuing growth. Compacted soils that have few or no large pores don't allow plants to be effectively rooted, thus limiting water and nutrient uptake.

What happens when root growth is limited? The root system will probably develop short, thick roots and few fine roots or root hairs (Figures 5.6 and 6.8). The few thick roots may be able to find some weak zones in the soil, often by following crooked patterns. These roots have thickened tissue and are inefficient at taking up water and nutrients. In many cases, roots in degraded soils do not grow below the surface layer into the subsoil (Figure 6.8); it's just too dense and hard for them to grow. Deeper root penetration is especially critical under rain-fed agriculture. The limitation on deep root growth by subsoil compaction reduces the volume of soil from which plant roots can extract water and nutrients, increasing the probability of yield loss from drought stress.

There is also a more direct effect on plant growth, beyond the reduced soil volume for roots to explore. A root system that's up against mechanical barriers sends a hormonal signal to the plant shoot, which then slows down respiration and growth. This plant response appears to be a natural survival mechanism similar to what occurs when plants experience water stress. In fact, because some of the same hormones are involved—and mechanical resistance increases when the soil dries—it is often difficult to separate the effects of compaction from those of drought.

We have learned much about the effects of compaction on root growth, but we know less about the effects on soil organisms. However, it is well established that a diverse soil ecosystem requires organisms to have spaces for habitation and movement. Earthworms and insects, for example, need large pores to move around and access organic materials, while aerobic bacteria and fungi need air exchange. Therefore, compacted soils typically have much lower populations of these beneficial organisms, but they return remarkably quickly when better practices are adopted.

THE WATER RANGE FOR BEST PLANT GROWTH

The limitations to plant growth caused by compaction and water extremes can be combined into the concept of the *optimum water range* for plant growth: the range of water contents under which plant growth is not reduced by drought, mechanical stress or lack of aeration (Figure 6.15). This range, referred to by scientists as the *least-limiting water range*, is bounded on two sides: when the soil is too wet and when it's too dry.

The optimum water range in a well-structured soil has its *field capacity* on the wet end, as water above that moisture content is quickly drained out by gravity. On the dry end is the *wilting point*, beyond which the soil holds water too tightly to be used by plants. However, the soil water range for best growth in a compacted soil is much narrower. Even after a severely compacted soil drains to field capacity, it is still too wet because it lacks large pores and is thus poorly aerated. Good aeration requires at least 20% of the pore space (about 10% of the volume of the whole soil) to be air filled. On the dry end, plant growth in a compacted soil is commonly limited by soil hardness rather than by lack of available water. Plants in compacted soils therefore experience more stress during both wet and dry periods than plants in soils with good tilth. The effects of compaction on crop yields usually depend on the length and severity of excessive wet or dry periods and when those periods occur relative to critical times for plant growth.

CHEMICAL CONTAMINATION OF SOIL

Soils can be contaminated with chemicals, either naturally or by human activity, to such an extent that crops are adversely affected. Problems of saline and sodic (alkaline) soils are most found in arid and semiarid regions, or in soil affected by coastal flooding. Other types of contamination may derive from natural toxic chemicals or pollution.

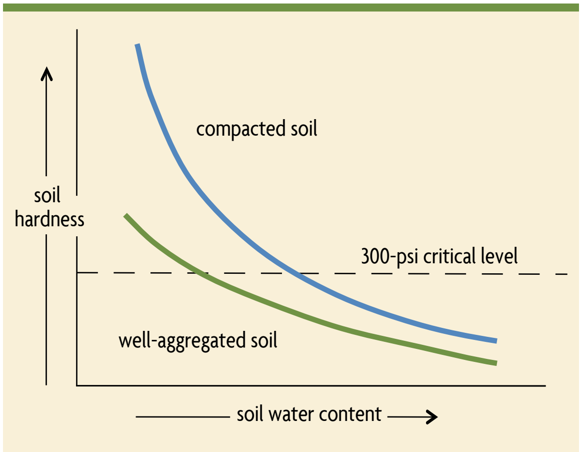

Figure 6.14. Compacted soils harden more quickly upon drying than well-aggregated soils.

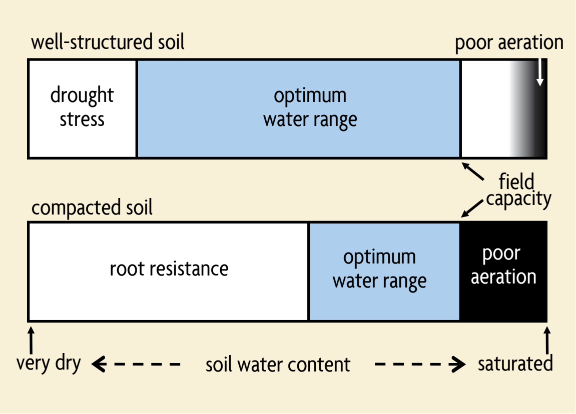

Figure 6.15. The optimum water range for crop growth for two different soils.

Saline and Sodic Soils

Special soil problems are found in arid and semiarid regions, including soils that are high in salts, called *saline* soils, and those that have excessive sodium (Na^+),

SALINE SOIL

Electrical conductivity of a soil extract is greater than 4 ds/m, enough to harm sensitive crops.

SODIC SOIL

Sodium occupies more than 15% of the cation exchange capacity (CEC). Soil structure can significantly deteriorate in some soils at even lower levels of sodium.

called *sodic* soils. Sometimes these go together and the result is a *saline-sodic* soil. Saline soils usually have good soil tilth, but plants can't get the water they need because the high salt levels in the soil inhibit water uptake as the soil exerts an osmotic force that counters the plant's own osmotic potential.

Sodic soils tend to have very poor physical structure because the high sodium levels cause clays to disperse, leading aggregates to break apart. Aggregates of sodic soils disperse when they are saturated, and the solids then settle as individual particles and make the soil very dense (Figure 6.16). These soils become difficult to work with and are very inhospitable for plants because of both compaction and greatly reduced aeration. When a sodic soil is fine textured its consistency and appearance are something like that of chocolate pudding. It causes serious problems with drainage, seedling emergence and root development. A soil like that must be remediated before growing crops.

Also, the ionic strength of the cations in the soil can affect aggregate stability. Some believe that soils with high magnesium-over-calcium ratios tend to have weaker aggregates and would benefit from calcium applications, but that has limited support from research except in unusual situations.

Saline and sodic soils are commonly found in the semiarid and arid regions of the western United States and in similar climate zones in many countries around the world. They are difficult to remediate. After major hurricanes, coastal flooding areas may also experience temporary saline-sodic conditions until the salts are washed out by rains.

Although some soils are naturally saline, sodic, or both, there are a number of ways that surface soils may become contaminated with salts and sodium. When irrigation water containing significant salt content is used without applying extra water to leach out the salts, accumulation of salts can create salinity. Also, routine use of irrigation water with high sodium levels relative to calcium and magnesium will create a sodic soil over time. Over-irrigating, which often occurs with conventional flood or furrow irrigation, can create salinity

Figure 6.16. A sodic soil in Tasmania, Australia, that lacks aggregation and has problems with waterlogging when wet and with hardsetting when dry. Photo by Richard Doyle.

SALT PRESENCE IN ALL SOILS

Salts of calcium, magnesium, potassium and other cations, along with the common negatively charged anions chloride, nitrate, sulfate and phosphate, are found in all soils. However, in soils in humid and subhumid climates, with from 1–2 to well over 7 inches of water percolating beneath the root zone every year, salts don't usually accumulate to levels where they can be harmful to plants. Even when high rates of fertilizers are used, salts usually become a problem only when you place large amounts in direct contact with seeds or growing plants. Salt problems also frequently occur in greenhouse potting mixes because growers regularly irrigate their greenhouse plants with water containing fertilizers and may not add enough water to leach the accumulating salts out of the pot.

problems in the topsoil by raising water tables to within 2–3 feet of the surface. Shallow groundwater can then be wicked up by capillary action to the surface, where the water evaporates and the salts remain. Sometimes the extra moisture accumulated during a fallow year in semiarid regions causes field seeps, in which salty water high in sodium comes to the surface, leading to the development of saline and sodic patches.

Other Types of Chemical Contamination

Soils can become contaminated with many sorts of chemicals from oil, gasoline or pesticides to a variety of industrial chemicals and mining wastes. This contamination may occur through unintended spills, but in the past, waste materials were often deliberately disposed of by dumping on fields. In urban areas it is common to find lead-contaminated soils as a result of the past use of lead-based gasoline and paint. Lead, as well as other contaminants, frequently makes creating an urban garden a real challenge. Often, new topsoil is brought in, mixed with a large quantity of compost, and placed in raised beds so that plant roots grow above the contaminated soil, and the lead is made less available by organic chelates. Agricultural soils that have a history of applications of sewage sludge (*biosolids* is the current term) may have received significant quantities of heavy metals such as cadmium, zinc and chromium, as well as antibiotics, pharmaceutical drugs and an assortment of toxic organic chemicals contained in the sludge. Some phosphorus fertilizers contain cadmium that can build up in soils. Toxicity related to such contaminants may impact plants and humans, like *itai-itai* disease among Japanese rice growers in the 1950s.

There are a number of ways to remediate chemically

URBAN SOILS

Severe soil degradation can be observed in urban areas where soil is often intensively used, physically disturbed or contaminated by a wide variety of chemicals. In addition, urban ecosystems are challenged by a difficult microclimate (so-called heat islands). On the positive side, urban spaces are very valuable—many people use them—and there are therefore more financial resources available to invest in remediation. Also, urban areas concentrate organic materials that can be used for soil improvement, like food waste and street leaves turned into compost to help build soil organic matter, and urban tree branches that are chipped and used for mulch. For more on the special issues of growing plants on urban soils see Chapter 22.

contaminated soils. Sometimes adding manure or other organic amendments and growing crops stimulates soil organisms to break down organic chemicals into less harmless forms. For example, pesticides, organic wastes and oils can be naturally broken down in soils. Some plants are especially good at taking up certain metals from soil and can be used to clean contaminated soil (but they then must be disposed of carefully). Adding organic matter can also reduce the availability of heavy metals by forming chelates (Figure 2.5).

SUMMARY

Soil degradation is one of the world's great environmental problems. At the same time as rivers are contaminated with sediments eroded from soils, severe erosion in many parts of the world results in a significant decrease in soil productivity. Although the immediate cause for water erosion may be intense rainfall, there are a number of reasons soil loss is especially severe in some situations. Compaction, another form of soil degradation, can go unnoticed unless one looks for the symptoms, but it can have a damaging effect on plant growth. Chemical contamination, whether from salts, metals or organics can also affect plant and human health. Many of these concerns can be addressed through good management practices. For a discussion of tried and true ways of reducing erosion and compaction, see chapters 14 and 15. For how to reclaim saline, sodic and saline-sodic soils, see Chapter 20.

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Chapter 7

CARBON AND NUTRIENT CYCLES AND FLOWS

Global grain exports for corn and soybeans are dominated by the US and Brazil, while cereal crops derive from many countries. Asia, especially China, accounts for 43% of all grain imports.

—RABOBANK, 2016

Nutrient cycling can occur in various settings and scales: on a farm, in a grassland or forest, or even globally. But the cycling of soil nutrients is intimately connected to organic matter, over half of which is carbon. So we'll discuss both nutrients and carbon in this chapter. We use the term *cycle* when discussing the flow of nutrients from soil to plant to animal and back to soil, as well as global carbon and nitrogen cycles (Chapter 2). Some farmers minimize their use of nutrient supplements and try to rely more on natural soil nutrient cycles—as contrasted with purchased commercial fertilizers—to provide fertility to plants. But is it really possible to depend forever on the natural cycling of all the carbon and nutrients to maintain soil health and meet a crop's needs? Let's first consider what carbon and nutrient cycles are and how they differ from the other ways that carbon and nutrients move.

When carbon or nutrients move from one place to another, that is a *flow*, and it connects a source with a destination. There are many different types of nutrient flows that occur. When you buy fertilizers, nutrients are "flowing" onto the farm. When you buy animal feed, both nutrients *and* carbon are flowing onto the farm. When you sell sweet corn, apples, alfalfa hay, meat or milk, nutrients and carbon are flowing off the farm. Flows that involve products entering or leaving the farm gate are managed intentionally, whether or not you are thinking about those products in terms of nutrients or carbon. Other flows are unplanned—for example, when nitrate is lost from the soil by leaching to groundwater or when runoff waters take nutrients along with eroded topsoil to a nearby stream.

When crops are harvested and brought to the barn to feed animals, that is a nutrient flow, as is the return of animal manure to the land. Together these two flows are a cycle because nutrients and carbon return to the fields from which they came. In forests and natural grassland, the cycling of nutrients is very efficient, nearly 100%. Nutrient cycling was also efficient in the early stages of agriculture, when almost all people lived near their

Photo by iStock

fields. However, in many types of agriculture, especially modern specialized farming, there is little real cycling of nutrients because there is no easy way to return the large quantity of nutrients and carbon shipped off the farm (and sometimes across continents and oceans). In addition, nutrients in crop residues don't cycle very efficiently when the soil is without living plants for long periods; and nutrient runoff and leaching losses are much larger compared to natural systems.

CARBON AND NUTRIENT FLOWS IN HISTORY

Did you ever wonder why some civilizations were able to sustain agriculture for large populations while others exhausted their soils? One key component is the natural flow of carbon and nutrients. In the early days of agriculture, the productive areas were generally in low-lying locations where rivers and streams converged and flooded low-lying soils with water that contained sediments eroded from upriver soils. This annual flooding provided repeated deposits of nutrients and organic matter contained in the river's sediments. For example, the Nile River Basin is over 1.2 million square miles in size and reaches from east-central Africa all the way to the Mediterranean. Through erosion and leaching (even under natural conditions), each area in the basin contributes small amounts of minerals (nutrients) and organic matter (carbon) that converge into the narrow downstream valley as sediment (Figure 7.1). Through the monsoonal rains in the upper basin, an annual supply of naturally fertile sediments (alluvium) was deposited on fields in the lower Nile valley and delta. This sustained a large population for several millennia. Other similar major confluence areas that were centers of ancient civilizations:

- The Indo-Gangetic Plain in parts of current day Pakistan, India, Bangladesh and Nepal, which is supplied by rivers—the Indus, Ganges and Brahmapatura—and sediment derived from the Himalayas
- The North China Plain, which is supplied by the sediment-laden Yellow River from the loess plateau in inner China
- The land between the rivers Euphrates and Tigris (Mesopotamia) in present day Syria and Iraq, which contains sediment derived from the Armenian Highlands in Turkey
- The Valley of Mexico, where ancient Lake Texcoco was fed by rivers from the surrounding fertile volcanic mountains and supported sustained wetland crop production by the Aztec civilization using raised beds (chinampas)
- Many other larger or smaller zones of alluvial deposits that were settled by tribes, including Native Americans, where they provided fertile soils and nearby sources of fish and land animals

The continuous water, carbon and nutrient supplies allowed for highly productive crop production but also came with frequent flooding. In the past century, dams and levees have been constructed to reduce the impacts of flooding (and oftentimes to generate energy as well), but this means that the benefits of soil rejuvenation have ceased. Moreover, these ancient confluence zones have also become the most urbanized areas in the world, further reducing agricultural land areas. Notably, the lake in central Mexico was drained and is now occupied by the megalopolis Mexico City.

Contrasting these convergence zones in valleys and deltas, there are other regions from which the water

Alluvial soils are formed from sediments deposited along the banks of streams and rivers, and in the deltas where flowing water meets the still water of a lake or ocean and sediments settle to the bottom. They tend to be very fertile because of the small-size mineral particles, organic matter (carbon) and nutrients deposited over long periods of time.

Figure 7.1. Basin-wide nutrient, carbon and water flows converge towards productive confluence zones.

and sediments originate, and where carbon, nutrients and water are *lost*. These are extensive areas away from the valleys and deltas, typically hilly or mountainous, from which resources tend to move away due to runoff, erosion and leaching. Their losses are gains for the regions downriver. In ancient times, these less productive areas were mostly used for pasturing where low-producing perennial vegetation was still valuable for extensive animal grazing, supporting small populations. Whenever such lands were taken into crop production, soils soon became exhausted from tillage, carbon and nutrient exports off the farm, and high soil erosion (Figure 7.2). Many regions thereby became unsuitable for annual crops and were converted back to pasture or to tree or vine crops (olives, grapes) that grow with low soil fertility (Figure 7.2). These farming conditions could not support large civilizations and often resulted either in declines or conquests. Notably, the low agricultural potential of the degraded hills of central Italy drove Roman conquests of the Egyptian breadbasket in the lower Nile.

Carbon and Nutrient Concentration in Soils by Human Activity

With growing global populations, more of the marginal areas were brought into production. Some were naturally productive (e.g., grassland areas in the central United States and Asia), while others were more fragile (e.g., the eastern United States). Before the availability of nutrient replenishment with artificial fertilizers, farmers sometimes built soil fertility through periodic flooding and deliberately bringing organic materials and nutrients to their crop fields, sometimes even creating soils so strongly influenced by this human activity that

Figure 7.2. Degraded land on Crete, Greece, with olive trees.

Figure 7.3. Two cases of soils enhanced through human activity, producing anthropogenic soil (from left): Plaggen soil in Belgium (by Karen Vancampenhout) and Terra Preta del Indio soil in Brazil (by Biqing Liang).

they're called Anthrosols. One example is the so-called *plaggen* soil of northwestern Europe (Figure 7.3). These are found on low-fertility sandy soils that were not good for crop production but were suitable for pasturing. Farmers would keep areas from forest succession by cutting away the heath sod, containing plants of low nutritional value and palatability, and promoting new vegetation that could feed grazing animals, mostly sheep. But there was still a need to grow food crops. Therefore, the slices of rich sod were brought to barns where they were used as bedding for the overnighting sheep. The sod was further enriched with the sheep excrements (containing carbon and nutrients harvested from the pastures during the day), creating fertile compost that was in turn applied onto the small fields that were used to grow crops for human consumption. In this crop-pasture system, the carbon and nutrients were partly *cycled* on the pastures and partly *flowed* in a way that *concentrated* onto crop fields. This human ingenuity allowed for sustained animal and crop production on naturally marginal soils.

There are other examples of "dark earths" found in many settled areas around the world, notably the Amazonian Terra Preta soils that were enriched with char (as we discuss in Chapter 2). In this case, food and fuel were collected from the surrounding rainforest and were concentrated onto the soils in and around the ancient settlements. Unlike the plaggen soils, the charring of some of the organic materials created very stable organic matter that, centuries later, still keeps the soil fertile. There are many other examples of the concentration of carbon and nutrients around population settlements, including early New Englanders who used byproducts from the bountiful cod fishing industry to enhance the fertility of their croplands.

Why is this historical perspective relevant? Because today there are good opportunities to enhance soil fertility by better using organic materials. In fact, most organic farmers do just that. They bring organic materials that are often considered "wastes" onto their fields to replace the nutrients that are exported with the crops (they especially need phosphorus and potassium). Typically, this is done through compost made with tree leaves and food wastes in urban areas or through excess manure from livestock farms. Like in the past, these farmers are taking advantage of the availability of organic materials and nutrients external to their farms and are bringing them onto their fields to build soil fertility, as we discuss in detail in part 3 of this book. Different rotations and integrating cropping and livestock also offer many opportunities to "grow your own" soil organic matter and improve nutrient cycling.

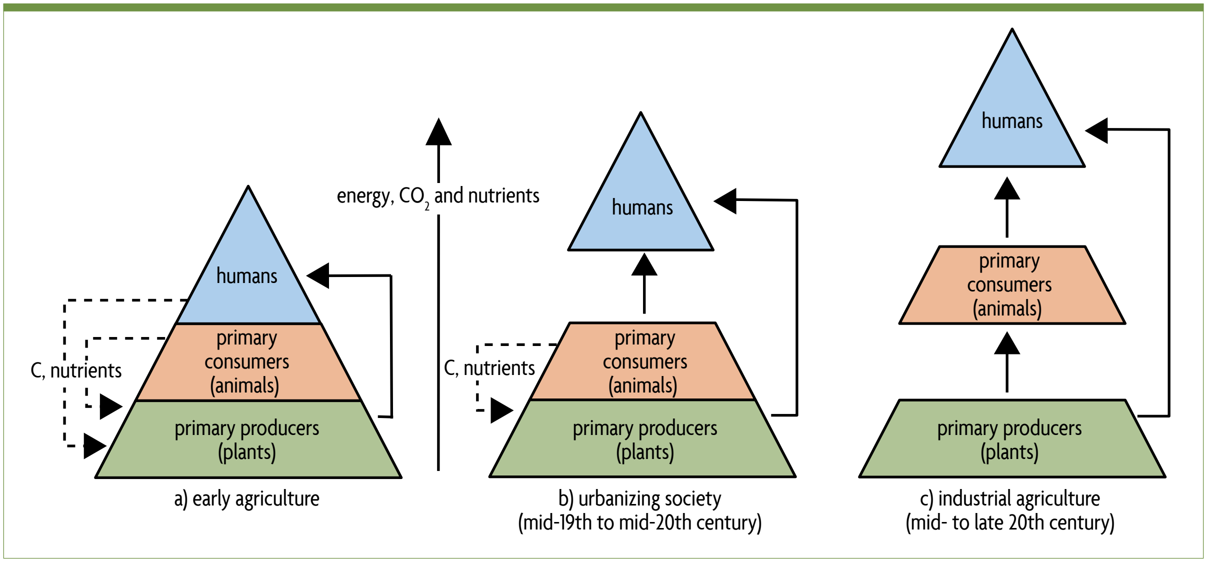

Figure 7.4. The patterns of nutrient and carbon flows change over time. Modified from Magdoff, Lanyon, and Liebhardt (1997).

CYCLING AND FLOWS IN MODERN AGRICULTURE

Older farming styles with integrated crops and animals had good cycling of carbon and nutrients. In the process of living, farm animals and humans used some of the energy and nutrients derived from plants with the remaining nutrients and carbon returned to the soil (organic residues of plants and waste materials of farm animals and humans). The first major break in this cycle occurred as cities developed and carbon and nutrients began to routinely travel with farm products to feed the growing urban populations many miles away. It is rare for the carbon and nutrients to return to the soils on which the crops and animals were originally raised (Figure 7.4b). Thus, nutrients and carbon accumulated in urban sewage and polluted waterways around the world. Even with the building of many new sewage treatment plants in the 1970s and 1980s, effluent containing nutrients still flows into waterways, and sewage sludges are not always handled in an environmentally sound manner.

The trend toward farm specialization, mostly driven by economic forces, has resulted in the second break in nutrient and carbon cycling due to the separation of animals from the land that grows their feed. With specialized large-scale animal facilities (Figure 7.4c), nutrients and carbon accumulate in manure while crop farmers purchase large quantities of inorganic fertilizers to keep their fields from becoming nutrient deficient, but they don’t usually replace all of the carbon that is lost because organic matter decomposes during the year.

FLOW PATTERNS AT FARM SCALE

With relatively undisturbed forests or grasslands, the nutrients used by plants are mostly cycled back with leaf litter and the periodic dieback of roots. Carbon flows are different from the cycling that occurs when nutrients such as nitrogen, phosphorus, potassium and calcium are taken up from soil by plants, used and then returned to soil. Carbon enters the field as plants use atmospheric CO$_2$ to carry out photosynthesis, providing the basis for all the various chemicals needed for their growth and reproduction. The portion of the plant that remains after harvest is thus added to the soil as “new” carbon in the form of organic residues; commonly this represents as much or more organic matter than was decomposed by organisms during the year.

When considering the whole farm, there are three main nutrient flow patterns, each one with implications for the long-term functioning of the farm and the environment: 1) imports of nutrients are less than exports, 2) imports are greater than exports or 3) imports are equal to exports.

Imports are less than exports. Farms with a negative *nutrient balance* are "living off capital" and drawing down the supplies of nutrients from minerals and organic matter. This can continue for a while, just like a person can live off savings in a bank account until the money runs out. But at some point, the availability of one or more nutrients or organic matter (carbon) becomes so low that crop yields decrease. If this condition is not remedied, the farm becomes less and less able to produce food, and its economic condition will decline. This is clearly not a desirable situation for either the farm or the country. Unfortunately, the low productivity of much of Africa's agricultural lands is partially caused by this pattern of nutrient and carbon flows, as increasing populations put pressure on farmers to increase land-use intensity, fertilizer prices are high for poor farmers and little attention is paid to soil organic matter. In previous times under the system of shifting cultivation, agricultural fields would have been allowed to return to forest for 20 or more years, during which time there would have been a natural replenishment of nutrients and organic matter. One of the greatest challenges of our era is to increase the fertility of the soils of Africa, both by using fertilizers and by using ecologically sound practices that increase soil health.

Imports and exports are close to balanced. From the environmental perspective and for the sake of long-term soil health, fertility should be raised to, and then maintained at, optimal levels. The best way to keep desirable levels once they are reached is to roughly balance inflows and outflows. Soil tests can be very helpful in fine-tuning a fertility program and making sure that levels are not building up too high or being drawn down too low (see Chapter 21). This can be a challenge and may not be economically possible for all farms. Farms that exclusively grow grain or vegetables have a lot of nutrients flowing onto the farm and relatively high annual carbon and nutrient exports when crops are sold (Figure 7.5a). Nutrients usually enter these farms as either commercial fertilizers or various amendments and leave the farm as plant products. Some cycling occurs as crop residues are returned to the soil and decompose. But a large outflow of carbon and nutrients is common on farms that sell considerable volumes of grains and vegetables per acre. For example, the annual export of nutrients is about 135 pounds of nitrogen, 25 pounds of phosphorus and 35 pounds of potassium per acre for corn grain and about 150 pounds of nitrogen, 20 pounds of phosphorus and 130 pounds of potassium per acre for grass hay. An acre of tomatoes or onions usually contains over 100 pounds of nitrogen, 20 pounds of phosphorus and 100 pounds of potassium. Generally, 50–60% of the carbon is harvested and exported off the farm, which in the case of corn grain amounts to about 3 tons of carbon per acre per year. But, of course, the whole point of farming in a modern society is to produce food and fiber for the non-farming public. This by necessity implies the off-farm export of carbon (sugars, starches, proteins and so on) and crop nutrients.

It should be fairly easy to balance nutrient inflows and outflows on crop farms, at least theoretically, but carbon cycling is difficult. In practice, under good management, nutrients are gradually depleted by crops until soil test levels fall too low, and then they're raised again with fertilizers. But leftover residue (carbon-based plant material in aboveground residue and roots) from annual crops doesn't normally replace the organic matter lost during the year of cropping. Replenishing extra soil carbon occurs only when applying organic fertilizers like manure or compost, through intensive cover cropping, or by adding perennial hay (grass/legume) crops to the rotation.

On integrated crop-livestock farms that produce their own feed, imports and exports of nutrients should be relatively small relative to the land farmed and close to balanced. Few nutrients or carbon leave the farm (they leave only as sold animals) and few are brought onto the farm (Figure 7.5b). Most of the nutrients on this type of operation complete a true cycle on the farm: They are taken up from the soil by plants, which are eaten by the animals, and most of the nutrients are then returned to the soil as manure and urine. And most of the carbon fixed by plants stays on the farm with crop residues and animal manure. A similar flow pattern with few nutrients coming onto the farm and few leaving occurs on a grass-fed beef operation that uses little to no imported feed.

It is easier to balance nutrient imports and exports on a mixed crop-livestock and grass-fed beef farms than on either a crop farm or a livestock farm that depends significantly on imported feeds. So if all the feeds are farm grown, adding an animal enterprise to a crop farm may lower the nutrient and carbon exports (Figure 7.5b).

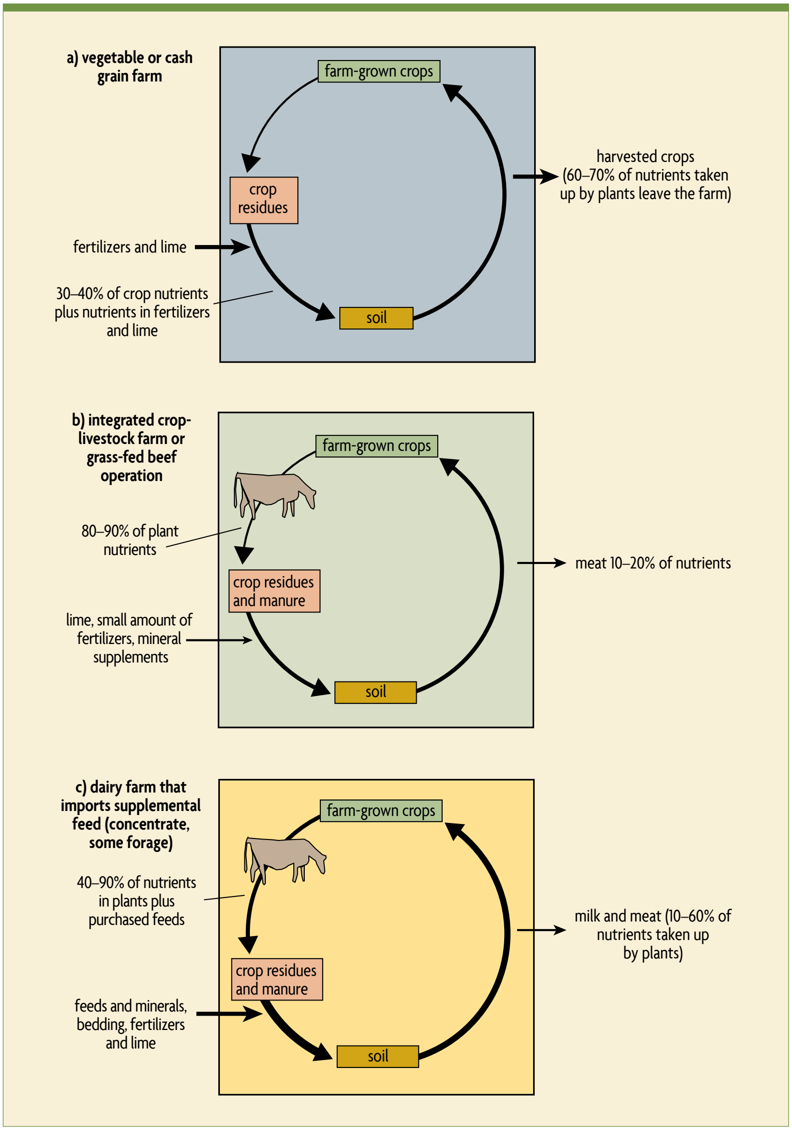

Figure 7.5. Nutrient flows and cycles on (a) a crop farm, (b) a grass-fed beef or other integrated crop-livestock farm, and (c) a dairy farm.

Imports are larger than exports. Animal farms with inadequate land bases to produce all needed feed pose a different type of problem (Figure 7.5c). As animal numbers increase relative to the available cropland and pasture, larger purchases of feeds (containing nutrients) are necessary. As this occurs, there is less land available, relative to the nutrient loads, to spread manure. If the excess manure is not moved to another farm, the operation may exceed the capacity of the land to assimilate all the nutrients, and pollution of ground and surface water occurs. For example, in a study of New York dairy farms, as animal density increased from around 1/4 of an animal unit per acre (1 AU = one 1,000-pound animal, or a number of animals that together weigh 1,000 pounds) to over 1 AU per acre, the amount of N and P remaining on farms increased greatly. When there was 1/4 AU per acre, imports and exports were pretty much in balance. But at 1 AU per acre, around 150 pounds of N and 20 pounds of P remained on the farm per acre each year.

Many dairy farms do not have the land base to grow all their needed feed and tend to emphasize growing forage crops. But the cows also need grain supplements and this situation involves additional sources of nutrients coming onto the farm. Concentrates (commonly mixtures containing corn grain and soy) and minerals usually comprise a larger source of nutrient inputs than fertilizers. In a study of 47 New York dairy farms, an average 76% of nitrogen came onto the farms as feeds and 23% as fertilizers. The percentages were pretty much the same for phosphorus (73% as feeds and 26% as fertilizers). Most of the nutrients consumed by animals end up in the manure, from 60% to over 90% of the nitrogen, phosphorus and potassium. A portion of carbon even comes onto the farm in purchased concentrate feed, and sometimes as bedding for the cows. The nutrients and carbon in manure that came from farm-grown feed sources are completing a true cycle. But the portion of nutrients in manure that originally entered the farm as purchased feeds and mineral supplements are *not* participating in a true cycle. These are completing a flow that might have started in a far-away farm, mine or fertilizer factory and are now being transported from the barn or feedlot to the field.

Compared with crop farms, where a high percentage of the crop grown is sold, fewer nutrients and carbon flow from dairy farms per acre and more stay on the farm, either completing a true cycle (soil to plant to animal to soil) or completing a flow (imported concentrate feed and minerals to cows to manure to soil). Because of the additional feed imports, nutrients will tend to

N BALANCE AS AN ENVIRONMENTAL INDICATOR

Higher nutrient imports than exports is not limited to livestock-based operations, especially with nitrogen. Most grain farms in the developed world import more nitrogen than they export through their crops, meaning the *N balance* is positive. As we discuss in Chapter 19, nitrogen is difficult to manage and some losses as nitrate leaching and N_2O gaseous losses are unavoidable. The extent of losses is heavily dependent on how the farm manages the nitrogen through good timing and rates of applications, and through using the best product formulations and placement methods when applying commercial fertilizers. Recent research explored the use of the *N balance* as a simple and easily measured metric for sustainable N use. It is calculated as *N inputs through nutrient additions minus N outputs through crop harvest* on a seasonal basis. Optimum N balances are generally between 0 and +50 pounds per acre. If the N balance is below 0, the soil is being mined of nitrogen. If it is above 50 pounds per acre, there is excess that causes environmental damage. The 50 pounds per acre allowance reflects the fact that N use is never 100% efficient and some modest losses are often unavoidable under current practices. It is difficult for farmers to reach the optimum N balance range if they don't carefully manage the nitrogen through the 4R practices (Chapter 18) and through the use of cover crops to catch excess nitrogen at the end of the season (Chapter 10). Better rotations that include crops that leach very low amounts of nitrate will reduce the *average* losses over the period of the rotation.

accumulate on the farm and may eventually cause environmental harm from excess nitrogen or phosphorus. This problem of continual nutrient buildup exists for any animal farm that imports a significant percentage of its feed. The reliance on perennial forages plus imported feed and minerals, and certain types of bedding material, may increase carbon (soil organic matter) levels in the soil until they reach the soil's saturation level. To put it another way, these farms don't have an adequate land base to produce all their feed and therefore also have an inadequate land base on which to apply their manure at environmentally safe rates. The ultimate situations of this kind are found with animal operations that import all feeds and have a limited land base to use the manure; these have the greatest potential to accumulate high amounts of nutrients. Contract growers of poultry, with tens of thousands of chickens and few acres of land, are an example of this.

If there is enough cropland to grow most of the grain and forage needed, the result will be low amounts of imported and exported (as animal products) nutrients. It is therefore easier to rely on nutrient cycling on a mixed livestock-crop farm that produces most of its feed than on a farm growing only crops. An alternative is exchanges among neighboring farms. Since crop farms tend to have nutrient and carbon deficits, and livestock farms have excesses, transferring the excess manure or compost offers opportunities for more cycling and less environmental losses, as well as for improving soil health on the recipient farm (see Chapter 12).

The situation of imports greatly exceeding exports does not only occur on animal farms without sufficient land to grow all the needed feed. Organic vegetable farmers commonly import composted manure to supply nutrients and maintain or increase soil organic matter levels. In a survey from 2002 through 2004 of 34 organic farms from seven states in the Northeast, approximately half of the fields were found to have excessive levels of phosphorus. Other ways need to be found to add organic matter through on-farm practices such as the use of green manures, cover crops and rotations with perennial forages.

Distribution on the farm. A farm may aim to balance imports and exports of nutrients and carbon, but it also needs to aim for an optimum *distribution* onto its fields. For a portion of the year livestock farms typically concentrate their animals in barns or lots where the feed is brought in and the manure accumulates. It then needs to be returned to the fields, which in some cases may be distant from the barns/feedlots and more difficult to reach, especially with adverse weather. In the past, fields around barns received much more manure and typically had excess nutrients compared to those farther away. But with regular soil testing and good manure management planning, farms can balance nutrients and carbon for each individual field. Moreover, livestock farms that use well-planned rotational pasture systems, common in places like New Zealand, don't have manure transportation issues and prevent nutrient concentration.

FLOW PATTERNS AT LARGE SCALE

We have looked at carbon and nutrient balances on farms, but a larger-scale break in nutrient cycling occurs as agricultural products are shipped long distances across continents or even oceans. When you deliver a train or boat load of grain from the Midwest to the eastern United States, or even from Brazil to Asia, *a lot* of carbon and nutrients are flowing and don't return. The international trade in agricultural commodities such as corn, soybeans and wheat means that significant quantities of the basic ingredient of soil health are shipped overseas. (It is worth noting because it takes so much water to produce grains: around 110 gallons (approximately 900 pounds) of water to produce one pound of corn grain or soybeans. In essence, water is also being shipped abroad embedded in the agricultural exports.)

Long-distance transportation of nutrients and carbon is central to the way the modern food system

UNINTENDED NUTRIENT LOSSES

Potential problems can occur even when fertilizer imports and crop exports are more or less in balance.

This chapter considers the planned flows of nutrients and carbon purchased from off the farm as fertilizers, lime and feeds, and leaving the farm in the agricultural products sold. But what about the unintended losses of nutrients? When imports are greater than exports, nutrients accumulate on the farm and significant amounts may be lost by leaching to groundwater or in runoff waters with resulting environmental damage. Nitrogen and phosphorus are the main nutrients that flow from farms that become water pollutants.

However, even when imports and exports are approximately the same, significant unintended losses may occur. This is a concern with many crops but especially with corn production, and it becomes a substantial regional problem when a large portion of the land is devoted to this crop. With high-yielding corn, the amount of N fertilizer applied may be similar to the amount taken up by the corn: perhaps 150–160 pounds of N applied in fertilizer versus 160 pounds in the corn grain. But a lot of the N applied is tied up in organic matter or lost by leaching or denitrification. On the other hand, soil organic matter decomposes during the season and can provide a lot of nitrogen to plants. Potential pollution problems arise when the *combination* of soil-derived and fertilizer-derived available nitrogen greatly exceeds the crop's need.

When corn goes through its two-month-long growth spurt, it increases rapidly in height and then fills its grain. During this phase it needs to take up large quantities of nitrogen each day, usually as nitrate. This means that high concentrations of nitrate in the soil solution are needed during this period. The problem occurs when such large amounts are supplied from fertilizer or manure applications, and when the soil is *also* continuing to supply even more nitrate from decomposing organic matter. In most years there's a lot of nitrate left over after corn harvest that can leach into groundwater during the fall, winter or early spring. Rates of loss depend on the amount of precipitation during these periods but can be in the range of 30–70 pounds per acre (excess nitrate may also be converted into the greenhouse gas nitrous oxide).

The best ways to decrease soil nitrate at the end of the season and to limit nitrate losses are to 1) precisely predict the crop's seasonal needs, accounting for all N sources including fertilizer and organic; 2) time N application close to when the crop needs it; and 3) plant a quick-establishing cover crop such as cereal rye to catch excess N. But, rotations with corn appearing less frequently would also help reduce nitrate pollution of water.

functions. On average, the food we eat has traveled about 1,300 miles from field to processor to distributor to consumer. Exporting wheat from the Pacific Northwest and soybeans from the Midwest of the United States to China involves even longer distances, as does importing apples from New Zealand to Los Angeles. The nutrients in concentrated commercial fertilizers also travel large distances from the mine or factory to distributors and then to the field, like potassium from Saskatchewan to Ohio, or phosphorus from Morocco to Germany. The specialization of the corn and soybean farms of the Midwest and the hog and chicken mega farms centralized in a few regions, such as Arkansas, the East Coast's Delmarva Peninsula and North Carolina, has created a unique situation. This regional specialization of farms appears to make economic sense (or perhaps not?) but disrupts the nutrient and carbon cycles that maintain soil health. The nutrients from crop farms travel a long way to animal farms and are replaced with fertilizers from a completely different place. Meanwhile, the animal farms become overloaded with nutrients. The carbon exported from the crop farms never replaces the organic matter lost during the year.

Of course, the very purpose of agriculture in the modern world—the growing of food and fiber and the use of the products by people living away from the farm—results in a loss of nutrients from the soil, even under the best possible management. In addition, leaching losses of nutrients, such as calcium, magnesium and potassium, are accelerated by acidification, which occurs naturally or can be caused by the use of some fertilizers. Soil minerals, especially in the "young" soils of glaciated regions and in arid regions not subject to much leaching, may still supply lots of phosphorus, potassium, calcium, magnesium and many other nutrients even after many years of cropping. A soil with plentiful active organic matter also may supply nutrients for a long time. A mixed crop-livestock system that exports only animal products cycles the nutrients and carbon well, and it may take a long time to deplete a rich soil because few nutrients are exported with those products.

But for crop farms, especially in humid regions, the depletion occurs more rapidly because more nutrients are exported per acre each year. Eventually a continually cropped soil becomes nutrient depleted, and sooner or later you will need to apply some phosphorus or potassium. Nitrogen is the only nutrient you can "produce" on the farm: legumes and their bacteria working together can remove nitrogen gas from the atmosphere and change it into forms that plants can use.

The issue eventually becomes not whether nutrients will be imported onto the farm but rather what source of nutrients you should use. Will the nutrients brought onto the farm be commercial fertilizers; traditional amendments (limestone); biologically fixed nitrogen; imported feeds or minerals for livestock; organic materials such as manures, composts, and sludges; or some combination of sources? Some nutrient sources are nutrient dense and therefore efficiently transported and applied, like inorganic fertilizers. But they don't provide the benefits of carbon, which is critical to the biological processes in the soil. Organic sources provide the benefits of both nutrients and carbon, but the nutrients are in low concentrations and expensive transport effectively restricts their application to nearby locations.

Finally, a few words about a positive aspect of large-scale nutrient flows. National and international food trade occasionally provides benefits by reducing the effects of regional micronutrient deficiencies in the importing country. For example, selenium is a trace element that most humans and animals acquire from the soil through their diets. European selenium intake is enhanced by importing wheat grown on U.S. soils, which are naturally higher in the nutrient.

SUMMARY

The cycling and flow of nutrients and carbon have been critical to agriculture since its beginning. Soils along water courses amassed sediments and nutrients from upriver regions and allowed for sustained productivity. Most other areas experienced losses associated with soil degradation. There is good nutrient cycling when crop residues or animal manures are returned to the soil and feed the subsequent crops. However, there are potentially large flows of nutrients and carbon into and out of farms, and we are concerned about cases where the flows are very unbalanced. The inflow occurs as commercial and organic fertilizers or animal feeds are imported onto the farm. Managed exports are mainly in the form of crops and animal products. In general, larger amounts of nutrients are exported off the farm in vegetation (grains, forages, vegetables, etc.) than in animal products. This happens because a high percent of the nutrients and carbon in the feeds pass through the animal and stay on the farm as manure, and relatively few are exported in the form of milk, meat, wool, etc.,

GLOBAL GRAIN TRADE AND NUTRIENT-CARBON FLOWS

Several grain and oil crops are heavily traded around the world, including wheat, corn, soybeans, rice and oilseeds. They greatly impact the global flow of nutrients and carbon, the basic ingredients for healthy soil. The most prominent transfers involve corn and soybeans shipped from the Americas to East Asia, Europe and the Middle East. Why is that?

The import of these grain crops is heavily driven by higher demand for animal protein and edible oils as a result of rising living standards and diversifying diets. Growing these crops also requires a large land base that many countries do not have. Japan and Korea are populous but also quite mountainous. The Middle East and Mexico are dry, and Europe has more animals than it can feed from its own land. China is by far the largest grain importer, especially of soybeans, because of agronomic constraints and domestic policies that prioritize growing cereal crops that meet basic food security. A large portion of the crops that feed its animals are therefore imported. (China raises about half the world's pigs.)

The Americas have a large agricultural land base and are the primary exporter of those grains, with the United States, Brazil and Argentina accounting for almost 90% of the soybean and 75% of the global corn exports that are mostly used to raise animals in other parts of the world (Figure 7.6). These countries also have policies that promote grain production and exports. U.S. grain areas have been fairly stable over the past decades, but the South American countries have met the higher global demand by putting extensive areas of grassland, savannah and even rainforest into crop production.

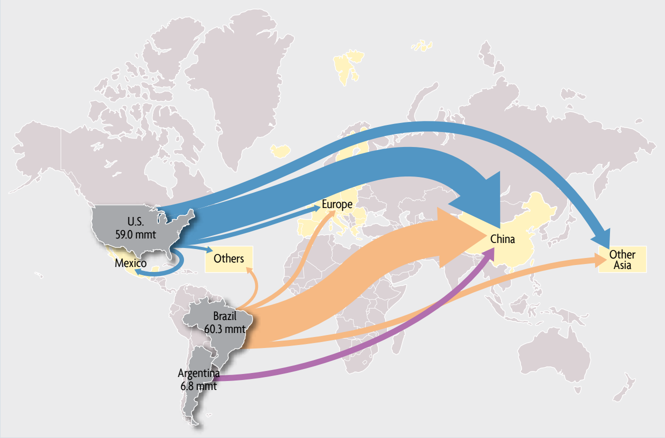

Figure 7.6. Leading exporters and destinations of soybeans during 2016/2017. Carbon and nutrients are reallocated and impact soils on both sides. *Source*: USDA-ERS.

Wheat and rice are different, not only because they are mostly consumed directly by humans. Wheat export is more balanced among countries with Russia (20%), Canada (14%), the United States (13%), France (10%), Australia (8%) and Ukraine (7%) being the top exporters. Rice tends to be grown more for domestic consumption and therefore not exported as much, but India (30%) and Thailand (23%) are the main international suppliers.

With the large transfer of grains, and associated carbon and nutrients, from one region to another, deficiencies are created with the exporters and excesses with the importers. Evidence is emerging that the breadbasket soils in the Americas are becoming less healthy and have lost organic matter. The importing countries have many livestock farms that accumulate nutrients and have water pollution concerns. Hypoxia (dead zones) is an increasing problem in the seas around Japan, Korea, China and northern Europe.

compared to farms exporting their crops.

Our modern agricultural system has intensified problems with nutrient flows. Negative balances of nutrient and carbon flows are of great concern because the soil degrades as their levels decline. On the other hand, when nutrient balances are highly positive and build up on the farm, they tend to be more readily lost to the environment. Cash grain farm regions like the Midwestern United States and Brazil export a lot of nutrients and carbon, and also lose nutrients to the environment due to inefficient fertilizer use to replace the lost nutrients. Regions that import a lot of grain to feed livestock create excessive levels of carbon and nutrients. All these farms negatively impact water quality, marine ecosystems and greenhouse gas emissions.

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PART
3

ECOLOGICAL SOIL MANAGEMENT

Photo by Francesco Ridolfi

Chapter 8

SOIL HEALTH, PLANT HEALTH AND PESTS

There are few farms in this or any country that
are not capable of great improvement.

—LUCIUS D. DAVIS, 1830

SOIL PROPERTIES AND THEIR INTERRELATIONSHIPS

Healthy soils occur when their biological, chemical and physical conditions are all optimal (Figure 8.1), enabling high yields of crops and other important soil functions. When this occurs, roots are able to proliferate easily; plentiful water enters and is stored in the soil; the plant has a sufficient nutrient supply; there are no harmful chemicals in the soil; and beneficial organisms are very active and able to keep potentially harmful ones in check as well as stimulate plant growth.

A soil's various properties are frequently related to one another, and the interrelationships should be kept in mind. For example, when a soil is compacted, there is a loss of the large pore spaces, making it difficult or impossible for some of the larger soil organisms to move or even survive. (You often don't find earthworms in compacted soils.) In addition, compaction may make the soil waterlogged, causing chemical changes such as when nitrate (NO_3^-) is denitrified and lost to the atmosphere as nitrogen gas (N_2) and the greenhouse gas N_2O. When soils contain a lot of sodium, common in arid and semiarid climates, aggregates may break apart and cause the soils to have few pore spaces for air exchange as well as water drainage into the subsoil. Plants will grow poorly in a soil that has low organic matter content and degraded structure even if it contains an optimum amount of nutrients. Therefore, to prevent problems and develop soil habitat that is optimal for plants, we can't just focus on one aspect of soil but must approach crop and soil management from a holistic point of view.

ECOLOGICAL PRINCIPLES FOR AGRICULTURE

Approaching agriculture and soil management from an ecological point of view means first understanding the characteristics that comprise resilient and relatively stable natural systems. Then, let's take a look at overall strategies that can contribute to similar resilience and health of crops, animals and farms. Finally, we'll briefly discuss practices that contribute to creating vital and strong agricultural systems (discussed in more detail in later chapters).

Photo courtesy Judy Brossy

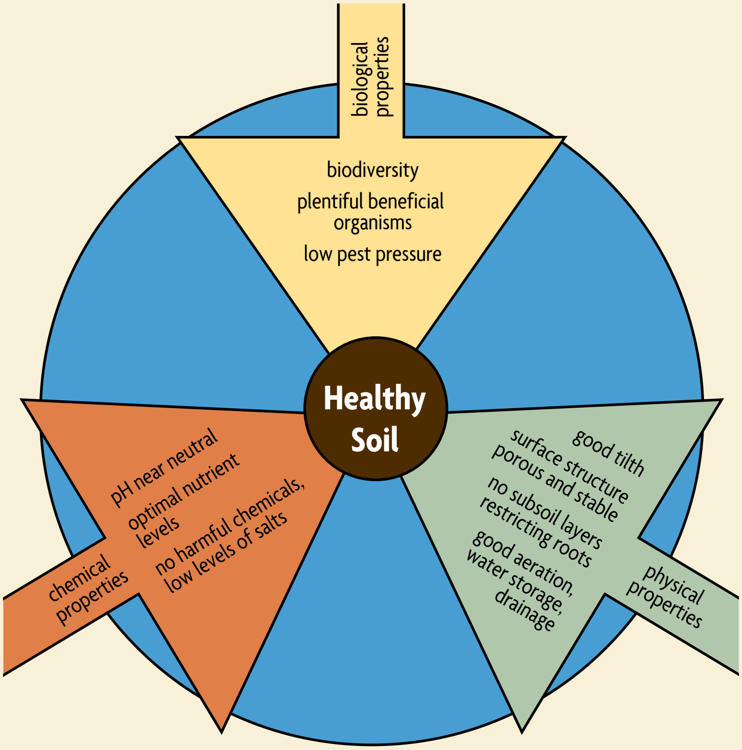

Figure 8.1. Optimal chemical, biological and physical properties promote healthy soils.

Ecological crop and soil management practices can be grouped under one or more of three strategies:

- grow healthy plants with strong defense capabilities
- suppress pests
- enhance beneficial organisms

These overall strategies are accomplished by practices that maintain and enhance the habitat both aboveground and belowground. And as the field habitat improves, so does the environment in general: less pollution of groundwater and surface water and more wildlife habitat in and surrounding the field.

Ecological approaches call for designing the field and farm to take advantage of the inherent strengths of natural systems. Most of this is done prior to, and during, planting a crop and has the goal of preventing problems from developing by contributing to one or more of the three overall strategies. In other words, it requires forethought and good planning.

Many natural, relatively undisturbed, systems are generally stable, and when disturbed by natural forces such as fire, wind or excess rain they are able to bounce back fairly rapidly. In other words, they are *resilient*. These resilient systems tend to have similar general characteristics:

Efficient. Natural systems have energy flows that efficiently use resources. The sun's energy captured by green plants is used by many organisms, as fungi and bacteria decompose organic residues and are then fed upon by other organisms, which are themselves fed upon by others higher up the food web. Natural

MANAGING SOILS AND CROPS TO MINIMIZE PEST PROBLEMS

It is well established and known by most farmers that crop rotation can decrease many disease, insect, nematode and weed pressures. A few other examples of management practices that reduce crop losses:

- Insect damage can be reduced by avoiding excess inorganic nitrogen levels in soils by using precision nitrogen management.
- Adequate nutrient levels reduce disease incidence. For example, calcium applications have reduced diseases in crops such as wheat, peanuts, soybeans and peppers, while added potassium has reduced the incidence of fungal diseases in crops such as cotton, tomatoes and corn.
- Damage from insects and diseases (such as fungal diseases of roots) can be decreased by lessening soil compaction.
- The severity of root rots and leaf diseases can be reduced with composts that contain low levels of available nitrogen but still have some active organic matter.
- Many pests are kept under control by having to compete for resources or by direct antagonism from other insects (including the beneficials feeding on them). Good quantities of a variety of organic materials help maintain a diverse group of soil organisms.
- Root surfaces are protected from fungal and nematode infection by beneficial mycorrhizal fungi. Most cover crops, especially in reduced tillage systems, help keep mycorrhizal fungi spore counts high and promote higher rates of colonization by the beneficial fungi in the following crop.
- Parasitic fungal and nematode infections can be suppressed by selected cover crops.
- Weed seed numbers are reduced in soils that have high biological activity, with both microorganisms and insects helping the process.
- Weed seed predation by ground beetles is encouraged by reduced tillage and maintenance of surface residues. Reduced tillage also keeps the weed seeds at the soil surface, where they are accessible to predation by other organisms, such as rodents, ants and crickets.
- Residues of some cover crops, such as cereal rye, produce chemicals that reduce weed seed germination.

ecosystems also tend to be efficient in capturing and using rainfall and in mobilizing and cycling nutrients. This helps to keep the ecosystem from “running down” because of excessive loss of nutrients and at the same time helps maintain the quality of the groundwater and surface waters. Rainfall tends to enter the porous soil, rather than run off, providing water to plants as well as recharge to groundwater, slowly releasing water to streams and rivers.

Diverse. High biological diversity, both aboveground and in the soil, characterizes many resilient natural ecosystems in temperate and tropical regions. It provides nutrients to plants, checks on disease outbreaks, etc. For example, a diversity of plants—trees versus understory, grasses versus legumes—captures and supplies different resources. And competition for resources and specific antagonisms (such as antibiotic production) from the multitude of soil organisms usually keeps soilborne plant pathogens from causing diseases in a natural grassland or forest.

Self-sufficient. A consequence of efficiency and diversity in natural terrestrial ecosystems is that they become mainly self-sufficient, requiring only inputs of sunlight and rainfall.

Self-regulating. The great diversity of organisms decreases the risk of outbreaks (or huge population increases) of pathogens or insects severely damaging plants or animals. In addition, plants have a number of defense mechanisms that help protect them from attack.

These ecological characteristics provide a good framework for sustainable management of fields and farms, but we must also recognize that crop production (and even urban landscaping for that matter) is a process that greatly disturbs natural ecosystems in order to favor one or a few organisms (crop plants) over the competing interests of others. And systems are also disturbed in other ways to be able to produce crops. Routine management practices that occur during the season cause disturbances even if you have invested heavily in preventive management. For example, irrigation is frequently needed for high-value crops such as fresh market vegetables, even in humid regions. Some practices have little direct disturbance, such as scouting for pests and beneficial insects during the season. If an unanticipated problem, such as an insect outbreak, arises, remedial action, such as applying the most ecologically sound pesticide or releasing purchased beneficials into the field, may be required to reduce crop losses.

With currently available pesticides, the temptation exists to simply wipe out competitors—for example through soil fumigation or broad-spectrum herbicides like glyphosate—but this creates dependency on purchased materials from off the farm and weakens the overall resilience of the soil and cropping system. It also promotes genetically induced resistance to these chemicals and makes them less effective in the long run. The goal of ecological crop and soil management is to be *proactive* and *preventive* by creating conditions that help grow healthy plants, promote beneficials and suppress pests, and thereby minimize the extent of *reactive management* (which responds to unanticipated occurrences). The discussion below and in the rest of this book focuses on ways to maintain soil health and to enhance habitat in order to promote one or more of the three strategies listed above.

ECOLOGICAL CROP AND SOIL MANAGEMENT

We'll discuss ecological crop and soil management practices as part of a general framework (Figure 8.2). The heart of the matter is that the strength of the system is enhanced by creating improved habitat both aboveground and in the soil. Although it is somewhat artificial to talk separately about aboveground and the soil habitat—many practices help both at the same time—it makes many issues clearer. Not all of the aboveground discussion refers directly to management of soil, but most does. In addition, the practices we'll discuss contribute to one or more of the overall strategies: 1) growing healthy plants with strong defense capabilities in healthy soils, 2) suppressing pests, and 3) enhancing beneficial organisms.

Aboveground Habitat Management

There are numerous ways that the aboveground habitat can be improved:

- Select crops and varieties that are resistant to local pests (in addition to having other qualities such as yield, taste, etc.).
- Use appropriate planting densities (and companion crops) to help crops grow vigorously, smother weeds and (with companion crops) provide some protection against pests. In some cases, use blends of two or more varieties (cultivars) of the same crop. For example, combining one variety that is susceptible to a pest or drought but has a higher yield potential with one that's resistant and resilient has shown potential for increasing total yields for wheat and rice. Even though the farmer is growing the same crop, increased genetic diversity due to using dif-

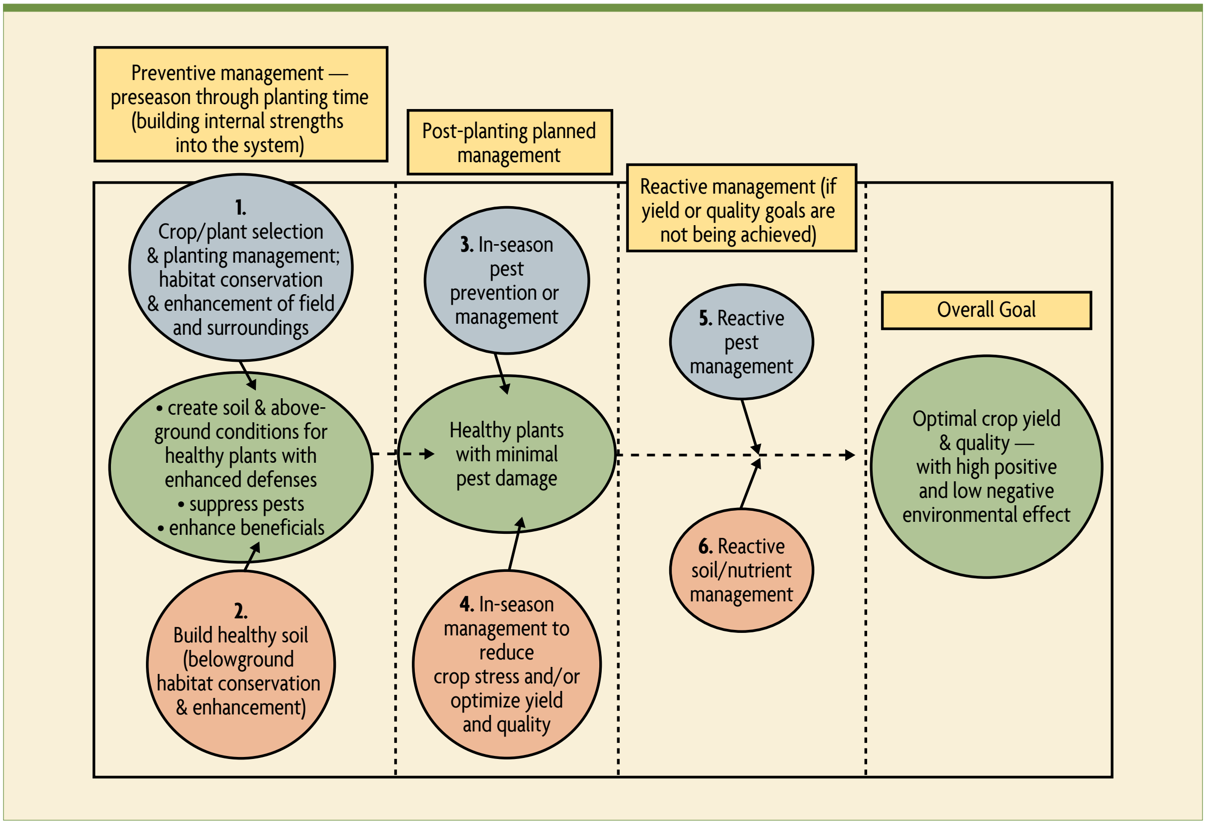

Figure 8.2. A whole-system approach to soil and crop management at the field level. Modified from Magdoff (2007).

ferent varieties seems to provide some protection. Perhaps there are possibilities for intercropping with rows of different crop types such as sunflowers with soybeans or peas.

- Plant perimeter (trap) crops that are more attractive to a particular pest than the economic crop(s) growing in the middle of the field and so can intercept incoming insects. This has been successfully practiced by planting Blue Hubbard squash on the perimeter of summer squash fields to intercept the striped cucumber beetle. The push-pull system practiced in East Africa goes a step further by planting the low-growing legume *Desmodium* within corn rows as a repellent plant for stem borers (push), and grasses along the field perimeter to attract the adult insect moths (pull), while also providing nitrogen and suppressing weeds.
- Create field boundaries and zones within fields that are attractive to beneficial insects. This usually involves planting a mix of flowering plants around or as strips inside fields to provide shelter and food for beneficials.
- Use cover crops routinely for multiple benefits, such as providing habitat for beneficial insects, adding nitrogen and organic matter to the soil, reducing erosion and enhancing water infiltration into the soil, retaining nutrients in the soil, and much more. It is possible to supply all of the nitrogen to succeeding crops by growing a vigorous winter legume cover crop, such as crimson clover in the southern United States and hairy vetch in the north.

- Use rotations that are complex, involve plants of different families and, if at all possible, include sod crops such as grass/clover hay that remain without soil disturbance for a number of years.
- Reduce tillage. This is an important part of an ecological approach to agriculture. Tillage buries residues, leaving the soil bare and more susceptible to the erosive effects of rainfall, while also breaking up natural soil aggregates. (The use of practices that reduce erosion is critical to sustaining soil productivity.) Some of these practices, such as the use of cover crops and more complex rotations, and reducing tillage, will also be mentioned below under "Enhancing Soil Habitat" and discussed in detail in later chapters.

Belowground Habitat Management

The general practices for improving the soil as a place for crop roots and beneficial organisms are the same for all fields and are the focus of our discussions in the next chapters. The real questions: which ones are best implemented, and how are they implemented in a specific situation (farm or other)? The approaches and practices are discussed in detail in Part 3 of this book, but Table 8.1 summarizes these management approaches and refers the reader to the appropriate chapters. In the final chapter (24) we discuss how all these considerations can be put together into an integrated soil health management approach.

PLANT DEFENSES, MANAGEMENT PRACTICES AND PESTS

After discussing the key ecological principles and approaches to soil management, let's do a deeper dive and see how amazing plants really are. They use a variety of systems to defend themselves from attack by insects and disease-causing pathogens. Sometimes they can just outgrow a small pest problem by putting out new root or shoot growth. Many plants also produce chemicals that slow down insect feeding. While not

Table 8.1
Management Goals, Approaches and Practices of Soil Health

Overall Goals grow healthy plants, suppress pests, enhance beneficial organisms, all while improving the surrounding environment	
Management Approaches and Practices	**Where Discussed**
Minimize soil disturbance and reduce compaction using reduced tillage, better rotations, controlled field traffic, staying off wet soils, compaction remediation, etc.	**Chapters 11** (rotations), **14** (reducing runoff and erosion), **15** (addressing compaction), **16** (reducing tillage), **22** (urban soils)
Keep soil covered with crop residue, rotations with perennial forages, and by growing cover crops, which also helps to maintain continual presence of living roots in soil.	**Chapters 10** (cover crops), **11** (rotations), **16** (reduced tillage)
Maximize biodiversity in soil and aboveground through more complex rotations, frequent cover crops, integrated livestock and crop farming, and applying different types of organic matter amendments such as animal manures and composts.	**Chapters 10** (cover crops), **11** (rotations), **12** (livestock-crop integration), **13** (making and using composts)
Manage water to promote timely fieldwork and crop needs.	**Chapters 14** (reducing runoff and erosion), **15** (preventing and lessening compaction), **17** (irrigation and drainage)
Maintain pH within desired range and nutrients at levels that supply plants with sufficient amounts but without excess loss to the environment by routinely testing soils and applying nutrients, lime and other amendments based on results, frequently using cover crops, addressing salt problems, and integrating livestock and crop farming.	**Chapters 18** (nutrient management), **19** (managing nitrogen and phosphorus), **20** (nutrients, CEC, alkalinity, and acidity), **21** (soil tests and their interpretation), **23** (use soil health testing)

A DIFFICULT PEST: SYMPHYLANS

Throughout this publication we emphasize the importance to soil health of organic matter and biodiversity, as well as of developing and maintaining good soil structure. However, there is a soilborne arthropod that thrives in soils with good organic matter content and that can cause major damage to a wide variety of crops. *Symphylans*, which are white and look like a centipede, feed mainly on root hairs and rootlets. They can move around easily with favorable soil structure, lots of old root channels and connecting pores. They occur usually with a spotty, circular distribution within certain parts of fields, and are more of a problem in certain geographic locations. Potatoes and beans appear to be less damaged by the pest, and it has been found that transplanted tomatoes do better than direct seeded ones when symphylans are present. While it is not established that other cover crops help reduce infestations, a spring oat cover crop may lessen damage to a subsequent crop. Increasing the planting density of squash has been shown to help maintain yields in the presence of the pest, though some thinning may be needed. Although some synthetic chemical controls are available, a lot more needs to be learned about how to manage this pest in ecologically sound ways. Care is essential when importing organic amendments: You do not want to introduce this pest by accident. And although there are organisms such as beetles, predatory mites and centipedes as well as fungal pathogens that feed on symphylans, a biologically active soil is not thought to be an adequate defense against this crop-damaging organism.

killing the insect, it at least limits the damage. Beneficial organisms that attack and kill insect pests need a variety of sources of nutrition, usually obtained from flowering plants in and around the field. However, when fed upon, by caterpillars for example, many plants produce a sticky, sweet substance from the wounds, called "extra-floral nectar," which provides some attraction and food for beneficial organisms. Plants under attack by insects also produce airborne (volatile) chemicals that signal to beneficial insects that the specific host it desires is on the plant. The beneficial insect, frequently a small wasp, then hones in on the chemical signal, finds the caterpillar and lays its eggs inside it (Figure 8.3). As the eggs develop, they kill the caterpillar. As one indication of how sophisticated this system is, the wasp that lays its eggs in the tomato hornworm caterpillar injects a virus along with the eggs that deactivates the caterpillar's immune system. Without the virus, the eggs would not be able to develop and the caterpillar would not die. There is also evidence that plants near those with feeding damage sense the chemicals released by the wounded leaves and start making chemicals to defend themselves even before they are attacked.

Leaves are not the only part of the plant that can send signals that recruit beneficial organisms when under assault. When attacked by the western corn rootworm, a major pest, the roots of some varieties of corn have been shown to release a chemical that attracts a nematode that infects and kills rootworm larvae. During the process of breeding corn in the United States, this ability to signal the beneficial nematode has apparently been lost. However, it is present in wild relatives and in European corn varieties and is, therefore, available for reintroduction into U.S. corn varieties.

Plants also have defense systems to help protect them from a broad range of viral, fungal and bacterial pathogens. Plants frequently contain substances that inhibit a disease from occurring whether or not the plant is exposed to the disease organism. In addition, antimicrobial substances are produced when genes within the

CONFLICTING DISEASE MANAGEMENT ADVICE?

In this book we promote reduced tillage and retention of crop residues at the soil surface. But farmers are often encouraged to incorporate crop residues because they can harbor disease organisms. Why the conflicting advice? The major difference is in the overall approach to soil and crop management. In a system that involves good rotations, conservation tillage, cover crops, other organic matter additions, etc., the disease pressure is reduced as soil biological diversity is increased, beneficial organisms are encouraged and crop stresses are reduced. In a more traditional system, the susceptibility dynamics are different, and a pathogen is more likely to become dominant, necessitating a reactive approach. A long-term strategy of building soil and plant health should reduce the need to use short-term cures.

plant are activated by various compounds or organisms—or a pest—in the zone immediately around the root (the rhizosphere) or by a signal from an infection site on a leaf. This phenomenon is called "induced resistance." This causes the plant to form various hormones and proteins that enhance the plant's defense system. The resistance is called systemic because the entire plant becomes resistant to a pathogen, even far away from the infection site.

Plants have a number of defense systems that protect them from disease. Beneficial bacteria in soil surrounding the root (the rhizosphere zone) provide a first line of defense against soil-borne diseases by competition or antagonism. If the disease organism (let's say a fungus like *Rhizoctonia solani* that causes root diseases in seedlings of diverse crops such as wheat, rice, potatoes, tomatoes and sugarbeets) makes it through the rhizosphere and contacts the root surface, beneficial organisms living inside roots provide another line of defense by producing chemicals that attach the fungus.

Then the plant itself also can produce chemicals that help it resist the attack. There are two major types of induced resistance that are induced in response to signals from microorganisms: systemic acquired resistance (SAR) and induced systemic resistance (ISR) (Figure 8.4). SAR is induced when plants are exposed to a pathogen or even to some organisms that do not produce disease. Once the plant is exposed to the organism, it will produce the hormone salicylic acid and defense proteins that protect the plant from a wide range of pathogens. ISR is induced when plant roots are exposed to specific plant growth, promoting rhizobacteria (PGPR) in the soil. Once the plants are exposed to these, hormones (jasmonate and ethylene) are produced that protect the plants from various pests.

PLANT PESTS

A variety of organisms can harm crops, from pathogens such as viruses, bacteria and fungi to nematodes to insects to weeds. Even larger animals such as deer (or, in Africa, elephants) can significantly damage crops. There is nothing inherently bad about these organisms we commonly call pests. They're just doing what they naturally do in order to survive and reproduce. But when growing crops we need to minimize the damage done by such organisms. The key is doing so in environmentally sound ways: building healthy soils, using crop varieties with natural resistance, and using rotations and cover crops that suppress pests while providing many other benefits as well.

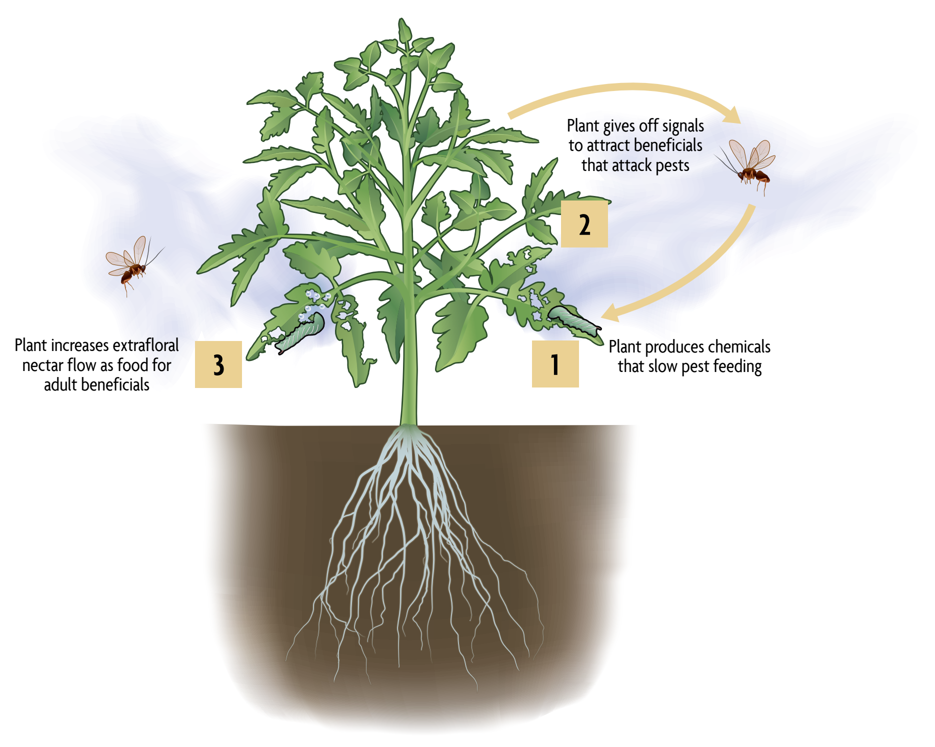

Figure 8.3. Plants use a number of defense strategies following damage by feeding insects. Modified from unpublished slide of W.J. Lewis. Illustration by Vic Kulihin.

Some organic amendments have been shown to induce resistance in plants, and farmers who have very biologically active soils high in organic matter may already be taking advantage of it, as well as of other ways pests are controlled in such soils. However, there currently are no reliable and cost-effective indicators to determine whether a soil amendment or soil is enhancing a plant's defense mechanisms. More research needs to be conducted before induced resistance becomes a dependable form of pest management on farms. Although the mechanism works very differently from the way the human immune system works, the effects are similar: the system, once it's stimulated, offers protection from attack by a variety of pathogens and insects.

When plants are healthy and thriving, they are better able to defend themselves from attack and may also be less attractive to pests. When under one or more stresses, such as drought, nutrient limitations or soil compaction, plants may "unwittingly" send out signals to pests saying, in effect, "Come get me, I'm weak." Vigorous plants, taller and with more extensive root systems, are also better competitors with weeds as they are able to shade them out or just compete well for water and nutrients.

Many soil management practices discussed in this chapter and in the other chapters in Part 3 help to reduce the severity of crop pests. Healthy plants growing in soils with good biological diversity can mount a strong defense against many pests (see text box). Ecological soil and plant management is so critical to plant health because it helps to suppress pest populations and also influences, as we have just seen, the ability of plants to

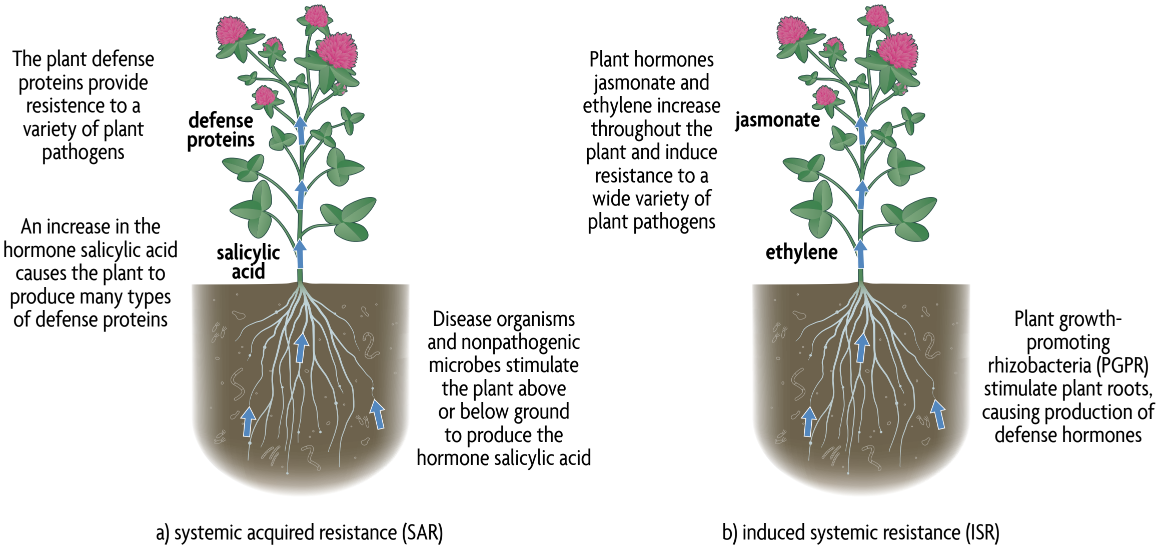

Figure 8.4. Types of induced resistance to plant diseases. Modified from Vallad and Goodman (2004) by Amanda Gervais. Illustration by Vic Kulihin.

resist pests. Developing optimal soil health is, therefore, the basis for management of crop pests on farms; it should be a central goal that underpins crop integrated pest management (IPM) programs.

INOCULATE WITH BENEFICIAL ORGANISMS?

The practices we discuss later in this part of the book—using cover crops, improving rotations, integrating animals and livestock, using composts and other organic materials, reducing tillage, reducing compaction, and so on—are all aimed at improving the soil's biological, chemical and physical health. Many of these are the same practices that people refer to when they discuss "biological soil management" or "biological fertility management." A result of following these practices should be soil rich in biological diversity with highly active organisms. In this soil condition there would usually be little advantage to applying beneficial organisms to seeds or transplant roots. However, even with high biological diversity with active organisms, it is still recommended to inoculate legume seeds with the appropriate nitrogen-fixing rhizobia bacteria. But there is growing interest in the possible use of other microorganisms that might promote plant growth by producing hormone-like chemicals to increase growth, helping plants defend themselves from diseases and insects, helping plants better access water and nutrients, and helping plants through stresses such as drought and wet conditions. A variety of growth-promoting beneficial bacterial and fungal species have been explored, but there are no general recommendations for their use. These types of inoculants may be especially helpful in situations in which plants might be under stress: in soils that are low in organic matter, in soils that tend to be dry and/or have moderate to high salinity, and in fields or plots newly used for farming, especially urban soils. And when transplanting vegetables, it might be worthwhile to dip into solutions containing mycorrhizae if the soil is one in which cover crops weren't grown that year and, especially, if you're planting following

PLANT DEFENSE MECHANISMS

Plants are not passive in the face of attack by insects, nematodes or diseases caused by fungi and bacteria. Genes activated when plants are attacked or stimulated by organisms produce chemicals that

- slow insect feeding
- attract beneficial organisms
- produce structures that protect uninfected sites from nearby pathogens
- produce chemicals that provide a degree of resistance to pathogenic bacteria, fungi and viruses
- host organisms in roots that protect against pathogens

a brassica (which does not form associations with mycorrhizal fungi).

SUMMARY

Ecologically sound crop and soil management focuses on combining *proactive* and *reactive* management to prevent most factors that might limit plant growth and to address the remaining problems when they occur. The three preventive goals are to grow healthy plants with enhanced defense capabilities, suppress pests and enhance beneficial organisms. There are a variety of practices that contribute to these overall goals and that have been discussed in this chapter as enhancing both aboveground habitat and soil habitat. There is some overlap because cover crops, crop rotations and tillage have effects both aboveground and belowground. The various practices that improve and maintain soil habitats are discussed in detail in the following chapters of Part 3. They contribute to soil building, maintaining soil health by increasing and maintaining the soil's organic matter, aggregation, waterholding ability and biological diversity.

As indicated in Figure 8.2, in addition to the work of prevention (mainly accomplished before and during planting), there are routine management practices that are carried out during the season, and remedial or reactive approaches may need to be used if prevention practices are not enough to take care of a potential threat to the crop. However, just as with our own health, prevention helps us better deal with the inevitable health challenges because we cannot always rely on a cure after they develop. For this reason, the remaining sections of the book are oriented towards this more-holistic approach with practices that help prevent problems from developing that might limit the growth or quality of plants or harm the surrounding environment.

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Chapter 9

MANAGING FOR HIGH-QUALITY SOILS:

FOCUSING ON ORGANIC MATTER MANAGEMENT

Because organic matter is lost from the soil through decay, washing and leaching,
and because large amounts are required every year for crop production,
the necessity of maintaining the active organic-matter content of the soil, to say nothing
of the desirability of increasing it on many depleted soils, is a difficult problem.

—A.F. GUSTAFSON, 1941

Increasing the quality of a soil—enhancing it as a habitat for plant roots and beneficial organisms—takes a lot of thought and action over many years. Of course, there are things that can be done right off: Plant a cover crop this fall or just make a New Year's resolution not to work soils that really aren't ready in the spring (and then stick with it). Other changes take more time. You need to study carefully before drastically changing crop rotations, for example. How will the new crops be marketed, and are the necessary labor and machinery available?

All actions taken to improve soil health should contribute to one or more of the following: 1) growing healthy plants, 2) suppressing pests or 3) increasing beneficial organisms. These should be done using practices that also reduce environmental impacts. Soil health management practices that contribute to these overall goals can be grouped as follows: 1) minimize soil disturbance; 2) keep soil covered; 3) maximize biodiversity; 4) manage water to reduce runoff and promote crop needs and timely fieldwork; and 5) maintain desired range of pH and nutrients to grow healthy crops without excessive nutrient loss.

First and foremost, various practices to build up and maintain high levels of soil organic matter are key to long-term sustainability because each practice has multiple positive effects, and all of the practices are related to enhancing soil and field habitat for growing plants. Second, developing and maintaining the best possible soil physical condition often require other types of practices in addition to those that directly impact soil organic matter. Last, although good organic matter management goes a long way toward providing good plant nutrition in an environmentally sound way, good nutrient management involves additional practices.

Photo by Jerry DeWitt

ORGANIC MATTER MANAGEMENT

Good organic matter management is a fundamental concept because it is associated with the other major goals of sustainable soil management: keeping the soil covered, maximizing biodiversity, maintaining desired ranges of pH and crop nutrients, improving water relations, and minimizing soil disturbance (to maintain aggregation and large water-conducting channels). These goals are all discussed in detail in later chapters of the book. In this chapter we'll focus more directly on organic matter management. As we reviewed in Chapter 3, soils with higher clay and silt content should have more organic matter than do coarser soils with higher sand contents. We can estimate the levels at which a soil becomes *saturated* with organic matter, and recent advances in soil health research are establishing guidelines for the amount of organic matter that is preferred in a particular soil. But it is difficult to be sure exactly why problems develop when organic matter is depleted in an individual field. However, even in the early 20th century, agricultural scientists proclaimed, "Whatever the cause of soil unthriftiness, there is no dispute as to the remedial measures. Doctors may disagree as to what causes the disease, but agree as to the medicine. Crop rotation! The use of barnyard and green manuring! Humus maintenance! These are the fundamental needs" (Hills, Jones and Cutler, 1908). More than a century later, these are still the main remedies available to us.

There appears to be a contradiction in our view of soil organic matter. On one hand, we want organic matter (crop residues, dead microorganisms and manures) to decompose. If soil organic matter doesn't decompose, no nutrients are made available to plants, no glue is manufactured to bind particles into aggregates, and no humus is produced to bind plant nutrients as water leaches through the soil. On the other hand, numerous problems develop when soil organic matter is significantly depleted through decomposition. This dilemma, wanting organic matter to decompose but not wanting to lose too much, means that organic materials must be continually added to the soil. A supply of active organic matter must be maintained so that soil organisms have sufficient food and so that humus can continually accumulate. Even the humic substances that make up much of the "very dead" organic matter are part of a continuous processing by the decomposer community toward smaller molecular sizes. This does not mean that organic materials must be added to each field every year, although that happens to a greater or lesser degree if crop roots and aboveground residues remain. However, it does mean that a field cannot go without a significant quantity of organic residue additions for many years without paying the consequences.

COVER CROPS FOR ORGANIC MATTER AND SOIL HEALTH MANAGEMENT

Using cover crops to maintain living plants in the field for as much of the year as possible helps to promote soil health in many ways. Although we devote an entire chapter to cover crops (Chapter 10), it is important to acknowledge their many benefits to soil health in this chapter as well. Living plants help to provide food for soil organisms by root secretions (exudates) and sloughed off cells, and through mutually beneficial relationships, as with mycorrhizal fungi. They help to build and maintain soil aggregates, contribute to increasing soil organic matter and reduce erosion (which also decreases organic matter loss). Cover crop mixes can provide a variety of residue characteristics, contributing to a goal of adding organic materials sources with different qualities to soil.

Table 9.1
Effects of Different Management Practices on Gains and Losses of Organic Matter, Beneficial Organisms and Pests

Management Practice	Gains Increase?	Losses Decrease?	Enhance Beneficials (EB), Stress Pests (SP)
Add materials (manures, composts, other organic materials) from off the field	yes	no	EB, SP
Better utilize crop residues and mulches	yes	no	EB
Include high-residue-producing crops in rotation	yes	no	EB, SP
Include high-residue-producing crops in rotation	yes	yes	EB, SP
Grow cover crops	yes	yes	EB, SP
Reduce tillage intensity	yes/no*	yes	EB
Use conservation practices to reduce erosion	yes/no*	yes	EB

*Practice may increase crop yields, resulting in more residue.

Do you remember that plowing a soil is similar to opening up the air intake on a wood stove? What we really want in soil is a slow, steady burn of the organic matter. You get that in a wood stove by adding wood every so often and making sure the air intake is on a medium setting. In soil, you get a steady burn by adding organic residues regularly and by not disturbing the soil too often or too greatly.

There are four general strategies for organic matter management. First, use crop residues more effectively and find new sources of organic residues to add to soils. New residues can include those you grow on the farm, such as cover crops, or those available from various local sources. Second, try to use a number of *different types* of materials: crop residues, manures, composts, cover crops, leaves, etc. It is important to provide varied residue sources to help develop and maintain a diverse group of soil organisms. Third, although use of organic materials from off the farm can be a good source for building soil organic matter and adding nutrients, some farmers overload their fields with excess nutrients because of excess imports of organic materials. Crop residues (including cover crops) as well as on-farm-derived animal manures and composts help to supply organic materials and cycle nutrients without a buildup of excessive levels of nutrients. Fourth, implement practices that decrease the loss of organic matter from soils because of accelerated decomposition or erosion.

All practices that help to build soil organic matter either add more organic materials than in the past or decrease the rate of organic matter loss. Practices that add enough organic matter to a soil to match or exceed the rate of loss by decomposition will also enhance beneficial organisms and/or stress pests (Table 9.1). Those that do both may be especially useful. Additions can come from manures and composts brought from off the field, crop residues and mulches that remain following harvest, or cover crops. Practices that reduce losses of organic matter either slow down the rate of decomposition or decrease the amount of erosion. Reduced tillage does both. When reduced tillage increases crop growth and residues returned to soil, it is usually a result of better water infiltration and storage, and less surface evaporation.

It is not possible in this book to give specific management recommendations for all situations because the production environments for crops vary hugely. Think of how a cash grain operation is different from a livestock-based farm, or from a fruit or vegetable farm. And how a 2,000 acre farm in the U.S. Corn Belt is different from a two-acre farm in New England (or India or Africa for that matter). In chapters 10 through 16, we will evaluate management options that enhance the soil environment and issues associated with their use. Most of these practices improve organic matter management, although they have many different types of effects on soils. We will also discuss the special needs of urban soils in Chapter 22.

Using Organic Materials

Amounts of crop residues. Crop residues are usually the largest source of organic materials available to farmers, considering that the majority of the organic materials and nutrients are generally removed with crop harvest. The amount of crop residue left after harvest varies depending on the crop (tables 9.2 and 9.3). Soybeans, potatoes, lettuce and corn silage leave little residue. Small grains, on the other hand, leave more residue, while sorghum and corn harvested for grain leave the most. A ton or more of crop residues per acre may sound like a lot of organic material being returned to the soil. However, keep in mind that after residues are decomposed by soil organisms, only about 10–20% of the original amount is converted into stable humus.

The amount of roots remaining after harvest also can range from very low to fairly high (Table 9.2). In addition to the actual roots left at the end of the season, there are considerable amounts of sloughed-off root cells, as well as exudates from the roots during the season. This may actually increase the plant's belowground inputs of organic matter by another 50%. Probably the most effective way to increase soil organic matter is to grow crops with large root systems. Compared to aboveground residues, the organic material from roots decomposes more slowly, contributes more to stable soil organic matter, and, of course, does not have to be incorporated into the soil to achieve deep distribution. When no-till is used, root residues, along with root exudates given off when they were alive, tend to promote formation and stabilization of aggregates, more so than surface-derived residue. One of the reasons many soils of the U.S. Midwest are so rich is because for thousands of years prairie plants with extensive and deep root systems grew there, annually contributing large quantities of organic matter deep into the soil. (We refer to these deep fertile soils as mollisols or chernozems.)

Table 9.2
Estimated Root Residue Produced by Crops

Crop	Estimated Root Residues (pounds per acre)[1]
Native prairie	15,000–30,000
Corn	3,000–4,000
Italian ryegrass	2,600–4,500
Red clover	2,200–2,600
Winter cereal	1,800–2,600
Spring cereal	1,500–2,600
Soybeans	500–1,000
Cotton	500–900
Potatoes	300–600

[1] Pound per acre equals about 1.1 kilogram per hectare.
Sources: Topp et al. (1995) and other sources.

Some farmers remove aboveground residues such as small grain straw from the field for use as animal bedding or to make compost. Later, these residues return to contribute to soil fertility as manures or composts. Sometimes residues are removed from fields to be used by other farmers or to make another product. There is increasing interest in using crop residues as a feedstock for the production of biofuels. This activity could cause considerable harm to soil health if sufficient residues are not allowed to return to soils.

Burning of wheat, rice and other crop residues in the field still occurs, although it is becoming less common in the United States and in other countries. Residue is usually burned to help control insects or diseases, or to make next year's fieldwork easier with less residue. Residue burning may be so widespread in a given area that it causes local air pollution, like in the plain of the northern Indian subcontinent where the Ganges and Indus rivers flow. Crop residues are burned during the

Table 9.3
Aboveground Crop Residues[1]

Crop residues in the San Joaquin Valley, California	
Crop	**Residue (tons per acre)**
Corn (grain)	5
Broccoli	3
Cotton	2.5
Wheat (grain)	2.5
Sugarbeets	2
Safflower	1.5
Tomatoes	1.5
Lettuce	1
Corn (silage)	1/2
Garlic	1/2
Wheat (after baling)	1/4
Onions	1/4
Residues of common crops in the Midwest and Great Plains after grain harvest	
Crop	**Residue (tons per acre)**
Corn (180 bushels)	4.5
Sorghum (100 bushels)	3.25
Wheat (50 bushels)	1.5
Soybeans (50 bushels)	2.5

[1] The amount of aboveground residue left in the field after harvest depends on the type of crop and its yield. The top table contains the amounts of residues found in California's highly productive, irrigated San Joaquin Valley. These residue amounts are higher than would be found on most farms, but the relative amounts for the various crops are interesting.
Source: Various sources.

winter months when the atmosphere also has an inversion layer that traps the smoke and creates severe smog. Burning also diminishes the amount of organic matter returned to the soil as well as the amount of protection against raindrop impact.

Sometimes important needs for crop residues and manures may prevent their use in maintaining or building soil organic matter. For example, straw may be removed from a grain field to serve as mulch in a strawberry field or as feed or bedding material for animals. These trade-offs of organic materials can sometimes cause a severe soil fertility problem if allowed to continue for a long time. This issue is of much more widespread importance in developing countries, where resources are scarce. There, crop residues and manures also serve as fuel for cooking or heating when gas, coal, oil and wood are not available. In addition, straw may be used in making bricks or used as thatch for housing or to make fences. Although it is completely understandable that people in resource-poor regions use residues for such purposes, the negative effects of these uses on soil productivity can be substantial. An important way to increase agricultural productivity in developing countries is to find alternate sources for fuel and building materials to replace the crop residues and manures traditionally used.

Also, improved machinery, even relatively small-scale versions, can help alleviate the problem of planting through surface residues and obtaining the seed-soil contact needed for good germination. Recently, sophisticated planters and seeders have been developed to guarantee good seed placement even in high-residue fields. New small-farm technologies include the Happy Seeder, a no-till drill developed for small tractors in India, and the Morrison seeder, a single-row strip tiller/seeder for use with two-wheel tractors.

Using residues as mulches. Crop residues or composts can be used as mulch on the soil surface. This occurs routinely in some reduced-tillage systems when high-residue-yielding crops are grown or when killed cover crops remain on the surface. In some small-scale vegetable and berry farming, mulching is done by applying straw from off site. Strawberries grown in the colder, northern parts of the country are routinely mulched with straw for protection from winter heaving. The straw is blown on in late fall and is then moved into the interrows in the spring, providing a surface mulch during the growing season.

Mulching has numerous benefits:

- enhanced water availability to crops due to better

CROP RESIDUES: FUEL VERSUS SOIL ORGANIC MATTER

Partial removal of corn stover after harvest for use as biofuel.

There is currently a huge effort underway to more efficiently convert structural plant material (cellulose) into fuel, either through direct combustion of biomass, or its conversion into ethanol. As we write this, only a few cellulosic ethanol plants have been built, and their long-term commercial viability is still uncertain—but this might change in the future. One of the dangers to soil health is that if the conversion of plant structural material (not grain) to ethanol becomes commercially viable, there may be a temptation to use crop residues as an energy source, thus depriving the soil of needed organic inputs. For example, most aboveground corn residue needs to return to the soil to maintain the soil's quality. It is estimated that between 2 and 5 tons of corn residue are needed to maintain a soil's favorable properties. A long-term study in New York indicated that, at least for that particular soil, modest removal of cornstalks causes only limited additional deterioration of soil compared to grain-only harvest *if no-till* is practiced. However, we must be very cautious when considering removing crop residue as a routine practice. As the legendary soil scientist Hans Jenny put it in 1980, "I am arguing against indiscriminate conversion of biomass and organic wastes to fuels. The humus capital, which is substantial, deserves being maintained because good soils are a national asset." This concern especially exists with cash grain fields where the residue removal is additional to grain export, conventional tillage is used, and there is no return of organic matter through manure or compost. This creates a very negative carbon balance. Although cover crops should be planted if crop residues are removed, they may not grow enough to make up for lost residue. Virginia Tech Extension research estimated that the costs of baling and storing residue from corn grain plus replacing the nutrients in the residue, the breakeven cost, depending on yields and percent of residue harvested, ranged between $49 to $69 per dry ton. This does not count any possible detrimental effect on soil health from loss of residue return. Farmers would need to be paid significantly above these prices to even have the residue export make economic sense in the long term.

If a perennial crop such as switchgrass is harvested to burn as an energy source or to convert into liquid fuel, at least soil organic matter may continue to increase because of the contributions of extensive root systems and the lack of tillage. On the other hand, large amounts of nitrogen fertilizer plus other energy-consuming inputs will reduce the overall life cycle conversion efficiency of switchgrass into liquid fuel, and thereby reduce the carbon benefits.

The attractiveness of using crop residues as an energy source appears to be declining because of the plunging costs of wind and solar energy, and the development of electric cars, trucks and even farm tractors. Perhaps the best remaining option is to grow biomass for energy on marginal lands that would otherwise not be used for crop production.

infiltration into the soil and less evaporation from the soil (approximately 1/3 of water loss in irrigated agriculture is from evaporation from the soil, which can be greatly reduced by using a surface mulch)

- weed control because the mulch shades the soil surface
- less extreme changes in soil temperature
- reduced splashing of soil onto leaves and fruits and vegetables (making them look better as well as reducing diseases)
- reduced infestations of certain pests (Colorado potato beetles on potatoes and tomatoes are less severe when these crops are grown in a mulch system)

On the other hand, residue mulches in cold climates can delay soil warming in the spring, reduce early season growth and increase problems with slugs during wet periods. When it is important to get a rotation crop in early, you might consider using a low-residue crop like soybeans the previous year. Of course, one of the reasons for the use of plastic mulches (clear and black) for crops like tomatoes and melons is to help warm the soil.

Residue management in arid and semiarid regions. In arid and semiarid regions water is usually the greatest limitation to crop yields. For winter wheat in semiarid regions, for example, the available water at planting often foretells final yields (Figure 9.1). Thus, in order to provide more available water for crops, we want to use practices that help store more water in soils and keep it from evaporating directly to the atmosphere. Standing residue allows more snow to be retained in the field after being deposited, which significantly increases available soil water in spring. (Sunflower stalks used in this way can increase soil water by 4–5 inches.) And a mulch during the growing season helps both to store water from irrigation or rainfall and to keep it from evaporating.

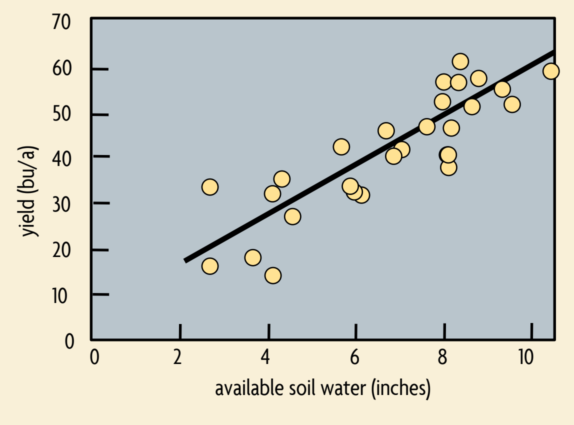

Figure 9.1. Relationship between winter wheat grain yield and soil water at wheat planting over six years. Modified from Nielsen et al. (2002).

Effects of Residue Characteristics on Soil

Decomposition rates and effects on aggregation. Residues of various crops and manures have different properties and, therefore, have different effects on soil organic matter. Materials with low amounts of harder-to-degrade hemicellulose, polyphenols and lignin, such as cover crops (especially legumes) when still very green and soybean residue, decompose rapidly (Figure 9.2) and have a shorter term effect on soil organic matter levels than residues with high levels of these chemicals (for example, cornstalks and wheat straw). Manures, especially those that contain lots of bedding (high in hemicellulose, polyphenols and lignin), decompose more slowly and tend to have more long-lasting effects on total soil organic matter than do crop residues and manures without bedding. Also, cows and other ruminants—because they eat a diet containing lots of forages that are not completely decomposed during digestion—produce manure with longer lasting effects on soils than nonruminants, such as chickens and hogs, that are fed exclusively a high-grain and low-fiber diet.

In general, residues containing a lot of cellulose and other easy-to-decompose materials will have a greater effect on soil aggregation than compost, which has already undergone decomposition and contains less

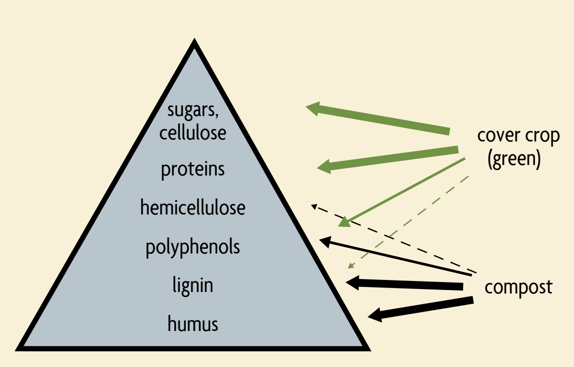

Figure 9.2. Different types of residues have varying effects on soils (thicker lines indicate more material, dashed lines indicate very small percentages). Modified from Oshins and Drinkwater (1999).

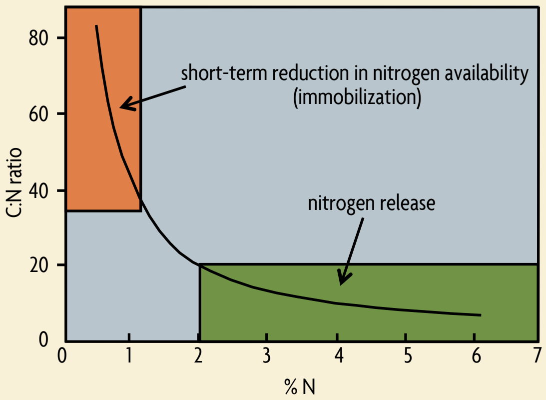

Figure 9.3. Nitrogen release and immobilization with changing nitrogen content. Based on data of Vigil and Kissel (1991).

active organic matter. Because aggregates are formed from byproducts of decomposition by soil organisms, organic additions like manures, cover crops, and straw will usually enhance aggregation more than compost. (However, adding compost does improve soils in many ways, including increasing the waterholding capacity.)

Although it's important to have adequate amounts of organic matter in soil, that isn't enough. A variety of residues are needed to provide food to a diverse population of organisms, provide nutrients to plants and furnish materials that promote aggregation. Residues low in hemicellulose and lignin usually have very high levels of plant nutrients. On the other hand, straw or sawdust (containing a lot of lignin) can be used to build up organic matter, but a nitrogen deficiency and an imbalance in soil microbial populations will occur unless a readily available source of nitrogen is added at the same time (see discussion of C:N ratios below). In addition, when insufficient nitrogen is present, less of the organic material added to soils actually ends up as humus.

C:N ratio of organic materials and nitrogen availability. The ratio of the amount of a residue's carbon to the amount of its nitrogen influences nutrient availability and the rate of decomposition. The ratio, usually referred to as the C:N ratio, may vary from around 15:1 for young plants, to between 50:1 and 80:1 for the old straw of crop plants, to over 100:1 for sawdust and wood chips. For comparison, the C:N ratio of soil organic matter is usually in the range of about 10:1–12:1 (higher for peaty soils), and the C:N of soil microorganisms is around 7:1.

The C:N ratio of residues is really just another way of looking at the percentage of nitrogen (Figure 9.3). A high C:N residue has a low percentage of nitrogen. Low C:N residues have relatively high percentages of nitrogen. Crop residues usually average 40% carbon, and this figure doesn't change much from plant to plant. On the other hand, nitrogen content varies greatly depending on the type of plant and its stage of growth.

If you want crops to grow immediately following the application of organic materials, care must be taken to make nitrogen available. Nitrogen availability from residues varies considerably. Some residues, such as fresh, young and very green plants, decompose rapidly in the

PLASTIC MULCH: CONVENIENT BUT NOT GOOD FOR SOIL HEALTH?

The presence of plastics in the environment, whether as macroplastic debris or microplastic fragments, is becoming an increasing concern. It is more dramatically seen in rivers and oceans, but plastics used on land can cause damage to the terrestrial environment as well as transfer to aquatic systems.

Plastics can enter the soil through several sources. It may come from the application of waste materials like sewage sludge, compost and controlled-release fertilizers, and also from the use of plastic mulches. The latter are convenient for warming the soil, controlling weeds and protecting seedlings, and are especially popular in high-value crops. Most mulches are made of polyethylene and are not biodegradable, while a minority is made from oxo-plastics that are supposedly biodegradable but in reality still contribute to plastic pollution of soils. If plastic mulch is collected after use it may be burned (giving off noxious gases) or landfilled. The health impacts of microplastic particles in soil are still unknown, but they can impact soil-borne organisms and also enter the food chain. Therefore, although plastic mulches are convenient and help farmers grow high-quality crops, their long-term sustainability may be a concern.

Organic mulches may be less convenient, but they have the advantage of helping build soil health while avoiding this pollution problem.

soil and, in the process, may readily release plant nutrients. This could be compared to the effect of sugar eaten by humans, which results in a quick burst of energy. Some of the substances in older plants and in the woody portion of trees, such as lignin, decompose very slowly in soils. Materials such as sawdust and straw, mentioned above, contain little nitrogen. Well-composted organic residues also decompose slowly in the soil because they are fairly stable, having already undergone a significant amount of decomposition.

Mature plant stalks and sawdust that have a C:N ratio over 40:1 (Table 9.4) may cause temporary problems for plants. Microorganisms using materials that contain 1% nitrogen (or less) need extra nitrogen for their growth and reproduction. They will take the needed nitrogen from the surrounding soil, diminishing the amount of nitrate and ammonium available for crop use. This reduction of soil nitrate and ammonium by microorganisms decomposing high C:N residues is called *immobilization* of nitrogen. The extent of immobilization is not only affected by the C:N ratio but also by the structure and granularity of the organic material. Sawdust, for example, has high immobilization concerns because it is fine grained and has high surface

Table 9.4
C:N Ratios of Selected Organic Materials

Material	C:N*
Soil	10–12
Poultry manure	10
Clover and alfalfa (early)	13
Compost	15
Dairy manure (low bedding)	17
Alfalfa hay	20
Green rye	36
Corn stover	60
Wheat, oat or rye straw	80
Oak leaves	90
Fresh sawdust	400
Newspaper	600

*Nitrogen is always 1 in the ratios.

area for microbial attack, while the same material as large woodchips decomposes more slowly and causes much lower nitrogen immobilization (woodchip incorporation into soils can also improve water retention).

When microorganisms and plants compete for scarce nutrients, the microorganisms usually win, because they are so well distributed in the soil. Plant roots are in contact with only 1–2% of the soil volume, whereas microorganisms populate almost the entire soil. The length of time during which the nitrogen nutrition of plants is adversely affected by immobilization depends on the quantity of residues applied, their C:N ratio, and other factors influencing microorganisms, such as fertilization practices, soil temperature and moisture conditions. If the C:N ratio of residues is in the teens or low 20s, corresponding to greater than 2% nitrogen, there is more nitrogen present than the microorganisms need for residue decomposition. When this happens, extra nitrogen becomes available to plants fairly quickly. Green manure crops and animal manures are in this group. Residues with C:N in the mid 20s to low 30s, corresponding to about 1–2% nitrogen, will not have much effect on short-term nitrogen immobilization or release.

Sewage sludge on your fields? In theory, using sewage sludge, commonly called biosolids, on agricultural land makes sense as a way to resolve problems related to people living in cities, far removed from the land that grows their food. However, there are some troublesome issues associated with agricultural use of sludges. By far the most important problem is that they frequently contain contaminants from industry and from various products used around the home. Although the metal contaminants naturally occur at low levels in soils and plants, their high concentrations in some sludges create a potential hazard. In addition, sludge may contain a variety of organic chemicals, some linked to serious human health problems, or inert contaminants like microplastics. Altogether, approximately 350 contaminants have been found in sludges and, when applied to fields, the effects of sludges containing these contaminants on soils, plants and people are mostly unknown. The U.S. standards for toxic materials in sludges are much more lenient than those in some other industrialized countries and permit higher loading of potentially toxic metals. So, although you are allowed to use many sludges, you should carefully examine a sludge's contents before applying it to your land. (This is also a good practice if you obtain a new source of manure from some other farm.)

Another issue is that sludges are produced by varied processes and, therefore, have different properties. Most sludges are around neutral pH, but, when added to soils, cause some degree of acidification, as do most nitrogen fertilizers. Because many of the problem metals are more soluble under acidic conditions, the pH of soils receiving these materials should be monitored and maintained at around 6.8 or above. On the other hand, lime (calcium hydroxide and ground limestone used together) is added to some sludges to raise the pH and kill disease bacteria. The resulting "lime-stabilized" sludge has extremely high levels of calcium relative to potassium and magnesium. This type of sludge should be used primarily as a liming source, and levels of magnesium and potassium in the soil should be monitored carefully to ensure they are present in reasonable amounts, compared with the high levels of added calcium.

The use of "clean" sludges—those containing low levels of metal and organic contaminants—for agronomic crops is certainly an acceptable practice. Sludges should not be applied to soils when growing crops for direct human consumption unless it can be demonstrated that, in addition to low levels of potentially toxic materials, organisms dangerous to humans are absent.

Application rates for organic materials. The amount of residue added to a soil is often determined by the cropping system. Crop residues can be left on the surface or incorporated either by tillage or, in no-till, biologically by earthworms and other organisms. Different amounts of residue will remain under different crops, rotations or harvest practices. For example, depending on yield, three or more tons per acre of leaf, stalk and cob residues remain in the field when corn is harvested for grain. If the entire plant is harvested to make silage, there is little left except the roots.

When "imported" organic materials are brought to the field, you need to decide how much and when to apply them. In general, application rates of these residues will be based on their probable contribution to the nitrogen nutrition of plants. We don't want to apply too much available nitrogen because it will be wasted. Nitrate from excessive applications of organic materials may leach into groundwater just as easily as does nitrate originating from purchased synthetic fertilizers. In addition, excess nitrate in plants may cause health problems for humans and animals.

Sometimes the fertility contribution of phosphorus may be the main factor governing application rates of organic material. Excess phosphorus entering lakes can cause an increase in the growth of algae and other aquatic weeds, decreasing water quality for drinking and recreation. In locations where this occurs, farmers must be careful to avoid loading the soil with too much phosphorus from either commercial fertilizers or organic sources. In the United States, conservationists and farm nutrient management planners use tools like the N Leaching Index and the P (runoff) Index to evaluate the loss potential of these nutrients and to guide the application of organics. P leaching can also be a concern in places where a lot of organic material is applied on soils with limited P absorption potential and shallow groundwater.

Effects of residue and manure accumulations. When any organic material is added to soil, it decomposes relatively rapidly at first. Later, when only resistant parts (for example, straw stems high in lignin) are left, the rate of decomposition decreases greatly.

PRACTICES PROMOTING WATER INFILTRATION AND RETENTION

Practices that enhance water entering the soil result in less runoff and erosion. It also means that there will be more refilling of water storage pores in the root zone for plants to use. Greater infiltration into the soil during the year also leads to more groundwater recharge. Researchers at the University of Nebraska looked at 89 studies from around the world to search out which practices contributed the most to rainfall infiltration into soil. Growing perennials such as grass/legume hay and using cover crops were the two that had the greatest effects. Surprisingly, no-till, while sometimes increasing infiltration, did not do so consistently. However, no-till did increase rainfall infiltration when combined with surface residues and with cover crops.

It is the combination of soil-improving practices and their careful implementation that helps to create not only better water infiltration but also generally healthy soils.

This means that although nutrient availability diminishes each year after adding a residue to the soil, there are still long-term benefits from adding organic materials. This can be expressed by using a "decay series." For example, 50%, 15%, 5% and 2% of the amount of nitrogen added in manure may be released in the first, second, third and fourth years following addition to soils. In other words, crops in a regularly manured field get some nitrogen from manure that was applied in past years. So, if you are starting to apply manure to a field, somewhat more will be needed in the first year than will be needed in years 2, 3 and 4 to supply the same total amount of nitrogen to a crop (because there will still be some residual nitrogen from past years' applications). After some years, you may need only half of the amount used in the first year to supply all the nitrogen you need. However, it is not uncommon to find farmers who are trying to build up high levels of organic matter actually overloading their soils with nutrients, with potential negative effects on crop quality and the environment. Instead of reducing the amount of off-farm residue with time, they use a standard amount annually. This may lead to excess amounts of nitrate, which lessens the quality of many plants and harms groundwater, as well as to excess amounts of phosphorus, which is a potential water pollution problem.

Organic Matter Management on Different Types of Farms

Animal-based farms. It is certainly easier to maintain soil organic matter in animal-based agricultural systems. Manure is a valuable byproduct of having animals. When they are given feed grown on the same farm, it is an excellent way to recycle carbon and nutrients. Over the past years, some of the most remarkable improvements in land productivity have been observed where farmers smartly integrated livestock and crops. In many cases we see a self-reinforcing productivity increas—an upward spiral in contrast to the downward spiral we discussed in Chapter 1—where 1) animal manure stimulates soil health, 2) higher crop productivity increases biomass production with more residue (Figure 9.4) and feed, and 3) more animals can be fed per acre and more manure is generated to boost soil health, etc.

Animals also can use sod-type grasses and legumes as pasture, hay and haylage (hay stored under airtight conditions so that some fermentation occurs). It is easier to justify putting land into perennial forage crops for part of a rotation when there is an economic use for the crops. Animals need not be on the farm to have positive effects on soil fertility. A farmer may grow hay to sell to a neighbor or horse owners in the area and trade for some animal manure, for example. Occasionally, formal agreements between dairy farmers and vegetable growers lead to cooperation on crop rotations and manure application. This may be especially appropriate when the dairy farmer imports supplemental feed grains and has a problem with excess organics and nutrients. (See Chapter 12 for discussion of integrated livestock-crop farms and manure characteristics and use, as well as the farm profile following that chapter.)

Figure 9.4. High levels of corn residues immediately after harvest (left) and after subsequent slurry application (right) on an integrated crop-livestock farm in Washington. Soil health boosts crop growth, which in turn boosts yields and produces more residue and manure to benefit the soil. Photos by Bill Wavrin.

Systems without animals. It is more challenging, although not impossible, to maintain or increase soil organic matter on non-livestock farms. It requires extra effort because there is less cycling of carbon and nutrients through manure. But it can be done by using reduced tillage, intensive use of cover crops, intercropping, living mulches, rotations that include crops with high amounts of residue left after harvest, and attention to other erosion-control practices. Organic residues, such as leaves or clean sewage sludges, can sometimes be obtained from nearby cities and towns. Straw or grass clippings used as mulch also add organic matter when they later become incorporated into the soil by tillage or by the activity of soil organisms. Some vegetable farmers use a "mow and blow" system in which crops are grown on strips for the purpose of chopping them and spraying the residues onto an adjacent strip. When you use off-farm organic materials such as composts and manures, soil should be tested regularly to ensure that it does not become overloaded with nutrients.

MAINTAINING SOIL BIODIVERSITY

The role of diversity is critical to maintaining a well-functioning and stable agriculture. Where many different types of organisms coexist in relatively similar numbers, there are commonly fewer disease, insect and nematode problems. There is more competition for food and a greater possibility that many types of predators will be found. This makes it more difficult for a single pest organism to reach a population high enough to cause a major decrease in crop yield. Don't forget that diversity below the soil surface is as important as diversity aboveground. We can promote a diversity of plant species growing on the land, as well as biological diversity in the soil, by using cover crops, intercropping and crop rotations. Adding manures and composts, minimizing soil disturbances and making sure that crop residues are returned to the soil are also critical for promoting soil organism diversity.

BESIDES ORGANIC MATTER MANAGEMENT

Although enhanced soil organic matter management practices go a long way towards helping all aspects of soil health, as we discussed at the beginning of this chapter, other practices are needed to maintain an enhanced physical and chemical environment. Plants thrive when roots can actively explore a large area, get all the oxygen and water needed, and maintain a healthy mix of organisms. Although the soil's physical environment is strongly influenced by organic matter, the practices and equipment used, from tillage to planting to cultivation to harvest, have a major impact. If a soil is too wet, whether it has poor internal drainage or receives too much water, some remedies are needed to grow high-yielding and healthy crops. Also, erosion, whether by wind or water, is an environmental hazard that needs to be kept as low as possible. Practices for management of soil physical properties are discussed in chapters 14–17.

Many of the practices that build up and maintain soil organic matter enrich the soil with nutrients or make it easier to manage nutrients in ways that satisfy crop needs and are also environmentally sound. For example, a legume cover crop increases a soil's active organic matter and reduces erosion, but it also adds nitrogen that can be used to nourish the next crop. Cover crops and deep-rooted rotation crops help to cycle nitrate, potassium, calcium and magnesium that might be lost to leaching below crop roots. Importing mulches or manures onto the farm also adds nutrients along with organic materials. However, specific nutrient management practices are needed, such as testing manure to check its nutrient content before applying additional nutrient sources.

Other examples of nutrient management practices not directly related to organic matter management include applying nutrients timed to plant needs, liming acidic soils and interpreting soil tests to decide on the appropriate amounts of nutrients to apply (see chapters

MAINTAINING ORGANIC MATTER IN SMALL GARDENS

There are a number of different ways that home gardeners can maintain soil organic matter. One of the easiest is using lawn grass clippings for mulch during the growing season. The mulch can then be worked into the soil or left on the surface to decompose until the next spring. Leaves can be raked up in the fall and applied to the garden (or used with composting of kitchen scraps and then applied to the garden). Cover crops can also be used on small gardens. Of course, manures, composts or mulch straw can also be purchased.

There are a growing number of small-scale market gardeners, many with insufficient land to rotate into a sod-type crop. They also may have crops in the ground late into the fall, making cover cropping a challenge. One possibility is to establish cover crops by overseeding after the last crop of the year is well established. Another source of organic materials, grass clippings, is probably in short supply compared with the needs of cropped areas but is still useful. It might also be possible to obtain leaves from a nearby town. These can either be directly applied and worked into the soil or be composted first. As with home gardeners, market gardeners can purchase manures,

18–21). Development of farm nutrient management plans and watershed partnerships improve soil while also protecting the local environment. And as discussed above, it is possible to overload soils with nutrients by bringing large quantities of organic materials such as manures or composts from off the farm for routine annual applications.

Also, when considering "carbon farming" (working to increase soil organic matter levels and carbon storage) as a way to reduce atmospheric carbon dioxide concentrations, the existing carbon status of the soil needs to be considered. The potential for storing additional carbon is low if large amounts of organic materials have been routinely applied and the soil is already near its carbon saturation point (e.g., some concentrated livestock operations or organic vegetable farms that applied a lot of compost). This implies that when additional organic matter is applied to the soil, little will be stored and more will be lost to the atmosphere as carbon dioxide. Conversely, carbon farming will be more effective with soils that are low in carbon due to past intensive management without replenishment with organics (like a typical cash grain farm). They are generally well below their maximum capacity to store organic matter and therefore will more effectively store the applied carbon.

SUMMARY

Improved soil organic matter management is at the heart of building better soils: creating a habitat below the ground that is suited to optimal root development and health. This means adding adequate annual quantities, tons per acre, of a variety of organic materials—crop residue, manure, composts, leaves, etc.—while not overloading the soil with nutrients from off the farm. It also means reducing the losses of soil organic matter as the result of excess tillage or erosion. But we're not just interested in the amount of organic matter in soil, we also need to consider its quality. Even if the organic matter content of the soil doesn't increase greatly—and it takes a while to find out whether it's increasing—better management will provide more active (particulate or "dead") organic matter that fuels the complex soil web of life, helps in formation of soil aggregates, and provides plant growth by stimulating chemicals and reducing plant pest pressures. For a variety of reasons, it is easier to build and maintain higher levels of organic matter in animal-based systems than in those growing only crops. However, there are ways to improve organic matter management in any cropping system.

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a case study

BOB MUTH
GLOUCESTER COUNTY, NEW JERSEY

Farming 118 acres in a bedroom community of Philadelphia, Bob Muth and his wife Leda raise a wide range of vegetables, small fruits, flowers and a little bit of small grains, which are sold to wholesalers, through a farmers' market in Collingswood, New Jersey, and at their home farm stand.

Muth's operation is based on his passion for soil building. Since he took over running the family farm about 30 years ago, Muth has been spreading thick layers of leaf mulch—provided for free by two local municipalities, one of which pays him a small fee—at the home farm, on rented fields, and later on two additional purchased tracts of land. Mulching forms part of a rotation scheme that he devised early on and to which he has remained faithful: only a fifth of his tillable acreage is planted in cash crops each year; the remaining area is put into cover crops. "When I started mulching and using this rotation, my [farmer] neighbors thought I was losing my marbles," he says. "The prevalent idea at the time was that you had to farm a lot of acreage as intensively as possible."

Muth's rotation consists of a high-value crop the first year, followed by a leaf application the second year, two to three years of cover crops—primarily rye and sudex—then a combination of rye and vetch as a cover crop seeded in late summer or fall of the year prior to returning to a high-value crop. Following this rotation has improved the quality of his sandy soils. "With this strategy, I get all the positive indicators such as high CEC, organic matter and nutrient levels, including enough N to grow good-quality crops without a lot of inputs," he notes.

Muth tests the soil in his fields annually and carefully monitors changes in the data. "I like having hard numbers to back up what I'm observing in the field and to make good decisions as the years go by," he says. Such careful attention to detail has led him to reduce the thickness of leaf applications once fields have cycled a few times through his rotation, in order to keep soil organic matter within an optimum range of 3.5–5%. "Anything higher than that, and I risk nutrient leaching," he notes.

Muth likes to use drip irrigation to reduce plant stress and disease, and to improve water use efficiency. "Water shortage is my biggest issue on the home farm. One well pumps only 40 gallons a minute and the second only pumps 20–22 gallons a minute," he says, noting it originally pumped over 100 gallons a minute. A residential development boom on the land surrounding his farm has drastically reduced the available groundwater. He says, "You have to be creative about breaking up your fields into zones in order to make water do what you need it to do." During dry periods, this may mean running the well 24/7 for a stretch of 60 days, watering one section for four hours at a time, until they get a decent rain.

Muth relies on a range of IPM (integrated pest management) techniques for pest and disease control. He scouts his fields daily and takes notes of his observations throughout each cropping cycle. "It's worth investing in a jeweler's loop," he advises, "because it's the pests that are most difficult to see—like the white flies, spider mites and thrips—that will get you." He regularly plants trap-crop borders around his high-value crop fields, which enable him to monitor pest populations and determine when and how much to spray. For example, he suggests using red kale or mizuna as a trap crop to prevent tarnished plant bug damage on savoy cabbage and other brassicas.

"You have to figure out what [pests] require in their life cycles and disrupt them," he says. After several years of observation, "you begin to recognize if you've got a crop for which you haven't figured out a good control strategy."

Muth likes to encourage beneficial insect populations by leaving flowering strips of cover crops unmowed on the borders of his crop fields. He has found that interplanting cover crops, adding buckwheat and dill to vetch, for example, significantly extends bloom time, thus fostering multiple generations of beneficial insects.

In high tunnels, where he grows berries, vegetables and flowers, he controls aphids and spider mites by releasing predatory mites. He selected a special film to cover the tunnels that enhances light diffusion, reduces condensate drip from the ceiling and purlins, and helps prevent overheated conditions, ensuring an overall superior growing environment.

"There are so many things you can do to help yourself," he says. He has learned how to prevent early-season pythium rot by waiting to plant crops until a preceding rye-vetch cover is fully broken down and the soil warms up. He keeps pythium, which also likes hot and wet conditions, in check later in the season by planting crops out on highly reflective metallic plastic mulch, under which soil temperatures are lower relative to those that occur under other colors of plastic mulch.

The reflective mulch also proved useful with his latest thrip outbreak. Muth planted his first tomato crop on black film because the soil is too cool to plant them on the metallic mulch in early May, which would stunt their growth, and they were damaged by the thrips. But the following tomato crops were all planted on the metallic mulch, and despite the large numbers of thrips still there, Muth says the tomatoes turned out perfect because that mulch repelled them.

Overall, instead of adhering to a strict spray schedule, which "may control one critter but make things worse if you also kill your beneficials in the process," Muth suggests "layering together" different types of controls, such as improving soil quality, creating insectaries of flowering covers, using sprays judiciously, and letting pest and disease management strategies evolve as time goes by.

Sometimes pest problems can't be avoided. Recently, thrips overwhelmed the early tomato crops growing in his high tunnel, and he was forced to sell them at a reduced price. But without his diverse rotation and having plantings staggered out, he says the outcome would have likely been worse. "If you had everything in one planting and got whacked like that, you'd be falling back on your savings," he says. "By doing the little plantings, diversifying and staggering [crops], you spread out your risk, so you're not totally dependent on one crop at one period of time."

Muth's decisions to "go with a good soil building program" and IPM methods also smoothed his transition into certified organic production, which he achieved in 2001. He recalls finding a fact sheet that had a dozen or so practices the certifier recommended for transitioning into organic and realized he was doing most of them.

"When I started getting into organics, people told me, 'Bob, you better be careful or you're going to end up with buggy stuff that's full of disease that people don't want.' But I haven't seen any of that," he says. "I haven't been overwhelmed; in general, pests and disease levels on my farm amount to no more than a minor annoyance."

Encouraged by his success and customer demand, Muth is applying his expertise to figuring out how to grow more "difficult" crops organically. For example, when area specialists said that growing organic super sweet corn in New Jersey would be impossible, he could not resist the challenge. "We decided to start our corn plugs in the greenhouse," he says, noting that "the people at Rutgers thought this was revolutionary." He transplants corn plugs after 10 or 11 days (to prevent plugs from becoming pot-bound, which reduces ear length) onto plastic mulch and keeps row covers over the plants until they are 12–18 inches tall.

Such strategies effectively foil corn earworm and corn borers, says Muth. “You can grow corn early, scout it closely, and with spot use of approved sprays for organic production, get three weeks of absolutely clean, fantastic-quality organic corn in July.” His customers are thrilled and are willing to pay him a premium price for the fruits of his discovery.

With so many new techniques emerging, and with consumers increasingly interested in buying locally and organically produced food, Muth says this is “an exciting time to be in agriculture. … If you’re savvy, you can farm a small piece of land and make a good living.”

“I wish I was twenty one again,” he says, “because I’d do it all over again. It’s a pleasure to get out there and get to work.”

Chapter 10

COVER CROPS

> *Where no kind of manure is to be had, I think the cultivation of lupines will be found the readiest and best substitute. If they are sown about the middle of September in a poor soil, and then plowed in, they will answer as well as the best manure.*
>
> —COLUMELLA, 1ST CENTURY, ROME

Cover crops have been used to improve soil and the yield of subsequent crops since antiquity. Chinese manuscripts indicate that the use of green manures is probably more than 3,000 years old. Green manures were also commonly used in ancient Greece and Rome. Today, there is a renewed interest in cover crops, and they are becoming important parts of many farmers' cropping systems.

A cover crop is usually grown with multiple objectives. One important goal is to protect and improve the soil with living vegetation during a time of the year when it would otherwise be bare, minimizing runoff and soil erosion, with green leaves intercepting precipitation and lessening its impact, and with living roots holding on to the soil. But cover crops can also have many other benefits: Using the sun's energy and CO_2 from the atmosphere, they increase soil organic matter with their roots and surface residue; protect nitrate from leaching; increase the amount of soil nitrogen (especially with legumes); break up soil compaction; provide habitat for beneficial organisms; and promote mycorrhizal fungi presence for the following crop.

Cover crops are usually killed on the surface or incorporated into the soil before they mature. (This is the origin of the term *green manure*.) Since annual cover crop residues are usually low in lignin content and high in nitrogen, they typically decompose rapidly in the soil.

BENEFITS OF COVER CROPS

Cover crops provide multiple potential benefits to soil health and to the following crops, while also helping to maintain cleaner surface water and groundwater (Figure 10.1). They prevent erosion, improve soil physical and biological properties, supply nutrients to the following crop, suppress weeds, improve soil water availability, and break pest cycles. Some cover crops are able to break into compacted soil layers, making it easier for the following crop's roots to more fully develop. The actual benefits from a cover crop depend on the

Photo by Tim McCabe

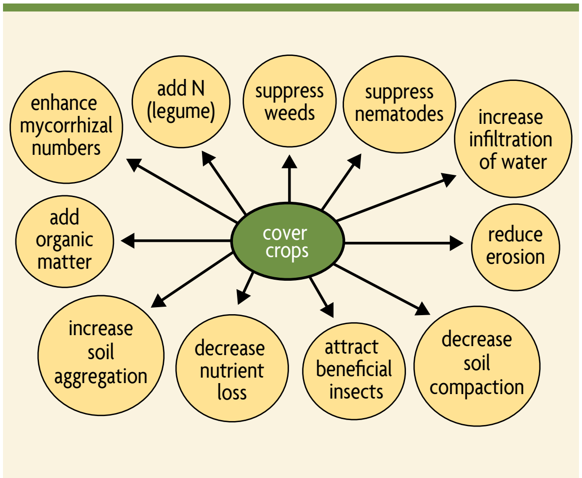

Figure 10.1. Cover crops enhance soil health in many ways.

species and productivity of the crop you grow and how long it's left to grow before the soil is prepared for the next crop. In this chapter we focus on the principles of cover cropping, which are more comprehensively discussed in a companion book by the same publisher, SARE, titled *Managing Cover Crops Profitably* (www.sare.org/mccp).

Organic matter. Grass cover crops are more likely than legumes to increase soil organic matter. The more surface residue and roots provided to the soil, the better the effect on soil organic matter. In that regard, we generally don't fully appreciate their rooting systems unless we dig them up because some cover crops grow as much or more biomass underground than above, thereby directly benefiting the soil.

Good production of hairy vetch or crimson clover cover crops may yield from 1 1/2 to more than 4 tons of dry weight per acre if allowed to grow long enough. Likewise, if a vigorous grass cover crop like cereal rye is grown to maturity, it can produce 3–5 tons of residue. However, the amount of residue produced by an early terminated cover crop may be very modest, as little as half a ton of dry matter per acre. While small cover crop plants add some active organic matter, they may add little to long-term build-up of soil organic matter if not enough root growth and residue are allowed to develop.

A five-year experiment with clover in California showed that cover crops increased organic matter in the top 2 inches from 1.3%–2.6% and in the 2- to 6-inch layer from 1%–1.2%. Researchers found, when the results of many experiments were examined together, that including cover crops led to an organic matter increase of 8.5% over original levels and an increase of soil nitrogen by 12.8%. The longer the cover crop grows and the less tillage that is used, the greater the increase in soil organic matter. In other words, the beneficial effects of reduced tillage and cover cropping can be additive, and the combination of practices has greater benefits than using them individually. Low-growing cover crops that don't produce much organic matter, for example, cereal rye that's killed before it has much chance to grow in the spring, may not be able to counter the depleting effects of intensive tillage. But even if they don't significantly increase organic matter levels, cover crops help prevent erosion and add at least some residues that are readily used by soil organisms.

Beneficial organisms. Cover crops help maintain high populations of mycorrhizal fungi during the period between main crops and thereby provide a biological bridge between cropping seasons. The fungus also associates with almost all cover crops (except brassicas), which helps maintain or improve inoculation of the next crop. (As discussed in Chapter 4, mycorrhizal fungi help promote the health of many crop plants in a variety of ways and also improve soil aggregation.)

Cover crop pollen and nectar can be important food sources for predatory mites and parasitic wasps, both of which are important for biological control of insect pests. A cover crop also provides good habitat for spiders, and these insect feeders help decrease pest populations. Use of cover crops in the Southeast has reduced the incidence of thrips, bollworm, budworm, aphids, fall armyworm, beet armyworm and white flies.

Earthworm populations may increase markedly with cover crops, especially if combined with no-till. Aggressive tillage harms earthworm populations and destroys their burrowing channels—as well as those from old roots—that reach the surface, reducing infiltration during intense rainfall.

TYPES OF COVER CROPS

Many plant species can be used as cover crops. Legumes and grasses (including cereals) are the most extensively used, but there is increasing interest in brassicas (such as rapeseed, mustard and oilseed radish, which is also known as forage radish) and continued interest in summer cover crops, including buckwheat, millets and summer legumes such as cowpeas and sunn hemp. Some of the most important cover crops are discussed below.

Legumes

Leguminous plants are often very good cover crops. Summer annual legumes, usually grown only during the summer, include soybeans, cowpeas and sunn hemp. Winter annual legumes that are normally planted in the fall and counted on to overwinter include winter field peas (such as Austrian), crimson clover, hairy vetch, Balansa clover and subterranean clover. Crimson clover reliably overwinters in hardiness zone 6 and farther south, and sometimes in zone 5. Winter peas have a similar region of adaptation as crimson clover, although it might be usable a little farther north if planted early

PURPOSES OF COVER CROPS

The term “cover crop” refers generally to plants that are grown but not harvested. While this term is used generally, different types of plants are grown as cover crops to achieve a number of primary purposes:

Catching and cycling nutrients: typically grasses such as cereal rye and oats. Especially useful in high-nutrient environments.

Fixing nitrogen via symbiotic relationship with *Rhizobium* bacteria (green manures): typically legumes (e.g., hairy vetch and red clover). Especially useful on organic farms or by others who want to “grow” their own nitrogen.

Smothering weeds: typically competitive, fast-growing species (e.g., buckwheat, sorghum-sudangrass, cereals). Especially useful when weed control is a challenge.

Biofumigating pests with glucosinolates and isothiocyanates: typically brassicas (e.g., mustards and radishes). Especially useful when growing disease-susceptible crops with limited chemical control.

Loosening compacted soil: typically strong-rooted crops (e.g., cereal rye, radishes, hairy vetch, alfalfa). Especially useful to improve a degraded soil.

Growing biomass and organic matter: typically fast-growing crops (e.g., sorghum-sudangrass, cereal rye, sunn hemp). Especially useful when soils are low in organic matter or when you aim to capture carbon.

Providing cover for the soil surface: typically crops that establish quickly during the off season to protect the soil, like rye or oats in cool climates.

Plant ecologists separate these into *canopy functions* (where benefits are primarily derived from the aboveground biomass) and *root functions* (where benefits are from the belowground biomass), and the selection of a cover crop may be based on the specific desired traits. If there are particular problems that need to be addressed, it certainly influences the choice of cover crops. However, most farmers grow cover crops specifically because of their *multiple* benefits (Figure 10.1).

FARMERS SAY COVER CROPS HELP THE BOTTOM LINE

A 2019–2020 national cover crop survey, which included perspectives from 1,172 farmers representing every U.S. state, found new insights into farmer experiences with cover crops. Most producers, working with their seed dealers, are finding ways to economize on cover crop seed costs, with 16% paying only $6–$10 per acre for cover crop seed, 27% paying $11–$15 per acre, 20% paying $16–$20 per acre, and 14% paying $21–$25 per acre. Only about one-fourth were paying $26 or more per acre.

This survey was conducted annually beginning in 2012 (except for 2018–2019). On average, reported yields were higher as a result of planting cover crops in all years, and most notably in the drought year of 2012 when soybean yields were improved by 12% and corn yields were 10% better. Yield gains were more modest in the wet year of 2019, when the average increase was 5% for soybeans and 2% for both corn and wheat. Farmers also reported significant savings on fertilizer and/or herbicide production costs in the 2019–2020 survey for the following crops:

- soybeans: 41% saved on herbicide costs and 41% on fertilizer costs
- corn: 39% saved on herbicide costs and 49% on fertilizer costs
- spring wheat: 32% saved on herbicide costs and 43% on fertilizer costs
- cotton: 71% saved on herbicide costs and 53% on fertilizer costs

In this survey, 52% of farmers "planted green" into cover crops on at least some of their fields. ("Planting green" is the term for seeding a cash crop into a standing cover crop and terminating the cover crop soon after.) Of those, 71% reported better weed control and 68% reported better soil moisture management, with 54% indicating that cover crops allowed them to plant earlier.

Of the horticulture producers surveyed, 58% reported an increase in net profit. Only 4% observed a minor reduction in net profit, and none reported a moderate loss in net profit.

Survey participants indicated an increase of 38% in land devoted to cover crops over the previous four years and the use of a range of cover crop seed and mixes to address their individual needs. This survey showed many positive aspects of cover crop integration and that farmers continue to find benefits to their use.

Source: CTIC-SARE-ASTA National Cover Crop Survey 2019–2020 (www.sare.org/covercropsurvey)

enough. Berseem clover will overwinter only in zones 8 and above. Hairy vetch is able to withstand fairly severe winter weather. Balansa clover is still being evaluated in colder regions but has in some cases overwintered in zone 5. Sweet yellow clover is an example of a biennial legume, while perennial legumes include red clover, white clover and alfalfa. Crops usually used as winter annuals can sometimes be grown as summer annuals in cold, short-season regions. Also, summer annuals that are easily damaged by frost, such as cowpeas, can be grown as a winter annual in the deep southern United States.

One of the main reasons for selecting legumes as cover crops is their ability to fix nitrogen from the atmosphere and add it to the soil. But legumes need to be grown later in the spring—typically until a few weeks after cereals elongate—to reach the early flowering stage and achieve near maximum nitrogen fixation. Legumes that produce a substantial amount of growth, such as hairy vetch, crimson clover, red clover and Austrian winter peas may supply over 100 pounds of nitrogen per acre to the next crop if allowed to grow to the flowering stage or longer. Other legumes may supply considerably less available nitrogen. Legumes also provide other benefits, including attracting beneficial insects, helping control erosion and adding organic matter to soils.

Inoculation. If you grow a legume as a cover crop, don't forget to inoculate seeds with the correct nitrogen-fixing bacteria. Different types of rhizobial bacteria are specific to certain crops. There are different strains for alfalfa, clovers, soybeans, beans, peas, vetch and cowpeas. Unless you've recently grown a legume from the same general group you are currently planting, inoculate the seeds with the appropriate commercial rhizobial

SELECTING COVER CROPS

Before growing cover crops, you need to ask yourself some questions:

- What are my goals in planting cover crops?
- What cover crops should I plant?
- When and how should I plant the cover crops?
- When should the cover crops be killed or incorporated into the soil?
- What is my next cash crop and when should it be planted?

When you select a cover crop, you should consider the soil conditions, climate and what you want to accomplish by answering these questions:

- Is the main purpose to add available nitrogen to the soil, or to scavenge nutrients and prevent loss from the system? (Legumes add N; other cover crops take up available soil N.)
- Do you want your cover crop to provide large amounts of organic residue?
- Do you plan to use the cover crop as a surface mulch or to incorporate it into the soil?
- Is erosion control in the late fall and early spring your primary objective?
- Is the soil very acidic and infertile, with low availability of nutrients?
- Does the soil have a compaction problem? (Some species, such as sudangrass, sweetclover and oilseed (forage) radish, are especially good for alleviating compaction.)
- Is weed suppression your main goal? (Some species establish rapidly and vigorously, while some also chemically inhibit weed seed germination.)
- Which species are best for your climate? (Some species are more winter hardy than others.)
- Will the climate and waterholding properties of your soil cause a cover crop to use so much water that it harms the following crop?
- Are root diseases or plant-parasitic nematodes problems that you need to address? (Cereal rye, for example, has been found to suppress a number of nematodes in various cropping systems. Brassica cover crops may also reduce populations of certain nematodes.)

In most cases, there are multiple objectives and multiple choices for individual cover crops and for cover crop mixes.

Figure 10.2. Root systems of five legume cover crops at early stages of growth (two months in a greenhouse). From left: alfalfa (winter perennial), yellow-blossom sweet clover (winter biennial), hairy vetch (winter annual), sunn hemp and cowpea (summer/tropical annual). Photos by Joseph Amsili.

inoculant before planting. The addition of water to the seed-inoculant mix, just enough to moisten the seeds, helps the bacteria stick to the seeds. Plant right away, so the bacteria don't dry out. Inoculants are readily available only if they are commonly used in your region. It's best to check with your seed supplier a few months before you need the inoculant, so it can be specially ordered if necessary. Keep in mind that the "garden inoculant" sold in many garden stores may not contain the specific bacteria you need. Be sure to find the right one for the crop you are growing and keep it refrigerated until used.

Winter Annual Legumes

Crimson clover is considered one of the best cover crops for areas with mild climates, like the southeastern United States and the southern Plains, such as Oklahoma and parts of Texas. Where adapted, it grows in the fall and winter, and matures more rapidly than most other legumes. It also contributes a relatively large amount of nitrogen to the following crop. Because it is not very winter hardy, crimson clover is not usually a good choice in hardiness zones 4 or colder, and it can be marginal in zone 5 (snow cover and/or early planting can help with winter survival). Crimson clover survival can also suffer from poorly drained soil conditions. In northern regions, crimson clover can be grown as a summer annual, but that prevents an economic crop from growing during that field season. Varieties like Chief, Dixie and Kentucky Select are somewhat winter hardy if established early enough before winter. Crimson clover does not grow well on high-pH (calcareous) or poorly drained soils.

Field peas are grown in colder climates as a summer annual and as a winter annual over large sections of the South and California. They have taken the place of fallow in some dryland, small-grain production systems. Austrian winter peas (bred for winter hardiness) and Canadian field peas (bred for good spring growth) tend to establish quickly and grow rapidly in cool moist climates, producing a significant amount of residue: 2 1/2 tons or more of dry matter. They fix plentiful amounts of nitrogen, from 100–150 or more pounds per acre. Austrian winter peas will perform best as a winter cover crop if seeded in early fall.

Hairy vetch is winter hardy enough to grow well in areas that experience hard freezing, and it can be planted later than most other legumes. Where adapted, hairy vetch produces a large amount of vegetation and has an impressive root system (Figure 10.2). It fixes a significant amount of nitrogen, thereby contributing 100 pounds of nitrogen per acre or more to the next crop. Hairy vetch residues decompose rapidly and release nitrogen more quickly than most other cover crops. This can be an advantage when a rapidly growing, high-nitrogen-demand crop follows hairy vetch. Hairy vetch will do better on sandy soils than many other green manures, but it needs good soil potassium levels to be most productive. Where wheat is part of the rotation, hairy vetch should be avoided, as hairy vetch may volunteer in the wheat, and the seed sizes are similar enough to make it hard to separate the vetch seed from the wheat seed during harvest.

Subterranean clover is a warm-climate winter annual that, in many situations, can complete its life cycle before a summer crop is planted. When used this way, it doesn't need to be suppressed or killed and does not compete with the summer crop. If left undisturbed, it will naturally reseed itself from the pods that mature belowground. Because it grows low to the ground and does not tolerate much shading, it is not a good choice to interplant with summer annual row crops.

Balansa clover is a new winter annual clover getting some use. The exact extent of its winter hardiness is still a question, and it is currently recommended for growing in zone 5 and farther south. It produces excellent spring growth, but because Balansa clover is a relatively new cover crop species, some small-scale testing for various uses may be appropriate for your location, including evaluation of how it does in mixes.

Summer Annual Legumes

Berseem clover is grown as a summer annual in colder climates. It establishes easily and rapidly and develops a dense cover, which makes it a good choice for weed suppression. It's also drought tolerant and regrows rapidly when mowed or grazed. Berseem has the advantage of being unlikely to cause bloat in grazing livestock. It can be grown in mild climates during the winter. Some newer varieties have done very well in California, with Multicut outyielding Bigbee. Frosty is another new berseem clover introduction that is supposed to have improved cold tolerance and is able to be cut multiple times in a season.

Cowpeas are native to Central Africa and do well in hot climates. The cowpea is, however, killed by even a mild frost. It is deep rooted and is able to do well under droughty conditions. It usually does better on low-fertility soils than crimson clover. Cowpeas can perform well in mixes with summer grass cover crops such as pearl millet or sorghum-sudan. The most common variety of cowpeas for cover crop use is the iron clay type.

Sunn hemp is a warm season tropical legume that grows vigorously as a summer legume for much of the United States; it is also a popular inter-seasonal cover crop in the tropics. Sunn hemp can grow from several feet to as much as 7 feet tall and is used frequently in mixes with other summer cover crops. It greatly reduces soybean cyst nematode populations and is a good nitrogen fixer. Sunn hemp has been noted as a summer cover that deer like to browse, which can be a positive or negative depending on the goals for cover crop use.

Soybeans, usually grown as an economic crop for their oil- and protein-rich seeds, can serve as a summer cover crop if a farmer has leftover seed and if allowed to grow only until flowering. They require a fertile soil for best growth. As with cowpeas, soybeans are killed by frost. If grown to maturity and harvested for seed, they do not add much in the way of lasting residues or nitrogen.

Velvet beans (mucuna) are widely adopted in tropical climates. It is an annual climbing vine that grows aggressively to several feet high and suppresses weeds well (Figure 10.3). In a velvet bean–corn sequence, the cover crop provides a thick mulch layer and reseeds itself after the corn crop. The beans themselves are sometimes used for a coffee substitute and can also be eaten after long boiling. A study in West Africa showed that velvet beans can provide nitrogen benefits for two successive corn crops.

Lablab beans (also called hyacinth beans) are another tropical legume being evaluated as a cover crop in the Southeastern U.S. Once established, they grow quickly in hot weather and can produce vines several feet long. Given their viney, climbing growth habit, they

Figure 10.3. Velvet beans grown on hillsides in Central America, as growing vines (left) and mulched under a corn crop (right). Photos by Ray Bryant.

might be best paired with an upright grass cover like pearl millet or sorghum-sudan. As with other warm season legumes, they are killed by a light frost.

Similar tropical cover crops include ***Canavalia*** and ***Tephrosia***, which can also be used as mulches after maturing. ***Pigeon peas*** are yet another tropical legume that may have some potential as a cover crop.

Biennial and Perennial Legumes

Red clover is vigorous, shade tolerant, winter hardy, and can be established relatively easily. It is commonly interseeded in early spring with small grains. Because it starts growing slowly, there is minimal competition between it and the small grain. Red clover also successfully interseeds with corn in the Northeast if the herbicides used do not have significant residual activity.

Sweet clover (yellow blossom) is a reasonably winter hardy, biennial, vigorous growing crop with an ability to get its roots into compacted subsoils. It is able to withstand high temperatures and droughty conditions better than many other cover crops. Sweet clover requires a soil pH near neutrality and a high calcium level; it does poorly in wet, clayey soils. As long as the pH is high, sweet clover is able to grow well in low-fertility soils. While it is sometimes grown for only a year, a good use for this legume is to allow it to flower and complete its life cycle in the second year, when it produces a large amount of biomass. Like red clover, a typical way that sweet yellow clover has been used is to overseed it into winter wheat in March, then let it grow after wheat harvest until the following spring. When used as a green manure crop, it is incorporated into the soil before full bloom, especially when followed by early spring corn planting.

White clover does not produce as much growth as many of the other legumes and is also less tolerant of droughty situations. (New Zealand types of white clover

Figure 10.4. Root systems of four grass cover crops at early stages of growth (two months in a greenhouse). From left: annual ryegrass, barley, triticale (winter biennials) and sorghum-sudangrass (summer annuals). Photos by Joseph Amsili.

Figure 10.5. Left: Cereal rye grows in late fall and early spring, and is an effective catch crop and soil conditioner in cool regions. It is widely used in Maryland to reduce nutrient loading into the Chesapeake Bay. Right: Buckwheat establishes quickly in hot and dry conditions, and is an excellent short-duration summer cover crop that improves soil and suppresses weeds. Photo by Thomas Bjorkman.

are more drought tolerant than the more commonly used ladino and Dutch white clovers.) However, because it does not grow very tall and is able to tolerate shading better than many other legumes, it may be useful in orchard-floor covers or as a living mulch. White clover has been evaluated for early summer interseeding into corn, but its survival in corn is often not as good as more shade-tolerant species such as annual ryegrass. White clover is also a common component of intensively managed pastures.

Grasses

Commonly used grass cover crops include the annual cereals (rye, wheat, triticale, barley oats), annual or perennial forage grasses such as ryegrass, and warm-season grasses such as sorghum-sudangrass. Grasses, with their fibrous root systems, are very useful for scavenging nutrients, especially nitrogen, left over from a previous crop. They tend to have extensive root systems (Figure 10.4), and some establish rapidly and can greatly reduce erosion. In addition, they can produce large amounts of residue and a large amount of roots. Both the residue and the roots can help add organic matter to the soil. The aboveground residue also can help suppress weed germination and growth.

A problem common to all the grasses is that if you grow the crop to maturity for the maximum amount of residue, you reduce the amount of available nitrogen for the next crop. This is because of the high C:N ratio (low percentage of nitrogen) in grasses near maturity, which ties up nitrogen when decomposing after termination, especially when plowed under. This problem can be avoided by killing the grass early or by adding extra nitrogen in the form of fertilizer or manure. Another way to help with this problem is to supply extra nitrogen by seeding a legume-grass mix.

Cereal rye, also called winter rye, is very winter hardy and easy to establish. Its ability to germinate quickly, together with its winter hardiness, means that it can be planted later in the fall than most other species, even in cold climates. Decomposing residue of cereal rye has shown to have an allelopathic effect, which means that it can chemically suppress germination of small broadleaf weed seeds. It grows quickly in the fall and also grows readily in the spring (Figure 10.5). It is often the cover crop of choice as a catch crop and also works well with a roll-crimp mulch system, in which the cover crop is terminated by rolling and crimping while the cash crop (for example, soybeans) is no-till planted or transplanted into the resulting mulch (see Figure 16.10).

Triticale, a cross between wheat and rye, is almost as winter hardy as cereal rye. It is also easy to establish and has good production of spring vegetation and roots (Figure 10.4), though is somewhat shorter than cereal rye. It can be used for fall or spring grazing. If triticale does go to seed, it is easier to control than many other cover crops that might be grown singly or in a cover crop mix.

Oats are another popular cover crop. Many farmers like to use spring oats for fall cover crop planting because they will not overwinter and thus don't need spring termination. Summer or fall seedings, usually planted about a month before the last seeding date for cereal rye, will winterkill under most cold-climate conditions. This provides a naturally killed mulch the following spring and may help with weed suppression. As a mixture with one of the clovers, oats provide some quick cover in the fall. Oat stems help trap snow and conserve moisture, even after the plants have been killed by frost. There are oat types that can overwinter in mild climates, such as winter oats or black oats. Black oats, which are a different species of oats compared to spring oats, are popular in no-till systems in South America, where crops such as soybeans are planted into the oat mulch. In the Midwest, black oats often get more fall growth than spring oats, but the seed of black oats can be harder to find and more expensive (note that they are also black-seeded winter oats, which are not true black oats).

> Buckwheat grown for grain ... "occupies the land only during three months of the year, and which consequently figures in the first rank among catch crops, which accommodates itself to all soils, requires little manure, has scarcely any exhausting effect upon the land, keeps the ground perfectly clean by the rapidity of its growth, and which, notwithstanding, yields on an average fifty-fold, and may easily be raised to double that quantity."
>
> —LÉONCE DE LAVERGNE (1855)

Annual ryegrass (not related to cereal rye) grows well in the fall if established early enough. It develops an extensive root system (Figure 10.4) and therefore provides very effective erosion control while adding significant quantities of organic matter. The roots may grow 3–4 feet deep even when aboveground growth is 6 inches or less. Annual ryegrass may winterkill in cold climates. Some caution is needed with annual ryegrass: because it requires a careful approach to termination, it may become a problem weed in some situations.

Sudangrass and sorghum-sudan hybrids are fast growing summer annuals that produce a lot of growth in a short time (Figure 10.4). Because of their vigorous nature, they are good at suppressing weeds. If they are interseeded with a low-growing crop, such as strawberries or many vegetables, you may need to delay seeding so the main crop will not be severely shaded. They have been reported to suppress plant-parasitic nematodes and possibly other organisms, as they produce highly toxic substances during decomposition in soil. Sudangrass is especially helpful for loosening compacted soil. It can also be used as a livestock forage and so can do double duty in a cropping system with one or more grazings and still provide many benefits of a cover crop. If grazing is not an option, periodic mowing helps to control excessive sudangrass stem growth and residue management issues. Mowing also stimulates root development, leaving more belowground residue. Dwarf and brown midrib (low lignin) varieties of sorghum-sudangrass are available and might be considered for cover cropping.

Millets are another group of summer annual grasses used as cover crops. There are actually several different plant species that are called millets, from

COVER CROPS IN PERENNIAL SYSTEMS

In perennial systems like orchards and vineyards, groundcover management (floor management) can help improve soil health and crop quality. In this case, the cover crop should be a perennial with special characteristics. It should not overly compete with the main crop, and it should be persistent with minimal maintenance and provide good erosion and weed control. Also, it should be able to tolerate the conditions of the orchard floor, such as shade, traffic and drought. Basically, it functions more as a *living mulch* and therefore should not be too aggressive or spread laterally. A good species for this purpose is Dutch white clover, which also provides modest amounts of nitrogen. Perennial grasses like certain fescues can be attractive as a ground cover if they have a low-growing habit with dense, fine roots and require minimal mowing. Combinations of legumes and grasses may also be attractive. Sometimes, cover crops are used to deliberately compete with grapevines to reduce excessive vegetative growth, but in this situation they are kept away from the immediate vicinity of the vines.

different regions of the world. The two most commonly used as cover crops in the United States are pearl millet (from Africa) and foxtail millet (from Asia). Forage types of pearl millet can be tall, vigorous crops similar to sorghum-sudan and are drought tolerant. Foxtail millet is also drought tolerant and a fast maturing cover crop, sometimes used in mixes or after vegetable crops.

Other Crops

Buckwheat is a summer annual that is easily killed by frost (Figure 10.5, right). It will grow better than many other cover crops in low-fertility soils but is less tolerant of compacted soils. It also grows rapidly and completes its life cycle quickly, taking around six weeks from planting into a warm soil until the early flowering stage. Buckwheat can grow more than 2 feet tall in the month following planting. If planted in early summer, it may get 3–4 feet tall at maturity but will stay shorter with late summer planting. It competes well with weeds because it grows so fast and, therefore, is sometimes used to suppress weeds following an early spring vegetable crop. It has also been reported to suppress important root pathogens, including Thielaviopsis and Rhizoctonia species. It is possible to grow more than one crop of buckwheat per year in warmer regions. Its seeds are not “hard” and do not persist for multiple years in the soil, but it can reseed itself and become a volunteer weed. Mow, roll, or till it before seeds develop to prevent reseeding. On the other hand, self-seeding can be taken advantage of, and if using tillage, work with a shallow pass with harrows.

Brassicas used as cover crops include mustard, rapeseed, oilseed radish, forage turnips and other species. They are increasingly used as winter or rotational cover crops in vegetable and specialty crop production, such as potatoes and tree fruits.

Rapeseed (***canola*** is a type of rapeseed) grows well under the moist and cool conditions of late fall, when other kinds of plants are going dormant for winter. Rapeseed is killed by harsh winter conditions but is grown as a winter crop in the middle and southern sections of the United States. Both winter annual and spring-types of rapeseed and canola are available in the market.

Oilseed (forage) radish has gained a lot of interest because of its fast growth in late summer and fall, which allows significant uptake of nutrients. It develops a large taproot, 1–2 inches in diameter and a foot or more deep, that can break through compacted layers,

Figure 10.6. Brassica cover crop roots. Growing oilseed (forage) radishes (left) and the soil hole built by a forage radish root (right). Photos by Ray Weil.

allowing deeper rooting by the next crop (Figure 10.6). Oilseed radish will winterkill and decompose by spring, but it leaves the soil in friable condition with remnant root holes that improve rainfall infiltration and storage. It also eases root penetration and development by the following crop. All of the brassicas get much better growth as fall cover crops if planted in late summer or early fall. For winter-hardy crops, such as canola, early fall planting is critical to ensure winter survival.

Rapeseed and other brassica crops may function as biofumigants, suppressing soil pests, especially root pathogens and plant-parasitic nematodes. Row crop farmers are increasingly interested in these properties. Don't expect brassicas to eliminate your pest problems, however. They are a good tool and an excellent rotation crop, but pest management results are inconsistent. More research is needed to further clarify the variables affecting the release and toxicity of the chemical compounds involved. Because members of this family do not develop mycorrhizal fungi associations, they will not promote mycorrhizae in the following crop.

> Florida farmer Ed James has found significant benefits to the health and productivity of his orange groves by using mixes of cover crops. "It helps to have a blend because if you have one species that doesn't take, you aren't left without any germination," he says. "As the buckwheat begins to play out, the hairy indigo and sunn hemp start to come on. As that begins to play out, the brassicas are coming. We already have a monoculture with the trees, so the mix of cover crops makes the soil feel like it is getting a crop rotation."
>
> —GILES (2020).

COVER CROP MANAGEMENT

There are numerous management issues to consider when using cover crops. Once you decide what your major goals are for using cover crops, select one or more to try out. Consider using combinations of species. You also need to decide where cover crops best fit in your system: planted following the main crop, intercropped during part or all of the growing of the main crop, or grown for an entire growing season in order to build up the soil. The goal, while not always possible to attain, should be to have something growing in your fields (even if dormant during the winter) all the time. Other management issues include when and how to kill or suppress the cover crop, and how to reduce the possibility of interference with your main crops either by using too much water in dry climates or by becoming a weed in subsequent crops.

Mixtures of Cover Crops

Although most farmers use single species of cover crops in their fields, mixtures of different cover crops offer combined benefits. The most common mixture is a grass and legume, such as cereal rye and hairy vetch, oats and red clover, or field peas and a small grain. Other mixtures might include a legume or small grain with oilseed radishes, or even just different small grains mixed together. Mixed stands usually do a better job of suppressing weeds than a single species. Growing legumes with small grains helps compensate for the decreases in nitrogen availability for the following crop when small grains are allowed to mature. In the mid-Atlantic region, the cereal rye-hairy vetch mixture has been shown to provide another advantage for managing nitrogen: When a lot of nitrate is left in the soil at the end of the season, the rye is stimulated (reducing leaching losses). When little nitrogen is available, the vetch competes better with the rye, fixing more nitrogen for the next crop. A crop that grows erect, such as cereal rye, may provide support for hairy vetch and enable it to grow better. Mowing close to the ground kills vetch supported by rye easier than vetch alone. In no-till production systems, this may allow for mowing instead of herbicide use.

Cover Crops and Nitrogen

Managing nitrogen supply is one of the critical challenges farmers face during a crop rotation; the aim is to have sufficient available N for the crops being grown while not having a lot of mineral N left in the soil after crop maturity, especially during seasons when it might leach out or be denitrified. Cover cropping can play an important role in N management, whether the need is to supply N for grains or vegetables, or to lower available N at the end of the season to reduce losses.

Estimating N available from cover crops. Legume cover crops can supply significant amounts of available N for the following crop. If a legume is productive and allowed to grow to the bud stage to gain sufficient size (biomass), quite a bit of N will be made available to the next crop, from 70 to well over 100 pounds per acre. But the amount of N supplied depends on the cover crop species (or mix of cover crops) and how long it's allowed to grow. Hairy vetch and crimson clover are two of the many choices that farmers frequently turn to in order to produce a lot of N, but other legumes may prove useful as sources of N.

The amount of N that will be made available to the following crop depends on the stage of growth, the amount of growth (biomass), and the N content of the cover crop or cover crop mix. Small cover crops whose leaves are deep green, for example, in early spring, will contain a high percent of N, over 3 percent. But because there is so little mass of material, the plants contain low total *amounts* of N. The N percent of a cover crop such as cereal rye tends to decrease (from over 3 percent) as the plant grows more leaves and then when the stem elongates and flowering and maturity occurs, ending up well below 1 percent N with a C:N ratio of 80 or more. If the crop has a low percent N (around 1.5%–2% N), as is common with small grains when stems elongate and flowering begins, little to no N can be counted on to help the following crop because soil organisms use all the N present as they decompose the residue. (See Figure 9.3 and Table 9.4 for an explanation of the C:N ratio and its relation to percent N in residue.)

If you estimate (or measure) the mass of a cover crop at the time of termination and its percent N, you can then estimate the amount of N that may be available to the following crop by using Table 10.1.

Minimizing residual N in fall. Another way to increase N availability to the following crop is through cover crops capturing end-of-season residual N and

Table 10.1
Estimated Available N from Previous Cover Crop[1]

Cover Crop Total N		Estimated Available N (pounds N per acre)
% N in Dry Matter (Biodegradable)	Pounds N per Ton	
1	20	0
1.5	30	10
2	40	14
2.5	50	20
3	60	28
3.5	70	37

[1]Modified from "Estimating plant-available nitrogen release from cover crops." PNW 636. A Pacific Northwest Extension Publication (Oregon State University, Washington State University and University of Idaho).

protecting it for use by the next commercial crop. At the end of the season in some cropping systems there may be significant amounts of residual N that then can be lost through leaching below the root zone or by denitrification over the winter and early spring. This is both an economic issue for the farm and an environmental issue. Corn-soybean crop alternation and corn-corn are especially prone to high N levels in the fall and to overwinter and early spring loss. Grass cover crops such as cereal rye can help by taking up mineral N in the fall. (As mentioned above, there are good reasons to use a grass-legume mix such as cereal rye-hairy vetch in a situation where you aren't sure whether there is or isn't a lot of N left at the end of the season.) When there may be a lot of mineral N throughout the root zone (not just near the surface), if planted early enough, a deep-rooted cover crop such as forage radish together with cereal rye can help retain N. The forage radish can bring up nitrate from deeper in the profile in the fall, and when frost kills the radish and the nitrate leaks out, it can be taken up by cereal rye.

Planting

There are three ways to time the planting of a cover crop in relation to your cash crops: 1) plant a cover crop for an entire growing season; 2) plant a cover crop after the harvest of a cash crop and before planting the next cash crop; and 3) interseeding, or planting a cover crop into a growing cash crop. The approach you take will depend on your reason for planting a cover crop, your cash crops, the length of the growing season and the climate.

Planting for an entire growing season. If you want to accumulate a lot of organic matter, it's best to grow a high-biomass mix of cover crops for the whole growing season (see Figure 10.7a), which means no income-generating crop will be grown that year. This may be especially useful with very infertile or eroded soils and when transitioning to organic farming. This is sometimes done on vegetable farms when no manure is available and in fallow systems in the western United States, but grain/oilseed farmers will not normally give up a year of production in a field.

Planting after cash crop harvest. Most farmers sow cover crops after the cash crop has been harvested (Figure 10.7b). In this case, as with the system shown in Figure 10.7a, there is no competition between the cover crop and the main crop. The seeds can be no-till planted with a grain drill or a row crop planter (no need for a high clearance interseeder) instead of broadcast, resulting in better cover crop stands. If possible, tillage should be avoided prior to cover crop seeding to maximize the soil health benefits that cover crops provide. In milder climates, you can usually plant cover crops after harvesting the main crop. In colder areas, there may not be enough time to establish a cover crop between harvest and winter. Even if you are able to get it established, there will be little growth in the fall to provide soil protection or nutrient uptake. The choice of a cover crop to fit between main summer crops (Figure 10.7b) is severely limited in northern climates by the short growing season and severe cold. Cereal rye is probably the most reliable cover crop for those conditions. In most situations, there are a range of establishment options.

Cover crops are also established following grain

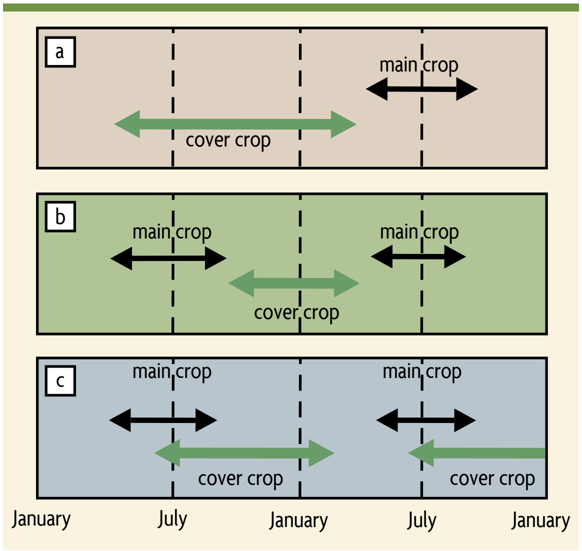

Figure 10.7. Three ways to time cover crop growth for use with a summer crop.

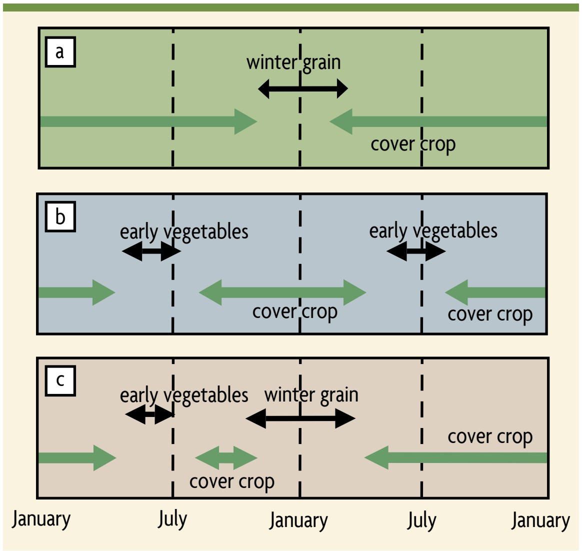

Figure 10.8. Timing cover crop growth for winter grain, early vegetable and vegetable-grain systems.

harvest in late spring (Figure 10.8a). With some early maturing vegetable crops, especially in warmer regions, it is also possible to establish cover crops in early summer (Figure 10.8b). Cover crops also fit into an early vegetable-winter grain rotation sequence (Figure 10.8c).

Interseeding. The third management strategy is to interseed cover crops during the growth of the main crop. Cover crops are commonly interseeded at planting in winter grain cropping systems or are frost-seeded in early spring. Seeding cover crops during the growth of cash crops (Figure 10.7c) is especially helpful for the establishment of cover crops in areas with a short growing season. Delaying the cover crop seeding until the main crop is off to a good start means that the commercial crop will be able to grow well despite the competition. Good establishment of cover crops requires moisture and, for small-seeded crops, some covering of the seed by soil or crop residues. High clearance grain drills can be used to obtain good seed-to-soil contact when interseeding a cover crop (Figure 10.9). Cereal rye is able to establish well without seed covering, as long as sufficient moisture is present. Farmers using this system will broadcast seed during or just after the last cultivation of a row crop. Aerial seeding, "highboy" tractors, or detasseling machines are used to broadcast green manure seed after a main crop is already fairly tall, like with corn. When growing is on a smaller scale, seed is broadcast with the use of a hand-crank spin seeder. This works best for some of the grasses, and its success depends on the soil surface being moist for germination and establishment to occur.

Intercrops and living mulches. Growing a cover crop between the rows of a main crop has been practiced for a long time. It has been called a living mulch or an orchard-floor cover, with the cover crop established before the main crop. Intercropping, with the cover crop established at or soon after planting, has many benefits. Compared with bare soil, a ground cover provides erosion control, better conditions for using equipment during harvest, higher water-infiltration capacity, and an increase in soil organic matter. In addition, if the cover crop is a legume, a significant buildup of nitrogen

COVER CROP SELECTION AND PLANT PARASITIC NEMATODES

If nematodes become a problem in your crops (common in many vegetables such as lettuce, carrots, onions and potatoes, as well as in some agronomic crops), carefully select cover crops to help limit the damage. For example, the root-knot nematode (*M. hapla*) is a pest of many vegetable crops, as well as of alfalfa, soybeans and clover, but all the grain crops—corn, as well as small grains—are nonhosts. Growing grains as cover crops helps reduce nematode numbers. If the infestation is very bad, consider two full seasons with grain crops before returning to susceptible crops. The root-lesion nematode (*P. penetrans*) is more of a challenge because most crops, including almost all grains, can be hosts for this organism. Whatever you do, don't plant a legume cover crop such as hairy vetch if you have an infestation of root-lesion nematodes; it will actually stimulate nematode numbers. However, sudangrass, sorghum-sudan crosses and ryegrass, as well as pearl millet (a grain crop from Africa, grown in the United States mainly as a warm-season forage crop) have been reported to dramatically decrease nematode numbers. Some varieties appear better for this purpose than others. The suppressive activity of such cover crops is due to their poor host status to the lesion nematode, general stimulation of microbial antagonists and the release of toxic products during decomposition. Forage-type pearl millet, sudangrass and brassicas such as mustard, rapeseed, oilseed radish and flax, all provide some biofumigation effect because when they decompose after incorporation, they produce compounds that are toxic to nematodes. Marigolds, grown sometimes as companion plants in gardens, can secrete compounds from their roots that are toxic to nematodes.

may be available to crops in future years. Another benefit is the attraction of beneficial insects, such as predatory mites, to flowering plants. Less insect damage has been noted under polyculture than under monoculture.

Growing other plants near the main crop also poses potential dangers. The intercrop may harbor insect pests, such as the tarnished plant bug. Most of the management decisions for using intercrops are connected with minimizing competition with the main crop. Intercrops, if they grow too tall, can compete with the main crop for light, or may physically interfere with the main crop's growth or harvest. Intercrops may compete for water and nutrients. Using intercrops is not recommended if rainfall is barely adequate for the main crop and supplemental irrigation isn't available.

Soil-improving intercrops established by delayed planting into annual main crops are usually referred to as interseeded cover crops. Herbicides, mowing and partial rototilling are used to suppress the cover crop and give an advantage to the main crop. Another way to lessen competition from the cover is to plant the main crop in a relatively wide cover-free strip (Figure 10.10). This provides more distance between the main crop and the intercrop rows. When establishing orchards and vineyards, one way to reduce competition is to plant the living mulch after the main perennial crops are well established.

Cover Crop Termination

No matter when you establish cover crops, they are usually killed or drastically weakened before or during soil preparation for the next cash crop. This preparation is usually done by one of the following approaches: mowing once they've flowered (most annuals can be killed that way), using herbicides and no-till, plowing into the soil (with or without use of herbicides), or mowing, rolling and crimping and no-till planting in the same operation, or naturally by winter injury. In

Figure 10.9. Cover cropping strategies. Left: Interseeding a cover crop into soybeans (photo by Cornell University Sustainable Cropping Systems Lab); Middle: a mixture of legume cover crops (cover crop cocktail) interseeded in corn; Right: clover frost seeded in rye (photo by Practical Farmers of Iowa).

some cases it is a good idea to leave a week or two between the time a cover crop is tilled in or killed and the time a main crop is planted. Studies have found that a sudex cover crop is especially allelopathic and that tomatoes, broccoli and lettuce should not be planted until six to eight weeks to allow for thorough leaching of residue. This allows some decomposition to occur and may lessen problems of nitrogen immobilization and allelopathic effects, as well as avoiding increased seed decay and damping-off diseases (especially under wet conditions) and problems with cutworm and wireworm. It also may allow for the establishment of a better seedbed for small-seeded crops, such as some of the vegetables. Establishing a good seedbed for crops with small seeds may be difficult because of the lumpiness caused by the fresh residues.

Cover crops can also be terminated by partially or wholly harvesting the biomass. You might argue that cover crops should be grown for the purpose of improving the soil, not to be harvested or grazed. But sometimes farmers use a hybrid or adaptive system, especially if they have livestock. For example, if a cereal rye crop comes up quickly after the winter in a warm spring, a farmer might decide to harvest the extra biomass for hay or haylage. In other cases it might be worthwhile to allow animals to graze the cover crop, which still cycles much of the carbon and nutrients (see Chapter 12). Even though much of the aboveground biomass is harvested, the soil still benefits from the root biomass and, in the case of grazing, from the manure.

Management Cautions

Cover crops can cause serious problems if not managed carefully. They can deplete soil moisture; they can become weeds; and, when used as an intercrop, they can compete with the cash crop for water, light and nutrients. They also tend to be somewhat costly in terms of seed and establishment, so you want to ensure that the benefits pay off.

In drier areas and on droughty soils, such as sands, late killing of a winter cover crop may result in moisture deficiency for the main summer crop. In that situation,

Figure 10.10. A wide cover-free strip and living mulch, which is also used for traffic.

the cover crop should be killed before too much water is removed from the soil. However, in warm, humid climates where no-till methods are practiced, allowing the cover crop to grow longer means fewer problems with soil being very wet or saturated at planting, and more residue and water conservation for the main crop later in the season. Cover crop mulch may more than compensate for the extra water removed from the soil during the later period of green manure growth.

Greater formation of large (macro) pores with cover crops leads to more rainfall infiltration, while higher organic matter levels following their use leads to greater soil waterholding capacity. Surface residue also slows runoff of rainfall, which allows more to infiltrate into the soil. In addition, greater mycorrhizal fungi presence following cover crops may aid water uptake, and cover crops may lead to cash crops rooting deeper and reaching more water. Considering all their effects, cover crops normally greatly enhance the water status of soils for cash crops. In addition, in very humid regions or on wet soils, the ability of an actively growing cover crop to "pump" water out of the soil by transpiration may be an advantage (see Figure 15.8). Letting the cover crop grow as long as possible results in more rapid soil drying and allows for earlier planting of the main crop.

Using bin-run cover crop seed that hasn't been properly cleaned can result in introducing weed seeds into fields. And on rare occasions cover crops may become unwanted weeds in succeeding crops. Cover crops are sometimes allowed to flower to provide pollen to bees or other beneficial insects. However, if the plants actually set seed, the cover crop may reseed unintentionally. On organic farms the hard seed of vetch allows it to become a pest in small grains such as wheat. Cover crops that may become a weed problem include buckwheat, ryegrass and hairy vetch, but there is usually no concern with timely termination. On the other hand, natural reseeding of subclover, crimson clover or velvet beans might be beneficial in some situations.

Another issue to consider is that a cover crop might harbor a disease of crop plants and form a habitat bridge from one growing season to another. For example, oilseed radishes increase clubroot in broccoli. Finally, thick-mulched cover crops make good habitat for soil organisms and also for some undesirable species. Animals like rats, mice and snakes (in warm climates)

"PLANTING GREEN" INTO COVER CROPS

In the past, the recommendation was to leave a week or two between the time the cover crop was killed and when the cash crop was planted. That is still the best approach in certain situations, such as in a dry spring. In fact, in a dry spring, terminating a few weeks ahead of the cash crop may be needed. However, more and more farmers are now "planting green," where the cash crop is directly seeded into a still living cover crop. (In a 2019–2020 national survey, 54% of farmers reported that they plant green. See the box "Farmers Say Cover Crops Help the Bottom Line.") Most often, the cover crop is sprayed with an herbicide shortly after the cash crop is planted. Mechanical control of the cover crop is another option. For example, good suppression of hairy vetch in a no-till system has been obtained with the use of a modified rolling stalk chopper at early bloom. Farmers are also experiencing good cover crop suppression using cereal rye and a roller-crimper that goes ahead of the tractor, allowing the possibility of no-till planting a main crop at the same time as suppressing the cover crop (see Figure 16.10). Although not recommended for most direct-seeded vegetable crops, this has been successfully used for soybeans, corn and cotton.

may be found under the mulch, which might affect yields and crop quality, and caution is recommended when manual fieldwork is performed.

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a case study

GABE BROWN
BISMARCK, NORTH DAKOTA

It's fair to say that Gabe Brown didn't see change coming when he and his wife Shelly purchased their now-5,000-acre ranch from Shelly's parents upon their retirement in 1991. The ranch, which had been operated by Brown's in-laws, produced monocultures of small grains and relied on conventional production methods, including frequent tillage, fertilization, season-long grazing and chemical treatments. As Brown himself had been taught those production models for most of his life, he continued to work the ranch as it had been run for decades.

But 1995 and 1996 brought devastating hailstorms that destroyed his crops, and a drought in 1997 decimated that year's crop. As if that wasn't punishment enough, another hailstorm followed in 1998, destroying his crops once again. If the ranch was going to survive, things needed to change, and the land needed to recover. Bismarck is not an easy place to farm—the temperature can drop below freezing more than 220 days a year and annual rainfall averages around 16 inches, most of which falls during May and June thunderstorms. These extremes make severe weather events even more hazardous, and Brown was experiencing that firsthand.

At risk of losing his ranch, Brown was suddenly thrust into the position where he had to change his practices in order to save his business. He had heard about and learned of the successes of other farmers who chose a soil-first strategy for their operations. Those regenerative agriculture practices focused on reducing or eliminating tillage, ending the habitual use of synthetic chemicals for pest management and fertilization, and planting cover crops to reduce erosion and to capture nutrients in the soil. Though there was no way to control the climate or to stop extreme weather events, shifting to holistic management could make the property more resilient by strengthening the soil to protect it from wind and water, improving water infiltration and waterholding capacities to reduce drought risks, and shielding the land from temperature extremes by keeping it covered with either a living cover crop or crop residues. If he could rehabilitate the soil and bring it back to life by treating his land as a living organism, it was likely his business would not only survive but would also thrive.

Committed to saving his land and bringing the ranch back to life, Brown made a choice. Step by step, he experimented with and integrated regenerative, holistic production methods into the operation of Brown's Ranch, which now produces a variety of cash crops, cover crops, and grass-finished beef and lamb, as well as pastured laying hens, broilers and pork. "We haven't used synthetic fertilizers since 2008, and we use no fungicides or other pesticides," notes Brown. As a result of shifting to regenerative agriculture practices, the no-till ranch has seen immense improvements in all aspects of the operation, including reduced erosion, improved yields, increased soil organic matter, several new inches of topsoil and increased profitability.

During the transition, Brown fully committed to using a diverse mix of cover crops, which have increased his soil organic matter, reduced weed pressure, promoted beneficials, improved waterholding capacity and improved infiltration by breaking up soil compaction. His cover crop mixes include up to 25 different species. "Our goal is to have a living root in the soil as long as possible," Brown states. Every acre of his cropland has "either a cover crop growing before the cash crop, after the cash crop, or with the cash crop." Cover crop residue then helps to maintain desired soil temperature and to feed beneficial organisms.

Soil organic matter levels were 1.7–1.9% when he purchased the operation, and the precipitation infiltration rate was a scant half an inch per hour. But after more than 20 years of cover cropping, livestock integration and diverse crop rotations, Brown's Ranch has soil organic matter levels that hover around 5.3–7.9%, and the infiltration rate has skyrocketed to more than 30 inches of rainfall per hour, which means that precipitation always enters the soil and runoff never occurs.

Livestock are thoroughly integrated throughout his ranch, including on the 2,000 acres of cropland. Brown believes grazing livestock plays a critical role in improving soil health. The integration of livestock into the cropping system results in deposits of dung and urine on the land. Those deposits are consumed by macro- and microorganisms that provide nutrients to the living crops and subsequent covers.

When there is a nutrition and forage need that arises during the season, Brown relies on his cover cropping plan to fill that gap. Fall-season biennials like winter triticale and hairy vetch meet nutrient requirements for calving while also providing "armor" for the soil. Soil sample data shows that grazed fields with a diverse cover crop mix have increased availability of all nutrients, thus adding to profitability.

Brown's increased crop yields and financial savings have shown to be quite impressive: "We have a 127-bushel-proven dryland corn yield, while the county average is under 100. So we're over 25% higher than county average, without many of the costs involved. We're saving a tremendous amount on inputs." Brown's Ranch relies on its healthy soil to provide the necessary nutrients for its crops: The diverse cover crop mix feeds soil organisms, which in turn provide necessary nutrients for crop growth.

Pasture management at Brown's Ranch is guided by the principles of getting adequate organic residue into contact with the soil through animal impact and then allowing forages plenty of time to recover from grazing. This means Brown's rotational grazing strategy is very intensive: Stocking rates are high and rotations are frequent. Permanent pastures are 15–40 acres in size and are divided further with portable fencing into paddocks one sixth of an acre to 5 acres. The 300-pair cowherd is typically moved once a day, and 200–600 yearlings are moved 1–5 times a day. While this seems like a lot of work, solar-powered gate openers that operate on a timer allow the animals to move themselves.

In this system, cattle will usually consume 30–40% of the aboveground biomass in a particular paddock and will trample most of the remaining sward. Most paddocks receive at least 360 days of recovery before they're grazed again. The ranch has its own marketing label for its grass-finished beef, lamb, pastured pork, eggs, broilers and honey.

Gabe Brown is a soil health convert. When he's not on the farm working with his son Paul, he is speaking at events and conferences, giving farm tours or teaching at a Soil Health Academy school. His 2018 book *Dirt to Soil: One Family's Journey into Regenerative Agriculture* shares the tale of the evolution of Brown's Ranch and offers solutions to many soil-health difficulties experienced by farmers and ranchers across the United States. By choosing to focus on the health of his living land, and by not being afraid to fail a little along the way, Brown has transformed his business and has made his operation more resilient to any challenges the future may hold.

Chapter 11

DIVERSIFYING CROPPING SYSTEMS

Photo courtesy the Rodale Institute

> *… with methods of farming in which grasses form an important part of the rotation, especially those that leave a large residue of roots and culms, the decline of the productive power is much slower than when crops like wheat, cotton, or potatoes, which leave little residue on the soil, are grown continuously.*
>
> —HENRY SNYDER, 1896

There are multiple ways to diversify cropping systems, and there are good reasons to do so. One important ecological principle is that diversity contributes to stability and productivity (see discussion in Chapter 8). Diversity over time in a field, year to year, is achieved by using cover crops and by ***rotating*** a number of crops. You can also diversify spatially, or across your farm's landscape, by planting different crops in different fields or in strips within fields. A well-planned crop rotation—for example, one that might use the same sequence of crops but staggered differently from one field to the next in a given year or season—provides diversification both over time and across the farm landscape. Crop diversification can also occur with less frequent rotations by using perennials. For example, dairy farmers may grow alfalfa for three to four years before it is rotated to corn. ***Agroforestry***, the growing of tree species together with annual crops or other perennials, affords another way of adding habitat diversity to a farm. ***Integrating livestock and cropping*** brings yet another dimension of diversity by introducing animals onto the farm. Of course, all three—crop rotations, agroforestry and integrating livestock—can be practiced together. In this chapter we'll discuss crop rotations and agroforestry. Integrating crops and livestock is discussed separately in the following chapter (Chapter 12).

WHY ROTATIONS?

Rotating crops usually means more income diversity and fewer problems with insects, parasitic nematodes, weeds and diseases caused by plant pathogens. Rotations that include nonhost plants are effective for controlling insects like corn rootworms, nematodes like the soybean cyst nematode, and diseases like root rot of field peas. In order to suppress specific soil diseases, the length of time between growing the same or a similar crop may vary from relatively short (one to two years for leaf blight of onions) to fairly long (seven years for clubroot of radishes or turnips). Crops that actually suppress a disease may do so by encouraging diversity

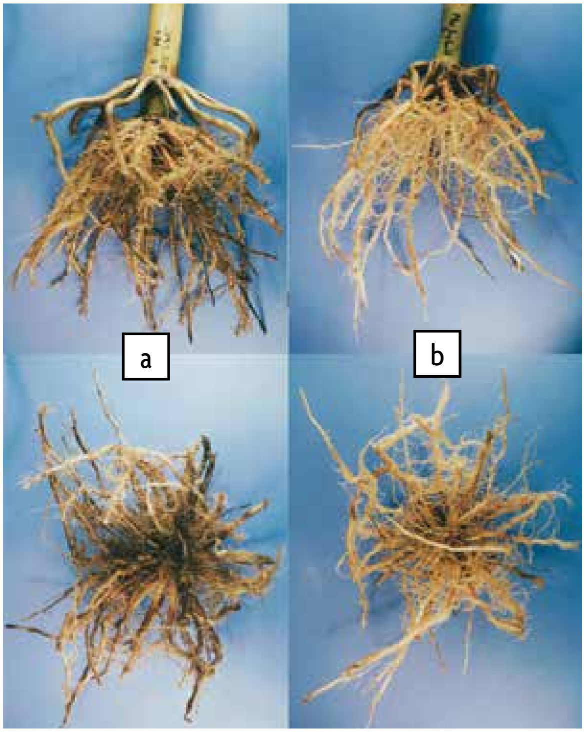

Figure 11.1. Corn roots: (a) continuous corn with mineral fertilizer, (b) corn following alfalfa with dairy manure compost. Photos by Walter Goldstein (Michael Fields Institute).

of soil organisms that outcompete or consume plant pathogens. Root growth may be adversely affected when continuously cropping to any single crop (see Figure 11.1). This means that the crop may be less efficient in using soil nutrients and added fertilizers. In addition, rotations that include legumes may supply varying amounts of nitrogen to succeeding crops. An annual legume harvested for seed, such as soybeans, provides little nitrogen for the following crop. On the other hand, a multiyear legume sod such as alfalfa may well supply all the nitrogen needed by the following crop. Growing sod-type forage grasses, legumes and grass-legume mixes as part of the rotation also increases soil organic matter. When you alternate two warm season crops, such as corn and soybeans, you have a very simple rotation that, unless cover crops are used as well, leaves the soil bare for long periods of time. More complex rotations with both warm- and cool-season crops require three or more crops and a five- to 10-year (or more) cycle to complete.

Rotations are an important part of any sustainable agricultural system. Yields of crops grown in rotations are typically 10% higher than those of crops grown in monoculture in normal growing seasons and as much as 25% higher in droughty growing seasons. Rotations involving three or more crops with different characteristics generally lead to positive changes in soil health, thus enhancing crop growth. And when you grow a grain or vegetable crop following a forage legume, the extra supply of nitrogen certainly helps. In fact, yields of crops grown in rotation are often still higher than those of crops grown in monoculture, even when both are supplied with plentiful amounts of nitrogen. Research in Iowa found that even using 240 pounds of nitrogen per acre when growing corn after corn, yields were not as good as corn following alfalfa with little or no nitrogen applied. In addition, following a nonlegume crop with another nonlegume produces higher yields

CROP AND VARIETAL MIXTURES

Not only do rotations help in many ways, but growing mixtures of different crops and even different varieties (cultivars) of a given crop sometimes offers real advantages. For example, faba (fava) beans help corn to get phosphorus on low phosphorus soils by acidifying the area around its roots. Also, when some varieties of a species are prized for a certain quality, such as taste, but are susceptible to a particular pest, growing a number of rows of the susceptible variety alternating with rows of resistant varieties tends to lessen the severity of the pest damage.

than a monoculture, when using recommended fertilizer rates. For example, when you grow corn following grass hay, or cotton following corn, you get higher yields than when corn or cotton is grown year after year. This yield benefit from rotations is sometimes called a *rotation effect*. Another important benefit of rotations is that growing a variety of crops in a given year spreads out labor needs and reduces risk caused by unexpected climate or market conditions. Other benefits may occur when perennial forages (hay-type crops) are included in the rotation, including decreased soil erosion and nutrient loss. Yields of corn in complex rotations are greater compared to a monoculture or simple rotation both in years of favorable conditions as well as in years when conditions are unfavorable, such as droughty or excessively wet years.

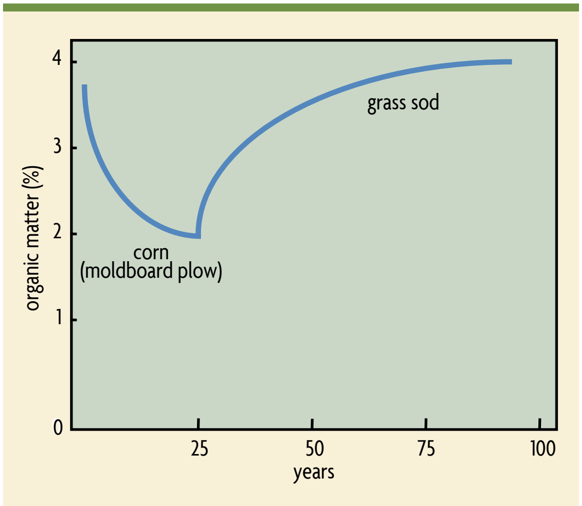

Figure 11.2. Organic matter changes in the plow layer during long-term cultivation followed by hay crop establishment (generalized drawing based on research).

ROTATIONS AND SOIL ORGANIC MATTER LEVELS

You might think you're doing pretty well if soil organic matter remains the same under a particular cropping system. However, if you are working soils with depleted organic matter, you need to build up levels to counter the effects of previous practices. Maintaining an inadequate level of organic matter won't do.

The types of crops you grow, their yields, the amount of roots produced, the portion of the crop harvested and how you manage crop residues will all affect soil organic matter. Soil fertility itself influences the amount of organic residues returned because more fertile soils grow higher-yielding crops, with more residues aboveground and belowground. Therefore, when soils have become depleted of organic matter due to simple rotations and nutrients being supplied only through inorganic fertilizers, stopping the application of those fertilizers is not the solution. Fertility levels still need to be maintained while also changing the rotation to improve soil health.

The decrease in organic matter levels when row crops are planted on a virgin forest or prairie soil is very rapid for the first five to 10 years, but, eventually, a low level equilibrium is reached. After that, soil organic matter levels remain stable, as long as production practices aren't changed. An example of what can occur during 25 years of continuously grown corn is given in Figure 11.2. Soil organic matter levels increase when the cropping system is changed from a cultivated crop to a grass or mixed grass–legume sod. However, the increase is usually much slower than the decrease that occurred under continuous tillage because rotations that include perennials reduce the total amount of tillage and the associated soil organic matter losses.

A long-term cropping experiment in Missouri compared continuous corn to continuous sod and various rotations. More than 9 inches of topsoil were lost during 60 years of continuous corn. The amount of soil lost each year from the continuous corn plots was equivalent to 21 tons per acre. After 60 years, soil under continuous corn had only 44% as much topsoil as that under continuous timothy sod. A six-year rotation consisting of corn, oats, wheat, clover and two years of timothy resulted in about 70% as much topsoil as was found in the timothy

ROTATIONS AND ENERGY USE, CLIMATE CHANGE IMPACTS AND POTENTIAL HUMAN HEALTH IMPACTS

An experiment comparing a typical corn-soybean crop alternation with a rotation that adds a year of oats and red clover (harvesting oats and straw) or a two-year alfalfa crop found many improvements with the more complex rotations: they resulted in less energy use, lower greenhouse gas emissions and better air quality without "compromising economic or agronomic performance." We know from many other experiments that complex rotations improved soil health in many ways: biologically, physically and chemically.

—HUNT ET AL. (2020)

soil, a much better result than with continuous corn. Differences in erosion and organic matter decomposition resulted in soil organic matter levels of 2.2% for the unfertilized timothy and 1.2% for the continuous corn plots.

In an experiment in eastern Canada, continuous corn led to annual increases in organic matter of about 100 pounds per acre, while two years of corn followed by two years of alfalfa increased organic matter by about 500 pounds per acre per year, and four years of alfalfa increased organic matter by 800 pounds per acre per year. Keep in mind that these amounts are small compared to the amounts of organic matter in most soils: 3% organic matter represents about 60,000 pounds per acre to a depth of 6 inches. Also, as soil organic matter increases to such an extent that mineral surfaces are fully saturated with organic matter and the soil is already highly aggregated, organic matter content increases plateau no matter how much is added in crop residue, manures and composts.

Two things happen when perennial forages are part of the rotation and remain in place for some years during a rotation. First, the rate of decomposition of soil organic matter decreases because the soil is not continually being disturbed. (This also happens when using no-till planting, even for non-sod crops such as corn.) Second, grass and legume sods develop extensive root systems, part of which will naturally die each year and add new organic matter to the soil. Crops with extensive root systems stimulate high levels of soil biological activity and soil aggregation. The roots of a healthy grass or legume-grass sod return more organic matter to the soil than do roots of most other crops. Older roots of grasses die, even during the growing season, and provide sources of fresh, active organic matter. Rotations that included three years of perennial forage crops have been found to produce a very high-quality soil in the corn and soybean belt of the Midwest.

We are not only interested in total soil organic matter; we want a wide variety of different types of organisms living in the soil. We also want to have a good amount of active organic matter (to provide food for soil life), high levels of organic matter inside aggregates (to help form and stabilize them), and well-decomposed soil organic matter, or humus (to provide more cation exchange capacity). Although most experiments have compared soil organic matter changes under different cropping systems, few experiments have looked at the effects of rotations on soil ecology. The more residues your crops leave in the field, the greater the populations of soil microorganisms. Experiments in a semiarid region in Oregon found that the total amount of microorganisms in a two-year wheat-fallow system was only about 25% of the amount found under pasture.

Conventional moldboard plow tillage systems are known to decrease the populations of earthworms and other soil organisms. More complex rotations increase soil biological diversity. Including perennial forages in the rotation enhances this effect.

RESIDUE AVAILABILITY

More residues are left in the field after some crops than others, as pointed out in chapters 3 and 9. High-residue-producing crops, especially those with extensive root systems, should be incorporated into rotations whenever possible. There is considerable interest in the possible future use of crop residue for a variety of purposes, such as small grain straw for bedding and mulching, or corn stover for producing biofuel. However, farmers should keep in mind that frequent removal of significant quantities of residue from their fields—and there may be more pressure to remove them if production of biofuels from crop residue becomes economically viable—can have a very negative effect on the soil's health.

SPECIES RICHNESS AND ACTIVE ROOTING PERIODS

In addition to the quantity of residues remaining following harvest, a variety of types of residues is also important. The goals should be to 1) rotate annuals and perennials, and 2) include different species in a rotation, three or more if possible. When compared with row crop monocultures, rotations tend to increase soil organic matter, nitrogen and the mass of microorganisms. Cover crops can help achieve the same goals but may not reach the full benefits of a perennial or biennial crop.

The percent of the time that living roots are present during a rotation is important. The period that active roots are present varies considerably, ranging from 32% of the time for a corn-soybean rotation to 57% for a soybean-wheat rotation to 76% for a three-year, soybean-wheat-corn rotation (Table 11.1). Just adding winter wheat to a corn-soybean alternation can greatly increase the time that active roots are present. (Doing so also assists in controlling weeds, increases corn yields and provides another crop to sell.) This is primarily the result of the fact that winter annuals, perennials and cover crops extend the growing period compared to summer annuals. As mentioned above, when soils are covered with living vegetation for a longer period of time, there tends to be decreased erosion, decreased loss of nitrate and less groundwater contamination.

Table 11.1
Comparison of Rotations:
Percent of Time Active Roots Are Present and Number of Species

Rotation	Years	Active Rooting Period (%)	Number of Species
Corn–soybeans	2	32	2
Dry beans–winter wheat	2	57	2
Dry beans–winter wheat/cover crop	2	92	3
Dry beans–winter wheat–corn	3	72	3
Corn–dry beans–winter wheat/cover crop	3	76	4
Sugar beets–beans–wheat/cover crop–corn	4	65	5

Source: Cavigelli et al. (1998).

ROTATIONS, WATER QUALITY AND GASEOUS LOSSES OF N

Diversified rotations offer many benefits when compared to very simple ones. For example, an experiment in South Dakota compared the simple corn-soybean crop alternation with a four-year corn-field pea-winter wheat-soybean rotation. Researchers found that, compared to corn-soybean alternation, soybean yields were higher in the four-year rotation, more organic matter accumulated in the soil, and less nitrous oxide gas (N_2O), a greenhouse gas, was lost to the atmosphere. When annual crops are grown and planted in the spring, such as with corn and soybeans, there is a considerable amount of time when the soil is not occupied by living plant roots. This means that for a large portion of the year there are no living plants to take up nutrients, especially nitrate, that can leach out of the soil. This is especially a problem in the midwestern and northeastern United States, where many soils have tile drainage, which accentuates the discharge of high-nitrate water into streams and rivers. In addition to not taking up nutrients, the lack of growing plants means that the soils are wetter and more apt to produce runoff, erosion and leaching. Thus, rotations that include perennial forages and winter grains help maintain or enhance the quality of both ground and surface waters. And, while intensive use of cover crops helps water quality in a similar way, cover crops should not be viewed as a substitute for a good rotation of economic crops. It's the combination of the positive effects of both good rotations and routine cover crop use that provides the greatest improvements in soil physical, chemical and biological characteristics.

FARM LABOR AND ECONOMICS

Before discussing appropriate rotations, let's consider some of the possible effects on farm labor and finances. If you grow only one or two row crops, you must work incredibly long hours during planting and harvesting seasons, and not as much at other times. Including forage hay crops and early harvested crops along with those that are traditionally harvested in the fall would allow you to spread your labor over the growing season, which would make the farm more easy to manage by family labor alone. In addition, when you grow a more diversified group of crops, you are less affected by price fluctuations of one or two crops. This may provide more year-round income and year-to-year financial stability. On the other hand, you can add diversity to the farm even without changing your rotation by growing cover crops that don't need to be harvested or sold (see Chapter 10).

While there are many possible benefits of rotations, there are also some costs or complicating factors. It is critically important to carefully consider the farm's labor, management capacity and markets when exploring diversification opportunities. You may need more equipment to grow a number of different crops. There may be conflicts between labor needs for different crops, like weed cultivation and side-dressing nitrogen fertilizer for corn at the same time as harvesting hay. In addition, some tasks, such as harvesting dry hay (mowing, tedding when needed, baling and storing) can require quite a bit of labor that may not always be available. And the more

CROP ROTATIONS AND PLANT DISEASES

Carefully selected rotations, especially when alternating between grains and broadleaf plants, can greatly assist control of plant diseases and nematodes. Sometimes a one-year break is sufficient for disease control, while for other diseases a number of years of growing a nonhost crop is needed to sufficiently reduce inoculum levels. Inclusion of pulse crops in a rotation seems to stimulate beneficial organisms and reduce the severity of cereal root diseases. Severity of common root rot of wheat and barley is reduced by taking a multiyear break to grow broadleaf plants. Rotations can be relatively easy to develop for control of diseases and nematodes that have a fairly narrow host range. However, some diseases or nematodes have a wider host range, and more care is needed in developing or changing rotations if these are present. In addition, some diseases enter the field on contaminated seed, while others, like wheat leaf rust, can travel with the wind for long distances. Other tactics, aside from rotations, are needed to deal with such diseases.

—KRUPINSKY ET AL. (2002)

diversified the farm, the less chance for time to relax.

For many farmers the solution is to diversify even further and bring livestock onto the farm. Well-integrated livestock-crop operations with multi-species grazing have less need for specialized equipment, and the animals can do much of their own harvesting and manure spreading during the grazing season, saving human labor. It also diversifies farm income and overall helps cycle nutrients and carbon on the farm.

GENERAL PRINCIPLES

Try to consider the following principles when you're thinking about a new rotation:

1. Follow a legume forage crop, such as clover or alfalfa, with a high-nitrogen-demanding crop, such as corn, to take advantage of the nitrogen supply.
2. Grow less of nitrogen-demanding crops, such as oats, barley and wheat, in the second or third year after a legume sod.
3. If possible, grow the same annual crop for only one year to decrease the likelihood of insects, diseases and nematodes becoming a problem. (Note: For many years, the western corn rootworm was effectively controlled by alternating between corn and soybeans. Recently, populations of the rootworm with a longer resting period have developed in isolated regions, and they are able to survive this simple two-year rotation.)
4. Don't follow a crop with a closely related species, since insect, disease and nematode problems are frequently shared by members of closely related crops.
5. If specific nematodes are known problems, consider planting nonhost plants, such as grain crops for root-knot nematodes, for a few years to decrease populations before planting a very susceptible crop such as carrots or lettuce. High populations of plant parasitic nematodes will also affect the choice of cover crops (see Chapter 10 for a discussion of cover crops).
6. Use crop sequences that promote healthier crops. Some crops seem to do well following a particular crop (for example, cabbage family crops following onions, or potatoes following corn). Other crop sequences may have adverse effects, as when potatoes have more scab following peas or oats.
7. Consider livestock as part of a rotational cropping system. Perennial fodder crops have many benefits, and these benefits are enhanced when livestock are grazing them in pastures. In fact, a rotational grazing system can be incorporated as a rotation of animals within a rotation of crops.
8. Use crop sequences that aid in controlling weeds. Small grains compete strongly against weeds and may inhibit germination of weed seeds; row crops permit midseason cultivation; and sod crops that are mowed regularly or grazed intensively help control annual weeds. Also, rotations including both cool season crops and warm season crops may aid in lowering weed populations. And as weeds develop resistance to more pesticides, it is increasingly important to explore crop sequences that give more opportunities to suppress them.
9. Use longer periods of perennial crops, such as a forage legume, on sloping land and on highly erosive soils. Using sound conservation practices, such as no-till planting, extensive cover cropping or strip cropping (a practice that combines the benefits of rotations and erosion control), may lessen the need to follow this guideline.
10. Try to grow a deep-rooted crop, such as alfalfa, safflowers or sunflowers, as part of the rotation. These crops scavenge the subsoil for nutrients and water, and channels left from decayed roots can promote water infiltration.
11. Grow some crops that leave a significant amount of residue, provide a surface mulch for reduced tillage systems, and, together with their roots, maintain or increase organic matter levels. Examples include sorghum or corn harvested for grain.

12. When growing a wide mix of crops, as is done on many direct-marketing vegetable farms, try grouping into blocks according to plant family, timing of crops (group all early season crops together, for example), type of crop (root versus fruit versus leaf) or cultural practices (for example, if irrigation or plastic mulch are used).
13. In regions with limited rainfall, the amount of water used by a crop may be a critically important issue, usually one of the most important issues. The amount of soil water at the time of planting may determine whether to grow a particular crop. Without plentiful irrigation, growing high-water-use crops such as hay, as well as sunflowers and safflowers, may not leave sufficient moisture in the soil for the next crop in the rotation.
14. Be flexible enough to adapt to annual climate and crop price variations, as well as to development of soil pathogens and plant parasitic nematodes. For example, dryland rotations have been introduced in the Great Plains to replace the wheat-fallow system, resulting in better water use and less soil erosion. (It is estimated that less than 25% of the rainfall that falls during the 14-month fallow period in the Central High Plains is made available to a following crop of winter wheat.) (See the box "Flexible Cropping Systems" and Table 11.2 for discussion and information on flexible, or dynamic, cropping systems.) Growing winter small grains in a rotation offers a number of possibilities depending on weather and the farm's needs. Winter grains can serve as a cover crop (killed in the spring while still in the vegetative state), be grazed in the spring if feed is needed, or, if it's very wet in the spring, be allowed to mature and the grain harvested.

ROTATION EXAMPLES

It's impossible to recommend specific rotations for a wide variety of situations. Every farm has its own unique combination of soil and climate, and of human, animal and machine resources. The economic conditions and needs are also different in each region and on each farm. You may get useful ideas by considering a number of rotations with historical or current importance.

A five- to seven-year rotation was common in the mixed livestock-crop farms of the northern Midwest and the Northeast during the first half of the 20th century. An example of this rotation:

Year 1. Corn
Year 2. Oats (mixed legume–grass hay seeded)
Years 3, 4 and 5. Mixed grass–legume hay
Years 6 and 7. Pasture

The most nitrogen-demanding crop, corn, followed the pasture, and grain was harvested only two of every five to seven years. A less-nitrogen-demanding crop, oats, was planted in the second year as a "nurse crop" when the grass-legume hay was seeded. The grain was harvested as animal feed, and oat straw was harvested to be used as cattle bedding; both eventually were returned to the soil as animal manure. This rotation maintained soil organic matter in many situations, or at least didn't cause it to decrease too much. On prairie soils, with their very high original contents of organic matter, levels still probably decreased with this rotation.

In the Corn Belt region of the Midwest, a change in rotations occurred as pesticides and fertilizers became readily available, animals were fed in large feedlots instead of on integrated crop-livestock farms, and grain export markets were developed. Once the mixed livestock farms became grain-crop farms or crop-hog farms, there was little reason to grow sod crops. In addition, government commodity price support programs unintentionally encouraged farmers to narrow production to just two feed grains. The two-year corn-soybean rotation is better than monoculture, but it has a number of problems, including erosion, groundwater pollution with nitrates and herbicides, soil organic matter depletion, and in some situations, increased insect problems. Soybeans leave minimal amounts of residues. But research indicates that with high yields of corn grain in a soybean-corn rotation there may be sufficient residues to maintain organic matter. For many years, the Thompson mixed crop-livestock (hogs and beef) farm in Iowa practiced an alternative five-year Corn Belt rotation similar to the first rotation we described: corn-soybeans-corn-oats (mixed/grass hay seeded)-hay. For fields that are convenient for pasturing beef cows, the Thompson eight-year rotation is as follows:

Year 1. Corn (cereal rye/hairy vetch cover crop)
Year 2. Soybeans
Year 3. Oats (mixed/grass hay seeded)
Years 4 to 8. Pasture

Organic matter is maintained through a combination of practices that include the use of manures and municipal sewage sludge, green manure crops (oats and rye following soybeans, and hairy vetch between corn and soybeans), crop residues and sod crops. These practices have resulted in a porous soil that has significantly lower erosion, higher organic matter content and more earthworms than neighbors' fields.

A four-year rotation researched in Virginia used mainly no-till practices as follows:

Year 1. Corn, with winter wheat no-till planted into corn stubble
Year 2. Winter wheat grazed by cattle after harvest; foxtail millet no-till planted into wheat stubble and hayed or grazed; alfalfa no-till planted in fall
Year 3. Alfalfa harvested and/or grazed
Year 4. Alfalfa harvested and/or grazed as usual until fall, then heavily stocked with animals to weaken it so that corn can be planted the next year

This rotation follows many of the principles discussed earlier in this chapter; it was designed by researchers, Extension specialists and farmers, and is similar to the older rotation described earlier. A few differences exist: this rotation is shorter; alfalfa is used instead of clover or clover-grass mixtures; and there is a special effort to minimize pesticide use under no-till practices. Weed-control problems occurred when going from alfalfa (fourth year) back to corn. This caused the investigators to use fall tillage followed by a cover crop mixture of cereal rye and hairy vetch. Some success was achieved suppressing the cover crop in the spring by just rolling over it with a harrow (with similar effects as a roller/crimper) and planting corn through the surface residues with a modified no-till planter. The heavy cover crop residues on the surface provided excellent weed control for the corn.

Traditional wheat-cropping patterns for the semiarid regions of the Great Plains and the Northwest commonly include a fallow year to allow storage of water and more nitrogen mineralization from organic matter for the next wheat crop to use. However, the two-year wheat-fallow system has several problems. Because no crop residues are returned during the fallow year, soil organic matter decreases unless manure or other organic materials are provided from off the field. Water infiltrating below the root zone during the fallow year moves salts through the soil to the low parts of fields. Shallow groundwater can come to the surface in these low spots and create "saline seeps," where yields will be decreased. Increased soil erosion, caused by either wind or water, commonly occurs during fallow years, and organic matter decreases (at a rate of about 2% per year, in one experiment). In this wheat monoculture system, the buildup of grassy weed populations, such as jointed goat grass and downy brome, also indicates that crop diversification is essential.

Farmers in the dryland regions trying to develop more sustainable cropping systems are considering using a number of species, including deeper-rooted crops, in a more diversified rotation. This would increase the amount of residues returned to the soil, reduce tillage, and lessen or eliminate the fallow period. (See "Flexible Cropping Systems" box.) In the 1970s some farmers began switching from the two-year wheat-fallow system to a three year rotation, commonly winter wheat-grain sorghum (or corn)-fallow. When this rotation is combined with no-till, accumulated surface residues help maintain higher soil moisture levels. A four-year wheat-corn-millet-fallow rotation under evaluation in Colorado was found to be better than the traditional wheat-fallow system. Wheat yields have been higher in this rotation than wheat grown in monoculture. The extra residues from the corn and millet are also helping to increase soil organic matter.

Many producers are including sunflowers, a deep-rooting crop, in a wheat-corn-sunflower-fallow rotation. Sunflowers are also being evaluated in Oregon as part of a wheat cropping sequence.

Another approach to rotations in the semi-arid Great Plains of North Dakota combines crop and livestock farming; it uses a multi-species rotation in place of continuous hard red spring wheat. This five-year rotation includes only two cash crops (wheat and sunflowers) with grazing crops grown for three years:

Year 1. Hard red spring wheat (cash crop) with winter triticale and hairy vetch planted after wheat harvest in September
Year 2. Triticale-vetch hay harvested in June. A cover crop consisting of a seven- to 13-species mix is seeded as soon as possible after the hay harvest and then grazed by either cows or yearling steers
Year 3. A silage-type corn variety is planted and grazed first by yearling steers and then by cows in a "leader-follower" grazing plan
Year 4. A field pea-forage barley mix is grazed by yearling steers
Year 5. Sunflowers (cash crop)

Sodic seeps and subsurface sodic clay layers are sometimes found in semi-arid regions and may limit crop growth. (See Chapter 6 for discussion of saline and sodic soils, and for their reclamation see Chapter 20). During the cover crop year of a multi-crop rotation such as the one discussed just above, including adapted crop-types with taproots such as tillage radishes, sunflowers, safflowers, mustard, and canola, as well as sodium-tolerant crops like barley, aids in remediating problem soils when coupled with a diverse crop rotation on all farm acres.

Vegetable farmers who grow a large selection of crops find it best to rotate in large blocks, each containing crops from the same families or having similar production schedules or cultural practices. Many farmers are now using cover crops to help "grow their own nitrogen," utilize extra nitrogen that might be there at the end of the season, and add organic matter to the soil. A four- to five-year vegetable rotation might be:

Year 1. Sweet corn followed by a hairy vetch/cereal rye cover crop
Year 2. Pumpkins, winter squash or summer squash followed by a rye or oats cover crop
Year 3. Tomatoes, potatoes or peppers followed by a vetch/cereal rye cover crop
Year 4. Crucifers, greens, legumes, carrots, onions and miscellaneous vegetables followed by a cereal rye cover crop
Year 5. (If land is available) oats and red clover or buckwheat followed by a vetch/cereal rye cover crop

Another rotation for vegetable growers uses a two- to three-year alfalfa sod as part of a six- to eight-year cycle. In this case, the crops following the alfalfa are high-nitrogen-demanding crops, such as corn or squash, followed by cabbage or tomatoes, and, in the last two years, crops needing a fine seedbed, such as lettuce, onions or carrots. Annual weeds in this rotation are controlled by

Table 11.2
Comparison of Monoculture, Fixed-Sequence Rotations and Dynamic Cropping Systems

	Monoculture	Fixed-Sequence Rotations	Dynamic Cropping Systems
Numbers and types of crops	Single crop	Multiple crops; number depends on regionally adapted species, economics, farmer knowledge and infrastructure	Multiple crops; number depends on regionally adapted species, economics, farmer knowledge and infrastructure
Crop diversity	None	Diversity depends on the length of the fixed sequence	Diversity high due to annual variation in growing conditions and marketing opportunities, as well as changes in producer goals
Crop-sequencing flexibility	None	None, although fixed-sequence cropping systems that incorporate opportunity crops increase flexibility	High; all crops, in essence, are opportunity crops
Biological and ecological knowledge	Basic knowledge of agronomy	Some knowledge of crop interactions is necessary	Extended knowledge of complex, multiyear crop and crop-environment interactions
Management complexity	Generally low, though variable depending on crop type	Complexity variable depending on the length of the fixed sequence and diversity of crops grown	Complexity inherently high due to annual variation in growing conditions, market and producer goals

Source: Modified from Hanson et al. (2007)

FLEXIBLE CROPPING SYSTEMS

As discussed in point 14 under “General Principles,” it may be best for many farmers to adopt more “dynamic” crop sequences rather than to strictly adhere to a particular sequence. Many things change from year to year, including prices paid for crops, pest pressures and climate. And many farmers do deviate from plans and change what they plant in a particular field; for example, in a wetter-than-normal field a dry spring opens the opportunity for a vegetable farmer to plant an early season crop, thus potentially enhancing the diversity of crops grown in that field. However, this issue is especially important for dryland farmers in water-limiting regions such as the Great Plains. In dryland agriculture, low water availability is usually the greatest limitation to crop growth. In such regions, where much of the water needed for a crop is stored in the soil at planting time, growing two heavy water users in a row may work out well if rainfall was plentiful the first year. However, if rainfall has been low, following a heavy-water-using crop (such as sunflowers or corn) with one that needs less water (such as dry peas or lentils) means that water stored in the soil may be enough, along with rainfall during the growing season, to result in a reasonable yield. Caution is needed when making flexible cropping decisions because carryover of herbicides from the previous crop may interfere with your ability to use a different crop than the one planned. University Extension weed control guides are reliable sources of information relating to herbicide chemical plant-back intervals for various crops (including cover crops). Overall, using an adaptive approach to cropping makes sense for many farm operations but requires a solid understanding of the agronomic principles on the part of the farmer.

CROP ROTATION ON ORGANIC FARMS

Crop rotation is always a good idea, but a sound crop rotation is essential on organic farms. Supplying nitrogen and controlling weeds is more challenging, and options for rescuing crops from disease are limited, making proactive planning through good crop rotations more important. Disease and weed management require a multiyear approach. Nutrients for organic crop production come largely through release from organic matter in soil. Therefore manure, compost, cover crops, and a crop rotation with regular organic matter inputs and large amounts of nitrogen and active soil organic matter are critical.

Organic farmers usually grow a high diversity of crops to obtain the benefits of a diverse crop rotation and to take advantage of specialty markets. Thus, organic field crop producers commonly grow five to 10 crop species, and fresh market vegetable growers may grow 30 or more. However, because of the large variation in acreage among crops and frequent changes in the crop mix due to weather and shifting market demands, planning crop rotations on highly diversified farms is difficult. Therefore, many organic farmers do not follow any regular rotation plan but instead place crops on individual fields (or parts of fields) based on the cropping history of the location and its physical and biological characteristics (e.g., drainage, recent organic matter inputs, weed pressure). Skilled organic growers usually have next year's cash crops and any intervening cover crops in mind as they make their placement decisions but find that planning further ahead is usually pointless because longer-term plans are so frequently derailed.

Although precise long-term rotation plans can rarely be followed on farms growing a diverse mix of crops, some experienced organic farmers follow a general repeating scheme in which particular crops are placed by the ad hoc approach described above. For example, some vegetable operations plant cash crops every other year and grow a succession of cover crops in alternate years. Many field crop producers alternate some sequence of corn, soybeans and small grains with several years of hay on a regular basis, and some vegetable growers similarly alternate a few years in vegetables with two to three years in hay. These rest periods in hay or in cover crops build soil structure, allow time for soilborne diseases and weed seeds to die off, and provide nitrogen for subsequent heavy-feeding crops. Some vegetable growers alternate groups of plant families in a relatively regular sequence, but this generally requires growing cover crops on part of the field in years when groups that require less acreage appear in the sequence. Within all of these generalized rotation schemes, the particular crop occupying a specific location is chosen by the ad hoc process described above. Organizing the choices with a general rotation scheme greatly simplifies the decision-making process.

Dividing the farm into many small, permanently located management units also greatly facilitates effective ad hoc placement of crops onto fields each year. By this means, a precise cropping history of every part of each field is easy to maintain. Moreover, problem spots and particularly productive locations can be easily located for planting with appropriate crops.

—CHARLES MOHLER, CORNELL UNIVERSITY

the harvesting of alfalfa a number of times each year. Perennial weed populations can be decreased by cultivation during the row-crop phase of the rotation.

Most vegetable farmers do not have enough land, or the markets, to have a multiyear hay crop on a significant portion of their land. Aggressive use of cover crops will help to maintain organic matter in this situation. Manures, composts or other sources of organic materials, such as leaves, should also be applied every year or two to help maintain soil organic matter and fertility.

Alternating cotton with peanuts is a common, simple rotation in the Southeast coastal region. The soils in this area tend to be sandy, low in both fertility and water-holding capacity, and have a subsoil compact layer. As with the corn-soybean alternation of the Midwest, a more complex system is very desirable from many viewpoints.

A rotation including perennial forage for at least a few years may provide many advantages to the cotton-peanut system. Research with two years of Bahia grass in a cotton-peanut system indicates greater cotton root growth, more soil organic matter and earthworms, and better water infiltration and storage.

The rapid expansion and intensification of agriculture in South America, notably Brazil and Argentina, is strongly driven by the increased global demand for grain crops like corn and soybeans. Many areas in this region also experience extended dry seasons. The system can be made more ecologically sustainable by using no-till and growing soybeans and corn. It is followed into the dry season by a tropical grass like brachiaria that is interseeded into the corn and grazed by beef cattle. While this makes the corn-soybean system less damaging, the participation of these countries in production for global distribution has resulted in the loss of significant portions of important tropical forests and the homelands of the people living in those forests.

Figure 11.3. Alley cropping involving walnut trees and wheat. Photo by USDA NRCS.

AGROFORESTRY

Agroforestry is the integration of trees and shrubs into crop and animal farming systems. The idea is that environmental, economic and social benefits are gained by intensively managing an integrated and interactive system. Here, trees do not just exist as an unmanaged plot of woods but rather benefit the crops and animals on the farm either directly or indirectly. In most cases, agroforestry benefits the farm through income diversification, a more favorable microclimate (shade or shelter from strong wind), and by providing wildlife habitat. Also, in many cases it can improve marginal lands that are not suitable for crop production. Agroforestry, however, requires a long-term commitment because the trees often don't produce income for several years, or even for decades in the case of timber species.

Alley Cropping

Alley cropping involves planting rows of trees at wide spacings with a companion crop grown in the alleyways between the tree rows. It is often done to diversify farm income, but it can also improve crop production and provide protection and conservation benefits to crops. In the United States, these systems often include cereals, row crops, hay or vegetable crops planted in the alleys between rows of high-value timber, fruit or nut trees

(Figure 11.3). High-value hardwoods like walnut and oak trees, or even ornamental trees like woody decorative florals or Christmas trees, are good species and can potentially provide long-term income while short-term proceeds are derived from a companion crop planted in the alleyways. Pecan and chestnut trees are good species for nut production, if that is desired from the tree rows.

Light interception by the trees is a concern when you grow crops in the alleys, especially at higher latitudes. (This is less a concern when the alley crop is shade tolerant, like certain herbs and forages). There are several ways to reduce this effect:

- Space the tree rows more widely.
- Orient tree rows in an east-west direction, which maximizes light interception because the tree obstruction mostly occurs when the sun is at a high angle. This may need to be balanced with other objectives like intercepting wind, which often requires north-south orientation.
- Use trees with fine leaves and less dense canopies that allow for more light penetration for the companion crop.
- Use tree species that leaf-out late or drop leaves early. For example, a late-leafing tree will not intercept light for winter wheat in the early season.
- Thin and prune (coppice) to control large tree canopies and enhance timber quality.

Farmers should tailor the tree layout to the type of species and product. Trees in single rows that are spaced farther apart within the row tend to take longer to close the canopy but also develop more branched crowns, which is desirable for some tree crops, like nut trees. Closely spaced trees in single or double rows encourage more self-pruning and straight trunk development, which is favorable for timber. Sometimes, a taller and shorter tree type can be grown together.

In tropical environments, alley cropping raises fewer concerns related to light interception because the sun is generally more intense and higher in the sky, and there are longer growing seasons. Also, in many tropical countries crop input costs, including fertilizers, are higher while labor costs and mechanization are lower. This creates a greater opportunity to use tropical leguminous trees interspersed with crops to increase the availability of organic nitrogen for the crops, fodder for animals, and firewood for cooking and heating (Figure 11.4).

Although alley cropping can offer advantages, there are some challenges that should be understood. As with other forms of multi-cropping, alley cropping requires more intensive technical management skill and marketing knowledge, and also may demand specialized equipment for tree management. It additionally removes land from annual crop production that may not provide a financial return for several years. Trees may be an obstacle to crop cultivation if their arrangement is not carefully planned and designed. The trees may also result in yield losses for the companion crops grown in the alleys by competing for sun, moisture and nutrients, and in some cases herbicide drift from crops may damage trees.

Other Agroforestry Practices

Forest farming does not separate the land into distinct growing zones like alley cropping but grows understory crops within an established forest, either a natural forest or a timber planting. In this system, the shade from the trees is actually a desired quality because the planted or wild understory crops thrive in such an environment. Typical examples are medicinal herbs like ginseng, certain types of mushrooms, fruits like elderberries, and ornamentals like rhododendrons and moss. Many of these understory crops can be quite profitable.

Silvopasture systems involve the integration of trees and grazing livestock operations on the same land (Figure 11.5). They provide both harvestable forest products and animal forage, offering both short- and long-term income sources. In temperate climates, cool-season grasses may grow better during the hotter

Figure 11.4. Examples of alley cropping in tropics. Left: Moringa trees grown for vegetable seed pods and herbal medicine together with sorghum-sudangrass grown for forage or soil improvement. Photo by Stuart Weiss. Right: Gliricidia legume trees where new growth is suppressed by regular harvesting of shoots, which are used for animal feed or organic fertilizer for corn (note: corn was not yet planted on ridges).

times of the year with partial shade provided by the trees (while critical early growth is not affected until leaf-out). In hotter climates, the trees help keep the grazing animals cool. Silvopasture systems still require the use of agronomic principles, like appropriate selection of forages, fertilization and rotational grazing systems that maximize vegetative plant growth and harvest. As discussed in Chapter 14, silvopasture systems may also be beneficial on landslide-prone slopes by stabilizing the soil (see Figure 14.12).

Figure 11.5. Animals grazing in a silvopasture system. Photo by USDA National Agroforestry Center.

Faidherbia albida is a tropical legume tree that thrives in seasonally dry climates and can be used both in silvopasture systems and in alley cropping systems. Its leaves are feather-like, and its canopy is therefore not overly dense and permits light penetration for crops like corn or pasture grasses. Also, it has a deep taproot and grows foliage in the dry season when other forage sources are limited. *Faidherbia* blooms at the end of the dry season and thereby provides food for bees. Its seed pods are feed for livestock or wild game, and the woody parts make good fuel.

Riparian buffer systems involve trees or shrubs that are planted along streams, rivers, lakes and estuaries to help filter runoff from upstream agricultural or urban lands. They also stabilize stream banks and provide habitat and shade for aquatic animals. Although mostly used as a conservation practice, interest has recently developed in using buffer zones for income production, including bioenergy crops by planting willows, decorative woody floral crops, and fruit and nut crops. Similarly, ***windbreaks*** and ***shelterbelts*** are generally planted for conservation purposes like reducing wind erosion, enhancing microclimates and promoting landscape biodiversity (see also Chapter 14), but they are increasingly valued for potential income from the trees themselves.

Transitional systems take advantage of the increased shading and changed microclimate as trees ma-ture. For example, landowners may initially use an alley cropping system where annual crops are grown between young trees, which is then transitioned into silvopasture, forest forming or an orchard. Alternatively they may decide to trim the trees and continue alley cropping.

SUMMARY

There are literally dozens of ways to increase crop diversity on a particular farm through crop rotations and agroforestry. The specific selection of practices depends on the climate and soils, the expertise of the farmer, whether there are livestock on the farm or nearby, equipment and labor availability, family quality-of-life considerations and financial reality. (While striving for relatively good returns from each crop—potential price minus the cost of production—vegetable farmers will sometimes include low-return crops in their rotations because customers expect to find them in the mix at a farm stand or farmers' market.) From an ecological view, longer and more complex rotations are preferred over shorter ones, and incorporating trees can provide stable long-term ecological benefits. Livestock can often make a soil-building rotation more attractive. It also makes a lot of sense, once equipment is in place, to stay flexible instead of having a rotation set in stone. If you're ready to adjust to rapid market changes, shifts in labor availability, crop pest outbreaks or unusual weather patterns, you'll be in a stronger economic position, while still maintaining a complex and diverse cropping system.

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a case study

CELIA BARSS
ATHENS, GEORGIA

When Celia Barss became the farm manager of Woodland Gardens Organic Farm, she knew cover crops were going to be a big part of the rotation from the start, a decision she's grateful she stuck with. "We built up slowly," she says. "Even the open ground, we just cover cropped it until we had time to start producing cash crops. Some fields got to be cover cropped for three years before we started growing in them."

The cover crops play a key role in diversifying the 12-acre operation's rotation, which now includes more than 80 different types of fruits and vegetables, as well as cut flowers, that are sold either to restaurants in Atlanta, to a local farmers' market or through their CSA. Cover cropping is also done in the greenhouses and hoop houses, which make up 1.5 acres of their eight tillable acres. The remaining acreage is in perennial production, which consists of blueberries, figs, muscadines (a native grapevine) and asparagus. The perennials are grown in their own separate areas on heavy slopes, with grass in between them to protect the soil instead of cover crops.

Barss uses cover crops primarily to build up soil organic matter, which, she says, they are "burning through" due to their climate and tillage practices. She explains that she tills because of their intensive planting schedule and tight crop spacing, but she is trying no-till on two open fields that get planted the earliest. With heavy clay soils and wet springs, Barss felt she was doing too much damage tilling under those conditions, so she decided to create beds, leave them fallow for two months, then cover them with silage tarps for a month prior to production. While it was a compromise for her to leave the soils bare like that, she was impressed with how ready to go the fields were after pulling off the silage tarps. She also makes sure to do a heavy summer cover crop on those fields since they are left bare longer than she prefers. Everything else gets planted with cover crops between cash crops.

The cover crops are also key to dealing with some production challenges, primarily weeds and nematodes. Amaranth has become the farm's biggest weed challenge in the summer, and Barss is also utilizing landscape fabric to help with suppression. "Weeds are all about prioritizing how you do stuff on the farm," she says. "Timing of getting [fields] weeded or into cover is everything, and just not letting [weeds] go to seed."

Nematodes, on the other hand, are a challenge that slowly crept up over the years. Barss started seeing nematode pressure around the tenth year of production in their stationary houses. All of those stationary houses have some level of pressure: the newest ones less, the oldest ones the most. Barss admits this problem occurred from not maintaining a longer period out of a host crop in the houses. But in order to reduce nematodes through rotation, she wouldn't be able to grow a cash crop for six months, because all of them are hosts for nematodes, she explains.

To help combat the nematodes, they were advised by Elizabeth Little, an Extension plant pathologist at the University of Georgia, to try sunn hemp as a cover crop for its nematicidal traits. But Barss can only have sunn hemp grow and break down before a cash crop in the houses for three months, which she's realizing is not long enough to break the life cycle. She has been solarizing too, which helps suppress the nematodes long enough for their tomato crops, but after tomatoes and most summer crops, the nematode populations have built back up enough to damage the crops that follow in the fall.

While Barss would be happy to do more cover cropping in the houses because of the difference they make in soil tilth—"it's amazing the difference when we go in after a cover crop," she says—the farm can't afford to be out of production for longer than three months. Instead, she's moving from solarizing to soil steaming so she can cover crop and treat for nematodes. This approach will still allow her to do more cover cropping because while solarizing takes six weeks, steaming only takes half an hour. "I can do a quick cover crop and then do the steamer before going into a cash crop, instead of solarizing in addition to the cover crop," Barss explains. But soil steaming requires a lot of energy and can be a big financial investment for the steamer, so it's considered an alternative when other options aren't available.

In addition to sunn hemp, Barss uses a lot of cowpeas and sorghum-sudangrass together in the summer because they do well in the heat. In areas where she has a shorter window, like six weeks, she'll use millet or buckwheat instead, since it's not enough time to let the cowpeas and sorghum-sudangrass grow. In the winter and cooler seasons, she'll use rye, hairy vetch and Austrian winter peas in fields that will be in cover for longer periods. In fields where she'll be planting early or needs to fill in shorter gaps in the spring and fall, she'll use oats because they're easier to terminate.

Oats will also follow in the spring in places where brassicas may have gone too late. Unlike the hoop houses, fields have a good three- or four-year rotation between plant families, Barss says, which is mostly dictated by the brassicas. "The brassicas really push the rotation, and that's the family I'm finding myself always doing less than I want to because of rotation." Her rotations vary by field, as she has to stay out of some later than others because they're too wet in the spring, but a typical rotation might include early spring brassicas, followed by the field peas and watermelons split 50/50 across the field, then two cycles of a cover crop.

Barss tries to get as much out of the cover crops as possible while they're growing by mowing sorghum-sudangrass, for example, to about a foot and letting them regrow. This extends their life while preventing them from going to seed. "Our goal is to have [the cover crops] go as long as possible and keep the ground covered because we have such a long summer," she says. When it is time to terminate them, she'll flail-mow and incorporate them into the soil.

Her focus on cover cropping has paid off. Barss says initially there were fields she didn't want to plant certain crops in because she didn't think the soil quality was good enough. Instead she would plant a crop that didn't need a lot of nutrients, such as field peas, and then focus on cover cropping it. Now she can plant any of their crops in those fields, stating: "it's amazing the difference in a field that I went into 10 years ago that hadn't been cover cropped."

"I attribute everything to the cover cropping, honestly, for the quality of our soils," Barss says. "I could grow a lot more, but I wouldn't be able to do the cover cropping the way I am. Just forcing yourself to stick to those ideals that you set up and making sure you stick to those rotations and not just trying to plant more and more. Because it's easy to start doing, but then you definitely see your soil quality start to go down."

WOODLAND GARDEN ORGANIC FARM'S ROTATION

Field	Season	2019 Season	2020 Season
2	Winter	strawberries, onions, flowers	cover crops (rye/peas/vetch) covers crops (sorghum-sudangrass/cowpeas)
	Spring		
	Summer	cover crop	
	Fall		brassicas
5	Winter	cover crop	herbs
	Spring	herbs	
	Summer		cover crop
	Fall		
6	Winter	cover crop	cover crop
	Sprin0g		
	Summer		beans/beets/flowers
	Fall	brassicas	
7-A	Winter	cover crop	cover
	Spring		tomatoes/flowers
	Summer	sunchoke, edamame, flowers	
	Fall	cover crop	cover crop
7-B	Winter	cover crop	cover crop
	Spring	peppers, eggplant	
	Summer		
	Fall	cover crop	brassicas
8-A	Winter	cover crop	cover crop
	Spring		peppers, eggplants, herbs
	Summer	watermelons, flowers, beans, cukes	
	Fall	cover crop	cover crop, herbs
8-B	Winter	cover crop	cover crop
	Spring	brassicas, scallions, beets	flower/cover crop
	Summer	squash, beans	unknown
	Fall	cover crop	cover crop
9-A	Winter	cover crop	strawberries/onions/flowers
	Spring	potatoes	strawberries/onions/flowers/beans
	Summer	cover crop	cover crop
	Fall	strawberries, onions, flowers	
9-B	Winter	cover crop	cover crop
	Spring		
	Summer		
	Fall		brassicas
9-C	Winter	cover crop	cover crop
	Spring		
	Summer		
	Fall		brassicas

(continues on next page)

Field	Season	2019 Season	2020 Season
10	Winter	cover crop	cover crop
	Spring	flowers, melons, corn, cukes	potatoes
	Summer	cover crop	cover crop
	Fall	bedded up for spring	
11	Winter	cover crop	cover crop
	Spring	brassicas	
	Summer	field peas, watermelon	corn, beans, squash
	Fall	cover crop	cover crop
12	Winter	cover crop	cover crop
	Spring		
	Summer		field peas/flowers
	Fall	brassicas, chicories	cover crop
13	Winter	garlic, cover crop	fallow
	Spring		brassicas, scallions, lettuce
	Summer	cover crop	squash, corn
	Fall	prep for spring	cover crop
14	Winter	cover crop	garlic, cover crop
	Spring		
	Summer	tuberoses, field peas to cover crop	cover crop
	Fall	garlic, cover crop	cover crop/prep for spring
15	Winter	cover crop	cover crop
	Spring		squash, corn
	Summer	sweet potatoes, melons	cover crop
	Fall	cover crop	garlic, cover crop
17-A	Winter	cover crop, herbs	cover crop
	Spring	peppers, herbs	sweet potatoes, tuberoses
	Summer	peppers, cover crop	
	Fall	cover crop, brassicas	cover crop
17-B	Winter	cover crop	fallow
	Spring	squash, corn, beans	brassicas
	Summer	cover crop	field peas, watermelons
	Fall	prep for early spring	cover crop
18	Winter	cover crop	cover crop
	Spring		cukes, melons, winter squash
	Summer	tomatoes, okra, flowers	
	Fall	cover crop	brassicas
19	Winter	cover crop	cover crops
	Spring		
	Summer	winter squash, corn, beans, summer squash	melons, watermelons, edamame, okra, beans, tuberoses
	Fall	brassicas	cover crops

Chapter 12

INTEGRATING CROPS AND LIVESTOCK

The quickest way to rebuild a poor soil is to practice dairy farming, growing forage crops, buying … grain rich in protein, handling the manure properly, and returning it to the soil promptly.

—J. L. HILLS, C. H. JONES AND C. CUTLER, 1908

There are good reasons why farmers tend to specialize in a few crops or in raising just one species of livestock; it provides economies of scale and fits into the regional agricultural system with its support infrastructure and established marketing channels. A substantial portion of the U.S. poultry, beef and hogs is raised in huge factory-size operations (concentrated animal feeding operations, or CAFOs), but there are many problems associated with these systems. Most such farms import some or all of their feed, sometimes from far away, requiring the supplying crop farms to use large amounts of fertilizers to replace nutrients exported to the animal operations. At the same time the large amounts of manure that accumulate on the animal farms—relative to their land base—may lead to applying quantities of manure that contain more nutrients than needed by crops, resulting in pollution of ground and/or surface waters. (see Chapter 7, “Nutrient Cycles and Flows” for a discussion of patterns of nutrient movement into and out of farms.) Storing large amounts of manure for periodic spreading (as occurs on CAFOs) creates a potential pollution problem and under certain conditions direct contamination of surface waters. The flooding in North Carolina caused by Hurricane Florence in September 2018 was not the first time that hog manure lagoons in that state were breached and surface water was contaminated.

When crops are fed to animals, most nitrogen, phosphorus and potassium contained in the feeds are excreted as waste products. Thus, when animal products are the main sales from the farm, relatively few nutrients (relative to what animals ate) leave the farm. On the other hand, farms that exclusively produce annual grain crops, such as corn, soybeans, wheat and sorghum, or even vegetables, export a lot of nutrients contained in their crops. Another issue is that farms concentrating on production of annual crops usually have no reason to include perennial forage crops in their rotations. Additional equipment is needed to manage the crop, and the sale of forages, bulky by nature, is sometimes difficult. Occasionally there may be a local demand for hay, but most commonly there is little

Photo by Edwin Remsburg

market for it in the wide expanse of regions growing annual crops. Exclusively growing annuals, especially only one or two crops, makes weed control more challenging, deprives the land of the improved soil health of multi-year grasses and legumes, allows disease and insect pests to flourish, and requires large amounts of nitrogen fertilizer to be applied for most crops. Integrating livestock into the farm operation can make it more sustainable but also makes it more complex. If not implemented in the right way it can also increase environmental problems.

TYPES OF CROP-LIVESTOCK FARMS

There are two general types of integrated livestock-crop farms in which all or nearly all of the animal feed is grown on the farm. There are those that mainly sell animal products and match their animal numbers to the carrying capacity of their land. They produce all or almost all of the feed needed for their own animals. Examples of these farms are beef operations based on pasture grazing and stored hay from the farm (“grass-fed”); hog farms with animals on pasture and supplemental feed produced on the farm; and dairy farms that produce all needed grain and forage, some relying on pastures for seasonal forage needs.

Second, there are diversified farms that raise all the feed for their animals but sell a range of crops and animal products. Combining and integrating the raising of livestock and multiple crops on individual farms has many advantages. Having a number of marketable products provides some protection against the seasonal failure of a single product and the vagaries of market price fluctuations.

Combined crop-and-livestock farms of various types have an inherent advantage for improving soil health. Crops can be fed to animals and manures are returned to the soil, thereby providing a continuous supply of organic materials. For many livestock operations, perennial forage crops are an integral part of the cropping system, thereby reducing erosion potential and helping maintain or increase soil organic matter while improving soil physical and biological properties. Soil health tests conducted on dairy farms consistently show good results for most soil health indicators, although compaction remains a concern. Nevertheless, crop-livestock farms have challenges. Silage harvests do not leave much crop residue, which needs to be compensated for with manure application or cover crops. Minimizing tillage is also important and can be done by injecting the manure or gently incorporating it with aerators or harrows, rather than plowing it under. Soil pulverization can be minimized by reducing secondary tillage, using strip or zone tillage, and establishing the crops with no-tillage planters and seeders. Also, many livestock farms grow row crops with perennial forages and use strip cropping to reduce erosion concerns.

Livestock farms require special attention to nutrient management to make sure that organic nutrient sources are optimally used around the farm and that no negative environmental impacts occur. This requires taking a comprehensive look at all nutrient flows on the farm, finding ways to most efficiently use them and preventing problems with excesses. It also requires matching the numbers of livestock to both the land base and the specific cropping pattern.

MANURE

Once cheap fertilizers became widely available after World War II, many farmers, Extension agents and scientists looked down their noses at manure. People thought more about how to get rid of manure than how to put it to good use. In fact, some scientists tried to find out the absolute maximum amount of manure that could be applied to an acre without reducing crop yields. Some farmers who didn’t want to spread manure actually piled it next to a stream and hoped that next spring’s flood waters would wash it away. We now know that manure, like money, is better spread around than concentrated in a few places. The economic contribution of farm manures can be considerable. On a national basis, the manure from 100 million cattle, 120 million hogs and 9 billion chickens contains about 23 million tons of nitrogen (and this doesn't even include the manure from 324 million layers and 250 million turkeys). At a value of 50 cents per pound, that works out to about $25 billion for just the nitrogen contained in animal manures. The value of the nutrients in manure from a 100-cow dairy farm may exceed $20,000 per year; manure from a 100-sow farrow-to-finish operation is worth about $16,000; and manure from a 20,000 bird broiler operation is worth about $6,000. The benefits to soil organic matter buildup, such as enhanced soil structure, and better diversity and activity of soil organisms, may double the value of the manure. If you're not getting the full fertility benefit from manures on your farm, you may be wasting money.

Types of Manure

Animal manures can have very different properties, depending on the animal species, feed, bedding, handling and manure-storage practices. The amounts of nutrients in the manure that become available to crops also depend on what time of year the manure is applied and how quickly it is worked into the soil. In addition, the effects of manure on soil organic matter and plant growth is influenced by soil type. In other words, it's impossible to give blanket recommendations for manure application. They need to be tailored for every situation. And although we are discussing manure as an important component of well-managed, integrated livestock-cropping systems, we will also examine the issues that occur with livestock farms that import a lot of feed and that have insufficient land to utilize all the manure produced in ecologically sound ways.

We'll start the discussion with dairy cow manure from confined spaces like barns and feedlots but will also offer information about the handling, characteristics and uses of other animal manures, as well as grazing systems.

MANURE HANDLING SYSTEMS

Solid, Liquid or Composted

The type of barn on the dairy farm farmstead frequently determines how manure is handled. Dairy cow manure containing a fair amount of bedding, usually around 20% dry matter or higher, is spread as a solid. This is most common on farms where cows are kept in individual stanchions or tie-stalls. Liquid manure-handling systems are common where animals are kept in a "free stall" barn and minimal bedding is added to the manure. Liquid manure is usually in the range of 2–12% dry matter (88% or more water), with the lower dry matter if water is flushed from alleys and passed through a liquid-solid separator or if large amounts of runoff enter the storage lagoon. Manures with characteristics between solid and liquid, with dry matter of 12–20%, are usually referred to as semi-solid. Pasture cow manure is unmixed with water or bedding and falls into this category.

Composting manures is becoming an increasingly popular option for farmers. With this, you help stabilize nutrients (although considerable ammonium is usually lost in the process), have a smaller amount of material to spread, and have a more pleasant material to spread, which is a big plus if neighbors have complained about manure odors. Although it's easier to compost manure that has been handled as a solid, it does take a lot of bedding to get fresh manure to a 20% solid level. Some farmers separate the solids from liquid manure and then irrigate with the liquid and compost the solids. Some separate solids following digestion for methane production and burn the gas to produce electricity or heat. Separating the liquid allows for direct composting of the solids without any added materials. It also allows for easier transport of the solid portion of the manure for sale or to apply to remote fields. For a more detailed discussion of composting, see Chapter 13.

Some dairy farmers have built what are called "compost barns." No, the barns don't compost, but they are set up similar to a free-stall barn where bedding and manure just build up over the winter and the pack is cleaned out in the fall or spring. However, with composting barns, the manure is stirred or turned twice daily with a modified cultivator on a skid steer loader or with a small tractor to a depth of 8–10 inches; ceiling fans are sometimes used to help aerate and dry the pack during each milking. Some farmers add a little new bedding each day, some do it weekly, and others do it every two to five weeks. In the spring and fall some or all of the bedding can be removed and spread directly or can be built into a traditional compost pile for finishing. Although farmers using this system tend to be satisfied with it, there is a concern about the continued availability of wood shavings and sawdust for bedding. More recently, vermicomposting has been introduced as a way to process dairy manure. In this case, worms digest the manure, and the castings provide a high-quality soil amendment (see Chapter 13).

Manure from hogs can also be handled in different ways. Farmers raising hogs on a relatively small scale sometimes use hoop houses, frequently placed in fields, with bedding on the floor. The manure mixed with bedding can be spread as a solid manure or can be composted first. The larger, more industrial-scale farms mainly use little to no bedding, with slatted floors over the manure pit, and they keep the animals clean by frequently washing the floors. The liquid manure is held in ponds for spreading, mostly in the spring before crops are planted, and in the fall after crops have been harvested. Poultry manure is handled with bedding (especially for broiler production) or with little to no bedding (industrial-scale egg production).

Storage of Manure

Researchers have been investigating how best to handle, store and treat manure to reduce the problems that come with year-round manure spreading. Storage allows the farmer the opportunity to apply manure when it's best for the crop and during appropriate weather conditions. This reduces nutrient loss from the manure caused by water runoff from the field, or leaching and gaseous losses. However, significant losses of nutrients from stored manure also may occur. One study found that during the year dairy manure stored in uncovered piles lost 3% of the solids, 10% of the nitrogen, 3% of the phosphorus and 20% of the potassium. Covered piles or well-contained, bottom-loading liquid systems, which tend to form a crust on the surface, do a better job of conserving the nutrients and solids than unprotected piles. Poultry manure, with its high amount of ammonium, may lose 50% of its nitrogen during storage as ammonia gas volatilizes, unless precautions are taken to conserve nitrogen. Regardless of storage method, it is important to understand how potential losses occur in order to select a storage method and location that minimize environmental impact.

Anaerobic digesters are sometimes used to process manure on large livestock farms and to generate biogas, mostly methane. This gas is used on the farm for heat and electricity generation, or possibly off the farm as a fuel for commercial or municipal vehicles. In addition, anaerobic digesters can reduce greenhouse gas emissions, odors and pathogens, and improve air and water quality. They are a major capital investment for a farm, and to make them profitable, farmers typically need to make full use of the energy, carbon credits, tipping fees from external organic wastes, and coproducts of the manure solids. Many digesters may not be economical without subsidies. Digesters separate liquid and solid manure, allowing for separate land application but generally do not change the overall nutrient content. Therefore, they provide some benefits but generally don't solve problems involving excess nutrients or runoff.

CHEMICAL CHARACTERISTICS OF MANURES

A high percentage of the nutrients in feeds passes right through animals and ends up in their manure.

Table 12.1
Typical Manure Characteristics

	Dairy Cow	Beef Cow	Chicken	Swine
Dry Matter Content (%)				
Solid	26	23	55	9
Liquid (fresh, diluted)	7	8	17	6
Total Nutrient Content (Approximate)				
Nitrogen				
Pounds per ton	10	14	25	10
Pounds per 1,000 gallons	25	39	70	28
Phosphate, as P_2O_5				
Pounds per ton	6	9	25	6
Pounds per 1,000 gallons	9	25	70	9
Potash, as K_2O				
Pounds per ton	7	11	12	9
Pounds per 1,000 gallons	20	31	33	34
Approximate amounts of solid and liquid manure to supply 100 pounds N for a given species of animal				
Solid manure (tons)	10	7	4	10
Liquid manure (gallons)	4,000	2,500	1,500	3,600

Source: Modified from various sources.

Depending on the feed ration and animal type, over 70% of the nitrogen, 60% of the phosphorus and 80% of the potassium fed may pass through the animal as manure. These nutrients are available for recycling on cropland. In addition to the nitrogen, phosphorus and potassium contributions given in Table 12.1, manures contain significant amounts of other nutrients, such as calcium, magnesium and sulfur. For example, in regions that tend to lack the micronutrient zinc, there is rarely any crop deficiency found on soils receiving regular manure applications.

The values given in Table 12.1 must be viewed with some caution, because the characteristics of manures from even the same type of animal may vary considerably from one farm to another. Differences in feeds, mineral supplements, bedding materials and storage systems make manure analyses quite variable. Yet as long as feeding, bedding and storage practices remain relatively stable on a given farm, manure nutrient characteristics will tend to be similar from year to year. However, year-to-year differences in rainfall can affect stored manure through more or less dilution.

Manure varies by livestock animal, mostly due to differences in feeds. Cattle manure is generally balanced in the ammonium/urea versus organic N forms, while nitrogen in swine manure is mostly in the readily available ammonium/urea form. Poultry manure is significantly higher in nitrogen and phosphorus than the other manure types. The relatively high percentage of dry matter in poultry manure is also partly responsible for the higher analyses of certain nutrients when expressed on a wet ton basis.

It is possible to take the guesswork out of estimating manure characteristics as most soil testing laboratories will also analyze manure. Manure analysis is of critical importance for routine manure use and should be a

FORMS OF NITROGEN IN MANURES

Nitrogen in manure occurs in three main forms: ammonium (NH_4^+), urea (a soluble organic form, easily converted to ammonium) and solid organic N. Ammonium is readily available to plants, and urea is quickly converted to ammonium in soils. However, while readily available when incorporated in soil, both ammonium and urea are subject to loss as ammonia gas when left on the surface under drying conditions—with significant losses occurring within hours of applying to the soil surface. Some manures may have half or three-quarters of their N in readily available forms, while others may have 20% or less in these forms. Manure analysis reports usually contain both ammonium and total N (the difference is mainly organic N), thus indicating how much of the N is readily available but also subject to loss if not handled carefully.

routine part of the nutrient management program on animal-based farms. For example, while the average liquid dairy manure is around 25 pounds of N per 1,000 gallons, there are manures that might be 10 pounds N or less, or 40 pounds N or more, per 1,000 gallons. Recent research efforts have focused on more efficient use of nutrients in dairy cows, and N and P intake can often be reduced by up to 25% through improved feed rations, without losses in productivity. This helps reduce nutrient surpluses on farms.

EFFECTS OF MANURING ON SOILS

Effects on Organic Matter

When considering the influence of any residue or organic material on soil organic matter, there is a key question to ask: How much solids are returned to the soil? Equal amounts of different types of manures will have different effects on soil organic matter levels. Dairy and beef manures contain undigested parts of forages (high in carbon) and may have significant quantities of bedding. They therefore have a high amount of complex substances, such as lignin, that do not decompose readily in soils. Using this type of manure results in a much greater long-term influence on soil organic matter than does a poultry or swine manure without bedding. More solids are commonly applied to soil with solid-manure-handling systems than with liquid systems because greater amounts of bedding are usually included. A number of trends in dairy farming mean that manures may have less organic material than in the past. One is the use of sand as bedding material in free-stall barns, much of which is recovered and reused. The other is the separation of solids and liquids, with the sale of solids or the use of digested solids as bedding. Under both situations much less organic solids are returned to fields. On the other hand, the bedded pack (or compost barn) does produce a manure that is high in organic solid content.

When conventional tillage is used to grow a crop such as corn silage, whose entire aboveground portion is harvested, research indicates that an annual application of 20–30 tons of the solid type of dairy manure per acre is needed to maintain soil organic matter (Table 12.2). As discussed above, a nitrogen-demanding crop, such as corn, may be able to use all of the nitrogen in 20–30 tons of manure. If more residues are returned to the soil by just harvesting grain, lower rates of manure application will be sufficient to maintain or build up soil organic matter.

An example of how a manure addition might balance annual loss is given in Figure 12.1. One Holstein “cow year” worth of manure is about 20 tons. Although 20 tons of anything is a lot, when considering dairy manure, it translates into a much smaller amount of solids. If the approximately 5,200 pounds of solid material in the 20 tons is applied over the surface of one

THE INFLUENCE OF MANURE ON SOIL PROPERTIES

The application of manures causes many soil changes: biological, chemical and physical. A few of these types of changes are indicated in Table 12.2, which contains the results of a long-term experiment in Vermont with continuous corn silage on a clay soil. Manure counteracted many of the negative effects of a monoculture cropping system in which few residues are returned to the soil. Soil receiving 20 tons of dairy manure annually (wet weight, including bedding, equivalent to approximately 8,000 pounds of solids) maintained organic matter and CEC levels, and close to the original pH (although acid-forming nitrogen fertilizers also were used). Manures, such as those from dairy and poultry, have liming effects and actually counteract acidification. (Note: If instead of the solid manure, liquid had been used to supply N and other nutrients for the crop, there would not have been anywhere near as large a beneficial effect on soil organic matter, CEC and pore space.) High rates of manure addition caused a buildup of both phosphorus and potassium to high levels. Soil in plots receiving manures were better aggregated and less dense and, therefore, had greater amounts of pore space than fields receiving no manure.

Table 12.2
Effects of 11 Years of Manure Additions on Soil Properties

		Application Rate (tons/acre/year)			
	Original Level	None	10 Tons	20 Tons	30 Tons
Organic matter	5.2	4.3	4.8	5.2	5.5
CEC (me/100g)	19.8	15.8	17	17.8	18.9
pH	6.4	6	6.2	6.3	6.4
P (ppm)*	4	6	7	14	17
K (ppm)*	129	121	159	191	232
Total pore space (%)	ND	44	45	47	50

*P and K levels with 20 and 30 tons of manure applied annually are much higher than crop needs (see Table 21.3A).
Note: ND = not determined.
Sources: Magdoff and Amadon (1980); Magdoff and Villamil (1977)

acre and mixed with the top 6 inches of soil (2 million pounds), it would raise the amount of soil organic matter by about 0.3%. However, much of the manure will decompose during the year, so the net effect on soil organic matter will be less. Let's assume that 75% of the solid matter decomposes during the first year, and the carbon ends up as atmospheric CO_2. At the beginning of the following year, only 25% of the original 5,200 pounds, or 1,300 pounds of organic matter, is added to the soil. The net effect is an increase in soil organic matter of 0.065% (the calculation is [1,300/2,000,000] x 100). Although this does not seem like much added organic matter, if a soil had 2.17% organic matter and 3% of that was decomposed annually during cropping, the loss would be 0.065% per year, and the manure addition would just balance that loss. Manures with lower amounts of bedding, although helping maintain organic matter and adding to the active ("dead") portion, will not have as great an effect as manures containing a lot of bedding material. Overall it is difficult to precisely determine the benefits of the manure, as fields that receive it also tend to have different crops (more perennial forages in dairy systems than grain systems). Still, an analysis of 300 samples from different farms in New York showed that fields with dairy crops that receive manure average 0.5% higher soil organic matter than cash grain crops (corn, soybeans, wheat).

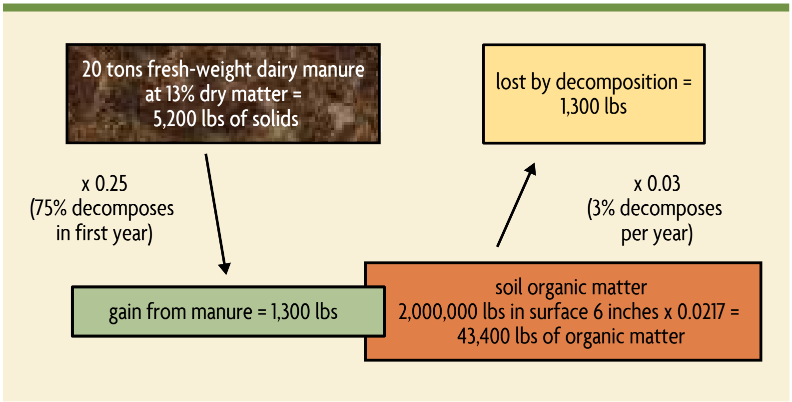

Figure 12.1. Example of dairy manure addition just balancing soil organic matter losses.

USING MANURES

Manures, like other organic residues that decompose easily and rapidly release nutrients, are usually applied to soils in quantities judged to supply sufficient nitrogen for the crop being grown in the current year. It might be better for building and maintaining soil organic matter to apply manure at higher rates, but doing so may cause undesirable nitrate accumulation in leafy crops and excess nitrate leaching to groundwater. High nitrate levels in leafy vegetable crops are undesirable in terms of human health, and the leaves of many plants with high N seem more attractive to insects. In addition, salt damage to crop plants can occur from high manure application rates, especially when there is insufficient leaching by rainfall or irrigation (also with covered ground like high tunnels). Very high amounts of added manures, over a period of years, also lead to high soil phosphorus levels (Table 12.2). It is a waste of money and resources to add unneeded nutrients to the soil, which will mostly be lost by leaching or runoff instead of contributing to crop nutrition. On soils with phosphorus significantly above the optimum level—indicating a long-term farm imbalance of imports and exports of phosphorus—manure applications may need to be based on satisfying crop needs of P instead of N. This may mean exporting a portion of manure from the farm so as to keep soil P from increasing even further.

Manure Application

A common per-acre rate of dairy manure application is 10–30 tons fresh weight of solid manure or 4,000–11,000 gallons of liquid manure. These rates will supply approximately 50–150 pounds of available nitrogen (not total) per acre, assuming that the solid manure is not too high in straw or sawdust and actually ties up soil nitrogen for a while (see discussion below on estimating N availability). If you are growing crops that don't need that much nitrogen, such as small grains, 10–15 tons (around 4,000–6,000 gallons) of solid manure should supply sufficient nitrogen per acre. For a crop that needs a lot of nitrogen, such as corn, 20–30 tons (around 8,000–12,000 gallons) per acre may be necessary to supply its nitrogen needs. Low rates of about 10 tons (around 4,000 gallons) per acre are also suggested for each of the multiple applications used on a grass hay crop. In total, grass hay crops need at least as much total nitrogen applied as does a corn crop. There has been some discussion about applying manures to legumes. This practice has been discouraged because the legume uses the nitrogen from the manure, and much less nitrogen is fixed from the atmosphere. However, the practice makes sense on intensive animal farms where there can be excess nitrogen, although grasses may then be a better choice for manure application.

Application methods. For the most nitrogen benefit to crops, manures should be incorporated into the soil in the spring immediately after spreading on the surface. About half of the total nitrogen in dairy manure comes from the urea in urine that quickly converts to ammonium (NH_4^+). This ammonium represents almost all of the readily available nitrogen present in dairy manure. As materials containing urea or ammonium dry on the soil surface, the ammonium is converted to ammonia gas (NH_3) and lost to the atmosphere (also causing odor concerns). If dairy manure stays on the soil surface, about 25% of the nitrogen is lost after one day and 45% is lost after four days, but that 45% of the total represents around 70% of the readily available nitrogen. This problem is significantly lessened if about half an inch or more of rainfall occurs shortly after manure application, leaching ammonium from the manure into the soil. Leaving manure on the soil surface is also a problem because runoff waters may carry significant amounts of nutrients from the field. When this happens, crops don't benefit as much from the manure application, and surface waters become polluted. Some liquid manures—those with low solids content—penetrate the soil more deeply. When applied at normal rates, these manures will not be as prone to losing ammonia by surface drying. However, in humid regions, much of the ammonia-N from manure may be lost if it is incorporated in the fall when no crops are growing. Fall injection of liquid manure, instead of broadcasting on the surface and then disking or plowing, may greatly reduce the loss of ammonia nitrogen.

Other nutrients contained in manures, in addition to nitrogen, make important contributions to soil fertility. The availability of phosphorus and potassium in manures should be similar to what is in commercial fertilizers. (However, some recommendation systems assume that only around 50% of the phosphorus and 90% of the potassium is available.) The phosphorus and potassium contributions contained in 20 tons of dairy manure are approximately equivalent to about 30–50 pounds of phosphate and 180–200 pounds of potash from fertilizers. The sulfur content as well as trace elements in manure, such as the zinc previously mentioned, also add to the fertility value of this resource.

Because half of the nitrogen and almost all of the phosphorus is in the solids, a higher proportion of these nutrients remain in sediments at the bottom when a liquid system is emptied without properly agitating the manure. Uniform agitation is recommended if the goal is to apply similar levels of solids and nutrients across target fields. A manure system that allows significant amounts of surface water penetration and then drainage, such as a manure stack of well-bedded dairy or beef cow manure, may lose a lot of potassium because it is so soluble. The 20% leaching loss of potassium from stacked dairy manure mentioned above occurred because potassium was mostly found in the liquid portion of the manure.

Timing of Applications

Manures are best applied to annual crops, such as corn, small grains and vegetables, in one dose just before soil tillage (unless a high amount of bedding is used, which might tie up nitrogen for a while—see the discussion of C:N ratios in Chapter 9). If the manure is surface applied, this allows for rapid incorporation by plow, chisel, harrow, disk or aerator. If injected, no further tillage may be needed, but application close to planting time is still best, because the possibility of loss by runoff and erosion is reduced. It also is possible to inject liquid manures either just before the growing season starts or as a sidedressing to row crops. Fall manure applications on annual row crops, such as corn, may result in considerable nitrogen loss, even if manure is incorporated. Fall-applied manure in humid climates allows ammonium conversion to nitrate and then leaching and denitrification before nitrogen is available to next year's crop. A three-year New York study showed about twice the N leaching losses from fall-applied compared to spring-applied liquid manure on corn silage, and the losses were greatest with early fall application when the soils were still warm and allowed for manure decomposition.

Without any added nitrogen, perennial grass hay crops are constantly nitrogen deficient. Application of a moderate rate of manure, about 50–75 pounds worth of available nitrogen, in early spring and following each harvest is the best way to apply manure. Spring applications may be at higher rates, but wet soils in early spring may not allow manure application without causing significant compaction. Manure applications on grass surfaces (when spread uniformly) have very low risk for nitrate leaching, but ammonia losses are higher unless disc injectors or tine aerators are used.

Although the best use of manure is to apply it near the time when the crop needs the nutrients, sometimes time and labor management or insufficient storage capacity causes farmers to apply it at other times. In the fall, manure can be applied to grasslands that don't flood, or to tilled fields that will either be fall plowed or planted to a winter cover crop. Although legal in most states, it is not a good practice to apply manures when the ground is frozen or covered with snow. The nutrient losses that can occur with runoff from winter applied manure are both an economic loss to the farm and an environmental concern. Ideally, surface applications of manure in winter would be done only on an emergency basis. However, there are windows of opportunity for incorporating and injecting winter applied manure during periods when the soil has a shallow frozen layer, 2–4 inches thick (frost tillage; see Chapter 16). Farmers in cold climates may use those time periods to inject manure during the winter (without runoff concerns) and relieve crunch time for spring application (Figure 12.2).

Figure 12.2. Injection of liquid manure into shallow frozen soils, which eliminates compaction concerns and reduces spring application volumes. Photo by Eleanor Jacobs.

ESTIMATING MANURE NUTRIENT AVAILABILITY

Nutrient management is challenging when it involves using manure because it is difficult to balance agronomic and environmental objectives. This is especially the case with nitrogen because it is the most dynamic nutrient, one that is easily lost with rain, and its availability from manure is very difficult to predict. Conversely, P, K and most other nutrients stay in the soil and can be assessed through soil testing.

Universities and government agencies offer guidelines for estimating manure N availability, but it is generally recognized that, while they are useful for planning purposes, they are imprecise. The estimated nitrogen availability factors for the northeastern United States are shown in Table 12.3. They reflect the following patterns:

- Spring applications of manure are more efficient than fall or winter applications. The latter can result in considerable losses because the winters in the northeastern United States are wet and can cause N losses. (This also holds for the West Coast and Southeast but is less the case in the midwestern and western United States due to drier winters.)
- The type of manure has a modest impact on N availability.

E. COLI 0157:H7

The bacteria strain known as E. coli 0157:H7 has caused numerous outbreaks of severe illness in people who ate contaminated meat and a few known outbreaks from eating vegetables, once when water used to wash lettuce was contaminated with animal manure and once from spinach grown near a cattle farm. This particular bacteria is a resident of cows' digestive systems. It does no harm to the cow, but, probably because of the customary practice of feeding low levels of antibiotics when raising cattle, it is resistant to a number of commonly used antibiotics for humans. This problem only reinforces the commonsense approach to manure use. When using manure that has not been thoroughly composted to grow crops for direct human consumption, especially leafy crops like lettuce that grow low to the ground and root crops such as carrots and potatoes, special care should be taken. Before planting your crop, avoid problems by planning a three-month period between incorporation and harvest. For short-season crops, this means that the manure should be incorporated long before planting. Although there has never been a confirmed instance of contamination of vegetables by E. coli 0157:H7 or other disease organisms from manure incorporated into the soil as a fertility amendment, being cautious and erring on the side of safety is well justified.

- Immediate versus delayed incorporation has a big impact on crop N availability because a lot of ammonia is lost when manure is on the soil surface. This effect is especially significant with poultry and swine manure because they contain relatively more ammonium and urea than ruminant manures.
- There is a large benefit of cover crops in conserving the manure N after fall and winter applications. They take up the manure N when it becomes available, store it in their root and shoot biomass, and return it to the soil when they are terminated to grow the following crop.

The estimated N availability values in Table 12.3 are based on total manure N, but they can be improved if the manure analysis separates ammonia-N from organic N. Additional N credits are appropriate if there were manure applications in previous years.

Most farmers follow these guidelines due to nutrient management regulations. However, they are imprecise if they are not based on a manure analysis that shows how much N is actually present. And even when combined with a lab analysis of manure, the guidelines are imprecise because they don't account for weather factors. In other words, they are reasonable planning tools for manure applications, but the actual N availability may be quite different due to subsequent weather conditions and management practices. Follow-up measurements are therefore recommended, like the pre-sidedress soil nitrate test, weather-driven simulation models, satellite, airplane or drone images, and in-field crop sensors (discussed in Chapter 18). These allow for in-season evaluation of a crop's N status and a more precise determination of the need for corrective N applications.

GRAZING

We have mostly discussed using manure from livestock that are confined in lots or barns and have forage brought in from fields. *Pastures* allow animals to graze their own feed and are most appropriate for ruminant animals (cattle, sheep, goats, etc.) that can digest forage crops. Nonruminant animals like chickens and pigs can also be raised on pastures, but they derive little feed from the field and need to be supplied additional feeds

Table 12.3
Estimated Nitrogen Availability from Manure Applications in the Northeast United States

			Nitrogen Availability Factor*		
Application Season	**Target Crop**	**Incorporation Management**	**Poultry Manure**	**Swine Manure**	**Other Manure**
Spring or summer	All crops	immediate	0.75	0.7	0.5
		1 day	0.5	0.6	0.4
		2–4 days	0.45	0.4	0.35
		5–7 days	0.3	0.3	0.3
		> 7 days or none	0.15	0.2	0.2
Early fall	Winter-spring crops	< 2 days	0.5	0.45	0.4
		3–7 days	0.3	0.3	0.3
		> 7 days or none	0.15	0.2	0.2
	Summer crops after cover crop	< 2 days	0.45	0.4	0.35
		3–7 days	0.25	0.25	0.25
		> 7 days or none	0.15	0.2	0.2
	Summer crops without cover crop	All methods	0.15	0.2	0.2
Late fall or winter	Winter-spring crops	All situations	0.5	0.45	0.4
	Summer crops	No cover crop	0.15	0.2	0.2
		Cover crop harvested	0.15	0.2	0.2
		Cover crop as green manure	0.5	0.45	0.4

*The nitrogen availability factor is the N fertilizer equivalent per pound of manure N.
Source: Penn State University (table simplified from original source; for illustration only)

such as grains. The benefits are then mostly for animal welfare and health, and perceived improved food quality rather than optimum feed and nutrient management, which many consumers are willing to pay for.

For years animals were grazed in large areas, out on rangeland or on farms, where they might be switched between two pastures during the grazing season. Dairy farmers commonly used one or two "night pastures" with cows turned out after the evening milking. But these continually grazed 0r very infrequently rotated pastures produced poorly as animals ate the regrowth again and again, weakening plants. Plants need to grow to a reasonable size before root reserves can be fully replenished, and continually regrazing early shoot regrowth depletes root reserves, making it harder for the plant to regrow again after grazing. But using what's sometimes called *management intensive grazing* (MIG), in which animals are rotated through many pastures and do not re-graze a paddock *until* plants have sufficiently regrown, has shown great improvement in pasture productivity and animal health. Depending on the season and weather, the rotation cycle can be as short as a week or 10 days and as long as 6–8 weeks. For dairy farms using MIG, cows are turned out to a fresh paddock after each milking (Figure 12.3). Other animals might be moved to a new pasture daily or every few days.

A well-managed grazing system has inherent efficiencies because the harvesting and fertilization require no (or limited) equipment and human labor. It is also attractive to those who are concerned with animal welfare, as it is more in line with the natural living environment for most farm animals. A common counterargument is that animals on pastures expend more energy on foraging compared to confined animals (reducing meat or milk yields) and that the most productive biomass crops, like corn and sorghum, don't lend themselves well to grazing. But in most cases cows grazing on high-quality, intensively managed pastures result in a lower cost of production once you factor in lower labor and machinery needs for such tasks as cleaning barns, spreading manure, harvesting crops, transporting animals to barns and feeding them out. The use of the newer styles of fencing and electric fence chargers make it easy to quickly set up new grazing paddocks, and once dairy or beef cows are trained to electric fences, a single-strand electric internal fence is enough to contain them in the paddock.

Grazing, especially involving small ruminants like sheep and goats that can handle rough terrain, permits productive use of marginal lands that generally aren't suitable for intensive crop production. In fact, much of the hillsides of the northeastern United States were pastures stocked with sheep during the 1800s, but due to a shift in agricultural and labor markets were then reforested. But in other countries hillsides are still productively managed as pastures (Figure 12.4).

Well-managed pastures promote good soil health because they combine three beneficial practices: perennial forage crops, absence of tillage and regular manure additions. A soil health study involving a wide range of New York cropping systems confirmed that pasture fields had far better scores than other cropping systems for soil organic matter content, active carbon, protein, respiration, available water capacity and aggregate stability.

Other grazing systems. In addition to management intensive grazing of permanent pastures, there are other grazing systems. Sometimes intensive grazing is taken to an extreme level through ***mob grazing***, where extremely high stocking densities (100,000 pounds of animals per acre) are used for very short time periods (8–12 hours). This approach is used as a soil amelioration technique, where animals suppress or kill poor quality plant species and with their hoofs help to reseed the paddock with more productive species. In some situations animals are allowed to roam over larger rangeland areas but are stocked densely during the night time. The carbon, nutrients and seeds gathered during the day are excreted into the smaller area and provide a significant boost for soil fertility and revegetation (as

Figure 12.3. Rotational grazing system for dairy cows with relatively high stocking densities for short durations. (White lines in the background are paddock separation wires.)

Figure 12.4. Grazing allows for productive use of marginal lands (New Zealand).

discussed with "plaggen soils" in Chapter 7). In general, however, pastures need to be managed with careful consideration of the biomass production potential of the land, which is typically defined by rainfall, temperature and soil quality. ***Overgrazing*** happens when farmers maintain excessive herd sizes, often based on normal or good growing conditions, during years that experience low rainfall. This causes excessive foraging, weakening or die-off of the pasture plants, and subsequently, soil degradation and further loss of productivity.

Farmers using management intensive grazing normally only sell animal products, not crops. *Integrated crop-livestock systems*, in which both crops and animal products are sold commercially, are increasingly used in drier regions of traditional grassland like the North American Great Plains. Several systems exist and may all be used on the same farm:

- **Grazing annual crop residue** works with an annual row crop system where the grain is harvested and the residues are grazed during the dormant periods in the autumn, winter or dry season. Although this does not meet annual feed needs, it reduces feed costs and improves nutrient and carbon cycling. Cattle grazing of corn residue in winter is common in the Great Plains and has been shown to increase soil health and crop yields. In some cases, farmers also leave some of the grain unharvested (corn or sunflowers, for example), enabling forage access for the grazing animals during the winter, even with deep snow.
- **Swath grazing** involves annual crops such as barley and triticale, cut in the autumn. They are left in swaths (heaped rows) for grazing, mostly for beef cattle (Figure 12.5). The grazing is typically controlled through temporary fencing. Swath grazing improves forage accessibility, especially when there is deep snow, by concentrating and stacking the forage into narrow swaths.
- **Grazing annual forages** involves livestock grazing on annual or short-season crops, which can also function as cover crops. Cool-season crops (winter wheat, rye or triticale) can be planted in the fall for spring grazing, or planted in the spring (oats, barley, wheat) for late-spring and early summer grazing. Brassicas like turnips, kale and legumes like forage peas are often mixed in. Warm-season annual grasses like sorghum, sorghum-sudangrass and millet can be planted in late spring to provide autumn grazing. These systems can be matched with cash crops after grazing, like the field in Figure 12.6. (This

Figure 12.5. Swath grazing of winter forage in the northern Great Plains. Photo by West-Central Forage Association.

Figure 12.6. Mixed winter cover crop used for grazing (Washington State). Photo by Bill Wavrin.

picture was taken in the month of April.) Controlled grazing of cover crops can significantly contribute to high-quality forage and can be used as a means to terminate a cover crop.

- **Grazing perennial forage crops that are part of a crop rotation on integrated crop-livestock farms** involves raising forages, usually for two to 10 years, that can be either hayed or grazed. One of the great advantages of integrated crop-livestock farms is that they provide a very good reason for growing perennial forages, which considerably enhance soil health.

Full reliance on pastures to provide all the animals' forage needs is generally not feasible, even with ruminants. Invariably pastures experience periods of limited growth during dry or cold seasons, and additional feed is needed. Sometimes pastures are "stockpiled" (that is, left ungrazed or not hayed) for use when crops aren't growing. In many cases baled hay has to be supplied from other sources. Most animals also require additional grains for optimum growth. Emergency feed may be required during unusual weather events like drought, high snow or ice.

POTENTIAL PROBLEMS USING MANURES

As we all know, there can be too much of a good thing. Excessive manure applications may cause plant growth problems. It is especially important not to apply excess poultry manure because the high soluble-salt content can harm plants. Plant growth can also be retarded when high rates of fresh manure are applied to soil immediately before planting. This problem usually doesn't occur if the fresh manure decomposes for a few weeks in the soil ,and it can be avoided by using a solid manure that has been stored for a year or more. Injection of liquid manure sometimes causes problems when used on poorly drained soils in wet years. The extra water applied and the additional use of oxygen by microorganisms may mean less aeration for plant roots, and loss of readily plant-available nitrate by denitrification may also be occurring.

Nutrient Imbalances and Buildup

When manures are applied regularly to a field to provide enough nitrogen for a crop like corn, phosphorus and potassium build up to levels way in excess of crop needs (see Table 12.2). It is often mistakenly believed that it results from the fact that manure nutrient ratios are out of balance with crop uptake requirements (especially more P). Nutrient ratios for most manures (Table 12.1) are actually equivalent to a crop's needs (roughly a 2:1 ratio for nitrogen and phosphorus). If most nitrogen was conserved through good timing and application methods—applied immediately prior to the growing season or in a standing crop, and injected or incorporated—the manure rate necessary to meet crop nitrogen requirement can be substantially lowered and the accumulation of P and K in soil reduced!

Erosion of phosphorus-rich topsoils contributes sediments and P to streams and lakes, polluting surface waters. When soil P levels have already built up and manure applications are restricted based on allowed P additions, as required by some nutrient management plans, N-conserving management means that less fertilizer N will be needed. When very high P buildup occurs, it may also be wise to switch the application to other fields or to use strict soil conservation practices to trap sediments before they enter a stream. Including rotation crops that do not need manure for N, such as alfalfa, allows a "draw-down" of phosphorus that accumulates from manure application to grains. (However, this may mean finding another location to apply manure. For a more detailed discussion of N and P management, see Chapter 19.) When P buildup is a concern, the *Phosphorus Index* is a tool used to assess the potential for P to move from agricultural fields to surface water. It considers soil and landscape features as well as soil conservation and P management practices in individual fields. These include so-called source factors such as soil test P, total soil P and rate, method and timing of P application. It also considers transport factors like sediment delivery, relative field location in the watershed, soil conservation practices, precipitation, runoff and tile flow/subsurface drainage. This allows a nutrient planner to estimate whether P movement risk is low, medium or high, and to suggest appropriate mitigation measures.

Nutrient Imports and Exports

On integrated crop-livestock farms it is commonly possible to produce all or nearly all the feed needs for the livestock. This helps to keep nutrient imports and exports close to balanced, one of the advantages of integrated farms. But there are different kinds of combinations of cropping and livestock. One extreme is farms that import all the feeds for their animals and then have to somehow get rid of the accumulating manure. More commonly, farms produce most of their own feed but animal numbers exceed the production from the farm's own land base. These farmers purchase additional amounts of animal feed and may have too much manure to safely use all the nutrients on their own land. Although they don't usually realize it, they are importing large quantities of nutrients in the feed that then remain on the farm as manures. If they apply all these nutrients on a limited area of land, nutrients start to build up and nutrient pollution of groundwater and surface water is much more likely. It is a good idea to make arrangements with neighbors to use the excess manure. Another option, if local outlets are available, is to compost the manure (see Chapter 13) and sell the product to vegetable farmers, garden centers, landscapers and directly to home gardeners. Even when manure is exported from the farm, if there is just too much manure in a given local region, shipping long distances will become very expensive. New manure treatments (like different types of drying and mass reduction methods) may offer ways to make it more transportable to areas of nutrient and carbon deficits.

Poultry and hogs are routinely fed metals such as copper and arsenic that appear to stimulate animal growth. However, most of the metals end up in the manure. In addition, dairy farmers using liquid manure systems commonly dump the used copper sulfate solutions that animals walk through to protect foot health into the manure pit. The copper content of average liquid dairy manures in Vermont increased about fivefold between 1992 and the early 2000s, from about 60 to over 300 parts per million on a dry matter basis, as more farmers used copper sulfate footbaths for their animals and disposed of the waste in the liquid manure. Although there are few reports of metal toxicity to either plants or animals from the use of animal manures, if large quantities of manure with a high metal content are applied over the years, soil testing should be used to track the buildup.

Another potential issue is the finding that plants can take up antibiotics from manure applied to soil. About 70% of the antibiotics used in animal agriculture ends up in the manure. Although the amounts of antibiotics taken up by plants are small, this is an issue that may be of concern when using manures from concentrated animal production facilities that use considerable amounts of these substances.

Nutrient Losses with Grazing

In grazing systems the animal excrements are directly deposited on the surface (in the case of cattle, colloquially referred to as "cow pies"). Some of the ammonium/urea is lost to the atmosphere as the manure dries, similar to non-incorporated manure from confined animal systems. Overall, this reduces concerns with N leaching, and runoff tends to be low due to high vegetative cover on pastures. But because these cow pies are unevenly distributed, they generate small areas with concentrated nutrients while areas in between the "pies" have less nutrients and may still benefit from additional fertilizer.

For this reason, nitrate leaching may still be a concern with intensively managed and fertilized dairy pastures.

SUMMARY

There are various ways to combine crops and animals into a farming operation, and if carried out well, there are usually numerous advantages to doing so. This is especially the case when the purpose of the farm is to sell multiple products, both crop and animal, which provides a degree of economic security through diversity. Another advantage is the improvement of soil health when establishing pastures (permanent or as part of a rotation) and growing hay crops. Intensively managed grazing systems, one general system of integrating livestock and crops, are very efficient, can be highly productive, and provide multiple benefits by improving soil health through perennial covers and manure applications. For a good example of integrating crops and livestock, see the Gabe Brown profile after chapter 10.

Another advantage of integrating crops and livestock is having access to animal manures, which is useful for building healthy soils and moving nutrients to fields that need them the most. Manures are high in nutrients needed by plants, and they help build and maintain soil organic matter levels. There is wide variability in the characteristics of manures, even from the same species, depending on feeding, bedding and manure handling practice, and it is important to analyze manures to more accurately judge the needed application rates. But some animal-based systems pose great environmental concerns because they do not adequately consider nutrient cycles and potentials for losses after manure application. It is important when using manures to keep in mind the potential limitations, including pathogen contamination of crops that are for direct human consumption; accumulation of potentially toxic metals from high application of certain manures; and overloading the soil with N or P by applying rates that are in excess of needs, as demonstrated by soil test and known crop uptake.

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a case study

DARRELL PARKS
MANHATTAN, KANSAS

Even if Darrell Parks didn't like working with hogs, he would still raise them on his 275-acre farm in the Flint Hills of Kansas, if only for the manure that makes up a key part of his soil fertility program. Each year, Parks' farm raises and finishes about 500 hogs from 40 sows, while also producing corn, milo, wheat, soybeans and alfalfa. He sells his hogs to the Organic Valley cooperative and as pork cuts at a local farmers' market.

Parks spot-treats his land with hog manure to help areas needing extra fertility. He likes how targeting problem areas with thicker applications of manure corrects soil micronutrient deficiencies. "Manure from the hogs doesn't supply all my fertility needs, but with cover crops and organic fertility additions that are more available now I have been able to maintain decent yields," says Parks, who received a grant from USDA's Sustainable Agriculture Research and Education (SARE) program to hone his use of manure on cropland. He was successful in that endeavor, and his cropland has been certified organic since 1996.

Parks' crops are raised mainly in two rotations. In one rotation, alfalfa is grown for three years, followed by a year each of corn and soybeans before returning to alfalfa. In the other, he plants Austrian winter peas in the late fall following wheat harvest. The peas, incorporated in the spring, are followed with a cash crop of milo or soybeans prior to a fall- or spring-planted wheat crop.

To ensure a sufficient nutrient supply for his wheat crops, Parks typically treats his wheat fields with liquid manure at a rate of approximately 660 gallons per acre. He collects this manure in a concrete pit adjacent to a building where sows are housed for brief periods during breeding or when being sold. The liquid manure, for which he does not typically obtain a nutrient analysis, "catches a lot of rainfall and is fairly dilute—[essentially] high-powered water," he says. "I avoid wet conditions when spreading and try to hit the wheat in March or April during a dry period on a still day, before [the wheat] is too big."

Parks sometimes lets older sows out to pasture on some of his fields, where they spread their own manure. He cautions, however, against pasturing young pigs on alfalfa. "You'd think they'd balance their ration better," he says, "but they don't—they overeat."

> *Manure from the hogs doesn't supply all my fertility needs, but with cover crops and organic fertility additions that are more available now I have been able to maintain decent yields.*

For most of their lives, Parks' hogs are raised on half of a 10-acre field. He plants the remaining five acres to corn. Once the corn is harvested, he moves the hogs and their pens over to the "clean ground" of corn stubble. "Going back and forth like this seems to work well in keeping the worms down," he says. And he notes that the 50–60 pounds of N per acre put down with the hogs' manure helps grow "some pretty good corn" in that field each year.

Parks notes that his tillage regime, on which he is dependent for weed control in his organic system, makes maintaining and improving his soil organic matter content especially challenging. That's why he remains committed to integrating the use of both animal and "green" manures on his farm.

Striving for economic sustainability, Parks is constantly weighing the pros and cons of becoming more self-sufficient by raising his own feed for the hogs versus taking advantage of the price premiums for organic grains.

"It's a hard decision," he says. "Right now, if I cut down on hogs, maybe it would be better economically. But if I get out [of raising hogs entirely], it's not easy to get back in."

For now, he is betting that over the longer term, he's better off keeping his hogs. "A lot of people don't like the idea of how pigs are raised" within a conventional operation, he says. "We're meeting [the demand of] a niche market in its infancy that is sure to grow."

Chapter 13

MAKING AND USING COMPOSTS

The reason of our thus treating composts of various soils and substances,
is not only to dulcify, sweeten, and free them from the noxious qualities they otherwise retain. …
[Before composting, they are] apter to ingender vermin, weeds, and fungous …
than to produce wholsome [sic] plants, fruits and roots, fit for the table.

—J. EVELYN, 17TH CENTURY

Decomposition of organic materials takes place naturally in forests and fields all around us. Composting is the art and science of combining available organic wastes so that they decompose to form a uniform and stable finished product. Composts are excellent organic amendments for soils. Composting reduces bulkiness of organic materials, stabilizes soluble nutrients and hastens the formation of humus. Most organic materials can be composted, and the process offers a win-win opportunity: reducing waste and improving soil.

In some ways, composting is microbe farming. If ingredients are combined to provide food (carbon and nitrogen), moisture, oxygen and shelter in proper proportions, a diverse cohort of organisms will efficiently process the feedstock. These microorganisms perform well at elevated temperatures with plenty of oxygen and moisture. They cover the range of warm (mesophilic) to hot (thermophilic) conditions. Thermophilic temperatures (from 110°F up to 160°F) help kill off weed seeds and disease organisms, which sets composting apart from other decomposition processes. At temperatures below 110°F, the more prolific mesophilic organisms take over and the rate of composting again slows down, especially as it drops toward ambient temperatures, a process known as "curing." At the other extreme, temperatures above 160°F can develop in compost piles; this overheating slows down the composting process

TYPES OF COMPOSTING

Some people talk about "low temperature" composting—including "sheet," worm (vermicomposting) and small-pile composting—and "high temperature" composting. We like to use the term "composting" only when talking about the rapid decomposition that takes place at high temperatures.

EVEN BIRDS DO IT

The male brush turkey of Australia gathers leaves, small branches, moss and other litter and builds a mound about 3 feet high and 5 feet across. It then digs holes into the mound repeatedly and refills them, helping to fragment and mix the debris. Finally, the pile is covered with a layer of sticks and twigs. The female lays her eggs in a hole dug into the pile, which heats to nearly 100°F around the eggs, while the outside can be around 65°F. The heat of the composting process frees the birds from having to sit on the eggs to incubate them.

—R.S. SEYMOUR (1991)

by killing off most organisms and by possibly causing extreme drying. High temperatures, in combination with high ambient temperatures and aeration, can also cause spontaneous combustion in barns and at compost facilities. In general, the composting process is slowed by anything that inhibits good aeration or the maintenance of high enough temperatures and sufficient moisture. It has been found that mesophilic temperatures may be more effective at breaking down some pharmaceuticals.

MAKING COMPOSTS

Common and Uncommon Feedstock

Composting of wastes and organic residues, both on and off farms, has become a more common practice. Farmers, municipalities and community composters accept many organic residuals, and tipping fees are often charged to offset the cost of managing this waste.

The list of source materials is endless and includes anything, plant or animal, that was alive and is now dead and needs to be managed. Some examples include crop residuals; food processing residuals; livestock carcasses; pet, zoo and human manure; chipped trees; mixed leaf and yard residuals; road kill; egg shells; glucose solutions; brewery waste; paper from document destruction; bakery excess; floral and cut flower production waste; coffee/tea grounds; off-spec human food; residuals from fish canneries and slaughterhouses; poultry feathers; livestock wool; butcher waste; fish from fish kills; aquatic weeds; biochar; whey and other milk products; fats/oils/greases; bagasse (the pulpy residue left from crushing and extracting liquid from sugar cane); drywall; and untreated small pieces of wood.

Feedstock materials cannot just be thrown together randomly; they require a recipe that allows for the appropriate physical conditions (e.g., allowing air flow and the right texture for handling) and lots of carbon and nitrogen available for the microorganisms to feed on. Compost piles are often built by alternating layers of these materials. Turning the pile mixes the materials. Composting occurs most easily if high-nitrogen materials are mixed with high-carbon materials, with the average C:N ratio of the materials being about 25–40

A SAMPLE RECIPE FOR BACKYARD COMPOSTING

Start with the following:

- grass clippings (77% moisture, 45% C and 2.4% N)
- leaves (35% moisture, 50% C and 0.75% N)
- food scraps (80% moisture, 42% C and 5% N)

The ratio of the materials needed to get 60% moisture and a C:N of 30:1 is 100 pounds of grass, 130 pounds of leaves and 80 pounds of food scraps.

—T. RICHARD (1996B)

parts carbon for every part nitrogen (see Chapter 9 for a discussion of C:N ratios). Therefore, manure mixed with straw, wood chips or bark can be composted as is, because it has the right C:N balance. Wood chips or bark also provide the coarse structural matrix (skeleton) needed for airflow and handling, and may be recycled by shaking the finished compost out of the bulking material and then used for the next composting cycle. Manure and sawdust would also provide a good C:N mix but the texture of sawdust is too fine to allow for effective air flow.

It's important to avoid using certain materials such as coal ash and especially wood chips from pressure-treated lumber. And it's a good idea to go easy using manure from pets or large quantities of fats, oils or waxes. These types of materials may be difficult to compost or may result in compost containing chemicals that can harm crops or humans. There are too many different combinations of materials to give blanket recommendations about how much of each to mix to get the moisture content and the C:N ratio into reasonable ranges for a good start on the process. One example is given in the box "A Sample Recipe for Backyard Composting." There are formulas to help you estimate the proportions of the specific materials you might want to use in the compost pile (see Cornell University's http://compost.css.cornell.edu). Sometimes it will work out that the pile may be too wet, too low in C:N (that means too high in nitrogen), or too high in C:N (too low in nitrogen). To balance your pile, you may need to add other materials or change the ratios used. Adding dry sawdust or wood chips will remedy the first two problems, and adding nitrogen fertilizer will remedy the third. If a pile is too dry, you can add water with a hose or sprinkler system.

One thing to keep in mind is that not all carbon is equally available for microorganisms. Lignin is not easily decomposed. (We mentioned this when discussing soil organisms in Chapter 4 and again in Chapter 9 when we talked about the different effects that various residues have when applied to soil.) Although some lignin is decomposed during composting, probably depending on factors such as the type of lignin and the moisture content, high amounts of carbon present as lignin may indicate that not all of the carbon will be available for rapid composting. This means that the effective C:N can be quite a bit lower than expected based on total carbon (Table 13.1). For some materials, there is little difference between the C:N calculated with total carbon and calculated with only biodegradable carbon.

Figure 13.1. On-farm composting facility, in which tarps are used to control moisture and temperature. The piles in the background are curing.

Pile Location and Size

Composting sites should be appropriately situated. They need to be readily accessible by equipment and because they will have some natural leakage (especially in humid climates), they need to be kept away from watercourses, sinkholes, flood plains, seasonal seeps, wells and other poorly drained areas. Also, depending on the feedstock, composting may be associated with undesirable odors, so it is best to be away from residential areas. Backyard composting can be done in piles or vessels and is best done in a safe location away from children and pets.

A compost pile or windrow (Figure 13.1) is a large, natural convective structure, something like a set of chimneys next to each other. Oxygen moves into the pile

Table 13.1
Total Versus Biodegradable Carbon and Estimated C:N Ratios

Material	% Carbon	C:N	% Carbon	C:N %	Lignin %	Cell Wall %	% Nitrogen
	(Total)		(Biodegradable)				
Newsprint	39	115	18	54	21	97	0.34
Wheat straw	51	88	34	58	23	95	0.58
Poultry manure	43	10	42	9	2	38	4.51
Maple wood chips	50	51	44	45	13	32	0.97

Source: T. Richard (1996a).

while carbon dioxide, moisture and heat rise out of it. The materials need to fit together in a way that allows oxygen from the air to flow in freely. On the other hand, it is also important that not too much heat escapes from the center of the pile. If small sizes of organic materials are used, a “bulking agent” may be needed to make sure that enough air can enter the pile. Dry leaves, wood shavings/chips and chopped hay or straw are frequently used as bulking agents, which need to be appropriately cut to size to prevent matting and slow composting. Composting will take longer when large particles are used, especially those resistant to decay like large wood chips, while overly fine particles like sawdust decompose well but cause the pile to become too dense for air flow.

Moisture

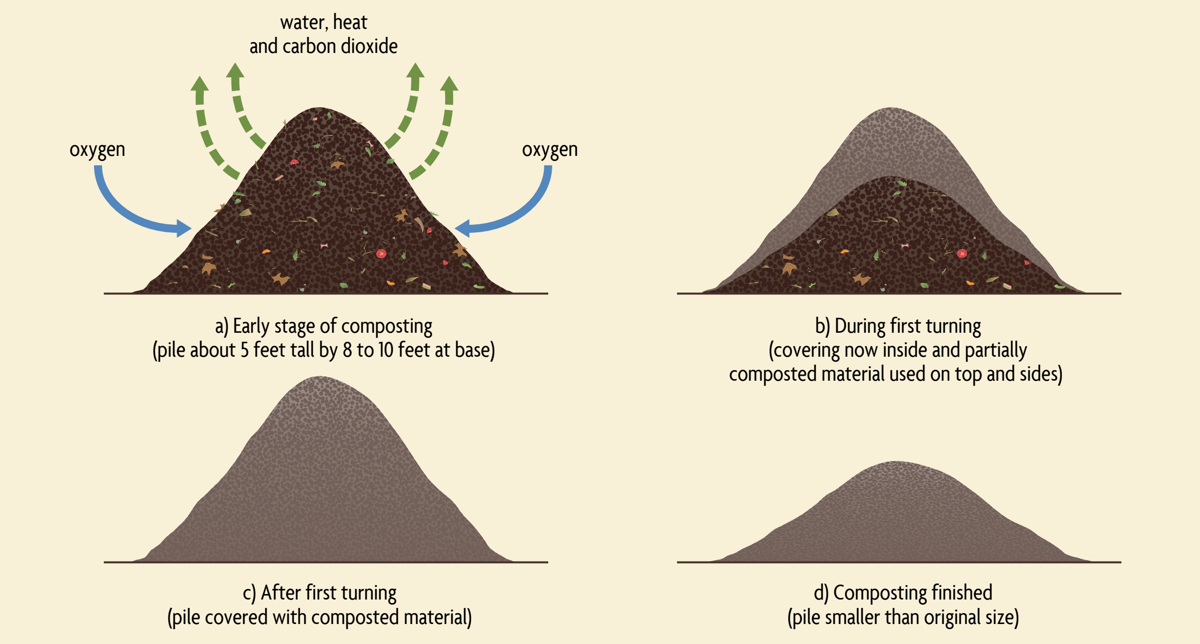
The amount of moisture in a compost pile is important. If the materials mat and rainwater can’t drain easily through the pile, it may not stay aerobic in a humid climatic zone. On the other hand, if composting is done inside a barn or under dry climatic conditions, the pile may not be moist enough to allow microorganisms to do their job. Moisture is lost during the active phase of composting, so it may be necessary to add water to a pile. In fact, even in a humid region, it is a good idea to moisten the pile at first, if dry materials are used. However, if something like liquid manure is used to provide a high-nitrogen material, sufficient moisture will most likely be present to start the composting process.

The ideal moisture content of composting material is about 40–60%, or about as damp as a wrung-out sponge. If the pile is too dry, 35% or less, ammonia is lost as a gas and beneficial organisms don’t repopulate the compost after the temperature moderates. Very dry, dusty composts become populated by molds instead of the beneficial organisms we want.

COMPOSTING DEAD ANIMALS

The compost pile should be prepared with a base layer of organic absorbent materials, typically 2 inches or less in size with some sizable 4- to 6-inch chunks included. The pile needs to be large enough to retain much of the heat that develops during composting, but not so large and compacted that air can’t easily flow in from the outside. Compost piles should be 3–5 feet tall and about 6–10 feet across the base after the ingredients have settled (see Figure 13.2). (You might want it on the wide side in the winter, to help maintain warm temperatures, while gardeners can make compost in a 3-foot-tall by 3-foot-wide pile in the summer.) Easily condensed material should initially be piled higher than 5 feet. It is possible to have long windrows of composting materials, as long as they are not too tall or wide.

—BONHOTAL ET AL. (2008)



a) Early stage of composting
(pile about 5 feet tall by 8 to 10 feet at base)

b) During first turning
(covering now inside and partially
composted material used on top and sides)

c) After first turning
(pile covered with composted material)

d) Composting finished
(pile smaller than original size)

Figure 13.2. Compost pile dimensions and turning techniques. Illustration by Vic Kulihin.

Monitoring and Turning the Pile

Turning the composting residues exposes all the materials to high-temperature conditions at the center of the pile, and heat convection further exposes upper reaches of the pile (Figure 13.3). Materials at the lower sides of the pile often barely compost. Turning the pile rearranges all the materials and creates a new center. Equipment is now available to quickly turn long compost windrows at large-scale composting facilities (Figure 13.3). Tractor-powered compost turners designed for composting on farms are also available, and some farmers use manure spreaders to build piles. Monitoring of the pile is done primarily by checking temperatures. Internal compost temperatures affect the rate of decomposition as well as the reduction of pathogenic bacteria, fungi and weed seeds. The most efficient temperature range for composting is generally between 104°F and 140°F (40°C and 60°C), however, piles can reach temperatures as high as 170°F (77°C). Spontaneous combustion can be a problem. On the other hand, if temperatures get too high, this can indiscriminately kill beneficial as well as pathogenic organisms, causing temperatures to drop.

Compost temperatures depend on how much of the heat produced by the microorganisms is lost through aeration or surface cooling. During periods of extremely cold weather, piles may need to be larger than usual to minimize surface cooling. As decomposition slows, temperatures will gradually drop and remain within a few degrees of ambient air temperature. Thermometers with long probes and data loggers are available to help monitor the process. Measuring oxygen will also indicate how well the process is progressing. With static piles it is important to keep oxygen levels high by using bulky carbon sources. Ideally, oxygen levels should be kept at 5–14%. If piles are gently turned every time the interior reaches and stabilizes for a few days at about 140°F, it is possible to complete the composting process within

Figure 13.3. Turning a compost windrow at a commercial facility. Photo by Alison Jack.

months, all other factors of moisture and aeration being optimal. On the other hand, if you turn the pile only occasionally, it may take longer to complete, especially if it has become compacted.

Although turning compost frequently speeds up the process, too much turning may dry out the pile and cause more nitrogen and organic matter loss. If the pile is too dry, you might consider turning it on a rainy day to help moisten it. If the pile is very wet, you might want to turn it on a sunny day, or cover it with moisture-protective material like chopped straw (like a thatched roof) or compost fleece, a type of breathing cover that is now widely available. Very frequent turning may not be advantageous because it can cause the physical breakdown of important structural materials that aid natural aeration. The right amount of turning depends on a variety of factors, such as aeration, moisture and temperature. Turn your compost pile to avoid cold, wet centers; to break up clumps; and to make the compost more uniform later in the process before use or marketing. Use caution when turning in cold, windy weather if the pile is warm, for it may not reheat.

Finally, piles should not be actively turned in all cases. When composting livestock or roadkill carcasses, the animals are placed in the middle of the pile above a base layer (and lanced to avoid bloating), covered with another 2 feet of organic materials and then allowed to sit for 4–6 months without turning to allow the carcass to fully degrade (see case study at end of chapter).

Controlling Pathogens

Pathogens are a large concern with composts, especially when they involve excrements and carcasses. Different methods of composting will result in varying levels of pathogen reduction. Turned piles will continue to move material into the center of the pile so that all material is exposed to thermophilic temperatures. Different regulators have different time-temperature requirements to meet certain needs. For example, the United States Environmental Protection Agency lists processes to further reduce pathogens, which requires temperature between 131°F and 170°F. To comply with

MINIMUM TURNING TECHNIQUE

Farm-quality composts can be produced by turning the pile only once or twice. You need to carefully construct the pile: build it up to reasonable dimensions, use and thoroughly mix materials that give good porosity, and make sure the pile stays moist. A pile that is uniformly heating is getting sufficient air to decompose and therefore may not need turning. As the heat declines, the pile may be getting too dense or not getting sufficient air, and it may need to be turned. A good example of this is composting animal mortalities in wood chips where the pile heats and organic materials degrade without turning.

the standard, composting operations that utilize an in-vessel or static aerated pile system must maintain a temperature within that range for a minimum of three days. Composting operations that utilize a windrow composting system must maintain a temperature within that range for a minimum of 15 days, during which time the materials must be turned five times. This protocol is set up to ensure that pathogen levels are low at the time of compost application. It may take longer to kill pathogens in passively aerated windrows than in-vessel or turned piles. Composts from feedstocks with potentially dangerous pathogens will be safer than the original source materials, but caution should still be exercised. It should not be topdressed onto crops that are directly used for human consumption, and composters and applicators need to take precautions for their own health, like wearing masks and protective clothing.

The Curing Stage

Following high-temperature composting, the pile should be left to cure for about one to three months. Usually, this is done once pile temperatures cool to 105°F and high temperatures don't recur following turning. Curing is especially needed if the active (hot) process is short or poorly managed. There is a reduced need to turn the pile during curing because the phase of maximum decomposition is over and there is significantly less need for rapid oxygen entry into the pile's center when the decomposition rate is slow. However, the pile may still need turning during the curing stage if it is very large or didn't really finish composting. Determining when compost is finished is sometimes difficult, but if it reheats, it is not finished. (The Solvita® test measures carbon dioxide losses from compost as a way to determine compost maturity.) Curing the pile furthers aerobic decomposition of resistant chemicals and larger particles. Common beneficial soil organisms populate the pile during curing, the pH becomes closer to neutral, ammonium is converted to nitrate, and soluble salts are leached out if the pile is outside and sufficient precipitation occurs. Be sure to maintain water content at the moisture-holding capacity (around 50% or less during curing) to ensure that active populations of beneficial organisms develop. It is thought that the processes that occur during the early curing stage give compost some of its disease-suppressing qualities. On the other hand, beneficial organisms require sources of food to sustain them. Thus, if composts are allowed to cure for too long, which can deplete all the available food sources, disease suppression qualities may decrease and eventually be lost.

Figure 13.4. An example of a belowground composting pit, often used by small farmers in tropical countries and when the soil is well drained.

OTHER COMPOSTING TECHNIQUES

High-temperature (thermophilic) piles or windrows account for most composting, but other methods are also used. Instead of making piles, small farmers in developing countries often dig pits for composting (Figure 13.4), especially in dry and hot climates. The pits can be covered with soil material to prevent animals from getting into them, and they retain moisture in the compost material better. Many home composters prefer using vessels to facilitate the turning process, to have better control over temperature and moisture conditions, and to keep out rodents. But these systems are generally not economical for large-scale commercial operations.

Vermicomposting involves the use of earthworms—typically red worms—to perform the decomposition process. The method is, in a way, still mostly bacteria based, but the process occurs in the gut of the worm. The end product is worm casts, coated with mucus consisting of polysaccharides that make them into somewhat stable aggregates. The system requires bedding materials like newspaper strips, cardboard, hay and similar carbonaceous materials that mimic the decaying dried leaves that worms find in their natural habitat. The process is fast and efficient: worms can process half their weight in organic material in one day. The final product has an attractive feel and smell, and is appealing to consumers.

Vermicomposting is most often used to process kitchen scraps and can be done indoors in small bins. Vermicomposting methods are also used in large commercial operations. Two main approaches are used: windrows or raised beds. With windrows, new materials are added on one side of the bed, and the other side is harvested for compost after about 60 days. With the raised-bed or container system, which is preferred for indoor operations in colder climates, the worms are fed at the top of the beds and the castings are removed at the bottom. Some vermicomposting operations are connected with livestock farms to process manure for export of excess nutrients off the farm as a value-added product.

Fermenting composting, or *bokashi*, is an anaerobic composting methodology developed in Korea and Japan. The organic feedstock is inoculated with *Lactobacilli* bacteria that generate a fermentation process under anaerobic conditions, converting a fraction of the carbohydrates to lactic acid. The process is similar to the making of silage and fermented foods (like kimchi and sauerkraut). It is mostly done on a small scale, with food scraps as the primary source material and using a sealed container, but some large-scale bokashi is done with tightly covered windrows. The preserve can be soil applied after a few weeks of fermentation or stored for later use. The process also releases some of the feedstock's water content, which is high in nutrients. The advantages of the bokashi process are that it is fast and that it produces less odor and fewer greenhouse gas emissions. Disadvantages are the need for sealed containers and ways to capture the liquid discharge, the purchase of fermentation bacteria, and the need to bury the compost into the soil (i.e., not use as topdressing).

USING COMPOSTS

Composts help reduce organic waste and are universally beneficial to the soil if applied at appropriate rates and managed well. They can be used on turf, in flower gardens, on trees, and for vegetable and agronomic crops. Composts can be spread and left on the surface or incorporated into the soil by plowing or rototilling. Composts also are used to grow greenhouse crops, and they form the basis of some potting soil mixes. Composts should not be applied annually at high rates. That is a recipe for overloading the soil with nutrients (see discussion in Chapter 7).

Composts benefit the soil by providing nutrients, enhancing biological processes and improving the physical structure. Organic farmers are especially keen on using composts as a way to replenish the nutrients that were extracted by their crops (as they cannot use synthetic fertilizers). Although they can "grow" their own nitrogen with legume rotations and cover crops, most other nutrients need to be restocked with organic materials from external sources. Good compost is ideal because it contains the nutrients and carbon that keep the soil healthy, and compost often suppresses pathogens. Conventional farmers, especially for high-value crops, also like to apply compost as a soil amelioration method to enhance crop yields and to reduce pest pressures and environmental impacts (e.g., by improving water infiltration). Composts are also extensively used in landscaping and gardening as urban soils are often compromised by construction activities and heavy traffic (see Chapter 22 on urban environments). You don't see a lot of compost use on crops growing on large acreage where the cost is generally too high to justify applications (animal manure application is more common). A recent trend in highway departments is to compost roadkill and apply the product to enhance roadside plantings.

> *I don't make compost because it makes me feel good. I do it because composting is the only thing I've seen in farming that costs less, saves time, produces higher yields and saves me money.*
>
> —CAM TABB, WEST VIRGINIA BEEF AND CROP FARMER

Finished composts provide relatively low amounts of readily available nutrients. During composting, much of the nitrogen is converted into more stable organic forms, although potassium and phosphorus availability remain unchanged. However, it should be kept in mind that composts can vary significantly, and some that have matured well may have high levels of nitrate. Even though most composts don't supply a large amount of available nitrogen per ton, they still supply fair amounts of other nutrients in available forms and greatly help the fertility of soil by increasing organic matter and by slowly releasing nutrients. Compost materials can be tested at selected commercial agricultural and environmental laboratories, which is especially important if certification is sought.

In some cases, the repeated use of compost, especially on some organic farms, may result in buildup of certain nutrients. For example, if high amounts of compost are applied to meet a crop's nitrogen needs (remember, compost is relatively low in available nitrogen), then nutrients like phosphorus and potassium are applied in excessive amounts and can accumulate in the soil. Also, salts may build up if there is not enough

DISEASE SUPPRESSION BY COMPOSTS

Research by Harry Hoitink and coworkers at Ohio State University shows that composts can suppress root and leaf diseases of plants. This suppression comes about because the plants are generally healthier (microorganisms produce plant hormones as well as chelates that make micronutrients more available) and are therefore better able to resist infection. Beneficial organisms compete with disease organisms for nutrients and either directly consume the disease-causing organisms or produce antibiotics that kill bacteria. Some organisms, such as springtails and mites, "actually search out pathogen propagules in soils and devour them," according to Hoitink. In addition, Hoitink found that potting mixes containing composts "rich in biodegradable organic matter support microorganisms that induce systemic resistance in plants. These plants have elevated levels of biochemical activity relative to disease control and are better prepared to defend themselves against diseases." This includes resistance to both root and leaf diseases.

Composts rich in available nitrogen may actually stimulate certain diseases, as was found for phytophthora root rot on soybeans, as well as for fusarium wilts and fire blight on other crops. Applying these composts many months before cropping, allowing the salts to leach away, or blending them with low-nitrogen composts prior to application, reduces the risk of stimulating diseases.

Composting can change certain organic materials used as surface mulches, such as bark mulches, from stimulating disease to suppressing disease.

PROTECTING DRINKING WATER SUPPLIES

Composting of manure is of special interest in watersheds that supply drinking water to cities, such as those that serve New York City. The parasites *Giardia lamblia* (beaver fever) and *Cryptosporidium parvum* cause illness in humans and are shed through animal manure, especially young stock. These organisms are very resistant in the environment and are not killed by chlorination. Composting of manure, however, is an economical option that kills the pathogen and protects drinking water.

rainfall to wash them out of the soil (like under high tunnels and in greenhouses). It is recommended to monitor the soil through regular soil tests and to change the fertility strategy accordingly (for example, by using a legume cover crop as a nitrogen source and reducing compost applications).

ADVANTAGES OF COMPOSTING

Composted material is less bulky than the original feedstock, making it less costly to transport. It is also easier and more pleasant to handle. During the composting process, carbon dioxide and water are lost to the atmosphere and the size of the pile decreases by 30–60%. In addition, many weed seeds and disease-causing organisms may be killed by the high temperatures in the pile. Unpleasant odors are also eliminated. Flies, a common problem around manures and other organic wastes, are much less of a problem with composts. Composting reduces or eliminates the decline in nitrogen availability that commonly occurs when organic materials, such as sawdust or straw, are added directly to soil. Compost application can also lower the incidence of plant root and leaf diseases, as mentioned. Moreover, the chelates and the direct hormone-like chemicals present in compost often further stimulate the growth of healthy plants. Then there are the positive effects on soil physical properties that are derived from improving soil organic matter (figures 13.5 and 13.6).

The composting process also helps us address the

Figure 13.5. Left: Compacted soil. Right: compost application prior mixing and planting. Photos by Urban Horticulture Institute, Cornell University.

concerns around nutrient flows we discussed in Chapter 7. When crops are sold off the farm, and sometimes transported over long distances, we remove carbon and nutrients from the fields that in many cases don't get recycled for economic reasons. Composting allows us to use carbon and nutrients from waste materials and apply them to the soil in a safe and cost-effective manner, thereby reducing the nutrient loss and excess issues that are now inherent in our agricultural system. Sure, we aren't able to recycle carbon and nutrients in corn or soybeans from an Iowa farm that ended up as manure from California beef or Chinese pigs—the logistics would be inhibitive. But composting that manure makes it easier and more economical to move off a farm with excess nutrients and to help improve nearby fields, gardens and landscapes with local organic resources that would otherwise mostly be a nuisance.

If you have a large amount of organic waste but not much land, composting may be very helpful and may create a valuable commercial product that improves farm profitability. Also, since making compost decreases the solubility of nutrients, composting may help lessen pollution in streams, lakes and groundwater. On many poultry farms and on beef feedlots, where high animal populations on limited land may make manure application a potential environmental problem, composting may be the best method for handling the wastes and removing the excess nutrients. Composted material, with about half the bulk and weight of manure, and a higher commercial value, can be economically transported over significant distances to locations where nutrients are needed. In addition, the high temperatures and biological activity during the composting process can help to decrease antibiotic levels in manures, which can be taken up by crops growing on manured land. Compost can also be stored more easily than the bulk feedstocks, so it can be applied when soil and weather conditions are optimal.

Without denying the good reasons to compost, there are frequently very good reasons to just add organic materials directly to the soil without composting. Compared with fresh residues, composts may not stimulate as much production of the sticky gums that help hold aggregates together. Also, some uncomposted materials have more nutrients readily available to feed plants than do composts. Plants may need readily available nutrients from residues if your soil is very deficient in fertility. Routine use of compost as a nitrogen source may cause high soil phosphorus levels to develop because of the relatively low N:P ratio. Finally, more

Figure 13.6. Three years of tree growth without (left) and with (right) compost application. Photos by Urban Horticulture Institute, Cornell University.

labor and energy usually are needed to compost residues than when simply applying the uncomposted residues directly. In general, composting makes most sense when 1) the feedstock materials are difficult to handle, unsafe in the open environment, or have odor concerns (like livestock carcasses, or food processing waste), 2) the waste material cannot be used locally and needs to be transported over distances before field application (like urban tree leaves), 3) there are concerns with pathogens (like pet, zoo or human waste) or 4) there is a good market for the use of compost (like farms near urban areas).

SUMMARY

Composting helps us use organic waste materials to benefit the soil and increase plant growth. It helps reduce problems with local excesses and deficiencies of carbon and nutrients by making them safe and transportable. Composting organic residues before applying them to soil is a tried and true practice that can, if done correctly, eliminate plant disease organisms, weed seeds and many (but not all) potentially noxious or undesirable chemicals. Compost provides extra waterholding capacity to a soil, provides a slow release of N and may help to suppress a number of plant disease organisms as well as enhance the plant's ability to fight off diseases. Critical to good composting is to have 1) a good balance of carbon (brown-dry) and nitrogen (green or colorful-wet), 2) good aeration, 3) moist conditions and 4) a mass of 4–5 cubic feet to reach and maintain high temperatures. It is also best to turn the pile or windrow to ensure that all the organic materials have been exposed to the high temperatures.

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a case study

CAM TABB
KEARNEYSVILLE, WEST VIRGINIA

During droughts in 2006, 2007 and 2010, West Virginia beef farmer Cam Tabb's crop yields exceeded the averages for his area. At times, neighbors have wondered whether Tabb enjoys some kind of miraculous microclimate, since he seems to make it through dry periods with seemingly little impact.

"I get blamed for getting more water than they got because the corn looks better," laughs Tabb, who raises 500 Angus beef cattle and grows small grains, hay and corn for grain and silage, using no-till methods, on 1,900 acres near Charles Town, West Virginia. Tabb credits his strong yields to a commitment to no-till practices, which he's been implementing since the early 1970s, as well as to three decades of applying composted horse, dairy and cattle manure to his fields. "I get a healthier plant with a better root system because my soil structure is better," he says. "So the rain that you do get really sinks in."

Tabb's composting efforts, combined with annual soil tests and rotations, have done more than improve his soil and crop yields; in fact, composting has become one of the farm's most important sources of income.

Tabb has come a long way since he piled manure on hard-packed ground and watched it ice over in the winter. "Before, I handled the manure as a waste, not a resource," he says. "I thought it had to smell bad to be any good. That was before I realized that I was smelling nitrogen being lost into the air as ammonia."

Inspired by a West Virginia University researcher's presentation on backyard composting, Tabb realized he needed to add a carbon source to his manure and to turn the piles to encourage aeration. Once he began mixing in sawdust from horse stalls and turning the piles, he was on his way to becoming a master composter. Now he earns money taking in and hauling away a wide range of compostable materials from a faithful clientele—including several municipalities, area fish hatcheries, horse operators and neighbors—that has developed simply through word of mouth. These materials include animal manure, animal carcasses, stumps, storm debris, scrap lumber, pallets, food waste, leaves and grass clippings. "People can pay me at half the cost it would take them to get their trash hauled away," he says. "We then process and sell the materials we take away."

The ingenuity of Tabb's composting operation lies in having found ways to make money several times off of these "waste" materials. For example, he chips scrap wood that he's been paid to haul from home construction sites and sells that material as bedding to horse operators. He rents containers to the horse owners to store used bedding, containing manure, which he hauls back to his farm, composts and sifts to create a high-grade compost product that he either sells or uses on his farm. He estimates that he composts at least 26,000 cubic yards of horse manure annually.

The fish wastes that Tabb receives from a federal fish hatching facility are composted with sawdust and horse manure. "This quickly creates a nice compost that contains 15–16 pounds N per ton, almost double the N content of our basic compost product," he says.

Tabb also rents out containers to contractors clearing land of trees and stumps. "When we get logs, we save them aside; they're better for [reselling as] firewood," he says. After the soil and rocks are removed from the scraps and split stumps, the wood is mulched and sold to nurseries. The stump dirt, which he describes as being "about 85% dirt and 15% compost" is sifted and screened, creating a topsoil product that he markets back to the contractors for landscaping purposes. "None of the topsoil we sell comes from our own farm," he says. "It is all from recycled materials that we have brought in." The topsoil that once was a byproduct of the stump removal service is now one of the top-grossing products he sells, now that he has the equipment to sift the rocks and foreign material out of it.

While "crop response and the reduction of manure volume" are what initially got Tabb excited about composting, today he is particularly motivated by the major role that composting plays in ensuring his farm's economic sustainability. He says it has paid to have a good compost supply on the farm, and in addition to longer-term benefits of increased organic matter and plant health, it's more cost efficient than traditional fertilizer.

The water-retention and slow-nutrient-release qualities of his compost have boosted Tabb's yields in good growing years and have buffered his operation during hard ones. One year, he recorded an 80-bushel corn yield advantage on an acre amended with his compost compared to an acre where no compost had been applied.

Tabb spreads 10–12 tons of compost per acre to his crop fields, depending on soil test results, just once every three years. His compost—which supplies 9, 12 and 15 pounds of nitrogen, phosphorus and potash per ton, respectively—provides, with the exception of nitrogen, sufficient nutrients for his grain and hay crops. The compost he spreads is never less than a year old. Over time, he has become more selective about where he spreads, focusing on fields with 2%–3% organic matter content instead of those that have attained 5%–7%.

Tabb's windrow piles of compost—"They're bigger than anything you've ever seen," he says—measure 100 feet long, 20–25 feet wide and 15 feet high. The piles are set up at eight different locations on his farm, which reduces the number of tractor trips, cost and risk of soil compaction while spreading. Since the materials that are used for compost come to the farm by way of truck, he aggregates them adjacent to the acreage where he is going to eventually use the compost.

He relies on experience and observation instead of adhering to strict rules while making compost. "Everyone around the farm knows what to look for in turning the piles," he says. Heat-loving fungi, stimulated into releasing spores once the pile heats up to temperatures above 140°F, form mushrooms as the pile cools down. "We wait until the temperature goes under 130°F and turn the pile when we see the fragile mushrooms," he explains. He adds, "We never turn a pile that is going upwards in heat," so that piles will reach sufficient temperatures to kill pathogens and weed seeds. Turning, which Tabb does with a front-end loader, pays for itself by reducing the volume of the pile. Turning also stimulates more rapid and thorough decomposition of materials in the pile, inducing temperatures hot enough to kill weed seeds and diseases. Based on his experience, Tabb recommends maintaining a large ratio of old to fresh materials within compost piles. This ensures that the moisture released from fresh materials will be absorbed by drier, older materials, thus preventing leachate formation and speeding the piles' overall inoculation and decomposition rates.

Tabb is pleased by the long-term results of applying compost at his farm in conjunction with no-till, where the soil has taken on a spongier feel and has become more abundant in earthworms. He also sees little to no runoff from his compost-treated fields. "Our land makes up a total small watershed, and our springs feed a federal fish hatchery. If there were any negative runoff in the water, it'd be ours, and we'd hear about it from the people downstream," he observes.

Impressed by his results, several of Tabb's neighbors now make and spread their own "black gold." says Tabb, "Almost any farmer would understand what I do. I hadn't realized that I was a practicing environmentalist, but almost every farmer is. These days, you can't afford not to be."

Chapter 14

REDUCING RUNOFF AND EROSION

So long! It's been good to know you.
This dusty old dust is a gettin' my home.
And I've got to be drifting along.

—WOODY GUTHRIE, 1940

The dust storms that hit the Great Plains of the United States during the 1930s, centered in parts of Oklahoma, Kansas and northern Texas, were responsible for one of the great migrations in our history. As Woody Guthrie pointed out in his songs, soil erosion was so bad that people saw little alternative to abandoning their farms. They moved to other parts of the country in search of work. Although changed climatic conditions and agricultural practices improved the situation for a time, there was another period of accelerated wind and water erosion during the 1970s and 1980s. (Ironically, some of the worst-struck areas during the Dust Bowl are now producing crops again when the Ogallala aquifer was tapped for irrigated agriculture, although the water will run out in a few decades).

In many other areas land degradation has forced families off the farm to urban areas or caused them to seek out new lands by developing natural areas like rainforests. Fertile soils on slopes in southern Honduras are now severely eroded (Figure 14.1) after years of slash-and-burn agriculture. Much of the land has turned to pasture or been abandoned, and the area has become depopulated.

Climate and soil type are important factors affecting erosion. Intense or prolonged rainstorms are major

Figure 14.1. Erosion on steep lands in Central America. Removal of the fine topsoil left mostly boulders behind. Sorghum plants show drought stress due to lack of rain and low waterholding capacity in soil.

Photo courtesy Harold van Es

EROSION IS A NATURAL PROCESS, BUT ...

Erosion of rock and soil is a natural process that over the eons has caused the lowering of mountains and the formation of river valleys and deltas. And natural erosion is going on all the time as water, ice and wind have their effects on rock and soil. One dramatic example of such erosion is the dust picked up by winds just south of Africa's Sahara Desert—the Sahel region of transition from desert to savannah—traveling some 3,000 miles to South America and the Caribbean, and occasionally reaching the southeastern United States. This dust is thought to be a major source of phosphorus for the Amazon River basin, balancing losses that occur there. The problem in agricultural soils is *greatly accelerated erosion* that is especially severe when the soil is bare, unprotected by living plants, their roots or residue mulch. Also, breaking up of soil aggregates with tillage lessens rainfall infiltration into soil, which worsens runoff and erosion.

causes of water erosion and landslides, while drought and strong winds are critical factors in wind erosion. More extreme weather conditions as a result of climate change are therefore adding to the concerns of both water and wind erosion. Soil type is important because it influences the susceptibility to erosion as well as the amount that can occur without loss of productivity. In Chapter 6 we discussed how some soils (especially silts) with poor aggregation are more susceptible than other soils, especially those with good aggregation. This is reflected in the soil *erodibility* ratings, which soil conservationists use to plan control practices.

"TOLERABLE" SOIL LOSS

Soil erosion is a geological process and some soil loss is always with us. On the other hand, there are ways to control the accelerated loss caused by tillage and other cropping practices. Our goal should be to minimize erosion caused by farming operations.

The estimated maximum amount of soil that can be lost to erosion each year has been called the *soil loss tolerance*, or T value. This concept is used for qualifying farm practices of the USDA Natural Resources Conservation Service (NRCS) cost-share programs. Practices used should bring estimated soil loss below the "tolerance" values estimated for the farm's soils. For a deep soil with a rooting depth of greater than 5 feet, the T value is 5 tons per acre per year (11 metric tons per hectare). Still, 5 tons is equal to about .03 inch of soil depth (about .08 centimeters), and if soil loss continued at that rate, at the end of 33 years about 1 inch would be lost. This "tolerable" soil loss rate is in essence a compromise and does not fully prevent soil degradation. On deep soils with good management of organic matter it would take many years to see a noticeable impact, which is part of the concern: following these guidelines potentially diminishes long-term productivity.

The soil loss "tolerance" amount is reduced for soils with less rooting depth. When rooting depth is less than 10 inches, the tolerable rate of soil loss is the same as losing 0.006 inches per year and is equivalent to 1 inch of loss in 167 years. Of course, on agricultural fields the soil loss is not evenly distributed over the field, and greater losses occur in areas where runoff water collects and continues to flow (Figure 14.2). When soil loss is greater than the tolerance value, productivity suffers in the long run. Yearly losses of 10–15 tons or more per acre occur in many fields. In extreme cases, as with croplands on steep slopes in tropical climates, losses of five or 10 times that much may occur.

Reducing erosion to the greatest extent possible can be achieved by combining practices that have many

Figure 14.2. A waterway scoured into a gully on a Midwestern cornfield after erosive spring rains. Photo by Andrew Phillips.

other positive effects aside from lessening soil loss. These practices include minimizing tillage, using cover crops and following better rotations. Farmers creatively using such practices customized for their conditions can maintain soil productivity over the medium to long term even if a small amount of erosion occurs, as long as new topsoil can be created as rapidly as soil is lost, estimated at about 0.5 tons per acre (about 1 ton per hectare).

OFF-SITE EFFECTS

The soil removed from fields also has significant negative effects off the farm, as sediment accumulates in streams, rivers, reservoirs and estuaries, or blowing dust reaches towns and cities. In fact, sediment remains the No. 1 contaminant for most waters around the world, and it often also carries other pollutants like nutrients, pesticides and other chemicals. From a purely economic perspective, the off-site costs of soil erosion affecting fisheries, recreation and industry can be greater than the lost agricultural productivity, especially if the receiving waters are used by many people. Many conservationists argue that any amount of erosion is unacceptable, even when losses are less than T. This is a good point, as small amounts of soil can have an outsize impact on water and air quality, meaning that soil losses less than T may be tolerable in terms of agricultural productivity but not in terms of environmental quality. This is especially the case when dealing with soils that are high in clay content, where the particles become suspended as colloids in runoff water. The particles do not settle out in ponds or filter strips and can be transported long distances from the source, along with nutrients and pesticides (Figure 6.2, right photo). Similarly, clay and silt particles suspended in the air can be transported long distances and can cause respiratory problems.

ADDRESSING RUNOFF AND EROSION

Management practices are available to help reduce runoff and soil losses. For example, an Ohio experiment in which runoff from conventionally tilled and no-till continuous-corn fields was monitored showed that over a four-year period, runoff averaged about 7 inches of water each year for conventional tillage and less than 0.1 inch for the no-till planting system. Researchers in the state of Washington found that erosion on winter wheat

COST OF EROSION PER BUSHEL OF CROP

One way to look at the amount of erosion is to compare it to the amount of crops raised. For example, it is estimated that the average yearly soil loss from Iowa farms is about 5.5 tons per acre. Average Iowa yields are around 180 bushels of corn and 60 bushels of soybeans per acre. Using those values and assuming a 5.5 ton annual soil loss, there is approximately 1 pound of soil lost per pound of corn produced and 3.3 pounds of soil lost per pound of soybeans produced. We previously discussed the exporting of nutrients from farms that are integral parts of the crops sold. But this is another pathway for nutrients to leave the farm in relatively large quantities.

fields was about 4 tons per acre each year when a sod crop was included in the rotation, compared to about 15 tons when it was not included.

Effective runoff and erosion control is possible without compromising crop productivity. However, it may require a new mindset, considerable investment or different management. The numerous methods of controlling soil and water can be grouped into two general approaches: *structural* measures and *agronomic* practices. Creating structures for reducing erosion generally involves engineering practices, in which an initial investment is made to build terraces, diversion ditches, drop structures, etc. Agronomic practices focus on changes in soil and crop management and on using vegetative solutions, such as reduced tillage, cover cropping and planting vegetation in critical areas. Appropriate conservation methods may vary among fields and farms, but recently there has been a clear trend away from structural measures in favor of agronomic practices. The primary reasons for this change:

- Agronomic measures help control erosion while also improving soil health and crop productivity.
- Significant advances have been made in farm machinery and methodologies for conservation tillage systems that make use of crop rotations and cover crops.
- Structures generally focus on containing runoff and sediment once erosion has been initiated, i.e., they trap sediment that has already eroded. Conversely, agronomic measures try to prevent erosion from occurring in the first place by decreasing runoff potential.
- Structures are often more expensive to build and maintain (with significant upfront expense) than are agronomic measures, while they also tend to be less effective.

Therefore, the use of soil-building conservation management practices is preferred for long-term sustainability of crop production, and they are also the first choice for controlling runoff and erosion. Structural measures still have a place but are primarily to complement agronomic measures.

Erosion reduction works by either decreasing the shear forces of water and wind or by keeping soil in a condition in which it can't easily erode. Many conservation practices actually reduce erosion by using both approaches. In general, the following are good principles:

- Keep the soil covered: water and wind erosion occur almost exclusively when the soil is exposed. Live plants are the best way to protect the soil and to stimulate soil health.
- Use management practices that increase aggregation and infiltration.
- Do not disturb the soil unless it is well covered. Loose, exposed soil is more erodible than stable soil, like in no-till systems. Loosening may initially

EROSION: A SHORT-TERM MEMORY PROBLEM?

It's difficult to fully appreciate erosion's damage potential because the most severe erosion occurs during rare weather events and climate anomalies. Wind erosion during the Dust Bowl days of the 1930s, which resulted from a decade of extremely dry years, was especially damaging. And about one-third of the water erosion damage that occurs in a particular field during a 30 year period commonly results from a single extreme rainfall event. Like stock market crashes and earthquakes, catastrophic erosion events are rare, but the impacts are great. We must do our best to understand the risks, prevent complacency and adequately protect our soils from extreme weather events.

reduce runoff potential, but this effect is generally short lived, as the soil will settle. If tilling is required to reduce compaction, do it with tools that limit disturbance (e.g., zone builders or strip tillers). Soil disturbance is also the single greatest cause of tillage erosion.

- Take a landscape-scale approach for additional control. Focus on areas with high risk—those where runoff water concentrates—and maximize the use of inexpensive biological approaches like grass seeding in waterways and filter strips.
- Focus on critical periods. For example, in temperate areas the soil is most susceptible after the winter fallow, and in semiarid regions it is most fragile after the dry period when heavy rains begin and there is little surface cover. In some regions, heavy rainfall is associated with hurricane or monsoon seasons.
- Evaluate whether areas of erodible land are better taken out of production. Sometimes an economic analysis of field yield patterns (for example, using yield monitor data) shows that yields in these fields or portions of fields are not sufficient to overcome the input costs. If these areas are not profitable, more benefit is gained from government payments as part of conservation reserve or set-aside programs.

Reduced Tillage

In the past decade it has become clear that the best way to reduce erosion is to keep the soil covered, and the best way to maintain strong aggregates is to disturb the soil as little as possible. Transitioning to tillage systems that increase surface cover and reduce disturbance (Figure 14.3) is therefore the single most effective approach to reducing erosion. Incidentally, reduced tillage also generally provides better economic returns than does conventional tillage. The effects of wind on surface soil are also greatly reduced by leaving crop stubble on untilled soil and anchoring the soil with roots. These measures facilitate infiltration of precipitation where it falls, thereby reducing runoff and increasing plant water availability. In cases where tillage is necessary, reducing its intensity and leaving some residue on the surface minimizes the loss of soil organic matter and aggregation. Leaving a rougher soil surface by eliminating secondary tillage passes and packers that crush natural soil aggregates saves considerable labor time and wear and tear on machinery. It also significantly reduces runoff and erosion losses by preventing aggregate dispersion and surface sealing from intense rainfall (see Figure 6.11). Reducing or eliminating tillage also diminishes tillage erosion and keeps soil from being moved downhill. The gradual losses of soil from upslope areas expose subsoil and may in many cases further aggravate runoff and erosion. We discuss tillage practices further in Chapter 16.

Significance of Plant Residues and Competing Uses

Reduced tillage and no-tillage practices result in less soil disturbance and leave significant quantities of crop residue on the surface. Surface residues are important because they intercept raindrops and can slow down water running over the surface. The amount of residue on the surface may be less than 5% for the moldboard plow, while continuous no-till planting may leave 90% or more of the surface covered by crop residues. Other

Figure 14.3. No-till soybeans with corn residue.

reduced tillage systems, such as chiseling and disking (as a primary tillage operation), typically leave more than 30% of the surface covered by crop residues. Research has shown that 100% soil cover virtually eliminates runoff and erosion on most agricultural lands. Even 30% soil cover reduces erosion by 70%.

As discussed in Chapter 9, there are many competing uses for crop residues as fuel sources, as well as building materials. Unfortunately, permanent removal of large quantities of crop residues will have a detrimental effect on soil health and on the soil's ability to withstand water and wind erosion, especially when there is no return of organic materials as manure.

Cover Crops

Cover crops result in decreased erosion and increased water infiltration in a number of ways. They add organic residues to the soil and help maintain soil aggregation and levels of organic matter. Cover crops frequently can be grown during seasons when the soil is especially susceptible to erosion, such as the winter and early spring in temperate climates, or early dry seasons in semiarid climates. Their roots help to bind soil and hold it in place. Because raindrops lose most of their energy when they hit leaves and drip to the ground, less soil crusting occurs. Cover crops are especially effective at reducing erosion if they are cut and mulched or rolled and crimped, rather than incorporated. Ideally, this is done when the cover crop has nearly matured (typically, milk stage)—that is, when it is somewhat lignified but seeds are not yet viable and C:N ratios are not so high as to cause nutrient immobilization. In recent years, new methods of cover cropping, mulching and no-tillage crop production, often jointly referred to as conservation agriculture, have been worked out by innovative farmers in several regions of the world (Figure 14.4; see also the farmer case study at the end of this chapter). This practice has revolutionized farming in parts of temperate South America, with rapid and widespread adoption in recent years. It has been shown to virtually eliminate runoff and erosion, and also appears to have great benefits for moisture conservation, nitrogen cycling, weed control, reduced fuel consumption and time savings, which altogether can result in significant increases in farm profitability. See Chapter 10 for more information on cover crops.

Perennial Rotation Crops

Grass and legume forage crops can help lessen erosion because they maintain a cover on most of the soil surface for the whole year. Their extensive root systems hold soil in place. When they are rotated with annual row crops, the increased soil health helps maintain lower erosion and runoff rates during that part of the crop cycle.

Benefits are greatest when such rotations are combined with reduced- and no-tillage practices for the annual crops. Perennial crops like alfalfa and grass are often rotated with row crops, and that rotation can be readily combined with the practice of strip cropping (Figure 14.5). In such a system, strips of perennial sod crops and row crops are laid out across the slope, and erosion from the row crop is filtered out when the water reaches the sod strip. This conservation system is quite effective in fields with moderate erosion potential and on farms that use both row and sod crops (dairy farms, for example). Each crop may be grown for two to five years on a strip, which is then rotated into the other crop.

Permanent sod, as hayland or pasture, is a good choice for steep soils or other soils that erode easily, although slumping and landslides may become a concern with extremely steep slopes.

Adding Organic Materials

Maintaining good soil organic matter levels helps keep topsoil in place. A soil with more organic matter usually has better soil aggregation and less surface sealing/crusting. These conditions ensure that more water is

Figure 14.4. Field and closeup views of soybeans grown in a black oat cover crop mulch in South America. Photos by Rolf Derpsch.

able to infiltrate the soil instead of running off the field, taking soil with it. When you build up organic matter, you help control erosion by making it easier for rainfall to enter the soil. Reduced tillage and the use of cover crops already help build organic matter levels, but regularly providing additional organic materials like compost or manure stimulates earthworm activity and results in larger and more stable soil aggregates.

The adoption rate for no-till practices is lower for livestock-based farms than for grain and fiber farms. Manures often need to be incorporated into the soil for best use of nitrogen, protection from runoff and odor control. Also, the severe compaction resulting from the use of heavy manure spreaders may need to be relieved by tillage. Direct injection of liquid organic materials in a zone-till or no-till system is a recent approach that allows for reduced soil disturbance and minimal concerns about manure runoff and odor problems (Figure 14.6).

Other Practices and Structures for Soil Conservation

Soil-building management practices are the first approach to runoff and erosion control, but structural measures may still be appropriate. For example, *diversion ditches* are channels or swales that are constructed across slopes to divert water across the slope to a waterway or pond (Figure 14.7). Their primary purpose is to channel water away from upslope areas and prevent the downslope accumulation and concentration of runoff water that would then generate scouring and gullies.

Grassed waterways are a simple and effective way to reduce scouring in areas where runoff water accumulates; they also help prevent surface water pollution by filtering sediments out of runoff (Figure 14.8). They require only small areas to be taken out of production and are used extensively in the Grain Belt region of the United States, where long gentle slopes are common.

Figure 14.5. Corn and alfalfa grown in rotation through alternating strips. Photo by Tim McCabe, USDA-NRCS.

Figure 14.6. Equipment for manure injection with minimal soil disturbance.

Figure 14.7. A hillside ditch in Central America channeling runoff water to a waterway on the side of the slope (not visible). A narrow filter strip is located on the upslope edge to remove sediment.

Terracing soil in hilly regions is an expensive and labor-intensive practice for conserving soil structure, but it is also one that results in a more gradual slope and reduced erosion. Well constructed and maintained structures can last a long time. Most terraces have been built with significant cost-sharing from government soil conservation programs prior to the widespread adoption of no-tillage and cover cropping systems.

Contour tilling and planting is a simple practice that helps control erosion without equipment investments. It was therefore one of the first conservation practices promoted after the Dust Bowl of the 1930s. When you work along the contour, instead of up- and downslope, wheel tracks and depressions caused by the plow, harrow or planter will retain runoff water in small puddles and allow it to slowly infiltrate. However, this approach is not very effective when dealing with steeper erodible lands, does not have significant soil health benefits and does not eliminate tillage erosion.

There are a number of other practices that can help mitigate the off-site effects of soil erosion but do little to build soil health. ***Filter strips*** remove sediment and

Figure 14.8. A grassed waterway in a Midwestern cornfield safely channels and filters runoff water. Photo by Ann Staudt, Iowa Learning Farms.

Figure 14.9. Edge-of-field filter strips control sediment losses to streams. Photo courtesy of USDA-NRCS.

Figure 14.10. Top: A sediment control basin in a Central European landscape where conventional tillage is widely used. Bottom: Sediment regularly fills the basin and needs to be dredged.

nutrients before runoff water enters ditches and streams (Figure 14.9). ***Sediment control basins*** have been constructed in many agricultural regions to allow sediment to settle before stream water is further discharged; they are often used in areas where conventional soil management systems still generate a lot of erosion (Figure 14.10). For both practices, their effectiveness varies depending on the time of year (less in winter and in the wet season) and whether soil particles readily settle out of runoff water (less settling out for clayey than sandy soils).

Wind erosion is reduced with most of the same practices that control water erosion by keeping the soil covered and increasing aggregation: reduced tillage or no-till, cover cropping and perennial rotation crops. In addition, practices that increase the roughness of the soil surface diminish the effects of wind erosion. The rougher surface increases turbulent air movement near the land surface and reduces the wind's shear and ability to sweep soil material into the air. Therefore, if fields are tilled and cover crops are not used, it makes sense to leave soil in a rough-tilled state when crops aren't growing. Also, ***tree shelterbelts*** planted at regular distances perpendicular to the main wind direction act as windbreaks and help reduce evaporative demand from

Figure 14.11. A field shelterbelt reduces wind erosion and evaporative demand, and increases landscape biodiversity.

Figure 14.12. An experiment with wide-spaced poplar trees planted in a New Zealand pasture to reduce landslide risk.

dry winds (Figure 14.11). They have recently received new attention as ecological corridors in agricultural landscapes that help increase biodiversity and may fit with the principles of alley cropping (Chapter 11).

Finally, a few words about landslides. They are difficult to control, and unstable steep slopes are therefore best left in forest cover. This is generally the case in most developed countries, but steep slopes are sometimes farmed in poor agricultural regions of the world. A compromise solution is the use of wide-spaced trees that allow for some soil stabilization by roots but that leave enough sunlight for a pasture or crops (Figure 14.12), a form of silviculture we also discussed in Chapter 11. In some cases, *horizontal drains* are installed in critical zones to allow dewatering and to prevent supersaturation during prolonged rains. But these are expensive to install and are more commonly used in urban areas and along roads where landslides on steep slopes are great hazards.

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Chapter 15

ADDRESSING COMPACTION

A lasting injury is done by ploughing land too wet.

—S.L. DANA, 1842

We've already discussed the benefits of cover crops, rotations, reduced tillage and organic matter additions for improving soil structure. However, these practices still may not prevent compacted soils unless specific steps are taken to reduce the impact of heavy loads from field equipment and inappropriately timed field operations. The causes of compaction were discussed in Chapter 6, and in this chapter we discuss strategies to prevent and lessen soil compaction. If measures to loosen a severely compacted soil are not taken, yield losses may be significant. One study in the Upper Midwest estimated a median 21% yield reduction for corn and soybeans on lands that experienced deep wheel traffic compaction at harvest. Urban areas also often experience big problems with soil compaction, which we discuss separately in Chapter 22.

DIAGNOSING DIFFERENT TYPES OF COMPACTION

The first step is to decide whether compaction is a problem and which type is affecting your soils. The symptoms, as well as remedies and preventive measures, are summarized in Table 15.1.

Surface Sealing and Crusting

This type of compaction occurs at the immediate soil surface when the soil is exposed. It may be seen in the early growing season, especially with clean-tilled soil, and in the fall and spring after a summer crop (Figure 15.1). Certain soil types, such as sandy loams and silt loams, are particularly susceptible. Their aggregates

Figure 15.1. Rainfall energy destroys weak soil aggregates and creates a surface seal that increases runoff potential. This photo is of soil in the wheat-growing Palouse region of Washington state. When it dries, the seal turns into a hard crust that prevents seedling emergence.

Table 15.1
Types of Compaction and Their Remedies

Compaction Type	Indications	Remedies/Prevention
Surface seal or crust	Breakdown of surface aggregates and sealing of surface Poor seedling emergence Accelerated runoff and erosion	Eliminate tillage or reduce tillage intensity Maximize surface cover: leave residues on surface, grow cover crops Add organic matter
Surface layer	Deep wheel tracks Prolonged saturation or standing water Poor root growth and more disease symptoms Hard to dig and resistant to penetrometer Cloddy after tillage	Use zone builders or strip tillers to break compaction but minimize soil disturbance Use cover crops or rotation crops that can break up compacted soils Add organic matter Use better load distribution with equipment Use controlled traffic Don’t travel on soils that are wet Improve soil drainage
Subsoil	Roots can’t penetrate subsoil Resistant to penetrometer at greater depths	Don’t travel on soils that are wet Improve soil drainage Till deeply with a zone builder or strip tiller Use cover crops or rotation crops that penetrate compact subsoils Use better load distribution Use controlled traffic Don’t use wheels in open furrows

usually aren’t very stable, and once broken down, the small particles fill in the pore space between the larger particles, making very dense crusts.

The impact of surface sealing and crusting is most damaging when heavy rains occur between planting and seedling emergence, when the soil is most susceptible to raindrop impact. Keep in mind that this may not happen every year. The hard surface crust may delay seedling emergence and growth until the crust mellows with the next rains. If such follow up showers do not occur, the crop may be set back. Crusting and sealing of the soil surface also reduce water infiltration capacity, which can increase runoff and erosion and lessen the amount of available water for crops.

Surface Layer Compaction

Compaction of the layer immediately below the surface can often be observed in the field through deep wheel tracks, extended periods of saturation, or even standing water following rain or irrigation. Compacted surface layers also tend to be extremely cloddy when tilled (Figure 15.2). A field penetrometer, which we discuss in greater detail in Chapter 23, is an excellent tool to assess soil compaction (you can also push a simple wire flag into the soil). Digging with a shovel allows for direct visual evaluation of soil structure and rooting, as well as of the overall quality of the soil. This is best done when the crop is in an early stage of development but after the rooting system has had a chance to establish.

Well-structured soil shows good aggregation, is easy to dig and will fall apart into granules when you throw a shovelful on the ground. If you find a dense rooting system with many fine roots that protrude well into the soil, you probably do not have a compaction problem. Conversely, roots in a compacted surface layer are usually stubby and have few root hairs (Figure 15.3). They often follow crooked paths as they try to find zones of weakness in the soil. Compare the difference between soil and roots in wheel tracks and nearby areas to observe compaction effects on soil structure and plant growth behavior. Note that recently plowed soils may give a false impression of compaction: they are initially loose but will likely compact later in the season. No-tilled soils generally are firmer but have stronger structure and contain large pores from worm activity.

Compaction may also be recognized by observing crop growth. A poorly structured surface layer will settle into a dense mass after heavy rains, leaving few large pores for air exchange. If soil wetness persists, anaerobic conditions may occur, causing reduced growth and high denitrification losses (exhibited by leaf yellowing), especially in areas that have drainage problems. In addition, these soils may "hard set" if heavy rains are followed by a drying period. Crops in their early growth stages are very susceptible to these problems (because roots are still shallow), and the plants may go through a noticeable period of stunted growth on compacted soils.

Figure 15.2. Large soil clods after tillage are indicative of compaction and poor aggregation.

Figure 15.3. Corn roots from a compacted surface layer are thick, show crooked growth patterns, and lack fine laterals and root hairs.

Reduced growth caused by compaction also affects the crop's ability to fight or compete with pathogens, insects and weeds. These pest problems may become more apparent, therefore, simply because the crop is weakened. For example, during wet periods, dense, poorly aerated soils are more susceptible to infestations of fungal root diseases such as *Phytophthora*, *Sclerotinia*, *Fusarium*, *Pythium*, *Rhizoctonia* and *Thieviopsis* and plant-parasitic nematodes such as northern root-knot. These problems can be identified by observing washed roots. Healthy roots are light colored, while diseased roots are black or show lesions. In many cases, soil compaction is combined with poor sanitary practices and lack of rotations, creating a dependency on heavy chemical inputs.

Subsoil Compaction

Subsoil compaction is difficult to diagnose because the lower soil layers are not visible from the surface. The easiest way to assess compaction in deeper soil layers is to use a penetrometer, which should be done when the soil is field-moist (not too wet, not too dry). It is surprising how often you find the tool hitting much higher resistance once it reaches the bottom of the plow

CROPS THAT ARE HARD ON SOILS

Some crops are particularly hard on soils:

- Root and tuber crops like potatoes require intensive tillage and a lot of disturbance at harvest. They also return low rates of residue to the soil.
- Silage corn and soybeans return low rates of residue.
- Many vegetable crops require a timely harvest, so field traffic occurs even when the soils are too wet.

Special care is needed to counter the negative effects of such crops. Counter measures may include selecting soil-improving crops to fill out the rotation, using cover crops extensively, using controlled traffic, and adding extra organic materials such as manures and composts. Some potato farmers in New York and Maine are known to rotate fields with dairy farmers who convert them into soil-building alfalfa and grass. In an 11-year experiment in Vermont with continuous corn silage on a clay soil, we found that applications of dairy manure were critical to maintaining good soil structure. Applications of 0, 10, 20 and 30 tons (wet weight) of dairy manure per acre (1 ton per acre equals 2.2 metric tons per hectare) each year of the experiment resulted in pore spaces of 44%, 45%, 47% and 50% of the soil volume, respectively.

layer—typically down 6–8 inches—even if it has not actually been tilled for awhile. Rooting behavior below the surface layer is also a good indicator for subsoil compaction, assuming you are willing to expend some effort digging to that depth. Roots are almost completely absent from the subsoil below severe plow pans and often move horizontally above the pan (see Figure 6.8). Keep in mind, however, that naturally shallow-rooted crops, such as spinach and some grasses, may not necessarily experience problems from subsoil compaction.

Some soils are naturally susceptible to the formation of dense subsoils when they become intensively cropped. When soil aggregates become weaker from loss of the organic matter, silt and clay particles can wash down and settle in the subsoil pores, thereby creating a dense layer. This is especially a concern with soils that contain about equal amounts of sand, silt and clay, and where the clay minerals are of the non-swelling 1:1 type. Also, tropical oxisols have naturally high clay contents with very strong aggregates, but when they are limed, the raised pH causes the clay particles to disperse and wash into pores in the lower soil.

RELIEVING AND PREVENTING COMPACTION

Preventing or reducing soil compaction generally requires a comprehensive, long-term approach to addressing soil health issues and rarely gives immediate results. Compaction on any particular field may have multiple causes, and the solutions are often dependent on the soil type, climate and cropping system. With some exceptions, let's go over some general principles of how to solve these problems.

Reducing surface sealing and crusting. Crusting is a symptom of the breakdown of soil aggregates that occurs especially with intensively and clean-tilled soils. As a short-term solution, farmers sometimes use tools like rotary hoes to break up the crust. The best long-term approach is to reduce tillage intensity (or eliminate tillage altogether), leave residue or mulch on the surface, plant cover crops, and improve aggregate stability with organic matter additions. Even residue covers as low as 30% of the soil surface area will greatly reduce crusting and provide important pathways for water entry. A good, heavy duty conservation planter—with rugged coulter blades for in-row soil loosening, tine wheels to remove surface residue from the row, and accurate seed placement—can be a highly effective implement because it can successfully establish crops without intensive tillage (see Chapter 16). Reducing tillage and maintaining significant amounts of surface residues not only prevent crusting but also rebuild the soil by increasing aggregation. Soils with very low aggregate stability, especially those high in sodium, may sometimes benefit from surface applications of gypsum (calcium sulfate). Aggregation is promoted by the added calcium and the effect of the greater salt concentration in the soil water as the gypsum dissolves.

Reducing surface layer compaction through proper use of tillage. Tillage can either cause or lessen problems with soil compaction. Repeated intensive tillage reduces soil aggregation and compacts the soil over the long term, causes erosion and loss of topsoil, and may bring about the formation of plow pans. On the other hand, tillage can relieve compaction by loosening the soil and creating pathways for air and water movement and root growth. This relief, however, as effective as it may be, is temporary and would probably need to be repeated in the following growing seasons if poor soil management and traffic patterns are continued. Farmers frequently use more intense tillage to offset the problems of cloddiness associated with compaction of the plow layer. But this puts them in a downward cycle and it should be avoided.

The long-term solution to these problems is to eliminate or significantly reduce tillage and to better manage soil organic matter (see below), but not necessarily to stop tillage altogether right away. Compacted soils frequently become “addicted” to tillage, and converting to no-till “cold turkey” may result in failure. Practices that perform some soil loosening with minor disturbance at the soil surface may help in the transition from a tilled to an untilled management system. ***Aerators*** (Figure 15.4) have rotating tines that provide shallow compaction relief in dense surface layers but do minimal tillage damage and are especially useful when aeration is of concern. They are also used to incorporate manure with minimal tillage damage. ***Strip tillage*** (6–8 inches deep) employs narrow shanks that disturb the soil only where future plant rows will be located (Figure 15.4). It is

ORGANIC MATTER HELPS SOILS RESIST COMPACTION

Organic matter in all its forms—including living roots, soil organisms, fragments of crop residue and dead organisms, and the “very dead”—helps to resist soil compaction in a number of ways. Using cover crops, leaving residues on the surface and increasing soil organic matter levels are indicated in Table 15.1 as remedies for all forms of compaction. The ways in which organic matter help:

- Residue on the surface helps dissipate the compacting force of equipment.
- Soil organic matter is less dense than mineral particles.
- Remnants of plant residue and soil organisms (the dead) help stabilize aggregates.
- Roots and large soil organisms (the living) create channels and other spaces for air and water movement and storage.

Roots and mycorrhizal fungi secrete sticky substances that promote formation of stable aggregates and help bind smaller aggregates into larger ones. Some cover crops are able to break through compacted layers, allowing roots of the following commercial crops to better penetrate the soil. And the extensive root systems of perennial forage crops in a rotation, undisturbed by tillage, work to improve soil structure.

Figure 15.4. Tools that provide compaction relief with minimal soil disturbance: aerator (left) and strip tiller (middle and right). Right photo by Georgi Mitev.

especially effective at promoting root proliferation. This practice is a good transition to more pure no-till, but many farmers find strip tillage a good long-term strategy that gets them similar benefits to no-till with fewer concerns about compaction. Yeoman's plows achieve similar results with virtually no surface disturbance.

Another approach may be to combine organic matter additions (compost, manure, etc.) with reduced tillage intensity and a planter that ensures good seed placement with minimal secondary tillage. Such a soil management system builds organic matter over the long term. In general, the benefits of no-till take 2–5 years to be realized, but this timeline can be accelerated with the use of cover crops.

Relieving subsoil compaction through deep tillage. Deeper tillage may be beneficial on soils that have developed a plow pan or other deep compacted layers. Simply shattering this pan allows for deeper root exploration. To be effective, deep tillage needs to be performed when the entire depth of tillage is sufficiently dry and in the friable state, otherwise it causes smearing of the soil.

Subsoiling relates to a range of methods to alleviate compaction below the 6- to 8-inch depths of normal tillage and is often done with heavy duty rippers (Figure 15.5) and large tractors. Subsoiling is often erroneously seen as a cure for all types of soil compaction, but it does relatively little to address surface layer compaction that

Figure 15.5. Left: Subsoiler shank provides deep compaction relief (wings at the tip provide lateral shattering). Right: Zone building provides compaction relief and better rooting with minimal surface disturbance. Right photo by George Abawi.

Figure 15.6. Compaction and smearing from wet (plastic) soil conditions: wheel traffic (left), plowing (middle) and zone building leaving an open and smeared slot (right).

is caused by aggregate breakdown. Subsoiling is a rather costly and energy consuming practice, and its use is difficult to justify on a regular basis. Also, large rippers generally cause more soil disturbance than needed, and practices such as zone building and deep strip tillage (Figure 15.4) are better ways to loosen the soil below the plow layer. They have narrow shanks that disturb the soil less and leave crop residues on the surface (Figure 15.5).

Deep tillage tends to be more effective on coarse-textured soils (sands, gravels), as crops on those soils respond better to deeper rooting. In fine-textured soils, the entire subsoil often has high strength values, so the effects of deep tillage are less beneficial. In some cases it may even be harmful for those soils, especially if the deep tillage was performed when the subsoil was wet and caused smearing, which may generate drainage problems. After performing deep tillage, it is important to prevent future re-compaction of the soil by keeping heavy loads off the field and not tilling the soil when inappropriate soil moisture conditions exist, because otherwise the benefits are short lived. Soils that are naturally susceptible to subsoil compaction due to the washing down of fine particles may need repeated deep tillage.

Better attention to working the soil and field traffic. Compaction of the plow layer or subsoil is often the result of working the soil or running equipment when it is too wet (Figure 15.6). Avoiding this may require equipment modifications and different timing of field operations. The first step is to evaluate all traffic and practices that occur on a field during the year and determine which operations are likely to be most damaging. The main criteria should be:

- the soil moisture conditions when the traffic occurs, and
- the relative compaction effects of various types of

Lessening and preventing soil compaction are both important to improving soil health. The specific approaches should meet the following criteria:

- They should be selected based on where the compaction problem occurs (subsoil, surface layer, or at the very surface).
- They must fit the soil and cropping system and their physical and economic realities.
- They should be influenced by other management choices, such as the tillage system and use of organic matter amendments.

Figure 15.7. Reduction of soil compaction by increased distribution of equipment loads. Left: Tracks on a tractor. Middle: Dual wheels on a tractor that also increase traction. Right: Multiple axles and flotation tires on a liquid manure spreader.

field traffic (mainly defined by equipment weight and load distribution).

For example, with a late-planted crop, soil moisture conditions during tillage and planting may generally be dry, and minimal compaction damage occurs. Likewise, mid-season cultivations usually do little damage because conditions are usually dry and the equipment tends to be light. However, if the crop is harvested under wet conditions, heavy harvesting equipment and uncontrolled traffic by trucks that transport the crop off the field will do considerable compaction damage. In this scenario, emphasis should be placed on improving the harvesting operations. In another scenario, a high-plasticity clay loam soil is often spring plowed when still too wet. Much of the compaction damage may occur at that time, and alternative approaches to tillage and timing should be a priority.

Better load distribution. Using improved designs of field equipment may help reduce compaction problems by better distributing vehicle loads. The best example is the use of tracks (Figure 15.7), which greatly reduce the potential for subsoil compaction. But beware! Tracked vehicles may provide a temptation to traffic the land when the soil is still too wet. Tracked vehicles have better flotation and traction, but they can still cause compaction damage, especially through smearing under the tracks. Surface layer compaction may also be reduced by using flotation tires and lowering the air pressure in the tires. A rule of thumb: Cutting tire inflation pressure in half doubles the size of the tire footprint to carry an equivalent equipment load and cuts the contact pressure on the soil in half.

The use of multiple axles reduces the load carried by individual wheels and tires. Even though the soil receives more tire passes by having a larger number of tires, the resulting compaction is still reduced (most compaction occurs from the first tire and subsequent tires result in little additional damage). Using large, wide tires with low inflation pressures also helps reduce potential soil compaction by distributing the equipment load over a larger soil surface area. Use of dual wheels similarly reduces compaction by increasing the footprint, although this load distribution is less effective for reducing subsoil compaction because the pressure cones from adjacent tires (see Figure 6.12) merge at shallow depths. Dual wheels are very effective at increasing traction but, again, pose a danger because of the temptation (and ability) to do fieldwork under relatively wet conditions. Duals are not recommended on tractors for performing seeding and planting operations because of the larger footprint (see also discussion on controlled traffic below).

Improved soil drainage. Fields that do not drain in a timely manner often have more severe compaction problems. Wet conditions persist in these fields, and traffic or tillage operations often are done when the soil

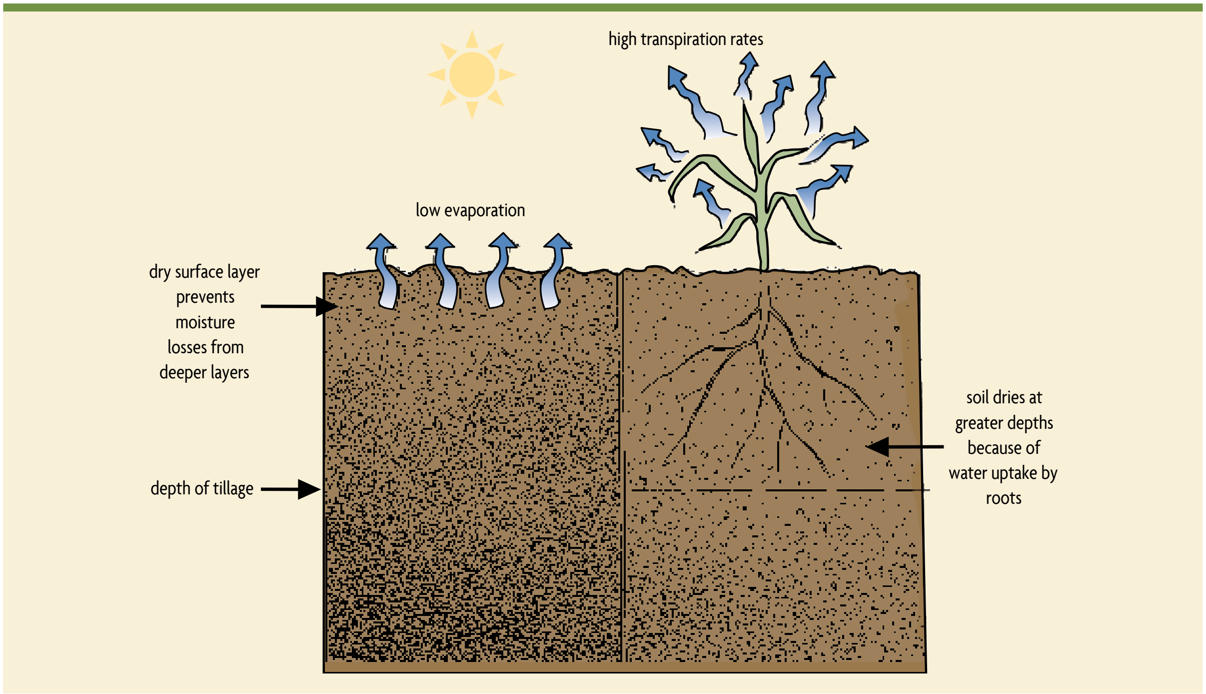

Figure 15.8. Cover crops enhance the drying of a clay soil. Without cover crops (left), evaporation losses are low after the surface dries. With cover crops (right), water is removed from deeper in the soil because of root uptake and transpiration from plant leaves, resulting in better tillage and traffic conditions.

is too wet. Sometimes, the fields are plowed when the bottom of the plow layer is still too wet, causing smearing and plow pans. Improving drainage may go a long way toward preventing and reducing compaction problems on poorly drained soils. Subsurface (tile) drainage improves timeliness of field operations, helps dry the subsoil and, thereby, reduces compaction in deeper layers. On heavy clay soils where the need for close drain spacing is very expensive, surface shaping and mole drains are effective methods. Drainage is discussed in more detail in Chapter 17.

Clay soils often pose an additional challenge with respect to drainage and compaction because they remain in the plastic state for extended periods after wet conditions. Once the upper inch of the soil surface dries out, it becomes a barrier that greatly reduces further evaporation losses. This is often referred to as *self-mulching*. This barrier keeps the underlying soil in a plastic state, preventing it from being worked or trafficked without causing excessive smearing and compaction damage. For this reason, farmers often fall-till clay soils. A better approach, however, might be to use winter cover crops to dry the soil in the spring. When a crop like cereal rye grows rapidly in the spring, the roots effectively pump water from layers below the soil surface and allow the soil to transition from the plastic to the friable state (Figure 15.8). Because these soils have high moisture-holding capacity, there is normally little concern about cover crops depleting water for the following crop.

Cover and rotation crops**.** Cover and rotation crops can significantly reduce soil compaction by creating and stabilizing large voids in the soil that allow for better water and air movement, and by supplying food for microbes. The choice of crop should be determined by the climate, cropping system, nutrient needs and the type of soil compaction. Perennial and cool-season crops commonly have active root growth early in the growing season and can reach into the compacted layers when they are still wet and relatively soft. Grasses generally have shallow, dense, fibrous root systems that have a very beneficial effect by alleviating compaction in the surface layer, but these shallow-rooting crops don't help ameliorate subsoil compaction. Crops with deep taproots, such as alfalfa, have fewer roots at the surface, but the taproots can penetrate into a compacted subsoil. Forage radish roots can penetrate deeply and form vertical "drill" holes in the soil (see Figure 10.6), as described and shown in Chapter 10. In many cases, a combination of cover crops with shallow and deep rooting systems is preferred (Figure 15.9). Ideally, such crops are part of the rotational cropping system, as is typically used on ruminant livestock farms.

Figure 15.9. A combination of deep alfalfa roots and shallow, dense grass roots helps address compaction at different depths.

The relative benefits of incorporating or mulching a cover or rotation crop are site specific. Incorporation through tillage loosens the soil, which may be beneficial if the soil has been heavily trafficked. This would be the case with a sod crop that was actively managed for forage production, sometimes with traffic under relatively wet conditions. Incorporation through tillage also encourages rapid nitrogen mineralization. Compared to plowing down a sod crop, cutting and mulching in a no-till or zone-till system reduces nutrient availability and does not loosen the soil. But a heavy protective mat at the soil surface provides some weed control and better water infiltration and retention. Some farmers have been successful with cut-and-mulch systems involving aggressive, tall cover or rotation crops, such as rye and sudangrass.

Addition of organic materials. Regular additions of animal manure, compost or sewage sludge benefit the surface soil layer onto which these materials are applied by providing a source of organic matter and glues for aggregation. The long-term benefits of applying these materials for addressing soil compaction may be very favorable, but in some cases the application procedure itself is a major cause of compaction. Livestock-based farms in humid regions often apply manure using heavy spreaders (sometimes with poor load distribution) on wet or marginally dry soils, which results in severe compaction of both the surface layer and the subsoil. In general, the addition of organic materials should be done with care to obtain the biological and chemical benefits while not aggravating compaction problems.

Controlled traffic and permanent beds. One of the most promising practices for reducing soil compaction is the use of controlled traffic lanes, in which all field operations are limited to the same lanes, thereby preventing compaction in all other areas. The primary benefit of controlled traffic is the lack of compaction for most of the field at the expense of narrow lanes that receive all the compaction. Because the degree of

Figure 15.10. A tractor with wide wheel spacing to fit a controlled traffic system.

soil compaction doesn't necessarily worsen with each equipment pass (most of the compaction occurs with the heaviest loading and does not greatly increase beyond it), damage in the traffic lanes is not much more severe than that occurring on the whole field in a system with uncontrolled traffic. Controlled traffic lanes may actually have an advantage in that the consolidated (firmer) soil better facilitates field traffic. Compaction also can be reduced significantly by guiding traffic of farm trucks along the field boundaries and by using planned access roads, rather than allowing them to randomly travel over the field.

Controlled traffic systems require adjustment of field equipment to ensure that all wheels travel in the same lanes, and they require discipline from equipment operators. For example, planter and combine widths need to be compatible (although not necessarily the same), and wheel spacing may need to be expanded (Figure 15.10). A controlled traffic system is most easily adopted with row crops in zone, strip or no-till systems (not requiring full-field tillage; see Chapter 16) because crop rows and traffic lanes remain recognizable year after year.

Adoption of controlled traffic has expanded in recent years with the availability of RTK (real-time kinematic) satellite navigation systems and auto-steer technology. With these advanced guidance systems, a single reference station on the farm provides the real-time corrections to high levels of accuracy, facilitating precision steering of field equipment. Controlled traffic lanes can therefore be laid out with unprecedented accuracy, and water (for example, drip irrigation) and nutrients can be applied at precise distances from the crop (Figure 15.11).

Ridge tillage dictates controlled traffic, as wheels

Figure 15.11. Controlled traffic farming with precision satellite navigation. Left: twenty-row corn-soybean strips with traffic lanes between the sixth and seventh row from the strip edge (Iowa; note that corn is still standing while soybean crop has been harvested). Right: Zucchini on mulched raised beds (Queensland, Australia).

should not cross the ridges. A permanent (raised) bed system is a variation on controlling traffic in which soil shaping is additionally applied to improve the physical conditions in the beds (Figure 15.11, right). Beds do not receive traffic after they've been formed. This system is especially attractive where traffic on wet soil is difficult to avoid (for example, with certain fresh-market vegetable crops, or rice production) and where it is useful to install equipment, such as irrigation lines, for multiple years.

SUMMARY

Compaction frequently goes unrecognized, but it can result in decreased crop yields or can negatively affect greenery. There are a number of ways to avoid the development of compacted soil, the most important of which is keeping equipment off wet soil. Draining wet soils and using controlled traffic lanes and permanent beds are ways to avoid compaction. Also, reduced tillage and organic matter additions make the surface less susceptible to the breakdown of aggregates and to crust formation, as does maintaining a surface mulch and routinely using cover crops. Reducing compaction once it occurs involves using cover crops that are able to break into subsurface compact layers and using equipment such as subsoilers and zone builders to break up compact subsoil.

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Chapter 16

MINIMIZING TILLAGE

... the crying need is for a soil surface similar to that which we find in nature ...
[and] the way to attain it is to use an implement that is incapable of burying the trash it encounters;
in other words, any implement except the plow.

—E.H. FAULKNER, 1943

Although tillage is an ancient practice, the question of which tillage system is most appropriate for any particular field or farm is still difficult to answer. But we know that soil disturbance is generally bad for long-term soil health. Before we discuss different tillage systems, let's consider why people started tilling ground in the first place. If we know that tillage is damaging to soils, why has it been so widely practiced?

Tillage was first done by farmers who grew small-grain crops, such as wheat, rye and barley, primarily in western Asia (the Fertile Crescent), Europe and northern Africa. The primary reason was to create a fine, clean seedbed, thereby greatly improving germination over broadcasting seed on untilled ground. It also gave the crop a head start against a new flush of weeds and stimulated mineralization of organic nutrients to forms that plants could use. In the early days of agriculture soil was loosened by a simple *ard* (scratch plow) in several directions. The loosened soil also tended to provide a more favorable rooting environment, facilitating seedling survival and plant growth. Animal traction (oxen, horses, etc.) was generally employed to accomplish this arduous task because the power and energy requirements for tilling entire fields are generally beyond human capabilities.

At the end of the growing season, the entire crop was harvested because the straw also had considerable economic value for animal bedding, roofing thatch, brick making and fuel. Sometimes, fields were burned after crop harvest to remove remaining crop residues and to control pests. Although this cropping system lasted for many centuries, it resulted in excessive erosion, organic matter loss and nutrient depletion, especially in the Mediterranean region, where it caused extensive soil degradation. Eventually deserts spread as the climate became drier.

Conversely, ancient agricultural systems in the Americas did not have oxen or horses to perform the arduous tillage work. So, interestingly, in the context of current interests in reduced tillage, Pre-Columbian

JETHRO TULL AND TILLAGE: A MIXED LEGACY AND AN IMPORTANT LESSON

Jethro Tull (1674–1741) was an early English agricultural experimentalist whose book *The New Horse Hoeing Husbandry: An Essay on the Principles of Tillage and Vegetation* was published in 1731. It was the first textbook on the subject and set the standard for soil and crop management for the next century. (It is now available online as part of core historical digital archives; see "Sources" at the end of the chapter). In a way, Tull's publication was a predecessor to this book, as it discussed manure, rotations, roots, weed control, legumes, tillage, ridges and seeding.

Tull noticed that traditional broadcast sowing methods for cereal crops provided low germination rates and made weed control difficult. He designed a drill with a rotating grooved cylinder (now referred to as a coulter) that directed seeds to a furrow and subsequently covered them to provide good seed-soil contact. Such row seeding also allowed for mechanical cultivation of weeds, hence the title of the book. This was a historically significant invention, as seed drills and planters are now key components of conservation agriculture and building soils. But the concept of growing crops in rows is attributed to the Chinese, who used it as early as the 6th century B.C.E.

Tull believed that intensive tillage was needed not only for good seed-soil contact but also for plant nutrition, which he believed was provided by small soil particles. He grew wheat for 13 consecutive years without adding manure; he basically accomplished this by mining the soil of nutrients that were released from repeated soil pulverization. He therefore promoted intensive tillage, which we now know has long-term negative consequences. Perhaps this was an important lesson for farmers and agronomists: Practices that may appear beneficial in the short term may turn out detrimental over long time periods.

American farmers did not use full-field tillage for crop production. They instead used mostly direct seeding with planting sticks (Figure 16.1), or manual hoes that created small mounds ("hills"). These practices were well adapted to the staple crops of corn, beans and squash, which have large seeds and require lower plant densities than the cereal crops of the Old World. In temperate or wet regions the hills were elevated to provide a temperature and moisture advantage to the crop. In contrast with the cereal-based systems (wheat, rye, barley, rice) of growing only one crop in a monoculture, these fields often included the intercropping of two or three plant species growing at the same time, like the corn, beans and squash ("Three Sisters") system in North America. Therefore, early American farmers were early adopters of both no-till and intercropping while the European invaders brought "improved" technologies that damaged the land in the long run (Figure 16.1).

TECHNOLOGIES THAT HAVE LESSENED THE NEED FOR TILLAGE

- herbicides
- new tillage tools that provide targeted decompaction within the crop row
- new planters and transplanters
- new methods for cover crop management

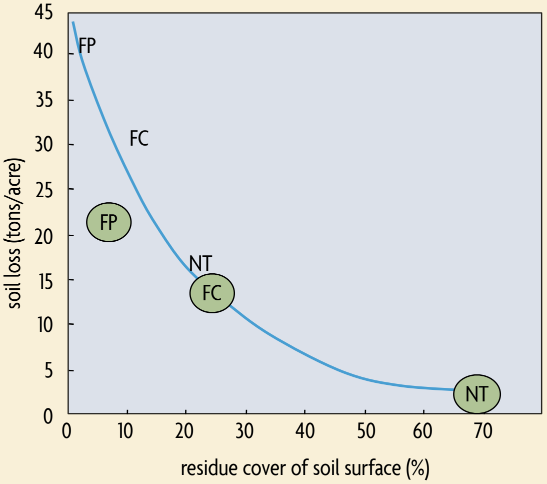
A third ancient tillage system was practiced as part of the rice-growing cultures in southern and eastern Asia. There, paddies were tilled to control weeds and

Figure 16.1. Artist rendering of Pre-Columbian American farmers using a planting stick (left) and plowing after the European invasion (right). Painting by Diego Rivera, Palacio Nacional, Mexico City.

puddle the soil to create a dense layer that limited downward losses of water through the soil. The puddling process occurs when the soil is worked while wet—in the plastic or liquid consistency state (see Chapter 6)—and is specifically aimed at destroying soil aggregates. This system was designed to benefit rice plants, which thrive under flooded conditions, especially relative to competing weeds. There is little soil erosion because paddy rice must be grown either on flat or terraced lands, and runoff is controlled as part of the process of growing the crop. Recent research efforts have focused on less puddling and ponding to conserve soil health and water.

Full-field tillage systems became more widespread because they are adapted to mechanized agriculture, and over time traditional hill crops like corn and beans became row crops. The moldboard plow was invented by the Chinese 2,500 years ago but was redesigned into a more effective tool in England in the 1700s and improved for American land development by blacksmith John Deere. It provided better weed control by fully turning under crop residues, growing weeds and weed seeds. Its benefits were compelling at first: it allowed for a more stable food supply and also facilitated the breaking of virgin lands. The development of increasingly powerful tractors made tillage an easier task (some say a recreational activity) and resulted in more intensive soil disturbance, ultimately contributing to the degradation of soils. The exposed plowed fields were more susceptible to erosion, higher organic matter decomposition, and reduction in the soil reservoir of nutrients and carbon that are critical to soil health.

Increased tillage and erosion have degraded many agricultural soils to such an extent that people think tillage is required to provide temporary relief from compaction. As aggregates are destroyed, crusting and compaction create a soil “addicted” to tillage. But new technologies have lessened the need for tillage. The development of herbicides reduced the need for soil plowing as a weed control method. Cover crops help to suppress weed growth, as do rotations that alternate annual and perennial crops. And new planters achieve better seed placement, even in a suppressed cover crop, without preparing a seedbed beforehand. Amendments, such as fertilizers and liquid manures, can be directly



This figure shows that:
- surface residue reduces erosion,
- reduced tillage (chisel and no-till) leaves more residue and results in less erosion than plowing, and
- corn (circled) returns more residue than soybeans.

Figure 16.2. Soil erosion dramatically decreases with increasing surface cover. *Note*: FP = fall plow, FC = fall chisel, NT = no-till; circles = corn, no circles = soybeans. Modified from *Manuring* (1979).

injected or band-applied. Now there are even vegetable transplanters that provide good soil-root contact in no-till systems. Except perhaps for most organic production systems, in which tillage is often needed because herbicides aren't used, a crop produced with limited or no tillage can generate better economic returns than one produced with conventional tillage systems.

TILLAGE SYSTEMS

Tillage systems can be classified by the amount of surface residue left on the soil surface. ***Conservation tillage*** systems leave more than 30% of the soil surface covered with crop residue. This amount of surface residue cover is considered to be at a level where erosion is reduced by more than half (see Figure 16.2). Of course, this residue cover partially depends on the amount and quality of residue left after harvest, which may vary greatly among crops and harvest method (corn harvested for grain versus silage is one example). Although residue cover greatly influences erosion potential, it also is affected by factors such as surface roughness and soil loosening.

Each pass of a tillage tool incorporates some residue and thereby reduces the amount of residue on the surface that helps reduce runoff and erosion. Table 16.2 shows estimates of the percent residue that remains on the soil surface after different tillage passes. In cases where one pass is followed by another, the remaining residue cover can be estimated by multiplication. For example, starting with 80% residue cover after a grain corn crop harvest and over-wintering, the sequence of 1) a chisel with straight points, 2) a tandem disk, 3) a field cultivator and 4) a row crop planter is expected to leave 0.8 (80%) x 0.7 (70%) x 0.45 (45%) x .75 (75%) = 0.19, or an estimated 19% of residue remaining on the surface, thereby not qualifying as conservation tillage. By eliminating the tandem disk and keeping the soil slightly rougher, the residue level will be 42%.

Another distinction of tillage systems is whether they are full-width systems or restricted-width systems. The former disturbs the soil across the entire field, while restricted tillage limits various degrees of soil loosening to narrow zones in the crop row. The benefits and

Figure 16.3. Conservation tillage leaves 30% or more residue on the surface. Photo courtesy of USDA-NRCS.

Table 16.1
Tillage System Benefits and Limitations

Tillage System	Agronomic Benefits	Agronomic Limitations	Economics and Environment
Full-Width Tillage			
Moldboard plow	Allows easy incorporation of fertilizers and amendments Buries surface weed seeds Allows soil to dry out fast Temporarily reduces compaction Leaves soil bare and easy for seeding	Destroys natural aggregation and enhances organic matter loss Commonly leads to surface crusting and accelerated erosion Causes compacted "plow pans" Requires secondary tillage	Highest cost for labor and fuel High energy consumption High equipment wear High off-site impacts for water quality and quantity, and carbon dioxide emissions
Chisel plow	Same as above, but leaves some surface residues Flexible tillage depth and residue retention	Same as above, but less aggressively destroys soil structure; leads to less erosion, less crusting, no plow pans	Lower energy use, costs and environmental impacts than moldboard plowing, but more than restricted tillage practices
Disk harrow	Same as above, but with repeated passes has limited benefits over plowing	Same as above, but restricted pan layer may develop at depth of harrowing.	Same as above
Restricted Tillage			
No-till	Leaves little soil disturbance Requires few trips over field Provides the most surface residue cover and runoff/ erosion protection Higher yields after initial conversion period	Makes it more difficult to incorporate fertilizers and amendments without specialized equipment Requires specialized planters to deal with firm soil and residues Wet soils dry and warm up slowly in spring Can't alleviate compaction except through cover cropping Steep learning curve for adopters, especially with fine-textured soils Possible yield reductions in early years after conversion	Low energy use Labor savings More economical than full-width tillage systems in long run Carbon capture and nutrient buildup stimulated Promotes soil biological activity Conserves water Low off-site impacts for water quality and quantity, although concerns may exist with higher preferential flow of nutrients and pesticides to tile lines
Strip-till (zone-till)	Same as above Generally good alternative to no-till on compacted and fine-textured soils Allows for deeper fertilizer placement Flexible depth of soil loosening	Same as above, but compaction is alleviated in the seed zone, allowing for better rooting and seed germination	Same as above, but somewhat higher cost and energy use compared to no-till
Ridge-till and bedding	Allows easy incorporation of fertilizers and amendments Provides some weed control as ridges are built Allows seed zone on ridge/bed to dry and warm more quickly Reduces soil saturation after excessive rainfall Fixed travel lanes reduce overall compaction	Is hard to use with sod-type or narrow-row crop in rotation Requires fixed travel lanes and wheel spacing to be adjusted to travel between ridges	Cost and energy use vary depending on intensity level of ridging and bedding Environmental impacts generally between plowing and no-till

Table 16.2
Estimated Crop Residue Levels Remaining After Field Operations[1]

Field Operation	After Corn or Cereals	After Soybeans
After harvest	90–95%	60–80%
Over-winter decomposition	80–95%	70–80%
Moldboard plow	0–10%	0–5%
Chisel (twisted points)	50–70%	30–40%
Chisel (straight points)	60–80%	40–60%
Disk plow	40–70%	25–40%
Disk, tandem-finishing	30–60%	20–40%
Field cultivator	60–90%	35–75%
Row-crop planter	85–95%	60–70%

[1] Speed, depth and soil moisture can affect the amounts.
Source: USDA-NRCS

limitations of various tillage systems are compared in Table 16.1.

Conventional Tillage

A full-width system manages the soil uniformly across the entire field surface. Such tillage systems typically involve a primary pass with a heavy tillage tool to loosen the soil and incorporate materials at the surface (fertilizers, amendments, weeds, etc.), followed by one or more secondary passes to create a suitable seedbed. Primary tillage tools are generally moldboard plows (Figure 16.4, left), chisels (Figure 16.4, right) and heavy disks (Figure 16.5, left), while secondary tillage is accomplished with finishing disks (Figure 16.5, right), tine or tooth harrows, field cultivators, roller-packers, etc. These tillage systems create a uniform and often finely aggregated seedbed over the entire surface of the field and thereby good conditions for seed germination and crop establishment. Before farming was mechanized, farmers would use broadcast seed applications by throwing seeds out by hand followed by harrowing, but this task is now accomplished with mechanical planters. If a good seedbed is prepared the planter does not require special attachments to deal with surface residues or firm soil.

But moldboard plowing is also energy intensive, leaves very little residue on the surface, tends to result in high organic matter (carbon) losses and requires secondary tillage passes (Table 16.1). It also tends to create dense pans below the depth of plowing (typically 6–8 inches deep). However, moldboard plowing has traditionally been a reliable practice and almost always results in reasonable crop growth. Chisel implements provide similar results but require less energy, allow for faster speeds and leave more residue on the surface.

Figure 16.4. Left: Moldboard plowing inverts the soil and leaves no surface protection. Right: Chisel plow shanks loosen soil and leave some residue cover.

Figure 16.5. Left: A heavy disk (disk plow) can be used for primary and secondary tillage. Photo by Mark Brooks. Right: A finishing disk.

Chisels also allow for more flexibility in the depth of tillage, generally from 5 to 12 inches, with some tools specifically designed to go deeper, which may be useful for breaking up compacted layers.

Disk plows come in a heavy version, as a primary tillage tool that usually goes 6–8 inches deep, or in a lighter version that performs shallower tillage and leaves residue on the surface (Figure 16.5). Disks also create concerns with developing tillage pans at their bottoms. They are sometimes used as both primary and secondary tillage tools through repeated passes that increasingly pulverize the soil. This limits the upfront investment in tillage tools, but it is not sustainable in the long run because it does a lot of soil disturbance.

Full-width tillage systems clearly have disadvantages, but they can help overcome certain problems such as surface compaction (temporarily at least, but they create more compaction over time), high weed pressures and the challenges of terminating a previous crop or cover crop. Although no-till options exist for some organic crop sequences, organic farmers often use moldboard plowing as a necessity to provide adequate weed control (a big challenge without herbicides) and to facilitate nitrogen release from incorporated legumes. Livestock-based farms often use a plow to incorporate manure and to help make rotation transitions from sod crops to row crops.

Besides incorporating surface residue, plowing with intensive secondary tillage crushes the natural soil aggregates and promotes decomposition of organic matter that had been protected inside but is now accessible to soil organisms. Some conservationists say that inverting the soil by moldboard plowing is very unnatural. Soil in its natural state is never turned over, inverting and burying surface plant residues. (Earthworms and other critters do that without inverting the entire soil.) The pulverized soil after plowing also does not take heavy rainfall well. The lack of surface residue causes sealing at the surface, which generates runoff and erosion and creates hard crusts after drying. Intensively tilled soil will also settle after moderate to heavy rainfall and may “hardset” upon drying, thereby restricting root growth.

Reducing secondary tillage also helps decrease negative aspects of full-width tillage. Compacted soils tend to till up cloddy, and intensive harrowing and packing are then seen as necessary to create a good seedbed. This additional tillage creates a vicious cycle of further soil degradation and intensive tillage. Secondary tillage often can be reduced with the use of modern conservation planters, which create a finely aggregated

Figure 16.6. Powered tillage tools used with horticultural crops: Left: rotary tiller; Right: A spader.

zone around the seed without requiring the entire soil to be pulverized. A good planter is perhaps the most important tillage tool because it helps overcome rough seedbeds without destroying surface aggregates over the entire field. A fringe benefit of reduced secondary tillage is that rougher soil often has higher water infiltration rates and reduces problems with settling and hardsetting after rains.

Vertical tillage is a concept that incorporates a range of tillage tools that do not move the soil from side to side but mostly move it vertically with limited compaction. This generally includes tools with large rippled or wavy coulters, and blades that are aligned with the direction of travel and cut into crop residue or push it into the soil. Sometimes they are combined with a field cultivator, light chisel-type tools, finishing tines or rolling baskets to level the ground. They may also be used with fertilizer applicators.

In more intensive horticultural systems, powered tillage tools are often used, which are actively rotated by the tractor power takeoff system (Figure 16.6). Rotary tillers (rotovators, rototillers) do very intensive soil mixing and create fine uniform tilth that is advantageous when establishing horticultural crops that are small seeded or sensitive to compaction. But it is quite damaging to soil in the long term, which can only be sustainable if the soil also regularly receives organic materials like cover crop residue, compost or manure. A spader is also an actively rotated tillage tool, but the small spades, similar to the garden tools, handle soil more gently and leave more residue or organic additions at the surface than a rototiller.

Restricted Tillage Systems

These systems are based on the idea that tillage can be limited to the zone immediately adjacent to the crop and does not have to disturb the entire area between crop rows. Several tillage systems—no-till, strip-till (similar to zone-till) and ridge-till—fit this concept.

No-till system. The no-till system was developed on the concept that soil disturbance is not needed as long as good seed placement and weed control can be achieved. The planter only loosens the soil in a very narrow and shallow zone immediately around the seed. This highly localized disturbance is typically accomplished with a no-till planter (for row crops; Figure 16.7) or seed drill (for crops seeded in narrow rows; Figure 16.8). This system represents the most extreme change from conventional tillage and is most effective in preventing soil erosion and building both organic matter and overall soil health.

Figure 16.7. A modern row-crop planter for conservation tillage systems. Coulters in front and closing wheels in the back allow for seed placement without soil preparation; equipment positioning is controlled by a GPS system; seed depth is controlled by hydraulics; seed is delivered by vacuum; and seed placement is digitally monitored. Photo by Larissa Smith.

No-till systems have been used successfully on many soils in different climates. The surface residue protects against water and wind erosion (Figure 14.3) and increases biological activity by protecting the soil from temperature and heat extremes. Surface residues also reduce water evaporation, which, combined with deeper rooting, lowers the susceptibility to drought. This tillage system is especially well adapted to coarse-textured soils (sands and gravels) and to well-drained soils, as these tend to be softer and less susceptible to compaction. No-till systems sometimes experience lower crop yields than conventional tillage systems in the early transition years but tend to outperform them after the soil ecosystem has adapted. Reasons for this are the lower availability of N in the early years of no-till, cooler soil conditions and the compaction that needs to be overcome through natural biological processes like earthworm activity and cover cropping. Knowing this allows you to compensate by adding increased N (legumes, manures, fertilizers) during the transition years.

The transition can be challenging because a radical move from conventional to no-till is a big shock to a soil system that has been routinely loosened. It can especially create challenges if the soil was previously degraded and compacted. It is then best to first build the soil with organic matter, cover crops and strip-till (zone-till) methods as described in the next sections. In the absence of tillage, seed placement, compaction prevention and weed control become more critical. No-till planters and drills (figures 16.7 and 16.8) are advanced pieces of engineering that need to be adaptable to different soil conditions yet also be able to place a seed

Figure 16.8. Left: A no-till seed drill requires no-till or seedbed preparation for narrow-seeded crops or cover crops. Right: The cross-slot opener used in no-till planters. The disk slices soil, the inverted T blade allows seed and fertilizer placement on opposite ends of the disk, and the packer wheels (right side) close and firm the seedbed.

Table 16.3
The Effect of 32 Years of Plow and No-Till Under Corn Production on Selected Soil Health Indicators in a New York Experiment

	Plow	No-till
Physical		
Aggregate stability (%)	22	50
*Bulk density (g/cm^3)	1.39	1.32
*Penetration resistance (psi)	140	156
Permeability (mm/hr)	2.1	2.4
Plant-available water capacity (%)	29.1	35.7
Infiltration capacity (mm/hr)	1.58	1.63
Chemical		
Early season nitrate-N (lbs/ac)	13	20
Phosphorus (lbs/ac)	20	21
Potassium (lbs/ac)	88	95
Magnesium (lbs/ac)	310	414
Calcium (lbs/ac)	7,172	7,152
*pH	8	7.8
Biological		
Organic matter (%)	4	5.4
Cellulose decomposition rate (%/week)	3	8.9
Potentially mineralizable nitrogen (µg/g/week)	1.5	1.7
Total protein (mg/g soil)	4.3	6.6

Note: Higher values indicate better health, except for those listed with an asterisk, for which lower values are better.
Source: Moebius et al. (2008)

precisely at a specified depth. This technology has come a long way since Jethro Tull's early seeders.

The quality of no-tilled soil improves over time, as seen in Table 16.3, which compares physical, chemical and biological soil health indicators after 32 years of plow and no-till in a New York experiment. The beneficial effects of no-till are quite consistent for physical indicators, especially with aggregate stability. Biological indicators are similarly more favorable for no-till, and organic matter content is 35% higher than with plow tillage. The effects are less apparent for chemical properties, except the pH is slightly more favorable for no-till, and the early season nitrate concentration is 50% higher. Other experiments have also demonstrated that long-term reduced tillage increases nitrogen availability from organic matter, which may result in significant fertilizer savings.

Strip (zone) and ridge tillage. These tillage systems are adapted to row crops. Their approach is to disturb the soil in a narrow strip along the plant row and leave most of the soil surface undisturbed. Strip-till involves the use of shanks and coulters (Figure 16.8) that create a loosened band that extends 6–16 inches into the subsoil. Lower depths may be appropriate in the first years after conversion from conventional tillage to promote deeper root growth and water movement. Strips at shallower depths can be used after soil health has been improved, saving energy. Strip-till is often followed by a row crop planter with coulters mounted on the front that can handle a range of soil tilth conditions (Figure 16.7). Strip-till provides soil quality

BEFORE CONVERTING TO NO-TILL

An Ohio farmer asked one of the authors of this book what could be done about a compacted field with low organic matter and low fertility that had been converted to no-till a few years before. Clearly, the soil's organic matter and nutrient levels should have been increased and the compaction alleviated before the change. Once you're committed to no-till, you've lost the opportunity to easily and rapidly change the soil's fertility or physical properties (aside from growing cover crops that can lessen compaction). The recommendation is the same as for someone establishing a perennial crop like an orchard or vineyard. Build up the soil and remedy compaction problems before converting to no-till. It's going to be much harder to do so later on.

Figure 16.9. Left: A strip-till tool with hilling disks and rolling basket to create a zone of loosened soil. Photo by Robert Schindelbeck. Right: Strip-till after corn harvest results in a narrow tilled zone that leaves much of the soil surface undisturbed. Photo by Georgi Mitev.

improvements similar to those of no-till, but it is more energy intensive. It is generally preferred over strict no-till systems on soils that have compaction problems (for example, fields that receive liquid manure or where crops are harvested when the soils are wet), have imperfect drainage, or are in humid, cool climates. In those situations the removal of residue, slight raising of strips, and soil loosening in the row are desirable for soil drying, warm-up and rooting. In temperate climates, strip-till and zone building are often performed in the fall before spring row crop planting to allow for soil settling. Some farmers inject fertilizers with the tillage operations, thereby reducing the number of passes on the field.

Zone tillage uses the same approach as strip-till: restricting soil loosening to a narrow zone along the crop row. It uses a narrow shank to slit-loosen the soil (Figure 15.5, right) and relies on fluted coulters on the planter to create a residue-free strip. The end result is similar to strip-till.

Ridge tillage combines limited tillage with a ridging operation and requires controlled traffic. This system is particularly attractive for cold and wet soils because the ridges offer seedlings a warmer and better drained environment. The minimal drainage derived from the slightly elevated ridge (often only a few inches) can be beneficial to get seedlings through a very wet period in the early season. The ridging operation can be combined with mechanical weed control and allows for band application of herbicides. This decreases the cost of chemical weed control, allowing for about a two-thirds reduction in herbicide use.

In vegetable systems, raised beds—basically wide ridges that also provide better drainage and warmer temperatures—are often used. Potatoes, for example, require hilling of the ridges to encourage new tubers and to keep them covered. In parts of Africa, contour ridges are popular as a soil conservation practice.

Tillage and cover crops. Combining reduced tillage and cover cropping provides great benefits for soil health. It also offers opportunities for organic crop production where weed suppression is generally a large challenge and the reason for using a plow. Researchers at the Rodale Institute in Pennsylvania have developed innovative cover crop management equipment that facilitates growing row crops in a no-till system. An annual or winter annual cover crop is rolled down with a specially designed heavy roller-crimper, resulting in a weed-suppressing mulch mat through which it is possible to plant or drill seeds (Figure 16.10, left) or to

Figure 16.10. It is possible to plant seeds or transplants through a cover crop mat. Left: A row crop is being planted immediately behind rye that has been flattened by the roller-crimper. Photo by Jeff Mitchell. Right: Planting green into a crimson clover cover crop. Photo by Heidi Kaye.

set transplants. For this system to work best, sufficient time must be allowed for the cover crop to grow large before rolling-crimping so that the mulch can do a good job of suppressing weeds. Cover crops must have gone through the early stages of reproduction in order for the roller-crimper to kill them but must not be fully matured to avoid viable seeds that could become weeds in the following crop.

A similar approach can be used with a wider variety of cover crop mixes, or even previous perennial rotation crops in non-organic systems. *Planting green* is a concept where a row crop is no-till planted into an actively growing cover crop (Figure 16.10, right). This allows the benefits of the cover crop to be maximized by extending its growing period rather than killing it 2–3 weeks ahead of planting, which is especially beneficial in cool climates. Planting green is still a relatively new practice but can provide good benefits with adequate attention to cover crop termination and planter equipment details.

WHICH TILLAGE SYSTEM IS RIGHT FOR YOUR FARM?

The correct choice of tillage system depends on climate, soils, cropping systems and the farm's production objectives. Although plowing may still be appropriate in some cases, one should strive to minimize tillage intensity and the number of passes, and to leave plentiful amounts of residue on the surface. One factor that is often not recognized: a good conservation planter (figures 16.7 and 16.8) may be your best tillage tool. It doesn't require the preparation of a smooth seedbed, can handle a lot of residue and allows you to reduce or eliminate tillage passes. Some general guidelines for tillage selection are as follows.

Conventional grain and vegetable farms have great flexibility for adopting reduced tillage systems because they are less constrained by repeated manure applications (needed on livestock farms) or by mechanical weed or rotation crop management (needed on organic farms). In the long run, limited disturbance and residue cover improve soil health, reduce erosion and boost yields. The transition period is critical, as discussed above, including possible compaction and nitrogen availability issues as well as changes in the weed spectrum from annual to perennial plants. This may require different timing and methods of weed control. Combining reduced tillage with the use of cover crops frequently helps reduce weed problems. Weed pressures typically decrease after a few years, especially if perennials are under control, because buried weed seeds are no longer tilled up. Mulched cover crops, as well as newly designed mechanical cultivators, help provide effective weed control in high-residue systems.

Farmers need to be aware of potential soil compaction problems with reduced tillage. If a strict no-till system is adopted on a compacted soil, especially on medium- or fine-textured soils, yield reductions may occur in the first years. As discussed in Chapter 6, dense soils have a relatively narrow water range in which plant roots can grow well, compared to uncompacted soil. When it is dry, roots have a more difficult time making their way through the soil, and when it is wet, roots tend to have less air. Compaction, therefore, makes crops weaker and more susceptible to pest pressures. In highly weathered tropical soils in Brazil (oxisols), new concerns have arisen with compacted layers developing in no-till soils that are limed to correct the high acidity. The change in soil pH causes dispersion of clay in natural aggregates, washing into a lower soil layer that becomes dense and impenetrable for roots.

Tools like strip tillers provide compaction relief in the row while maintaining an undisturbed soil surface. They are generally the best approaches for farmers who plowed for many years and want to reduce tillage intensity without the challenges of transitioning to pure no-till. Over time, soil structure improves, unless re-compaction occurs from other field operations. Crops grown on fields that do not drain in a timely manner tend to benefit greatly from ridging or bedding because the sensitive seedling root zone remains aerobic during wet periods. These systems also use controlled traffic lanes, which greatly reduce compaction problems, although matching wheel spacing and tire widths for planting and harvesting equipment is sometimes a challenging task, as we discussed in Chapter 15.

The two greatest challenges for organic farms are weeds and nitrogen. As with traditional farms before agrichemicals were available, reduced tillage is challenging and full-width tillage may be necessary for weed control and incorporation of manures and composts. Organic farming on lands prone to erosion may, therefore, involve trade-offs. Erosion can be reduced by using rotations with perennial crops, gentler tillage methods like spaders (Figure 16.6, right) and ridgers, and modern planters that establish good crop stands without excessive secondary tillage. Soil structure may be easier to maintain on organic farms because they heavily rely on organic inputs to maintain fertility.

Livestock-based farms face special challenges related to applying manure or compost to the soil. Some type of incorporation usually is needed to avoid large losses of

FROST TILLAGE!

Readers from temperate regions may have heard of frost-seeding legumes into a pasture, hayfield or winter wheat crop in very early spring, but perhaps not of tilling frozen soil. It seems a strange concept, but some farmers are using frost tillage as a way to be timely and reduce unintended tillage damage. It can be done after frost has entered the soil but before it has penetrated more than about 2 inches (5 centimeters). Water moves upward to the freezing front and the soil underneath dries. This frozen state makes the soil tillable as long as the frost layer is not too thick. Compaction is reduced because equipment is supported by the frozen layer. The resulting rough surface is favorable for water infiltration and runoff prevention. Some livestock farmers like frost tillage as a way to incorporate or inject manure in the winter without concerns about compaction from heavy equipment (see also Figure 12.2).

nitrogen by volatilization or losses of phosphorus and pathogens in runoff. Transitions from sod to row crops are also usually easier with some tillage. Such farms can still use manure injection tools with strip-till, thereby providing compaction relief while minimizing soil disturbance. As with organic farms, livestock operations apply a lot of manure and compost, and naturally have higher soil health.

Rotating Tillage Systems

A tillage program does not need to be rigid. Fields that are no-tilled may occasionally need a full-field tillage pass. Recent research in Nebraska and Australia indicates that *occasional* tillage, also called *strategic* tillage, does not have negative impacts on soil health. But it should only be done for a well-identified purpose like weed or insect control, incorporation of immobile amendments, or compaction relief (say, after a harvest during a wet period).

Tillage is one of the few practices that can decrease populations of the arthropod *Symphylans*. This pest feeds on root hairs and small roots of many crop plants, and uses large pores and channels to move through the soil (see box in Chapter 8). In some cases it can be controlled by making a fine seedbed, which is something we otherwise discourage because of its detrimental effects on soil crusting and water infiltration. So if strategic tillage is used, it should be done on a very limited basis (once every 5–10 years) and is best accomplished with tools that still leave surface residue. A flexible tillage program may offer benefits, but be aware that any tillage can readily destroy the favorable soil structure built up by years of no-till management.

Timing of Field Operations

The success of a tillage system depends on many factors. For example, reduced tillage systems, especially in the early transition years, may require more attention to nitrogen management (often higher rates are needed initially, lower rates eventually), as well as to weed, insect and disease control. Also, the performance of tillage systems may be affected by the timing of field operations. If tillage or planting is done when the soil is too wet (when its water content is above the plastic limit), cloddiness and poor seed placement may result in poor stands. Also, a strip-till or zone building operation done in plastic soil results in smeared surfaces and an open slot that does not allow for good seed-soil contact. A "ball test" (Chapter 6) helps ensure that field conditions are right and is especially important when performing deeper tillage. A no-till system has the great advantage of saving time because there is no need for prior tillage passes before planting. However, in cool, humid climates the high residue levels and lack of soil loosening slows soil drying and warming, and may require a short delay in planting.

Tillage is also not recommended when the soil is very dry because it may be too hard, clods may be very large or excess dust may be created, especially on compacted soils. Ideal tillage conditions generally occur when soils are at field-capacity water content (after a few days of free drainage and evaporation, except for fine-textured clays, which need more drying; see Chapter 15).

Because soil compaction may affect the success of reduced tillage, a whole-system approach to soil management is needed. For example, no-till systems that involve harvesting operations with heavy equipment succeed better if traffic can be restricted to dry conditions or to fixed lanes within the field. Even strip-till methods will work better if fixed lanes are used for heavy harvest equipment.

SUMMARY

We have learned that tillage can be very damaging to soil health. Reducing the intensity of tillage can help improve it in many ways. It is especially critical to building organic matter and soil health on fields that don't receive regular manure or compost additions.

Maintaining more residue on the surface reduces runoff and erosion, while the reduction in soil disturbance allows for earthworm holes and old root channels to rapidly conduct water from intense rainstorms into the soil. Also, reduced tillage in the long run increases soil organic matter levels and helps sequester carbon. There are many choices of reduced tillage systems, and a lot of innovative equipment is available to help farmers succeed. Using cover crops along with no-till or reduced tillage has been found to be a winning combination, as it provides surface cover rapidly and helps to control weeds.

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a case study

STEVE GROFF
LANCASTER COUNTY, PENNSYLVANIA

Steve Groff raises vegetables, grains and cover crop seeds on his 215-acre farm in Lancaster County, Pennsylvania, but his soil shows none of the degradation that can occur with intensive cropping. Mixing cash crops such as corn, pumpkins, squash and tomatoes with cover crops in a unique no-till system, Groff's farm has been untouched by the plow since 1995, with some portions having been no-tilled since 1982.

"No-till is a practical answer to concerns about erosion, soil quality and soil health," says Groff, who won a national no-till award in 1999. "I want to leave the soil in better condition than I found it."

Groff confronted a rolling landscape pocked by gullies when he began farming with his father after graduating from high school. They regularly used herbicides and insecticides, tilled annually or semiannually, and rarely used cover crops. Like other farmers in Lancaster County, they ignored the effects of tillage on a sloped landscape, which causes an average of 9 tons of soil per acre to wash into the Chesapeake Bay every year.

Tired of watching 2-foot-deep ditches form on the hillsides after every heavy rain, Groff began experimenting with no-till to protect and improve the soil. "We used to have to fill in ditches to get machinery in to harvest," Groff says. "I didn't think that was right."

Groff stresses, however, that switching to no-till alone isn't enough. He has created a new system, reliant on cover crops, rotations, diversity and no-till, to improve the soil. He's convinced such methods contribute to better yields of healthy crops, especially during weather extremes.

When the Pennsylvania chapter of the Soil and Water Conservation Society bought a no-till transplanter that could plant vegetable seedlings into slots cut into cover crop residue, Groff was the first farmer to try it, which led him to pioneer what he likes to call the "Permanent Cover" cropping system. The slots are just big enough for the young plants and do not disturb the soil on either side. The result: Groff can prolong the erosion-slowing benefits of cover crops. He now owns three no-till planters—one for transplanting tomatoes, one for corn, and one for squash and pumpkins—as well as a no-till drill for cover crops, all customized with parts and implements from several different equipment companies.

> *No-till is not a miracle, but it works for me. It's good for my bottom line, I'm saving soil, and I'm reducing pesticides and increasing profits.*

Groff's no-till system relies on a selection of cover crops and residues that blanket the soil nearly all year. "The amount of acreage I devote to different cover crops every year is really subjective," he says, noting that he constantly modifies his cropping plans based on field observations, weather conditions, timing considerations and other factors. In the fall, he uses a no-till seeder to drill a combination of rye and hairy vetch (at seeding rates of 40 and 15 pounds per acre, respectively). He likes the pairing because their root structures grow in different patterns, and the vegetation left behind after termination leaves different residues on the soil surface.

Introduced to a novel cover crop of forage radish through University of Maryland cover crop research trials hosted at his farm, Groff was so impressed by what he saw that he decided to integrate it into his cover crop combinations. Upon discovering that forage radish cover crop seed was not available, Groff decided to grow his own and sell the surplus to farmers. He then created a variety out of the forage radish and branded it Tillage Radish, which is now grown around the world.

His typical rotations include planting mixtures of Tillage Radish and oats or crimson clover before corn, as well as a mixture of Tillage Radish, cereal rye, vetch, crimson clover and balansa clover before pumpkins.

Several attributes make Tillage Radish a practical choice for no-till farmers. For example, its taproots can alleviate compaction problems, so much so that Groff now prefers using radishes instead of his deep ripper to loosen soil in his driveways. Complete dieback following hard frost, impressive weed suppression into spring and relatively rapid nutrient cycling add to Tillage Radish's appeal.

In the spring, Groff uses a modified Buffalo rolling stalk-chopper to terminate overwintering covers. He typically sprays glyphosate at low levels (half a pint per acre, or $1 per acre) before rolling to ensure a more complete kill. The chopper flattens and crimps the cover crop, providing a thick mulch. Once it's flat, he makes a pass with the no-till planter or no-till transplanter.

The system creates a very real side benefit in reduced insect pest pressure. Once an annual problem, Colorado potato beetle damage has all but disappeared from Groff's tomatoes. Since he began planting into the mulch, he has greatly reduced his use of pesticides. The thick mat also prevents soil splashing during rain, a primary cause of early blight on tomatoes. "We have slashed our pesticide and fertilizer bill nearly in half, compared to a conventional tillage system," Groff says. "At the same time, we're building valuable topsoil and not sacrificing yields."

"No-till is not a miracle, but it works for me," he says. "It's good for my bottom line, I'm saving soil, and I'm reducing pesticides and increasing profits." He emphasizes that benefits from no-till management have developed gradually, along with his experience in handling each field. Knowing when to stay off wet fields and choosing the right crop and cover crop rotations, he says, can help farmers new to no-till avoid potential compaction and fertility problems. "My soils have developed a stability that lets me get away with things that I couldn't do earlier," he says. "You earn the right to be out there as your soil gets more stable. Basically, the rules of the game change as the game is played."

Groff is convinced his crops are better than those produced in soils managed conventionally, especially during weather extremes. His soils foster high levels of earthworm and other biological activity deep in the soil. He promotes his system at annual summer field days that draw huge crowds of farmers and through his website, www.stevegroff.com.

Chapter 17

MANAGING WATER: IRRIGATION AND DRAINAGE

But the irrigation that nourished Mesopotamian fields carried a hidden risk. Groundwater in semiarid regions usually contains a lot of salts. … When evaporation rates are high, sustained irrigation can generate enough salt to eventually poison the crops.

—DAVID MONTGOMERY, 2007

Growing seasons around the world rarely have the right amount of precipitation, and deficits and excesses of water are the most significant overall yield-limiting factors to crop production. It is estimated that more than half of the global food supply depends on some type of water management. In fact, the first major civilizations and population centers emerged when farmers started to control water, resulting in more consistent yields and stable food supplies. Examples include Mesopotamia, literally the "land between the rivers" Tigris and Euphrates, the lower Nile Valley and northeastern China. High yields in drained and irrigated areas allowed for the development of trade specialization because crop surpluses no longer required everyone to provide their own food supply. This led to important innovations like markets, writing and transportation. Moreover, new water management schemes forced societies to get organized, work together on irrigation and drainage schemes, and develop laws on water allocations. But water management failures were also responsible for the collapse of societies. Notably, the salinization of irrigated lands in Mesopotamia and filling up of ditches with sediments, often dug and maintained by enslaved peoples, resulted in lost land fertility and an inability to sustain large centrally governed civilizations.

Shortage of water. It is estimated that drought results in more crop yield losses than by all pathogens combined. It is also projected that many of the world's agricultural regions will be drier in the future. Today, many of the most productive agricultural areas depend on some type of water management. In the United States, average crop yields of irrigated farms are greater than the corresponding yields of dryland farms by 118% for wheat and 30% for corn. At a global scale, irrigation is used on 18% of the cultivated areas, but those lands account for 40% of the world's food production.

Photo by Judy Brossy

WATER IN FIELDS

Soil conditions may vary significantly within a field, greatly influencing water infiltration and movement. Runoff with intense rainfall is common at the top of a slope or on a slope shoulder, and water tends to accumulate in depressions. Both areas may suffer during very dry periods, with the slope top or shoulder soil having low water storage and with the wet areas in depressions growing plants with shallow root systems that aren't deep enough to access water lower in the soil when it is dry. And there may be two or more soil types within a field with different physical properties that affect water infiltration and movement. The extent of these variations may be substantial. It is estimated that these areas of year-to-year unstable yields—because of either too little or too much soil moisture—represent from about a quarter to a third of fields in the U.S. Midwest, with possible economic losses of over $500 million per year. Thus, practices such as no-till and cover cropping, and drainage of depressions, can both increase yields and decrease annual variations caused by different patterns of precipitation.

The great majority of agricultural lands in the western United States and in other dry climates around the world would not be productive without irrigation water, and the majority of the U.S. horticultural crop acreage, especially in California, is entirely dependent on elaborate irrigation infrastructures. Even in humid regions most high-value crops are grown with supplemental irrigation during dry spells to ensure crop quality and steady supplies for market outlets.

Excess of water. To address excess water problems, the best fields in the United States have had drainage systems installed, which make those soils even more productive than they were naturally. Drainage of wet fields overcomes water-logged conditions and allows for a longer growing season because farmers can get onto those fields earlier in the spring and can harvest later in the fall without causing extreme compaction. Drainage also reduces yield losses or even prevents complete crop failures when fields experience excessive precipitation during the early growing season.

The benefits of irrigation and drainage in addressing shortages and excesses of water are thus obvious. They are critical to food security as well as to the agricultural intensification needed to feed a growing global population while protecting natural areas. Concerns with climate change, which is resulting in greater occurrences of deficits and excesses of precipitation, will increase pressure for more irrigation and drainage. But they also exact a price on the environment. Drainage systems provide hydrological shortcuts and are responsible for increased chemical losses to streams, rivers, lakes and estuaries. Similarly, irrigation systems can result in drastic changes in river and estuarine ecosystems, as well as in land degradation through salinization and sodium buildup, and they have been sources of international conflict.

IRRIGATION

There are different types of irrigation systems, depending on water source, size of the system and water application method. Two main water sources exist: surface water and groundwater. On smaller scales, recycled wastewater and even desalinized seawater are used in densely populated dry areas. Irrigation systems run from small on-farm arrangements using a local water supply to vast, regional schemes that involve thousands of farms and that are controlled by governmental authorities. Conventional water application involves flood (or furrow) irrigation, which

Table 17.1
Approximate Amounts of Water Needed for Food Production

Product	Gallons of Water per Pound
Wheat	150
Rice	300
Corn	50
Potatoes	19
Soybeans	275
Beef	1,800
Pork	700
Poultry	300
Eggs	550
Milk	100
Cheese	600
Almonds	1,900

Source: FAO

is done by gravity flow and is still the most common method around the world. Sprinkler and drip irrigation systems have also become widely adopted due to the increased availability of pumps.

Surface Water Sources

Streams, rivers and lakes have traditionally been the main source of irrigation supplies. Historical efforts to use these waters for irrigation involved the diversion of rivers and then the development of storage ponds. Small-scale systems, like those used by the Anazasi in the southwestern United States and those by the Nabateans in what is now Jordan, involved cisterns and retention ponds that were filled by stream diversions.

Small-scale irrigation systems nowadays tend to pump water directly out of streams or farm ponds (Figure 17.1). These water sources are generally sufficient for cases in which supplemental irrigation is used: in more humid regions where only limited amounts of additional water may be needed for good yields or high-quality crops. Such systems, generally managed by a single farm, have limited environmental impacts. Most states require permits for such water diversions to ensure against excessive impacts on local water resources.

Large-scale irrigation schemes have been developed around the world with strong involvement by governments. In the 1930s the U.S. government invested $3 billion to create the intricate Central Valley project in California that has provided a hundredfold return on investment. The Imperial Irrigation District, located in the dry desert of Southern California, was developed in the 1940s with the diversion of water from the Colorado River. Even today, large-scale irrigation systems, like the

FIRST CONSIDER SOIL IMPROVEMENT

Healthy soils with good and stable aggregation, enhanced organic matter levels and limited or no compaction go a long way toward “drought proofing” your farm. In addition, reduced tillage with residues on the surface also helps to enhance water infiltration and to reduce evaporation losses from the soil. Cover crops, while using water for their growth, can act as a water-conserving surface mulch once they are suppressed. But, of course, water is needed to grow crops, from 19 gallons to hundreds or more gallons of water for each pound of plant or animal product (Table 17.1). (*This represents literally hundreds of pounds of water to well over 1,000 pounds of water to produce one pound of food.*) And if it doesn’t rain for a few weeks, crops on even the best soils will start to show drought stress. Even in humid regions there can be stretches of dry weather that cause stress and reduce crop yield or quality. Irrigation, therefore, is an essential part of growing crops in many regions of the world. But the healthier your soil, the less irrigation water you will need.

Figure 17.1. A farm pond (left) is used as a water source for a traveling overhead sprinkler system (right) on a vegetable farm.

GAP project in southeastern Turkey (Figure 17.2), are being initiated. Such projects often drive major economic development efforts in the region and function as a source for national or international food or fiber production. On the other hand, large dams also frequently have the detrimental effects of displacing people and flooding productive cropland or important wetlands.

Groundwater

When good aquifers are present, groundwater is a relatively inexpensive source of irrigation water. A significant advantage is that it can be pumped locally and does not require large government-sponsored investments in dams and canals. It also has less impact on regional hydrology and ecosystems, although pumping water from deep aquifers requires significant amounts of energy. And deep groundwater generally contains more dissolved minerals and has greater potential to cause salt buildup over time. Center-pivot overhead sprinklers (Figure 17.3, right) are often used, and individual systems, irrigating 120–500 acres, typically draw from their own well. A good source of groundwater is critical for the success of such systems, and low salt levels are especially critical to prevent the buildup of soil salinity. Most of the western U.S. Great Plains—much of it part of the former Dust Bowl area—uses center-pivot irrigation systems supported by the large (174,000-square-mile) Ogallala aquifer, which is

Figure 17.2. The Ataturk Dam, part of the GAP project in Turkey, diverts water from the Euphrates River (left). The main canal (middle) conveys water to the Harran Plain for distribution to individual fields (right).

Figure 17.3. Left: Satellite image of southwest Kansas showing crop circles from center-pivot irrigation systems. Photo by NASA. Right: Overhead sprinkler irrigation system, Iowa.

a relatively shallow and accessible water source (Figure 17.3, left). It is, however, being used faster than it is recharging from rainfall, which is clearly an unsustainable practice. Deeper wells that require more energy and expense to pump water will make this mining of water an increasingly questionable practice. There are reports of fields that used to be irrigated by single wells now requiring as much as five wells. Similar concerns about excessive groundwater withdrawals exist in other regions, notably in the Upper Gangetic Plain in India, where crop production is very intensive (Figure 17.4).

Recycled Wastewater and Desalinized Seawater

In recent years, water scarcity has forced governments and farmers to look for alternative sources of irrigation water. Since agricultural water does not require the same quality as drinking water, recycled wastewater is a good alternative. It is being used in regions where 1) densely populated areas generate significant quantities of wastewater and are close to irrigation districts, and 2) where surface or groundwater sources are very limited or need to be transported over long distances. Several irrigation districts in the United States are working with municipalities to provide safe recycled wastewater, although some concerns still exist about long-term effects. Other nations with advanced agriculture and critical water shortages, notably Israel and Australia, have also implemented wastewater recycling systems for irrigation purposes (Figure 17.5).

In a few areas of the world, water scarcity has become so critical that seawater is desalinized using

MAIN TYPES OF IRRIGATION

- Flood (or furrow)
- Sprinkler
- Drip (or trickle)
- Manual

Figure 17.4. Small pump used for groundwater irrigation in northern India.

Figure 17.5. Recycled wastewater from the City of Adelaide, Australia, is pumped into an irrigation pond for a vegetable farm. Wastewater-conveying pipes are painted purple to distinguish them from freshwater conduits.

reverse osmosis to create fresh water. Most is used for direct human consumption, but increasingly it is also used in high-value specialty crop production. The technology is energy intensive but improvements are making it more efficient and cost effective.

Irrigation Methods

Flood (or furrow) irrigation is the historical approach and remains widely used around the world. It basically involves the simple flooding of a field for a limited amount of time, allowing the water to infiltrate. If the field has been shaped into ridges and furrows, the water is applied through the furrows and infiltrates down and laterally into the ridges (Figure 17.6). Such systems mainly use gravity flow and require nearly flat fields. These systems are by far the least expensive to install and use, but their water application rates are very inexact and typically uneven. Also, these systems are most associated with salinization concerns, as they can easily raise groundwater tables. Flood irrigation is also used in rice production systems, in which dikes are used to keep the water ponded.

Sprinkler irrigation systems apply water through pressurized sprinkler heads and require conduits (pipes) and pumps. Common systems include stationary sprinklers on risers (Figure 17.7) and traveling overhead sprinklers (center-pivot and lateral; figures 17.1 and 17.3). These systems allow for more precise water application rates than flooding systems and more efficient water use. But they require larger up-front investments, and the pumps use energy. Large, traveling gun sprayers can efficiently apply water to large areas and are also used to apply liquid manure.

Localized irrigation, especially useful for tree crops or landscaping in dry areas, can often be accomplished

Figure 17.6. Furrow irrigation is generally inexpensive but also inefficient with respect to water use (left: irrigation canal with irrigated hay field in background; right: excess tailwater is discharged at the other end of the field. Imperial Valley, California).

Figure 17.7. Portable sprinkler irrigation system commonly used with horticultural crops.

using micro-sprinklers that use small-diameter "spaghetti tubing" and relatively small pumps (Figure 17.8), making the system comparatively inexpensive.

Drip (or trickle) irrigation systems also use flexible or spaghetti tubing combined with small emitters. They are mostly used in bedded or tree crops using a line source with many regularly spaced emitters or are applied directly near the plant through a point-source emitter (figures 17.8 and 17.9). The main advantage of drip irrigation is the parsimonious use of water and the high level of control.

Drip irrigation systems are relatively inexpensive when used with high-value crops but are not economical for large-scale grain or forage crop production. They can be installed easily, use low pressure and have low energy consumption. In small-scale systems like market gardens, pressure may be applied through a gravity hydraulic head from a water container on a small platform or even through a human-powered treadle pump. In subsurface drip irrigation systems, lines and emitters are semi-permanently buried to allow field operations. Such systems require attention to the placement of the tubing and emitters; they need to be close to the plant roots, as lateral water flow from the trickle line through the soil is limited.

Manual irrigation involves watering cans, buckets, garden hoses, inverted soda bottles, etc. Although it doesn't fit with large-scale agriculture, it is still widely used in gardens and in small-scale agriculture in underdeveloped countries.

Fertigation is an efficient method to apply fertilizer to plants through pumped systems like sprinklers and drip irrigation. The fertilizer source is mixed with the irrigation water to provide low doses of liquid fertilizer that are readily absorbed by the crop. This also allows for "spoon feeding" fertilizers to the crop through

Figure 17.8. Drip irrigation. Left: A water emitter allows for slow release under line pressure; right: installed on grapevines. Photo by the University of California, Davis.

Figure 17.9. Drip irrigation for bean plants. Lateral movement of water to reach plant roots may be limited with drip systems (left), unless each crop row has its own drip line or the spacing between rows is decreased by using narrow twin rows (right). Note: The apparent leaf discoloration is due to a low sun angle.

multiple small applications, which would otherwise be a logistical challenge. The fertilizer material needs to be of very high quality with drip systems so that water emitters don't clog.

Environmental Concerns and Management Practices

Irrigation has numerous advantages, but significant concerns exist as well. The main threat to soil health in dry regions is the accumulation of salts, and in some cases also sodium. As salt accumulation increases in the soil, crops have more difficulty getting the water that's there. When sodium accumulates, aggregates break down and soils become dense and impossible to work (Chapter 6). Over the centuries, many irrigated areas have been abandoned due to salt accumulation, and it is still a major threat in several areas in the United States and elsewhere (Figure 17.10). Salinization is the result of the evaporation of irrigation water, which leaves salts behind. It is especially prevalent with flood irrigation systems, which tend to over-apply water and can raise saline groundwater tables. Once the water table gets close to the surface, capillary water movement transports soil water to the surface, where it evaporates and leaves salts behind. When improperly managed, this can render soils unproductive within a matter of years. Salt accumulation can also occur with other irrigation practices, even with drip systems, especially when the climate is so dry that leaching of salts does not occur through natural precipitation.

The removal of salts is difficult, especially when lower soil horizons are also saline. Irrigation systems in arid regions should be designed to *supply* water and also to *remove* water, implying that irrigation should be combined with drainage. This may seem paradoxical,

CONCERNS WITH IRRIGATION

- accumulation of salts and/or sodium in the soil
- energy use
- increased potential for nutrient and pesticide loss
- water use diverted from natural systems
- displacement of people by large dams and possible flooding of productive cropland, wetlands or archaeological sites
- competing users: urban areas and downstream communities

but salts need to be removed by application of extra water to dissolve the salts, leach them out of the soil and subsequently remove the leachate through drains or ditches, where the drain water may still create concerns for downstream areas due to its high salt content. The lower Nile Valley, one of the long-term success stories of irrigated agriculture, provided irrigation during the river's flood stage in the fall and natural drainage after it subsided to lower levels in the winter and spring. In some cases, deep-rooted trees are used to lower regional water tables, which is the approach used in the highly salinized plains of the Murray Darling Basin in southeastern Australia. Several large-scale irrigation projects around the world were designed only for the water supply component, and funds were not allocated for drainage systems, ultimately causing salinization.

The removal of sodium from the soil can be accomplished by exchanging it with another cation, calcium, which is typically done through the application of gypsum. In general, salinity and sodicity are best prevented through good water management. (See Chapter 20 for a discussion of reclaiming saline and sodic soils.)

Salt accumulation is generally not an issue in humid regions, but over-irrigation raises concerns about nutrient and pesticide leaching losses in these areas. High application rates and amounts can push nitrates and pesticides past the root zone and increase groundwater contamination. Soil saturation from high application rates can also generate denitrification losses.

A bigger issue with irrigation, especially at regional and global scales, is the high water consumption levels and competing interests. Agriculture consumes approximately 70% of the global water withdrawals. Humans use less than a gallon of water per day for direct consumption, but about 150 gallons are needed to produce a pound of wheat and 1,800 gallons are needed for a pound of beef or almonds (Table 17.1). According to the U.S. Geological Survey, 68% of high-quality groundwater withdrawals in the United States are used for irrigation. Is this sustainable? The famous Ogallala Aquifer mostly holds "ancient" water that accumulated during previous wetter climates. As mentioned earlier, withdrawals are currently larger than the recharge rates, and this limited resource is therefore slowly being mined. In the case of the Aral Sea—formerly the fourth largest inland freshwater body in the world—the diversion of rivers for irrigated cotton farming in the former Soviet Union resulted in a 90% decrease in the area of the sea. It also became severely contaminated with drainage water from agricultural fields.

Figure 17.10. Over-irrigation raised groundwater tables (visible at bottom of pit, left) in the Harran Plain, Turkey. Surface evaporation of water traveling upward through soil capillaries (very small channels) from the shallow groundwater causes salt accumulation (right).

GOOD IRRIGATION MANAGEMENT

- Build soil to be more resistant to crusting and drought by increasing organic matter contents, aggregation and rooting volume.
- Use water conservatively: consider deficit irrigation scheduling.
- Monitor soil, plants and the weather to precisely estimate irrigation needs.
- Use precise water application rates; do not over-irrigate.
- Use water storage systems to accumulate rainfall when feasible.
- Use good-quality recycled wastewater when available.
- Reduce tillage and leave surface residues.
- Use mulches to reduce surface evaporation.
- Integrate water and fertilizer management to reduce losses.
- Prevent salt or sodium accumulation by applying basic principles of salinity management: regularly test the soil and irrigation water; calculate the leaching requirements; leach out the salts beyond the root zone; reduce sodium contents through gypsum application; and in some cases, grow salt-tolerant crops.

Several large irrigation systems affect international relations. The high withdrawal rates from the Colorado River diminish it to a trickle by the time it reaches the U.S.-Mexico border and the estuary in the Gulf of California. Similarly, Turkey's decision to promote agricultural development through the diversion of Euphrates waters has created tensions with the downstream countries, Syria and Iraq, and has contributed to their political turmoil.

Irrigation Management at the Farm Level

Sustainable irrigation management and preventing salt and sodium accumulation require solid planning, appropriate equipment and monitoring. A first step is to build the soil so it optimizes water use by the crop. As we discussed in chapters 5 and 6, soils that are low in organic matter and high in sodium have low infiltration capacities due to surface sealing and crusting from low aggregate stability. Overhead irrigation systems often apply water as "hard rain," creating further problems with surface sealing and crusting.

Healthy soils have more water supply capacity than soils that are compacted and depleted of organic matter. It is estimated that for every 1% loss in organic matter content in the surface foot, soil can hold 16,500 gallons less of plant-available water per acre. Additionally, surface compaction creates lower root health and density, and hard subsoils limit rooting volume. These processes are captured by the concept of the *optimum water range* (which we discussed in Chapter 6) where the combination of compaction and lower plant-available water retention capacity limits the soil water range for healthy plant growth. Such soils therefore have less efficient crop water use and require additional applications of irrigation water. In fact, it is believed that many farms in humid climates have started to use supplemental irrigation because their soils have become compacted and depleted of organic matter. As we discussed before, poor soil management is often compensated for by increased inputs.

Reducing tillage, adding organic amendments and preventing compaction can increase water storage. A long-term experiment showed that

Table 17.2
Plant-Available Water Capacity in Long-Term Tillage and Rotation Experiments in New York

Tillage Experiments	Plant-Available Water Capacity (%)		
	Plow Till	No-till	% Increase
Silt loam (33 years)	24.4	28.5	17%
Silt loam (13 years)	14.9	19.9	34%
Clay loam (13 years)	16	20.2	26%
Rotation Experiment	**Continuous Corn**	**Corn after Grass**	**% Increase**
Loamy sand (12 years)	14.5	15.4	6%
Sandy clay (12 years)	17.5	21.3	22%

Source: Moebius et al. (2008).

reducing tillage and using crop rotations increased plant-available water capacity in the surface horizon by up to 34% (Table 17.2). When adding organic matter, consider stable sources that are mostly composed of "very dead" materials such as composts. They are more persistent in soil and are a primary contributor to soil water retention. But don't forget fresh residues (the "dead") that help form new and stable aggregates. Increasing rooting depth greatly increases plant water availability by extending the volume of soil available for roots to explore. When distinct plow pans are present, ripping through them makes subsoil water accessible to roots. Practices like strip-till can increase rooting depth and also result in long-term increases in organic matter and water storage capacity.

These practices have the most significant impact in humid regions, where supplemental irrigation is used to reduce drought stress during dry periods between rainfall events. Building a healthier soil will reduce irrigation needs and conserve water because increased plant water availability extends the time until the onset of drought stress and greatly reduces the probability of stress. For example, let's assume that a degraded soil with a plow pan (A) can provide adequate water to a crop for eight days without irrigation, and a healthy soil with deep rooting (B) allows for 12 days. A 12-day continuous drought, however, is much less likely. Based on climate data for the northeastern United States, the probability of such an event in the month of July is 1 in 100 (1%), while the probability for an 8-day dry period is 1 in 20 (5%). The crops growing on soil A would run out of water and suffer stress in July in 5% of years, while the crops on soil B would be stressed in only 1% of years. A healthy soil would reduce or eliminate the need for irrigation in many cases.

Increasing surface cover, especially with heavy mulch, significantly reduces evaporation from the soil surface. Cover crops can increase soil organic matter and provide surface mulch, but caution should be used with cover crops because when growing, they can consume considerable amounts of water that may be needed to leach salts or to supply the cash crop.

Conservative water use prevents many of the problems that we discussed above. This can be accomplished by monitoring the soil, the plants or weather indicators and applying water only when needed. Soil sensors like tensiometers (Figure 17.11), moisture blocks, TDR (time-domain reflectometry) and capacitance probes can evaluate soil moisture conditions. When the soil moisture levels become critically low, irrigation systems can be turned on and water applications can be made to meet the crop's needs without excess. The crop itself can also be monitored, as water stress results in increased leaf temperatures that can be detected with thermal or near infrared imaging.

Another approach involves using weather information from either government weather services or small, on-farm weather stations to estimate the balance between natural rainfall and evapotranspiration. Electronic equipment is available for continuously measuring weather indicators, and they can be read from a distance using wireless or phone communication. Computer technology and site-specific water and fertilizer application equipment, now available with large modern sprinkler systems, allow farmers to tailor irrigation to sub-acre-scale localized water and fertilizer needs. Researchers have also demonstrated that deficit irrigation—water applications that are less than 100% of evapotranspiration—can provide equal yields with reduced water consumption and promote greater reliance on stored soil water. Deficit irrigation is used purposely with grapevines that need a modest amount of water stress to enrich quality-enhancing constituents like anthocyanins.

Many of these practices can be effectively combined. For example, a vegetable grower in Australia plants on beds with subsurface drip irrigation and uses controlled traffic (Figure 17.12). A sorghum-sudan cover crop is planted during the wet season and mulched down after maturing, leaving a dense mulch. The subsurface drip irrigation is installed in the beds and stays in place for five or more years (in contrast, annual removal and reinstallation are necessary with tilled systems). No tillage is performed, and vegetable crops are planted using highly accurate GPS technology to ensure that they are within a couple of inches of the drip emitters.

Figure 17.11. Tensiometers used for soil moisture sensing in irrigation management. Photo courtesy of the Irrometer Company.

Figure 17.12. No-till irrigated vegetables grown on beds with cover crop mulch. Drip irrigation lines are placed at 1–2 inches depth in the beds (not visible).

DRAINAGE

Soils that are naturally poorly drained and have inadequate aeration are generally high in organic matter content. But poor drainage makes them unsuitable for growing most crops other than a few water-loving plants like rice and cranberries. When such soils are artificially drained, they become very productive, as the high organic matter content provides all the good qualities we discussed in earlier chapters. Over the centuries, humans have converted swamps into productive agricultural land by digging ditches and canals, later also combined with pumping systems to remove the water from low-lying areas. The majestic Aztec city of Tenochtitlan was located in a swampy area of Lake Texcoco where food was grown on *chinampas*, raised beds that were built up with rich mud from dug canals (the lake was subsequently drained by the Spanish and is now the Mexico City metropolitan area). Large areas of the Netherlands and eastern England were drained with ditches to create pasture and hay land to support dairy-based agriculture. Excess water was removed via extensive ditch and canal systems by windmill power (a signature landscape of Holland) and later by steam- and oil-powered pumping stations (Figure 17.13). In the 1800s and early 1900s clay drain tiles were increasingly installed (Figure 17.14, left) because they are buried and don't require fields to be broken up by ditches. Current drainage efforts are primarily accomplished

Figure 17.13. Left: the Wouda pumping station was built to drain large areas in Friesland, Netherlands, and is the largest steam pumping station ever built. It is now on the World Heritage List. Right: A drainage ditch removes excess water and lowers the water table in newly developed lands ("polders") in the Netherlands.

with subsurface flexible corrugated PVC tubes that are installed with laser-guided systems (Figure 17.14, right), and increasingly powerful drain plows allow drain lines to be installed rapidly. In the United States, land drainage efforts have been significantly reduced as a result of wetland protection legislation, and large-scale, government-sponsored projects are no longer initiated. But at the farm level, recent adoption of yield monitors on crop combines has quantified the economic benefits of drainage on existing cropland, and additional drainage lines are being installed at an accelerated pace in many of the very productive lands in the U.S. Corn Belt and elsewhere.

Benefits of Drainage

Drainage lowers the water table by removing water through ditches or tubes (Figure 17.15). The main benefit is that it creates a deeper soil volume that is adequately aerated for growing common crop plants. If crops are grown that can tolerate shallow rooting conditions, like grasses for pastures or hay, no artificial drainage may be needed and the water table can remain relatively

Figure 17.14. Left: clay (tile) pipes were commonly used to improve drainage. Painting by L.A. Ring. Right: Flexible corrugated PVC drains allow for rapid and durable installation. Photo by Morin Farm Drainage.

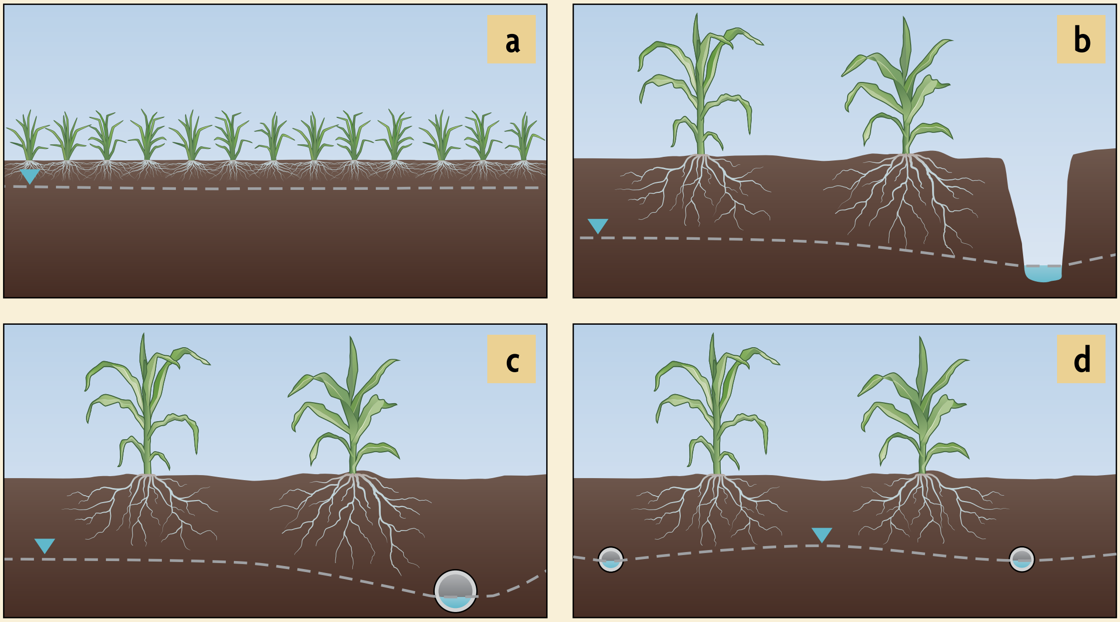

Figure 17.15. Drainage systems lower water tables and increase rooting volume. A: undrained with pasture; B: drainage ditch; C: subsurface tube drain (tile); and D: mole drain. The water table is indicated by a dashed line with an inverted triangle. Illustration by Vic Kulihin.

close to the surface (Figure 17.15a) or drainage lines can be spaced far apart, thereby reducing installation and maintenance costs, especially in low-lying areas that require pumping. But most commercial crops, like corn, alfalfa and soybeans, require a deeper aerated zone, and subsurface drain lines need to be installed 3–4 feet deep and spaced 20–80 feet apart, depending on soil characteristics (Figure 17.15b, c).

Drainage increases the timeliness of field operations and reduces the potential for compaction damage. Farmers in humid regions have limited numbers of dry days for spring and fall fieldwork, and inadequate drainage then prevents field operations prior to the next rainfall. With drainage, field operations can commence within several days after rain. As we discussed in chapters 6 and 15, most compaction occurs when soils are wet and in the plastic state, and drainage helps soils transition into the friable state more quickly during drying periods, except for most clays. Runoff potential is also generally reduced by subsurface drainage because compaction is reduced and soil water content is decreased by removal of excess water. This allows the soil to absorb more water through infiltration.

Installing drains in poorly drained soils therefore has agronomic and environmental benefits because it reduces compaction and loss of soil structure. This also addresses other concerns with inadequate drainage, like high nitrogen losses through denitrification. A large fraction of denitrification losses can occur as nitrous oxide, which is a potent greenhouse gas. As a general principle, croplands that are regularly saturated during the growing season should either be drained, or reverted to pasture or natural vegetation.

Types of Drainage Systems

Ditching was used to drain lands for many centuries,

IS DRAINAGE REALLY NEEDED?

Croplands with shallow or perched water tables benefit from drainage. But prolonged water ponding on the soil surface is not necessarily an indication of a shallow water table. Inadequate drainage can also result from poor soil structure (Figure 17.16). Intensive use, loss of organic matter and compaction make a soil drain poorly in wet climates. It may be concluded that the installation of drainage lines will solve this problem. Although this may help reduce further compaction, the correct management strategy is to build soil health and increase its permeability.

Figure 17.16. A soil with apparent drainage problems that are the result of poor soil structure.

but most agricultural fields are now drained through perforated corrugated PVC tubing that is installed in trenches and backfilled (Figure 17.14, right). (They are still often referred to as drain “tile,” although that word dates back to the clay pipes.) Subsurface drain pipes are preferred in a modern agricultural setting, as ditches interfere with field operations and take land out of production. A drainage system still needs ditches at the field edges to convey the water away from the field to wetlands, streams or rivers (Figure 17.13, right).

If the entire field requires drainage and the topography is flat, the subsurface drain pipes may be installed in mostly parallel lines or in *herringbone* patterns (Figure 17.17). On undulating lands, drain lines need to account for the field hydrology where water collects in swales and other low-lying areas. These are called *targeted* drainage patterns. *Interceptor* drains may be installed at the bottom of slopes to remove excess water from upslope areas.

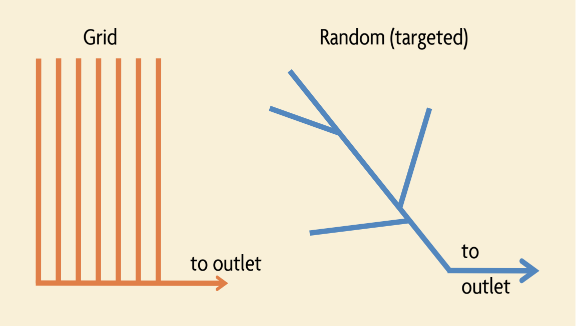

Figure 17.17. Grid drainage pattern for uniform flat land and natural (herringbone) pattern for sloping land.

Fine-textured soils are less permeable than coarse-textured ones and require closer drain spacing to be effective. A common drain spacing for a fine loam is 50 feet, while in sandy soil, drain pipes may be installed at 100-foot spacing, which is considerably less expensive. Installing conventional drains in heavy clay soils is often too expensive, especially in developing countries, due to the need for close drain spacing. But alternatives

COMMON TYPES OF DRAINAGE PRACTICES USED IN AGRICULTURE

- Ditches
- Subsurface drain lines (tile)
- Mole drains
- Surface drains
- Raised beds and ridges

Figure 17.18. A mole drain in a clay soil (left) is created with the use of a mole plow with a "bullet" and expander on a chain (right).

can be used. ***Mole drains*** are developed by pulling a tillage-type implement with a large "bullet" through soil in the plastic state at approximately 2 feet of depth (figures 17.15d and 17.18). The implement cracks the overlying drier surface soil to create water pathways. The bullet creates a drain hole, and an expander smears the sides to give it more stability. Such drains are typically effective for several years, after which the process needs to be repeated. Like PVC drains, mole drains discharge into ditches at the edge of fields.

Clay soils may also require ***surface drainage***, which involves shaping the land to allow water to discharge over the soil surface to the edge of fields, where it can enter a grass waterway (Figure 17.19). Soil shaping is also used to smooth out localized depressions where water would otherwise accumulate and remain ponded for extended periods of time.

Figure 17.19. Surface drainage on clay soils in Ontario, Canada. Excess water travels over the surface to a grass waterway.

A very modest system of drainage involves the use of ***ridges*** and ***raised beds***, especially on fine-textured soils. This involves limited surface shaping, in which the crop rows are slightly raised relative to the inter-rows. This may provide a young seedling with enough aeration to survive through a period of excessive rainfall. These systems may also include reduced tillage—ridge tillage involves minimal soil disturbance—as well as controlled traffic to reduce compaction (chapters 15 and 16).

Concerns with Drainage

Extensive land drainage has created concerns, and many countries are now strictly controlling new drainage efforts. In the United States, the 1985 Food Security Act contains the so-called Swampbuster provision, which mostly eliminated conversion of wetlands to cropland and has since been strengthened. The primary justification for such laws was the loss of wetland habitats and landscape hydrological buffers.

Large areas of wetlands are commonly found in those zones where water and sediments converge (as

Figure 17.20. A subsurface drain line discharges into an edge-of-field ditch, diverting groundwater to surface waters.

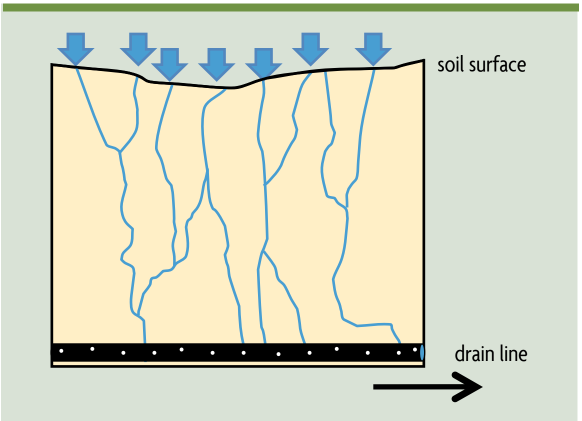

Figure 17.21. Continuous large (macro) pores may cause rapid movement of contaminants from the soil surface to drain lines, bypassing the soil matrix.

we discussed in Chapter 1) and these are among the richest natural habitats due to their high organic matter contents. They are critical to many animal species and also play important roles in buffering the hydrology of watersheds. During wet periods and snowmelt they fill with runoff water from surrounding areas, and during dry periods they receive groundwater that resurfaces in a lower landscape position. The retention of this water in swamps reduces the potential for flooding in downstream areas and allows nutrients to be cycled into aquatic plants and stored as organic material. When the swamps are drained, these nutrients are released by the oxidation of the organic materials and are mostly lost through the drainage system into watersheds. The extensive drainage of glacially derived pothole swamps in the north central and northeastern United States and Canada has contributed to significant increases in flooding and losses of nutrients into watersheds.

Drainage systems also increase the potential for losses of nutrients, pesticides and other contaminants by providing a hydrologic shortcut for percolating waters. While under natural conditions water would be retained in the soil and slowly seep to groundwater, it is captured by drainage systems and diverted into ditches, canals, streams, lakes and estuaries (Figure 17.20). This is especially a problem when medium- and fine- textured soils generally allow for very rapid movement of surface-applied chemicals to subsurface drain lines (Figure 17.21). Unlike sands, which can effectively filter percolating water, fine-textured soils contain structural cracks and large (macro) pores down to the depth of a drain line. Generally, we would consider these to be favorable

TO REDUCE RAPID CHEMICAL AND MANURE LEACHING TO DRAIN LINES

- Build soils with a crumb structure that readily absorbs rainfall and reduces the potential for surface ponding.
- Avoid applications on wet soils (with or without artificial drainage) or prior to heavy rainfall.
- Inject or incorporate applied materials. Even modest incorporation reduces flow that bypasses the mass of the soil.

Use the “4R” management practices to optimize timing, rates, formulations and placement of nutrients (see Chapter 18).

Figure 17.22. Water samples taken from a subsurface drain line when heavy rainfall followed liquid manure application. From left, water samples represent 15-minute sampling intervals from the onset of drain discharge. Photo by Larry Geohring.

because they facilitate water percolation and aeration. However, when application of fertilizers, pesticides or liquid manure is followed by significant precipitation, especially intense rainfall that causes short-term surface ponding, these contaminants can enter the large pores and rapidly (sometimes within one hour) move to the drain lines. These contaminants can enter drains and surface waters at high concentrations (Figure 17.22), bypassing the soil matrix and not filtered or adsorbed by soil particles. Management practices can be implemented to reduce the potential for such losses (see the box "To Reduce Rapid Chemical and Manure Leaching to Drain Lines").

Artificially draining the soil profile also reduces the amount of water stored in the soil and the amount of water available for a crop. Farmers strive to cover all their bases when it comes to weather by draining water out of the soil in case of excess rain but retaining it in case of drought. ***Controlled drainage*** allows for some flexibility and involves retention of water in the soil system through the use of weirs in the ditches at the sides of fields. In effect, this mostly keeps the water table at a higher level than the depth of the drains, but the weir can be lowered in case the soil profile needs to be drained to deeper depths. Controlled drainage is also recommended during winter fallows to slow down organic matter oxidation in muck (organic) soils and to reduce nitrate leaching in sandy soils.

SUMMARY

Irrigation and drainage allow for high yields in areas that otherwise have water shortages or excesses. There is no doubt that we need such water management practices to secure a food supply for a growing population and to provide the high yields needed to arrest the conversion of natural lands into agriculture. Some of the most productive lands use drainage or irrigation, and the ability to control water regimes provides great advantages. Yet there is a larger context: These practices exact a price on the environment by diverting water from its natural course and increasing the potential for soil and water contamination. Good management practices can be used to reduce the impacts of altered water regimes. Building healthy soils is an important component of making soil and water management more sustainable by reducing the need for irrigation and drainage. In addition, other practices that promote more judicious use of water and chemical inputs help reduce environmental impacts.

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Chapter 18

NUTRIENT MANAGEMENT: AN INTRODUCTION

> *The purchase of plant food is an important matter, but the use of a [fertilizer] is not a cure-all, nor will it prove an adequate substitute for proper soil handling.*
>
> —J.L. HILLS, C.H. JONES AND C. CUTLER, 1908

Most of the essential nutrients for plants, animals and humans are derived from weathered minerals in the soil. But plants also absorb carbon, oxygen and hydrogen from the air and water. Nitrogen is derived from the atmosphere by legumes, but other plants absorb it from the soil. Of the 17 elements needed by all plants (Table 18.1), only three—nitrogen (N), phosphorus (P) and potassium (K)—are commonly deficient in soils. Deficiencies of sulfur (S) are less prevalent but not uncommon. Other nutrients, such as magnesium (Mg), zinc (Zn), boron (B) and manganese (Mn), can be lacking in certain regions. Deficiencies of sulfur, magnesium and some micronutrients may be more common in regions with highly weathered minerals, such as the southeastern United States and many parts of the tropics, or those with high rainfall, such as portions of the Pacific Northwest. Sulfur deficiency is especially common on the sandy soils on the coastal plains of the Southeast and has become more common in areas with low organic matter soils with the decrease in sulfur air pollution from coal burning power plants. Keep an eye out for deficiencies of iron, zinc, copper and manganese on higher-pH calcareous soil, especially in drier regions. Low phosphorus availability is also common in calcareous soils. In contrast, in locations with relatively young soil that contains minerals that haven't been extensively weathered by nature, such as glaciated areas with moderate to low rainfall like the Dakotas, K deficiencies are less common.

Environmental concerns have resulted in more emphasis on better management of N and P over the past few decades. While these nutrients are critical to soil fertility management, their mismanagement also causes widespread environmental problems. In many regions of the United States and other countries, surface and groundwater pollution has been caused by poor soil management, overuse of fertilizers, mishandling of manures, sewage sludges (biosolids) and composts, and high animal numbers on limited land areas. Because N and P are used in large quantities and their overuse has potential environmental implications, we'll discuss them together in Chapter 19. Other nutrients, cation

Photo by Dennis Nolan

exchange, soil acidity (low pH) and liming, and arid and semiarid region problems with sodium, alkalinity (high pH), and excess salts are covered in Chapter 20.

THE BOTTOM LINE: NUTRIENTS AND PLANT HEALTH, PESTS, PROFITS AND THE ENVIRONMENT

Management practices are all related. The key is to visualize them all as part of whole-farm management, leading you to the goals of better crop growth and better quality. Plants should be healthy and have large root systems if a soil has good tilth, no subsurface compaction, good drainage, adequate water, a good supply of organic matter and a thriving soil biological community. This enables plants to efficiently take up nutrients and water from the soil and to use those nutrients to produce higher yields. Higher yields also imply indirect benefits like more carbon capture from the atmosphere and better water cycling.

Doing a good job of managing nutrients on the farm and in individual fields is critical to general plant health and management of plant pests. Too much available N in the early part of the growing season allows small-seeded weeds, with few nutrient reserves, to get well established. This early jump-start may then enable them to out-compete crop plants later on. Restricted plant growth may occur if nutrients aren't present at the right time of the season in sufficient quantities and in reasonable balance to one another. Plants under nutrient stress may be stunted if nutrient levels are low, or they may grow too much foliage and not enough fruit if N is too plentiful relative to other nutrients. Plants under nutrient stress grow abnormally, for example, in the presence of too low or too high N levels, and are not able to emit as much of the natural chemicals that signal beneficial insects capable of fighting insect pests that feed on leaves or fruit. Low K levels aggravate stalk rot of corn and winter damage to bermudagrass. On the other hand, pod rot of peanuts is associated with excess K within the fruiting zone of peanuts (the top 2–3 inches of soil). Blossom-end rot of tomatoes is related to low calcium levels, often made worse by droughty conditions, or irregular rainfall or poor irrigation.

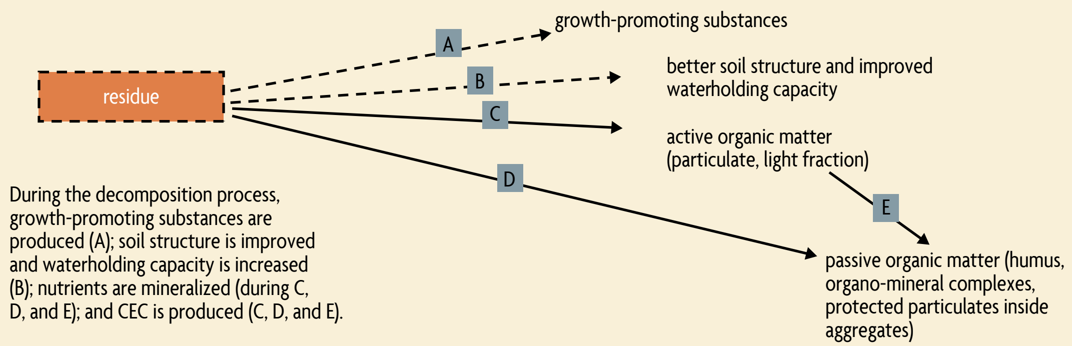
Economic returns will be reduced when plants don't grow well. Yield and crop quality usually are lower, reducing the amount of money received. There also may be added costs to control pests that take advantage

THE 4Rs OF NUTRIENT STEWARDSHIP

The risks of high environmental impacts and lower crop yields are reduced when fertilizer materials are properly managed. The concept of **4R** nutrient stewardship is a set of principles for good nutrient management (maximizing nutrient-use efficiency and minimizing environmental impacts) that recognizes that the best practices vary by local soil, climate and management factors. The 4Rs encapsulate the practices that we discuss in this chapter:

- Right fertilizer source at the
- Right rate, at the
- Right time, and in the
- Right place

Taking this concept even further, **4R-Plus** combines the 4R management practices with conservation practices that enhance soil health and improve the environment. 4R and 4R-Plus are therefore useful concepts that summarize some of the multi-faceted concepts we discuss in this book.



During the decomposition process, growth-promoting substances are produced (A); soil structure is improved and waterholding capacity is increased (B); nutrients are mineralized (during C, D, and E); and CEC is produced (C, D, and E).

Direct Effects on Nutrient Availability

1) Nutrients released during residue decomposition. Relatively high amounts of mineralization of available nutrients are produced by a *combination* of rapid decomposition plus previously accumulated POM or a high amount of added residues. Rapid decomposition is stimulated by intensive tillage, good soil drainage, coarse texture, and alternating wet and dry conditions. Greater biological activity in soil may help solubize mineral forms of phosphorus.

2) CEC and chelates produced during decomposition process. This increases retention of cations such as potassium, calcium and magnesium in forms that are available to plants.

Indirect Effects on Nutrient Availability

1) Growth-promoting substances. Substances produced by bacteria promote better root growth and healthier roots, and they lead to the exploration of more soil volume and more surface area for nutrient interception and mass flow of nutrients to roots.

2) Better soil structure and improved waterholding capacity. Better soil structure may enhance root development and exploration (see #1). Good soil structure and plentiful humus content contribute to higher amounts of plant-available water following rains or irrigation. This results in better plant growth and health, and in more nutrient movement to roots.

3) Greater biodiversity in soil lessens root diseases. A more extensive root system can take up more nutrients from soil.

Figure 18.1. Influence of residue decomposition on nutrient availability.

of crops with poor nutrient management. In addition, when nutrients are applied beyond plant needs, it's like throwing money away. Entire communities may suffer from poor water quality when N and P are lost from the soil by leaching to groundwater or running into surface water.

ORGANIC MATTER AND NUTRIENT AVAILABILITY

The best overall strategy for nutrient management is to enhance the level of organic matter in soils (Figure 18.1). This is especially true for N and P. Soil organic matter, together with any freshly applied residues, are well-known sources of N for plants. (However, as discussed in Chapter 9, unusual residues with high C:N ratios can reduce N availability for a period of time.)

Mineralization of P and sulfur from organic matter is an important source of these nutrients. Also, organic matter helps hold on to positively charged potassium (K^+), calcium (Ca^{++}) and magnesium (Mg^{++}) ions, and provides natural chelates that maintain micronutrients such as zinc, copper and manganese in forms that plants can use. In addition, the improved soil structure (tilth) and the growth-promoting substances produced during organic matter decomposition help the plant develop a more extensive root system, allowing it to obtain nutrients from a larger volume of soil. And a wide diversity of soil organisms helps maintain low populations of plant pathogens.

Cover crop roots (living soil organic matter) also contribute to nutrient management. They provide energy material that allows soil organisms to better thrive and mobilize soil nutrients, keep nutrients from being lost by leaching or runoff, add new N to the soil (if a legume), and maintain plentiful supplies of mycorrhizae spores that lead to better inoculation of the following crop, helping it to take up soil nutrients.

IMPROVING NUTRIENT CYCLING ON THE FARM

For economic and environmental reasons, it makes sense for plants to more efficiently utilize nutrient cycling on the farm. Goals should include a reduction in long-distance nutrient flows, as well as the promotion of "true" on-farm cycling, in which nutrients return in the form of crop residue or manure to the fields from which they came. There are a number of strategies to help farmers reach the goal of better nutrient cycling:

- ***Reduce unintended losses*** by promoting water infiltration and better root health through enhanced management of soil organic matter and physical properties. Methods to increase and improve organic matter status include additions of a variety of sources of organic materials as well as methods for reducing losses from tillage and adopting conservation practices. Proper irrigation water management involves applying the right amount of irrigation water needed to refill the root zone. Applying excessive irrigation water can cause both runoff and leaching losses of nutrients. (In arid climates occasional extra water applications will be needed to leach accumulating salts below the root zone.) In addition,

THE ABCs OF NUTRIENT MANAGEMENT

a. Balance nutrient inflows and removals to maintain optimal levels and allow a little "drawdown" if nutrient levels get too high.
b. Enhance soil structure to increase plant capture of soil nutrients and reduce their loss in runoff by minimizing tillage, reducing compaction and promoting deeper rooting to access nutrients lower in the soil.
c. Build up and maintain high soil organic matter levels for biodiverse soils and to develop healthy plant roots.
d. Test manures and credit their nutrient content before applying fertilizers or other amendments.
e. If using liquid manure, consider soil injection to reduce N volatilization and potential loss of nutrients in runoff.
f. Test soils regularly to determine the nutrient status and whether or not manures, fertilizers or lime are needed.
g. Use regionally adapted nutrient recommendation tools.
h. Apply most nitrogen close to the time of crop uptake, and use recommendation tools that account for soil, weather and management practices.
i. Use forage legumes or legume cover crops to provide N to subsequent crops and to develop good soil structure.
j. Use cover crops to tie up nutrients during the off-season, enhance soil structure, reduce runoff and erosion, and provide microbes with fresh organic matter.
k. Maintain soil pH in the optimal range for the most sensitive crops in your rotation.
l. When P and K are very deficient, broadcast some of the fertilizer to increase the general soil fertility level, and band apply some as well.
m. To get the most efficient use of a fertilizer when P and K levels are at or below the medium or lower categories, consider band application at planting, especially in cool climates.

NUTRIENT MANAGEMENT GOALS

- Satisfy crop nutrient requirements for optimum economic yield and quality.
- Minimize pest pressure caused by excess N fertilizer (such as from sap-feeding insects) or by a nutrient deficiency (low K causes less wheat resistance to rust and corn to stem rot).
- Minimize the environmental and economic costs of supplying nutrients.
- Use local sources of nutrients whenever possible.
- Get full nutrient value from fertility sources.

—MODIFIED FROM OMAFRA, 1997

compared to conventional annual row crops such as corn and soybeans, rotations that include cover crops and perennial grass and legume crops tend to result in less leaching loss of nitrate as well as runoff phosphorus loss.

- ***Enhance nutrient uptake efficiency*** by carefully using fertilizers and amendments, as well as irrigation practices. Better placing and synchronizing nutrient applications with plant growth improve efficiency of fertilizer nutrients. Sometimes changing planting dates or switching to a new crop creates a better match between the timing of nutrient availability and crop needs.
- ***Tap local nutrient sources*** by seeking local organic materials, such as leaves or grass clippings from towns, aquatic weeds harvested from lakes, produce waste from markets and restaurants, food processing wastes and clean sewage sludges (see discussion on sewage sludge in Chapter 9). Caution always makes sense when receiving organic materials from off the farm; for example, grass might have been treated with herbicide, and municipal leaves may contain extraneous materials. Although some of these do not contribute to true nutrient cycles, the removal of agriculturally usable nutrients from the “waste stream” makes sense and helps develop more environmentally sound nutrient flows. The Food Safety Modernization Act (FSMA) requires greater care with use of certain organic materials, such as manures, when growing produce for the fresh market due to the potential for food to be contaminated with pathogens. Composting the materials from on or off the farm may be needed to comply with these regulations.
- ***Promote consumption of locally produced foods*** by supporting local markets as well as by returning local food wastes to farmland. When people purchase locally produced foods, there are more opportunities for true nutrient cycling to occur. Some community supported agriculture (CSA) farms, where subscriptions for produce are paid before the start of the growing season, encourage their members to return produce waste to the farm for composting, and a portion of the nutrients in the produce complete a true cycle.
- ***Reduce exports of nutrients in farm products***

STRATEGIES FOR IMPROVING NUTRIENT CYCLES

- Reduce unintended losses.
- Enhance nutrient uptake efficiency.
- Tap local nutrient sources.
- Promote consumption of locally produced foods.
- Reduce off-farm exports of nutrients and carbon in farm products.
- Bring animal densities in line with the land base of the farm.
- Develop local partnerships to balance flows among different types of farms.

by adding animal enterprises to crop farms. The best way to reduce nutrient exports per acre, as well as to make more use of forage legumes in rotations, is to add an animal (especially a ruminant) enterprise to a crop farm. Compared with selling crops, feeding crops to animals and exporting animal products result in far fewer nutrients and carbon leaving the farm. Keep in mind that, on the other hand, raising animals with mainly purchased feed overloads a farm with nutrients.

- ***Bring animal densities in line with the land base of the farm***. Renting or purchasing more land—to grow a higher percentage of animal feeds and to have increased area for manure application—or limiting animal numbers are ways to accomplish this.
- ***Develop local partnerships to balance flows among different types of farms***. As pointed out in Chapter 9 when we discussed organic matter management, sometimes neighboring farmers cooperate with both nutrient management and crop rotations. This is especially beneficial when a livestock farmer has too many animals and imports a high percentage of feed, and a neighboring vegetable or grain farmer has a need for nutrients and an inadequate land base for allowing a rotation that includes a forage legume. Both farms win by cooperating on nutrient management and rotations, sometimes in ways that were not anticipated (see "Win-Win Cooperation" box), but it is more of a challenge as the distances become greater. As of January 2020, the Food Safety Modernization Act requires a range of practices and documentation for all farms selling more than $25,000 worth of products. The implications of this legislation for farm practices is discussed in Chapter 12, on integrating livestock and cropping.

Some livestock farms that are overloaded with nutrients would like to transfer manure to other farms but find that transportation costs are a factor (manures contain up to 90% water). Separating liquids (which are high in N) from solids using a settling or mechanical screw press system can be helpful. Also, farmers are finding that composting is an attractive alternative way to handle manure. During the composting process,

Table 18.1
Essential Nutrients for Plants

Element	Common Available Form	Source
Needed in Large Amounts		
Carbon	CO_2	atmosphere
Oxygen	O_2, H_2O	atmosphere and soil pores
Hydrogen	H_2O	water in soil pores
Nitrogen	NO_3^-, NH_4^+	soil (atmosphere for legumes)
Phosphorus	$H_2PO_4^-$, HPO_4^{-2}	soil
Potassium	K^+	soil
Calcium	Ca^{+2}	soil
Magnesium	Mg^{+2}	soil
Sulfur	SO_4^{-2}	soil
Needed in Small Amounts		
Iron	Fe^{+2}, Fe^{+3}	soil
Manganese	Mn^{+2}	soil
Copper	Cu^+, Cu^{+2}	soil
Zinc	Zn^{+2}	soil
Boron	H_3BO_3	soil
Molybdenum	MoO_4^{-2}	soil
Chlorine	Cl^-	soil
Nickel	Ni^{+2}	soil
Needed by Some Plants[1,2]		
Cobalt	Co^{+2}	soil
Sodium	Na^+	soil
Silicon	H_4SiO_4 and $H_2SiO_4^{-2}$	soil

[1] Cobalt has been shown to be essential only for legumes; sodium (Na) is considered an essential element for some plants; and silicon (Si) is considered essential for the normal growth and health of rice.

[2] Although selenium (Se) is not considered an essential element for plants, it is essential for animals, and so the Se content of plants is important for animal nutrition. On the other hand, plants growing on high-Se soils (such as locoweed, asters and saltbushes) accumulate enough Se to become toxic to grazing animals.

volume and weight are greatly reduced (see Chapter 13), resulting in less material to transport. Organic farmers are always on the lookout for reasonably priced animal manures and composts. The landscaping industry also uses a fair amount of compost. Local or regional compost exchanges can help remove nutrients from overburdened animal operations and place them on nutrient-deficient soils.

USING FERTILIZERS AND AMENDMENTS

There are four main questions to ask when applying nutrients:

- How much is needed?
- What source(s) should be used?
- When should the fertilizer or amendment be applied?
- How should the fertilizer or amendment be applied?

Chapter 21 details the use of soil tests to help you decide how much fertilizer or organic nutrient sources to apply. Here we will go over how to approach the other three issues.

Nutrient Sources: Commercial Fertilizers Versus Organic Materials

Numerous fertilizers and amendments are normally used in agriculture (some are listed in Table 18.1). Fertilizers such as urea, triple superphosphate and muriate of potash (potassium chloride) are convenient to store and use. They are also easy to blend to meet nutrient needs in specific fields and provide predictable effects. Their behavior in soils and the ready availability of the nutrients are well established. The timing, rate and uniformity of nutrient application are easy to control when using commercial fertilizers. However, there also are drawbacks to using commercial fertilizers. All of the commonly used N materials (those containing urea, ammonia and ammonium) are acid forming, and their use in humid regions, where native lime has been weathered and leached out, requires more frequent lime additions. The production of nitrogen fertilizers is also very energy intensive; it is estimated that, aside from solar energy that the crop uses, N fertilizers account for 25%–50% of the energy that goes into growing a corn crop. In addition, the high nutrient solubility can result in salt or ammonia damage to seedlings when excess fertilizer is applied close to seeds or plants. Nutrients in commercial fertilizers are readily available and allow for more precise timing with crop uptake, but if managed improperly they may become more readily lost to the environment compared to organic nutrient sources. (On the other hand, high rainfall events on a field with recently plowed-down alfalfa or applied manure may also result in significant nitrate leaching below the root zone.) Slow-release forms of synthetic nitrogen fertilizers such as sulfur- or polymer-coated urea help better match N availability to crop needs. Similarly, adding nitrification and urease inhibitors can

WIN-WIN COOPERATION

Cooperation between Maine potato farmers and their dairy farm neighbors has led to better soil and crop quality for both types of farms. As potato farmer John Dorman explains, after cooperating with a dairy farm on rotations and manure management, soil health "has really changed more in a few years than I'd have thought possible." Dairy farmer Bob Fogler feels that the cooperation with the potato farmer allowed his family to expand the dairy herd. He notes, "We see fewer pests and better-quality corn. Our forage quality has improved. It's hard to put a value on it, but forage quality means more milk."

—FROM HOARD'S DAIRYMAN, APRIL 10, 1999

Table 18.2
Composition of Various Common Amendments and Commercial Fertilizers (%)

	N	P_2O_5	K_2O	Ca	Mg	S	Cl
N Materials							
Anhydrous ammonia	82						
Aqua ammonia	20						
Ammonium nitrate	34						
Ammonium sulfate	21					24	
Calcium nitrate	16			19	1		
Urea	46						
UAN solutions (urea + ammonium nitrate)	28–32						
P and N+P Materials							
Superphosphate (ordinary)		20		20		12	
Triple superphosphate		46		14		1	
Diammonium phosphate (DAP)	18	46					
Monoammonium phosphate (MAP)	11–13	48–52					
K Materials							
Potassium chloride (muriate of potash)			60				47
Potassium–magnesium sulfate (“K-Mag”)			22		11	23	2
Potassium sulfate			50		1	18	2
Other Materials							
Gypsum				23		18	
Limestone, calcitic				25–40	0.5–3		
Limestone, dolomitic				19–22	6–13		1
Magnesium sulfate				2	11	14	
Potassium nitrate	13		44				
Sulfur (elemental S, gypsum, ammonium sulfate)						30–99	
Wood ashes		2	6	23	2		

facilitate more efficient nitrogen fertilizer use. Organic fertilizers generally contain a significant slow-release portion of N but are of such variable composition that it is difficult to know how much will be released in a given time. Feather meal, a commercially available processed organic fertilizer, is about 12%–13% nitrogen, with most released slowly.

Soils overloaded with either inorganic or organic sources of nutrients can be large sources of pollution. The key to wisely using either commercial fertilizers or organic sources is following recommendations based on soil tests, not applying more nutrients than the crop can use, and applying in ways and at times that minimize losses to the environment. Once the soil nutrient status is optimal, try to balance farm nutrient inflows and outflows. When nutrient levels, especially P, are in the high or very high range, stop application and try to maintain or “draw down” soil test levels. It usually takes years of cropping without adding P to lower soil test P appreciably. With grazing animals it can take a very long time because so few nutrients are being exported from the field and farm in animal products. On the other

ARE ORGANIC NUTRIENT SOURCES BETTER FOR SOIL AND THE ENVIRONMENT THAN SYNTHETIC FERTILIZERS? THE ANSWER IS COMPLICATED!

It is recommended to include organic nutrient sources as part of a nutrient management program to sustain soil health because they feed the plants while also better supporting soil biological functions. But on many farms commercial fertilizers are required to achieve good yields. Due to the structure of agriculture with associated nutrient flows (especially exports from grain production areas) and to the current inefficiencies in cropping systems, commercial fertilizers remain essential to feeding a growing global population. In fact, completely eliminating commercial fertilizers would not only cause a breakdown of the global food system, it would also negatively affect soil health. Inadequate nutrition of crops would reduce carbon capture from the atmosphere, biomass production and yields, and thereby also fresh carbon and nutrient supplies for the soil. Additional nutrients are critical to building organic matter in depleted soils (every ton of new carbon stored in the soil requires about 200 pounds of additional nitrogen and 30 pounds of phosphorus). Therefore, although organic matter is critical to building soil health, commercial fertilizers may be needed to achieve our goals.

At the global scale, commercial fertilizers are still critical to meeting the demands of our growing population until better practices (cover crops, better rotations, decreased tillage, integrating animal and plant agriculture, cooperating with nearby farms and towns, etc.) are used to lessen nutrient flows off the farm and until farms obtain more nutrients from local sources (legumes, leaves, composts, collected kitchen wastes, manures, clean sludges [biosolids]).

Regarding environmental losses, it is commonly assumed that the use of organic nutrient sources always results in lower impacts. This is only true if good management practices are followed. A study in Sweden compared conventional and organic crop production and found similar nitrate leaching losses. For example, in temperate climates a plowed alfalfa sod or a large manure application releases a lot of inorganic nitrogen that can easily meet all the needs of the following corn crop. However, if alfalfa is plowed too early—for example, in the early fall—much of the organic N is mineralized in the following months when the soil is still warm and can be lost through leaching or denitrification over the winter and spring. In this case N losses might be as high as when N fertilizer is applied too early. Organic sources may also create a problem with nutrient runoff if left on the surface, or with leaching when applied out of sync with plant uptake. While using organic nutrient sources has greater benefits for soil health than commercial fertilizers, the environmental impacts in both cases are best addressed through good agronomic management including 4R practices and careful consideration of environmental impacts.

hand, when hay is harvested and sold off the farm, P drawdown can happen more rapidly.

Organic sources of nutrients have many other good qualities. Compared to commercial fertilizers that only “feed the plants,” organic materials also “feed the soil,” increasing biological activity by providing soil organisms with sources of energy as well as nutrients. Aggregates and humus are formed as organisms use the added organic materials. Organic sources can provide a more slow-release source of fertility, and the N availability better coincides with the needs of growing plants. Sources like manures or crop residues commonly contain all the needed nutrients, including the micronutrients, but they may not be present in the proper proportion for a particular soil and crop; thus, routine soil testing is important. Poultry manure, for example, has about the same levels of N and P, but plants take up three to five times more N than P. Applying it based on N needs of plants will therefore load the soil with unneeded P, increasing the pollution potential of any runoff. A lot of N is commonly lost during the composting process, making the compost much richer in P relative to N. Thus, applying a large quantity of compost to a soil that has sufficient P might supply a crop's N needs but enriches the soil in unneeded P, creating a greater pollution potential.

One of the drawbacks to organic materials is the variable amounts and uncertain timing of nutrient release for plants to use. The value of manure as a nutrient source depends on the type of animal, its diet, and manure handling and application. For cover crops, the N contribution depends on the species, the amount of growth in the spring and the weather. In addition, manures typically are bulky and may contain a high percentage of water, so considerable effort is required to apply them per unit of nutrients. The timing of nutrient release is uncertain because it depends both on the type of organic materials used and the action of soil organisms. Their activities change with temperature and rainfall. Finally, the relative nutrient concentrations for a particular manure may not match soil needs. For example, manures may contain high amounts of both N and P when your soil already has high P levels.

Selection of Commercial Fertilizer Sources

There are numerous forms of commercial fertilizers given in Table 18.2. When you buy fertilizers in large quantities, you usually choose the cheapest source. When you buy bulk blended fertilizer, you usually don't know what sources were used unless you ask. All you know is that it's a 10-20-20 or a 20-10-10 (both referring to the percent of available N, P_2O_5 and K_2O) or another blend. However, below is a number of examples of situations in which you might not want to apply the cheapest source.

- Although the cheapest N form is anhydrous ammonia, the problems with injecting it into a soil with many large stones or the losses that might occur if you inject it into very moist clay or dry sandy soil may call for other N sources to be used instead.
- If both N and P are needed, diammonium phosphate (DAP) is a good choice because it has approximately the same cost and P content as concentrated superphosphate and also contains 18% N.
- Although muriate of potash (potassium chloride) is

UNDERSTANDING THE TERMS: ORGANIC FARMING VERSUS ORGANIC NUTRIENT SOURCES

For some, there is confusion around the term "organic." We have used the term "organic sources" of nutrients to refer to nutrients contained in crop residues, manures and composts—i.e., the nutrients are applied in organic forms. All farmers, "conventional" and "organic," use these types of materials. Both also use limestone and a few other materials. However, most of the commercial fertilizers listed in Table 18.2 are not allowed in organic production because they are synthetically derived. In place of sources such as urea, anhydrous ammonia, diammonium phosphate, concentrated superphosphate and muriate of potash, organic farmers use products that come directly from minerals, such as greensand, granite dust and rock phosphate. Other organic products come from parts of organisms, such as bone meal, fish meal, soybean meal and blood meal (see Table 18.3). Finally, to make matters more confusing, many countries, especially in Europe, label products as "bio" or "biological" when they are grown using organic practices.

the cheapest K source, it may not be the best choice under certain circumstances. If you also need magnesium and don't need to lime the field, potassium magnesium sulfate would be a better choice.

The choice of fertilizer should be based on the nutrient needs of the crop and their availability in the soil (ideally determined by a soil test). However, the availability of the right fertilizer source may depend on the region. In countries with sophisticated agricultural supply infrastructures (like North America and Europe), farmers have a lot of choices of fertilizer materials and blends that match their needs. But in many developing countries fertilizer markets are underdeveloped and products are more expensive due to high transportation costs. (A 2011 study found fertilizer prices in Sub-Saharan Africa to be four times higher than in Europe). This limits the choices of fertilizer materials, and oftentimes farmers use only one or two fertilizer types (like DAP) without knowing the true crop needs.

Method and Timing of Application

Fertilizer application timing and application methods are frequently related, so in this section both will be reviewed together.

Broadcast fertilizer application is evenly distributed over the whole field using a spin applicator (for granules) or sprayer (for liquids). If using plow or harrow tillage, it would usually be incorporated during tillage. Broadcasting is best used to increase the nutrient level of the bulk of the soil. It is especially useful to build P and K when they are very deficient. When using no-till, nutrients tend to be more stratified and care should be taken to lessen potential runoff that would be enriched in phosphorus—routine cover cropping will especially help. Broadcasting (with or without incorporation) usually occurs in the fall or in spring just before tillage. Broadcasting on top of a growing crop, called *topdressing*, is commonly used to apply N, especially to crops that occupy the entire soil surface, such as wheat or a grass hay crop. (Amendments used in large quantities, like lime and gypsum, are also broadcast over the soil surface.)

There are various methods of applying localized placement of fertilizer. Liquid nitrogen is often injected into the soil in ***bands*** because it reduces the potential for losses. Banding smaller amounts of fertilizer to the side and below the seed (usually two inches away) at planting is also a common application method. It is especially useful for row crops grown in cool soil conditions—early in the season, for example—on soils with high amounts of surface residues, with no-till management, or on wet soils that are slow to warm in the

Table 18.3
Products Used by Organic Growers to Supply Nutrients

	% N	% P_2O_5	% K_2O
Alfalfa pellets	2.7	0.5	2.8
Blood meal	13	2	—
Bone meal	3	20	0.5
Cocoa shells	1	1	3
Colloidal phosphate	—	18	—
Compost	1	0.4	3
Cottonseed meal	6	2	2
Fish scraps, dried and ground	9	7	—
Granite dust	—	—	5
Greensand	—	—	7
Hoof and horn meal	11	2	—
Linseed meal	5	2	1
Rock phosphate	—	30	—
Seaweed, ground	1	0.2	2
Soybean meal	6	1.4	4
Tankage	6.5	14.5	—
Feather meal	11–13	—	—

Notes:
1. Values of P_2O_5 and K_2O represent total nutrients present. For fertilizers listed in Table 18.2, the numbers are the amount that are readily available.
2. Organic growers also use potassium magnesium sulfate ("sul-po-mag" or "K-mag"), wood ashes, limestone and gypsum (listed in Table 18.2). Although some use only manure that has been composted, others will use aged manures (see Chapter 12). There are also a number of commercial organic products with a variety of trade names. (See materials listed by the Organic Materials Review Institute (OMRI) at www.omri.org.)
Source: R. Parnes (1990)

spring. It is also useful for soils that test low to medium (or even higher) in P and K. Band placement of fertilizer near the seed at planting, usually called ***starter fertilizer***, may be a good idea even in warmer climates when planting early. It still might be cool enough to slow root growth and release of nutrients from organic matter. Including N as part of the starter fertilizer appears to help roots use fertilizer P more efficiently, perhaps because N stimulates root growth. Starter fertilizer for soils very low in fertility frequently contains other nutrients, such as sulfur, zinc, boron or manganese. While liquid starter fertilizer applied along with the seed at planting has proven successful in no-till planting of small grains, nitrogen rates need to be matched to soil type and planter type, and to row and seed spacing to avoid salt or ammonia damage.

Splitting N applications is a good management practice, especially on sandy soils where nitrate is easily lost by leaching, or on heavy loams and clays, where it can be lost by denitrification. Some N can be applied before planting or in the starter fertilizer band, and the rest can be applied as a *sidedress* or *topdress* during the growing season. In almost all situations sidedressing a good portion of needed N fertilizer is recommended for efficient use. However, this can increase the risk of reduced yields if the weather is too wet to apply the fertilizer (and you haven't put on enough N in a preplant or starter application) or is too dry following an application. In the latter case the fertilizer stays on the surface instead of washing into the root zone. Although unusual nationally, recommendations for split K applications are made for very sandy soils with low organic matter, such as on Georgia's coastal plain, especially if there has been enough rainfall to cause K to leach into the subsoil. Almost all commercial vegetable farmers use irrigation and can easily apply fertilizer through the watering system during the season (this is called "fertigation"). This is especially attractive with drip irrigation, which allows

CROP VALUE, FERTILIZER COST AND FERTILIZER RATES

Most agronomic crops grown on large acreages are worth around $400–$1,000 per acre, and the fertilizer used may represent 25% of non-land growing costs. So, if a corn farmer uses 100 pounds of N that's not needed (at about $40), that may represent 5% or more of gross income. Add in some unneeded P and K and the implications for lost net revenue become clear. Some years ago, one of the authors of this book worked with two brothers who operated a dairy farm in northern Vermont that had high soil test levels of N, P and K. Despite his recommendation of no fertilizer, the normal practice was followed, and N, P and K fertilizer worth $70 per acre (in 1980s prices) was applied to their 200 acres of corn. The yields on 40-foot-wide, no-fertilizer strips that they left in each field were the same as where fertilizer had been applied, so while some of the P and K might be available to crops in future years, the $14,000 they spent on fertilizer was mostly wasted.

When growing fruit or vegetable crops worth thousands of dollars per acre, fertilizers represent about 1% of the value of the crop and 2% of the costs. But when growing specialty crops (medicinal herbs, certain organic vegetables for direct marketing) worth over $10,000 per acre, fertilizer costs are dwarfed by other costs, such as hand labor. A waste of $70 per acre in unneeded nutrients for these crops would cause a minimal economic penalty, assuming you maintain a reasonable balance between nutrients, but there may be environmental and crop quality reasons against applying too much fertilizer. In general, relative nutrient expenses are greatest for the low-value crops, but these are also grown on the most extensive acres where cumulatively they have the biggest environmental impacts.

FERTILIZER GRADE: OXIDE VERSUS ELEMENTAL FORMS

When talking or reading about fertilizer P or K, the oxide forms are used. They are also used in all recommendations and when you buy fertilizer. The terms "phosphate" (P_2O_5) and "potash" (K_2O) have been used for so long to refer to phosphorus and potassium in fertilizers, it is likely that they will be with us indefinitely, even if they are confusing. In fact, their use is codified in state regulations in the United States and by national regulations in Canada. When you apply 100 pounds of potash per acre, you actually apply 100 pounds of K_2O: the equivalent of 83 pounds of elemental potassium. Of course, you are really not using K_2O but are rather using something like muriate of potash (KCl). It's similar with phosphate—100 pounds of P_2O_5 per acre is the same as 44 pounds of P—and you're really using fertilizers like concentrated superphosphate (that contains a form of calcium phosphate) or ammonium phosphate. However, in your day-to-day dealing with fertilizers you need to think in terms of nitrogen, phosphate and potash, and not in actual amounts of elemental P or K you purchase or apply.

spoon feeding of the crop to maximize nutrient uptake efficiencies. Fertigation of agronomic row crops is common in some regions, frequently by center pivot systems.

Tillage and Fertility Management: To Incorporate or Not?

It is possible to incorporate fertilizers and amendments with systems that provide some tillage, such as moldboard plow and harrow, disk harrow alone, chisel plow, zone/strip-till and ridge-till. However, when using pure no-till production systems, it is not possible to mix fertilizer materials into the soil to uniformly raise the fertility level in that portion of the soil where roots are especially active. However, surface-applied fertilizers in no-till systems usually work their way down to the upper part of the root zone.

When broadcasting fertilizer without incorporation, as occurs with no-till, there are potential losses that can occur. For example, significant quantities of ammonia may be lost by volatilization when the most commonly used solid N fertilizer, urea, is left on the soil surface. Thus if rainfall isn't going to occur very soon after application, another solid source of N fertilizer or a liquid fertilizer should be used. Also, nutrients remaining on the surface after application are much more likely to be lost in runoff during rain events. Although the amount of runoff is usually lower with reduced tillage systems than with conventional tillage, the concentration of nutrients in the runoff may be quite a bit higher. This makes using cover crops as a routine management practice even more important. Over time, using no-till and cover crops, rainfall infiltration rates tend to increase, lessening runoff.

A special concern exists with heavy clay soils that develop continuous macropores from cracks and biological activity (especially deep-burrowing earthworms). Although this is generally good for the health of the soil and crop growth, it can also pose concerns with fertilizer and manure applications when the soils have subsurface (tile) drainage. When materials applied on the soil surface are not incorporated, nutrients can readily enter the macropores with heavy rains, move rapidly to the

SOIL TESTS

Routine soil tests, one of the key nutrient management tools, are discussed in detail in Chapter 21. For newer soil health tests see Chapter 23.

tile lines and then discharge into waterways.

If you are thinking about changing from conventional tillage to no-till or other forms of reduced tillage, incorporate needed lime, phosphate and potash, as well as manures and other organic residues, before making the switch. It's your last chance to easily change the fertility of the top 8 or 9 inches of soil.

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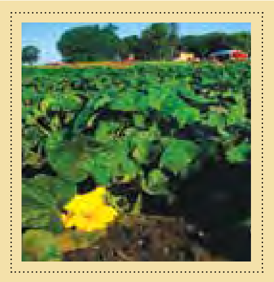
Chapter 19

MANAGEMENT OF NITROGEN AND PHOSPHORUS



… an economical use of fertilizers requires that they merely supplement the natural supply in the soil, and that the latter should furnish the larger part of the soil material used by the crop.

—T.L. LYON AND E.O. FIPPIN, 1909

Both nitrogen and phosphorus are needed by plants in large amounts, and both can cause environmental harm when present in excess. They are discussed together in this chapter because we don't want to prioritize the management of one nutrient and neglect the other; it's important to consider balanced nutrition. And when applying manures and composts, which contain N and P (as well as other nutrients, of course), there is no alternative to taking both into consideration. Nitrogen losses are an economic concern for farmers: If not managed properly, a large fraction (as much as half in some cases) of applied N fertilizer can be lost instead of used by crops. Environmental concerns with N include the leaching of soil nitrate to groundwater, excess N in runoff, and losses of nitrous oxide (a potent greenhouse gas). For P, the main concerns are losses to freshwater bodies through runoff and leaching into tile drains.

High-nitrate groundwater is a health hazard to infants and young animals because it decreases the blood's ability to transport oxygen. There is accumulating evidence that high-nitrate drinking water might have adverse health effects on adults as well. In addition, as surface waters become enriched with nutrients (the process is called eutrophication) there is an increase in aquatic plant growth. Nitrate stimulates the growth of algae and aquatic plants, just as it stimulates the growth of agricultural plants. The growth of plants in many brackish estuaries and saltwater environments is believed to be limited by a lack of N. So, undesirable microorganisms flourish when nitrate leaches through soil or runs off the surface and is discharged into streams, eventually reaching water bodies like the Gulf of Mexico, the Chesapeake Bay, Puget Sound or the Great Lakes, and increasingly many others around the world. In addition, the algal blooms that result from excess N and P cloud water, blocking sunlight to important underwater grasses that are home to numerous species of young fish, crabs and other bottom dwellers. The greatest concern, however, is the dieback of the algae and other aquatic plants. These plants settle on the

Photo by Dennis Nolan

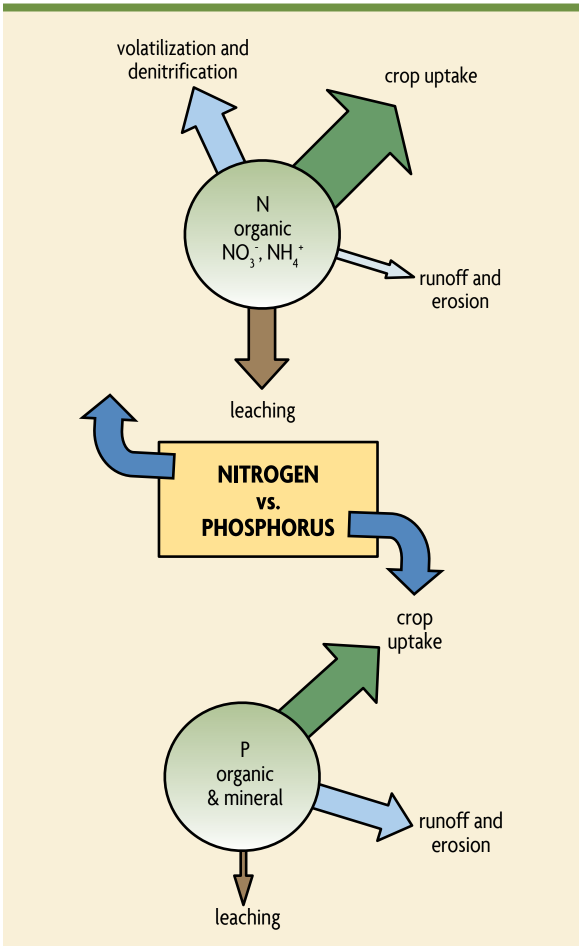


Figure 19.1. Different pathways for nitrogen and phosphorus losses from soils (relative amounts indicated by width of arrows). Based on an unpublished diagram by D. Beegle, Penn State University.

bottom of the affected estuaries, and their decomposition consumes dissolved oxygen in the water. The result is an extended area of very low oxygen concentrations in which fish and other aquatic animals cannot live. This is a serious concern in many estuaries around the world, and despite government efforts to curtail the flow of nutrients, most of these dead zones appear to be growing rather than shrinking (the Gulf of Mexico's dead zone still averages three times larger than the goal set by the U.S. Environmental Protection Agency).

Nitrogen can also be lost from soil by denitrification, a microbial process that occurs primarily when soils are saturated with water. It is especially problematic in soils with poor structure due to compaction or other causes, frequently a result of excessive tillage. Soil bacteria convert nitrate to both nitrous oxide (N_2O) and N_2. While N_2 (two atoms of nitrogen bonded together) is the most abundant gas in the atmosphere and not of environmental concern, each molecule of N_2O gas—largely generated by denitrification, with some contribution from nitrification—has approximately 300 times more climate change impact than a molecule of carbon dioxide. According to the U.S. Environmental Protection Agency, N_2O accounts for 55% of the agricultural greenhouse gas emissions and 5% of the total emissions of all economic sectors combined, which is equivalent to twice the impact from the aviation industry.

Phosphorus losses from farms are generally small in relation to the amounts present in soils. However, small quantities of P loss have great effects on water quality because P is the nutrient that frequently limits the growth of freshwater aquatic weeds, algae and cyanobacteria (also called "blue green algae"). Phosphorus damages the environment when excess amounts are added to a lake from human activities (agriculture, rural home septic tanks, or urban sewage and street runoff). This eutrophication increases algae growth, which makes fishing, swimming and boating unpleasant or difficult. When excess aquatic organisms die, decomposition removes oxygen from water and leads to fish kills. This is a large concern in the freshwater lakes near the authors' homes in Vermont and New York where dairy farming is prevalent, and in recent years it has created a very extensive low oxygen (hypoxia) zone in the western part of Lake Erie.

All farms should work to have the best N and P management possible for economic as well as environmental reasons. This is especially important near bodies of water that are susceptible to accelerated weed or algae

PROBLEMS USING EXCESS N FERTILIZER

There are quite a few reasons you should not apply more N than is needed by crops. N fertilizers are costly, and many farmers are judicious with application rates. However, there are other problems associated with using more N than needed: 1) groundwater and surface water become polluted with nitrates; 2) more N_2O (a potent greenhouse gas and source of ozone depletion) is produced during denitrification in soil; 3) a lot of energy is consumed in producing N, so wasting N is the same as wasting energy; 4) using higher N than needed is associated with accelerated decomposition and loss of soil organic matter; and 5) very high rates of N are frequently associated with high levels of insect damage. For many farmers, the challenge is knowing the correct N fertilizer rate for their crop in the particular growing season. With this uncertainty and with the risk of yield losses from insufficient fertilizer applications, they tend to apply more than needed in many years. Good N management tools can help address this concern.

growth. However, don't forget that nutrients from farms in the Upper Midwest are contributing to problems in the Gulf of Mexico over 1,000 miles away.

There are major differences between the way N and P behave in soils (Figure 19.1, Table 19.1). Both N and P can, of course, be supplied in applied fertilizers. But aside from legumes that can produce their own N because of the bacteria living in root nodules, crop plants get their N from decomposing organic matter. On the other hand, there is no biological process that can add P to soils, and plants get their P from soil minerals as well as from decomposing organic matter. Nitrate, the primary form in which plants absorb nitrogen from the soil, is very mobile in soils, while P movement in soils is very limited.

Most N loss from soils occurs when nitrate leaches, is converted into gases by the process of denitrification, or is volatilized from surface ammonium. When water exceeds plant needs, large amounts of nitrate may leach from sandy soils, while denitrification is generally more significant in heavy loams and clays. On the other hand, P is lost from soils in lesser quantities when it is carried away in runoff or in sediments eroded from fields, construction sites and other exposed soil (see Figure 19.1 for a comparison between relative pathways for N and P losses). But generally lower P losses are associated with higher impact per unit of nutrient on water quality, so the overall environmental concerns with both N and P are therefore significant.

Except for highly manured fields, P losses in runoff and erosion from healthy grasslands is usually quite low because both runoff water and sediment loss are very low. Phosphorus leaching is a concern in fields that are artificially drained. With many years of excessive manure or compost application, soils saturated with P (often sands with low P sorption capacity) can start leaking P with the percolating water and can discharge it through drain lines or ditches. Also, liquid manure can move through preferential flow paths (wormholes, root holes, cracks, etc., especially in clay soils) directly to subsurface drain lines and contaminate water in ditches, which is then discharged into streams and lakes (see also Chapter 17). Cover crops help lessen nutrient loss by preferentially filling many of the large continuous pores with roots, causing more water to flow through the main matrix of the soil and allowing for better nutrient retention.

Improving N and P management can help reduce reliance on commercial fertilizers. A more ecologically based system, with good rotations, reduced tillage and

Table 19.1
Comparing Soil N and P

Nitrogen	Phosphorus
Nitrogen becomes available from decomposing soil organic matter, commonly supplying about one third or more of crop uptake.	Phosphorus becomes available from decomposing soil organic matter and minerals.
N is mostly available to plants as nitrate (NO_3^-), a form that is very mobile in soils. Some ammonium (NH_4^+) and small nitrogen-containing organic molecules such as amino acids are also taken up by plants.	P is relatively immobile and is only available to plants in small concentrations as dissolved phosphorus in the soil solution, mainly as H_2PO_4– and HPO_4^{-2}.
Nitrate can be easily lost in large quantities by leaching to groundwater or by conversion to gases (N_2, N_2O).	P is mainly lost from soils through runoff and erosion. However, excessive fertilizer P or manure application on well-structured soils and on those with tile drainage has resulted in P loss to drainage water.
Nitrogen can be added to soils by biological N fixation (legumes). Cover crops can store nitrogen that would otherwise be lost by leaching and denitrification, providing the N to the following crop.	No equivalent reaction can add new P to soil, although many bacteria and some fungi (especially mycorrhizae) help plants take up more P. Cover crops can mobilize P from soil and store it in their tissue, providing extra P to the following crop.

more active organic matter, should provide a large proportion of crop N and P needs. Better soil structure and attention to the use of appropriate cover crops can lessen N and P loss by reducing leaching, denitrification and/or runoff. Reducing the loss of these nutrients is an economic benefit to the farm and, at the same time, an environmental benefit to society. The greater N and P availability may be thought of as a fringe benefit of a farm with an ecologically based cropping system.

In addition, the manufacture, transportation and application of N fertilizers are very energy intensive. Of all the energy used to produce corn (including the manufacture and operation of field equipment), the manufacture and application of N fertilizer represents close to 30%. In the late 2010s energy (and N fertilizer) costs decreased from their record high levels, but it still makes sense for both environmental and economic reasons to use N fertilizers wisely. Relying more on biological fixation of N and efficient cycling in soils reduces depletion of a nonrenewable resource and may save you money as well. Although P fertilizers are less energy consuming to produce, a reduction in their use helps preserve this nonrenewable resource—the world's P mines will run out at some time in the future.

MANAGEMENT OF N AND P

Nitrogen and phosphorus behave very differently in soils, but many of the management strategies are actually the same or very similar. They include the following:

1. Take all nutrient sources into account.
    - Estimate nutrient availability from all sources.
    - Use soil tests to assess available nutrients. (Nitrogen soil tests are not available for all states. Some make N fertilizer recommendations based on fertilizer trials and estimates of cover crop contributions. Other methods for making N recommendations are discussed later in this chapter.)
    - Use manure and compost tests to determine nutrient contributions.
    - Consider nutrients in decomposing crop residues (for N only).
2. Reduce losses and enhance uptake (use 4R-Plus principles, fertilizer application using the *right rate*, at the *right time*, in the *right place*, in the *right amount*, plus conservation practices; see Chapter 18).
    - Use nutrient sources more efficiently.
    - Use localized placement of fertilizers below the soil surface whenever possible.
    - Split fertilizer application if leaching or denitrification losses are a potential problem (almost always for N only).
    - Apply nutrients when leaching or runoff threats are minimal.
    - Reduce tillage.

- Use cover crops.
- Include perennial forage crops in rotation.

3. Balance farm imports and exports once crop needs are being met.

Cover crops combined with minimal or no tillage is a set of practices that work well together. They improve soil structure; reduce the loss of nutrients through leaching, runoff and erosion; reduce denitrification loss of nitrates; and tie up N and P that otherwise might be lost between cash crops by storing these nutrients in organic forms.

Estimating Nutrient Availability

Good N and P management practices take into account the large amount of plant-available nutrients that come from the soil, especially soil organic matter and any additional organic sources like manure, compost, or a rotation crop or cover crop. Fertilizer should be used only to supplement the soil's supply in order to provide full plant nutrition (Figure 19.2).

Organic farmers try to meet all demands through these soil sources because additional organic fertilizers are generally very expensive. This is typically done by incorporating a legume as a crop or cover crop into the rotation or by adding high-N organic nutrient sources. When using organic fertilizers, the higher the percent N in the compost or in the other material, the more N will become available to plants. Little to no N will be available to plants if the amendment is around 2% N or less (corresponding to a high C:N ratio). But if it's around 5% N, about 40% of the N in the amendment will be available. And if it's 10% or 15% N (corresponding to a very low C:N ratio), 70 percent or more of the N in the amendment will be available to crops. On integrated crop-livestock farms soil organic N and P sources are typically sufficient to meet the crop's demand, but not always.

Since most plant-available P in soils is relatively strongly adsorbed by organic matter and clay minerals, estimating P availability is routinely done through soil tests. The amount of P extracted by chemical soil solutions can be compared with results from crop response experiments and can provide good estimates of the likelihood of a response to P fertilizer additions, which we discuss in Chapter 21.

Estimating N fertilizer needs is more complex, and soil tests generally cannot provide all the answers. The primary reason is that the amounts of plant-available N, mostly nitrate, can fluctuate rapidly as organic matter is mineralized and as N is lost through leaching or denitrification. These processes are greatly dependent on soil organic matter contents, additional N contributions from organic amendments, and weather-related factors like soil temperature (higher temperatures increase N mineralization) and soil wetness (saturated soils cause large

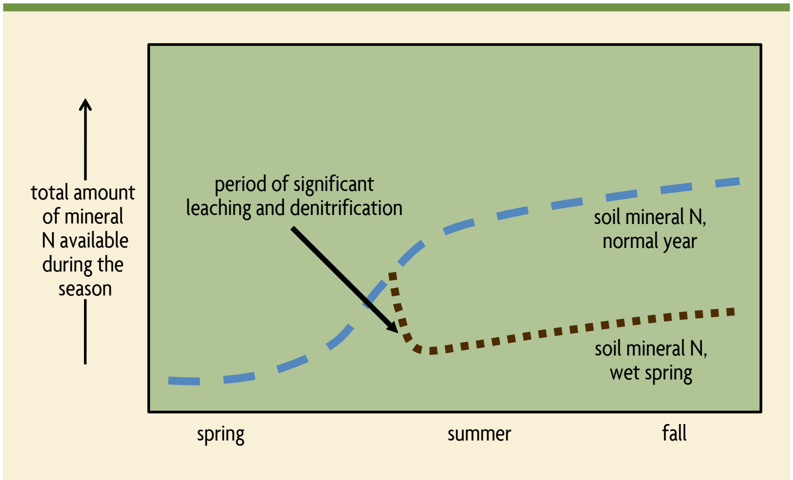


Figure 19.2. Available N in soil depends on recent weather. After increasing for a period, mineral N decreases during a wet spring because leaching and denitrification losses are greater than N being converted to mineral forms. More mineral N is available for plants when the spring is drier. (Gains and losses are greater when large amounts of organic applications, for example manure, are made.)

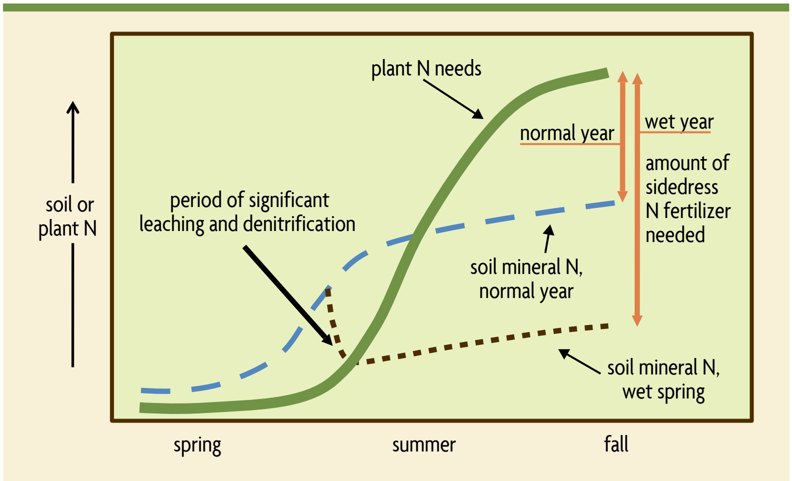


Figure 19.3. The need for supplemental N fertilizer depends on early season weather. Note: The amount of mineral N in soil will actually decrease (not shown) as plants begin to grow. They grow rapidly and take up large quantities of N faster than new N is converted to mineral forms.

leaching and denitrification losses, especially when soils are warm). Mineral forms of N begin to accumulate in soil in the spring but may be lost by leaching and denitrification during a very wet period (Figure 19.2). When plants germinate in the spring, it takes a while until they begin to grow rapidly and take up a lot of N (Figure 19.3). Weather affects the required amount of supplemental N in two primary ways. In years with unusually wet weather in the spring, an extra amount of sidedress (or topdress) N may be needed to compensate for relatively high mineral N loss from soil (Figure 19.3). The increasing rainfall intensity in some regions makes the use of sidedress N even more important. Research on corn in Minnesota from 2015 to 2019—where 75 percent of the sites evaluated had one month during the growing season with 150 percent of normal rainfall—indicated using sidedress N with some N applied before planting didn't decrease yields and actually increased yields by an average of 11 bushels an acre in a quarter of situations.

On the other hand, in dry years, especially drought spells during the critical pollination period, yields will be reduced, and the N uptake and needed N fertilizer are therefore lower (not shown in Figure 19.3). However, you really don't know at normal sidedress time whether there will be a drought during pollination, so there is no way to adjust for that. For a field with a given soil type and set of management practices, the actual amount of required N also depends on the complex and dynamic interplay of crop growth patterns with weather events, which are difficult to predict. In fact, optimum N fertilizer rates for corn without organic amendments in the U.S. corn belt have been found to vary from as little as 0 pounds per acre to as much as 250 pounds per acre. Those are the extremes, but, nevertheless, it is a great challenge to determine the optimum economic N rate. There may be different issues arising in other regions. In the Northwest's maritime region, large amounts of winter rainfall normally result in very low levels of available N in spring. Without much year-to-year carryover of mineral N and with low organic matter decomposition during the cool season, it is especially important to be sure that some readily available N is near the developing seedling of spring planted crops.

Fixed and Adaptive Methods for Estimating Crop N Needs

Several approaches are used to estimate crop N needs, and they can be grouped into *fixed* and *adaptive* approaches. Fixed (static) approaches assume that the N fertilizer needs do not vary from one season to another based on weather conditions, which may work well in drier climates but are very imprecise in a humid climate. Adaptive methods recognize that precise N fertilization requires additional data from field samples, sensors or computer models to modify the N rate for a particular production environment.

The mass-balance approach, a fixed approach, is the most commonly used method for estimating N fertilizer recommendations. It is generally based on a yield goal and associated N uptake, minus credits given for non-fertilizer N sources such as mineralized N from soil organic matter, preceding crops and organic amendments. However, studies have shown that the relationship between yield and optimum N rate is very weak for humid regions. While higher yields do require more N, the weather pattern that produces higher yields also implies 1) that larger and healthier root systems can take up more soil N, and 2) that frequently the weather pattern stimulates the presence of higher levels of nitrate in the soil. Conversely, very wet conditions cause reduced yields due to insufficient soil aeration and low soil N availability.

Several leading U.S. corn-producing states have adopted ***the maximum return to N (MRTN) approach***, another fixed method that largely abandons the mass-balance approach. It provides generalized recommendations based on extensive field trials, model-fitting and economic analyses. It is only available for corn at this time. The rate with the largest average net return to the farmer over multiple years is the MRTN, and the recommendations vary with grain and fertilizer prices. Adjustments based on realistic yield expectation are sometimes encouraged. The MRTN recommendations are based on comprehensive field information, but owing to generalizing over large areas and over many seasons, it does not account for the soil and weather factors that affect N availability and is therefore inherently imprecise for an individual field.

The ***adaptive approaches***, described in the following paragraphs, attempt to take into account seasonal weather, soil type and management effects, and require some type of measurement or model estimate during the growing season.

The pre-sidedress nitrate test (PSNT) measures soil nitrate content in the surface layer of 0–12 inches and allows for adaptive sidedress or topdress N applications. It implicitly incorporates information on early season weather conditions (Figure 19.2) and is especially successful in identifying N-sufficient sites: those that do not need additional N fertilizer. It requires a special sampling effort during a short time window in late spring, and it is sensitive to timing and mineralization rates during the early spring. The PSNT is usually called the late spring nitrate test (LSNT) in the midwestern United States.

Pre-plant nitrate and labile N tests measure soil nitrate, soil nitrate plus ammonium, or readily available organic nitrogen in the soil early in the season to guide N fertilizer applications at planting. These approaches are more effective in drier climates, like in the U.S. Great Plains where seasonal gains of inorganic forms of N are more predictable and losses from leaching or denitrification are generally minimal. Fall soil sampling can provide valuable information for N management for winter wheat while early spring season sampling is preferable for evaluating N needs for corn. These approaches cannot incorporate the seasonal weather effects, as the samples are analyzed prior to the growing season, which inherently limits its precision compared to the PSNT.

Recent advances in ***crop sensing*** and ***modeling*** allow adaptive approaches based on seasonal weather and local soil variation. Leaf chlorophyll meters that measure light transmission in leaves and satellite, aerial, drone or tractor-mounted sensors that determine light reflection from leaves are used for assessing leaf or canopy N status and biomass, which can then guide sidedress N applications. Environmental information systems and dynamic simulation models are now also being employed for N management, with successful applications for wheat and corn. This approach takes advantage of increasingly sophisticated environmental databases, such as radar-based, high-resolution precipitation estimates and detailed soil databases, and can be

Table 19.2
Comparison of N and P Management Practices

Nitrogen	Phosphorus
Use fixed-rate approaches for planning purposes and adaptive approaches to achieve precision.	Test soil regularly (and follow recommendations).
Test manures and credit their N contribution.	Test manures and credit their P contribution.
Use legume forage crops in rotation and/or legume cover crops to fix N for following crops, *and* properly credit legume N contribution to following crops.	No equivalent practice is available (although cover crop and cash crop mycorrhizae help mobilize soil P already there, making it more available to plants).
Time N applications as close to crop uptake as possible, and place to reduce runoff or gaseous losses.	Time and place P application to reduce runoff potential.
Reduce tillage in order to leave residues on the surface and to decrease runoff and erosion.	Reduce tillage in order to leave residues on the surface, to decrease runoff and erosion, and to keep mycorrhizal network intact.
Use sod-type forage crops in rotation to reduce nitrate leaching and runoff, making N more available to following crops.	Use sod-type forage crops in rotation to reduce the amount of runoff and erosion losses of P, making P more available to the following crop.
Use grass cover crops, such as cereal rye, to capture soil nitrates leftover following the economic crop.	Use grass cover crops, such as cereal rye, to protect soil against erosion.
Make sure that excessive N is not coming onto the farm (biological N fixation plus fertilizers plus feeds).	After soil tests are in the optimal range, balance the farm's P flow (don't import much more onto the farm than is being exported).

used to provide input information for computer models. We discuss these further in Chapter 21.

Evaluation at the End of the Season

To evaluate the success of a fertility recommendation, farmers sometimes plant field strips with different N rates and compare yields at the end of the season. This can be done for vegetable crops as well as for crops like grain corn. Another option is to sample for soil nitrate after harvest, sometimes called a "report card" assessment, to evaluate residual levels of available N. ***The lower stalk nitrate test*** is also sometimes used to assess, after the growing season, whether corn N rates were approximately right or too low or too high. These methods are neither fixed nor adaptive approaches for the current year, since evaluation is made at the end of the season, but they may help farmers make changes to their fertilizer application rates in following years. Adaptive management may therefore also include farmer-based experimentation and adjustment to local conditions.

PLANNING FOR N AND P MANAGEMENT

Although N and P behave very differently in soils, the general approaches to their management are similar (Table 19.2). The following considerations are important for planning management strategies for N and P.

Credit nutrients in manures, rotation crops, decomposing sods, cover crops and other organic residues. Before applying commercial fertilizers or other off-farm nutrient sources, you should properly credit the various on-farm sources of nutrients. In some cases, there is more than enough fertility in the on-farm sources to satisfy crop needs. If manure is applied before sampling soil, the contribution of much of the manure's P and all its potassium will be reflected in the soil test. The pre-sidedress nitrate test can estimate the N contribution of the manure (see Chapter 21 for a description of N soil tests). The only way to really know the nutrient value of a particular manure is to have it tested for its fertilizer value before applying it to the soil; many soil test labs also analyze manures. (Although a manure analysis test is recommended and will provide the most accurate result, estimates can be made based on average manure values, such as those given in Table 12.1.)

Because significant ammonia N losses can occur in as little as one or two days after application, the way to derive the full N benefit from surface-applied manure (or urea for that matter) is to incorporate it as soon as possible. Much of the manure N made available to the crop is in the ammonium form, and losses occur as some is volatilized as ammonia gas when manures dry on the soil surface. A significant amount of the manure's N may also be lost when application happens a long time before crop uptake occurs. Even if incorporated, about half of the N value of a fall manure application may be lost by the time it is needed by the crop in the following year.

Legumes, either as part of rotations or as cover crops, and well-managed grass sod crops can add N to the soil for use by the next crop (Table 19.3). Nitrogen fertilizer decisions should take into account the amount of N contributed by manures, decomposing sods and cover crops. If you correctly fill out the form that accompanies your soil sample, the recommendation you receive may take these sources into account. However, not all soil testing labs do that; most do not even ask whether you've used a cover crop. If you can't find help deciding how to credit nutrients in organic sources, take a look at chapters 10 (cover crops), 11 (rotations) and 12 (animal manures, discussed as part of integrated livestock-cropping systems). Also, some of the adaptive simulation models described above can incorporate such

Table 19.3
Examples of Nitrogen Credits for Previous Crops

Previous Crop	N Credits (pounds per acre)[1]
Corn and most other crops	0
Soybeans[2]	0–40
Grass (low level of management)	40
Grass (intensively managed, using N fertilizer for maximum economic yield)	70
2-year stand of red or white clover	70
3-year alfalfa stand (20–60% legume)	70
3-year alfalfa stand (>60% legume)	120
Crimson clover	110
Winter peas	110
Hairy vetch cover crop (excellent growth)	110

[1] Less credit should be given for sandy soils with high amounts of leaching potential.
[2] Some labs give 30 or 40 pounds of N credit for soybeans, while others give no N credit. Credits represent the amount of N that will be available to the crop (not the total amount contained in residue). Although the actual amount of N that will become available can be higher in dry years and lower in wet years (Figure 19.2), we still can't accurately predict the growing season weather. When following cover crops, the stage of growth and the amount of growth will strongly influence the amount of N available to the following crop.

Figure 19.4. A soybean crop generally provides 20–40 pounds N per acre to a following corn crop, which needs to be accounted for in making N recommendations.

MANURE APPLICATION, TILLAGE AND N LOSS

When using some tillage, it makes sense to incorporate manure as soon after application as weather and competing work priorities allow. With no-till there are low-disturbance manure injectors that place liquid manure in the soil with minimal N loss.

COVER CROPS ENHANCE P FOR FOLLOWING CROP

Cover crops mobilize and take up a significant amount of P through mycorrhizae and other organisms of the root microbiome. Later, as they decompose, this P becomes available for the following crops to use. While this is a very different mechanism than N fixation by legumes, it is another example of a crop together with microorganisms helping the following crop obtain particular nutrients.

credits into recommendations, while also accounting for variable weather conditions. For an example of crediting the nutrient value of manure and cover crops, see the section "Making Adjustments to Fertilizer Application Rates" in Chapter 21.

Relying on legumes to supply N to following crops. Nitrogen is the only nutrient of which you can "grow" your own supply. High-yielding legume cover crops, such as hairy vetch and crimson clover, can supply most, if not all, of the N needed by the following crop. Growing a legume as a forage crop (alfalfa, alfalfa/grass, clover, clover/grass) in rotation also can provide much, if not all, of the N for row crops. The N-related aspects of both cover crops and rotations with forages were discussed in chapters 10 and 11.

Animals on the farm or on nearby farms? There are many possibilities for actually eliminating the need for N fertilizer if you have ruminant animals on your farm or on nearby farms for which you can grow forage crops (and perhaps use the manure on your farm). A forage legume, such as alfalfa, red clover or white clover, or a grass-legume mix, can supply substantial N for the following crop. Frequently, nutrients are imported onto livestock-based farms as various feeds (usually grains and soybean meal mixes). This means that the manure from the animals will contain nutrients imported from off the farm, and this reduces the need to purchase fertilizers. When planting vegetable crops following a manure application, keep in mind the regulation that requires 120 days from application to harvest (see discussion in Chapter 12 for manure use and food safety issues).

No animals? Although land constraints don't usually allow it, some vegetable farmers grow a forage legume for one or more years as part of a rotation, even when they are not planning to sell the crop or feed it to animals. They do so to rest the soil and to enhance the soil's physical and biological properties, and nutrient status. Also, some cover crops, such as hairy vetch—grown off-season in the fall and early spring—can provide sufficient N for some of the high-demanding summer annuals. It's also possible to undersow sweet clover, planning for fall brassica crops the following year. (If tillage is used, it can be plowed under the next July to prepare for the fall crop.) Sunn hemp and cowpeas growing as cover crops in the Southeast during the summer months have been found to replace one-third to one-half of the N needed for fall broccoli.

Reducing N and P Losses

Manage N and P fertilizers more efficiently. You should have plenty of organic nutrients present if you've worked to build and maintain soil organic matter. These readily decomposable fragments provide N and P as they decompose, thereby reducing the amount of fertilizer that's needed.

When applying commercial fertilizers and manures, the timing and method of application affect the efficiency of use by crops and the amount of loss from soils, especially in humid climates. In general, it is best to apply fertilizers close to the time they are needed by plants, which is especially important when it involves N. Losses of surface-applied fertilizer and manure nutrients are also frequently reduced by soil incorporation with tillage (even a light incorporation can help a lot). Liquid N fertilizer, especially when dribble applied, penetrates the surface, better protecting it from possible gaseous loss. And no-tilled soils that have continual living roots by using cover crops tend to have vastly greater water infiltration and less runoff and gaseous losses.

If you're growing a crop for which a reliable in-season adaptive method is available, like the PSNT, a sensor or a computer model, you can hold off applying most of the fertilizer until the crop indicates a need. At that point, apply N as a sidedress or topdress. However, if you know that your soil is probably very N deficient (for example, a sandy soil low in organic matter), you may need to band-apply higher-than-normal levels of starter N at planting or broadcast some N before planting to supply sufficient N nutrition until the soil test indicates whether there is a need for more N (applied as a sidedress or topdress). About 15–20 pounds of starter N per acre (in a band at planting) is highly recommended for crops in colder climates. Even more starter N is needed when some cover crops like cereal rye or triticale are allowed to grow near maturity. The large amount of biomass, with its high C:N ratio, will tie up mineral sources of soil N for some weeks following cover crop termination. When organic farmers use fishmeal or seed meals to supply N to crops, they should plan on it becoming available over the season, with little released in the first weeks of decomposition. On the other hand, N contained in feather meal may become available more rapidly.

In-season topdressing N on wheat and on some other annual cereal or oilseed crops is sometimes needed, especially when wet conditions cause significant losses of available soil N. It's helpful if farmers put high-N strips within fields, in which they apply N at rates of 40–50 pounds per acre higher than other areas. The length and width of the strips aren't that important. The purpose of the strips is to see if you can tell the difference between the wheat in the high-N strip and the rest of the field. Top dressing N is recommended if the difference is very noticeable.

If the soil is very deficient in phosphorus, P fertilizers have traditionally been incorporated by tillage to raise the general level of the nutrient. Incorporation is not possible with no-till systems, and if a soil is very deficient, some P fertilizer should be incorporated before starting no-till. Nutrients accumulate near the surface of reduced tillage systems when fertilizers or manures are repeatedly surface applied. If P levels are good to start with, in later years small amounts of surface-applied P will work its way deeper into the soil surface. And P can be band applied as starter fertilizer at planting, or it can be injected, keeping it below the surface.

In soils with optimal P levels, some P fertilizer is still recommended, along with N application, for row crops in cool regions. (Potassium is also commonly recommended under these conditions.) Frequently, the soils are cold enough in the spring to slow down root development, P diffusion toward the root and mineralization of P from organic matter, thereby reducing P availability to seedlings. No-tilled soils with plentiful surface residue will stay cool for a longer period in the spring, thereby decreasing both N and P availability. However, if cover crops are used together with no-till—a combination that provides many benefits—soils will dry and warm more rapidly, lessening the concern with early P deficiency in row crops. But for no-till without cover crops in cool climates it is a good idea to use a small amount of starter P for the young crop—even if the soil is in the optimal P soil test range.

Use the right fertilizer products. Some of the N in surface-applied urea, the cheapest and most commonly used solid N fertilizer, is lost as a gas if it is not rapidly incorporated into the soil. If as little as a quarter inch of rain falls within a few days of surface

SOIL REACTIONS WITH N FERTILIZERS

Urea is converted to ammonia (lost to the atmosphere or dissolved in water to form ammonium as a gas, or converted to nitrate).

Ammonia and ammonium are nitrified to nitrate (easily lost by leaching and/or denitrification).

urea application, N losses are usually less than 10%. However, losses may be 30% or more in some cases (a 50% loss may occur following surface application to a calcareous soil that is over pH 8). When urea is used for no-till systems, it can be placed below the surface or surface applied in the form of chemically stabilized urea, greatly reducing N loss. Stabilized urea is the most economical source when N fertilizer is broadcast as a topdress on grass, on cereals such as wheat, or on row crops. Solutions of urea and ammonium nitrate (UAN) are also used as a topdress or are dribbled on as a band. (Although once widely used, solid ammonium nitrate fertilizer is expensive and not always readily available due to concerns about explosivity. But like calcium ammonium nitrate [CAN], its N is generally not lost as a gas when left on the surface and therefore is a good product for topdressing.)

Anhydrous ammonia, the least expensive source of N fertilizer, causes large changes in soil pH in and around the injection band. The pH increases for a period of weeks, many organisms are killed, and organic matter is rendered more soluble. Eventually, the pH decreases, and the band is repopulated by soil organisms. However, significant N losses can occur when anhydrous is applied in a soil that is too dry or too wet. In humid regions, even if stabilizers are used, anhydrous applied long before crop uptake significantly increases the amount of N that may be lost. For this reason, fall-applied anhydrous ammonia is a practical N source only in the more arid western portion of the Corn Belt, and only after the soil has cooled below 50 degrees F. But fall application of anhydrous ammonia remains relatively common even in the more humid parts of the region due to price and logistical benefits, but this raises environmental concerns.

In some cases, nutrients are applied individually through separate fertilizer products, while multi-nutrient compounds (like monoammonium phosphate) or *blended* materials are used in other cases. When

Common Nitrogen Fertilizer Efficiency Enhancement Products

Mode of Action	Formulation and Use	Common Enhanced Efficiency Products[1]
Urease inhibition	Additive for urea-based; manure	NBPT, MIC
Nitrification inhibition	Additive for anhydrous ammonia, urea- and ammonium-based	Nitrapyrin, DCD, MIC
Urease and nitrification inhibition	Stand-alone fertilizer product	Ammonium and calcium thiosulfates
Controlled release	Stand-alone fertilizer product	Polymer-coated prilled nitrogen or other nutrients

[1] This list is not comprehensive but includes the most widely used products. Inclusion or omission of a product in this list does not imply an endorsement by the authors or publisher.

Source: Cantarella, H., R. Otto, J.R. Soares and A.G. de Brito Silva. 2018. Agronomic efficiency of NBPT as a urease inhibitor: A review. *Journal Advanced Research* 13: 19–27.

NEW TECHNOLOGY FOR CORN NITROGEN FERTILIZATION

Corn is a tropical plant that is more efficient at utilizing N than are most other crops: it produces more additional yield for each extra pound of N absorbed by the plant. But corn production systems as a whole have low efficiency of fertilizer N, typically less than 50%. Environmental N losses (leaching, denitrification and runoff) are much higher for corn than for crops such as soybeans and wheat, and especially when compared to alfalfa and grasses. This can be attributed to different crop growth cycles, fertilizer rates, fertilizer application schedules, timing of crop water and N uptake, and rooting depths. Intensive corn production areas have therefore become the focus of policy debates that address environmental concerns like groundwater contamination and hypoxia zones in estuaries.

Nitrogen management for corn is still mostly done without recognizing how seasonal weather, particularly precipitation, can cause high N losses through leaching and denitrification. The PSNT was the first approach that addressed these dynamic processes and therefore provided inherently more precise N fertilizer recommendations and eliminated a lot of unnecessary N applications. Still, many farmers like to apply additional “insurance fertilizer” because they want to be certain of an adequate N supply in wet years. But they may actually need it in only, say, one out of four seasons. For those other years, excess N application creates high environmental losses.

New technologies are emerging in addition to the PSNT that allow us to more precisely manage N. Computer models and climate databases can be employed to adapt N recommendations by accounting for weather events and in-field soil variability. Also, crop reflectance of light, which is affected by the degree of N nutrition in the plant, can be measured using aerial and satellite images or tractor-mounted sensors, and can then be used to adjust sidedress N fertilizer rates, even for small zones in a field (precision management).

applying multiple nutrients at once, aim to use combinations that proportionally fit the nutritional needs of your crop, thereby reducing unnecessary applications and buildup of nutrients that are overapplied. Or otherwise use multi-nutrient fertilizer in combination with single-nutrient products to achieve the right proportions.

Use nitrogen efficiency enhancement products. Field nitrogen losses can be high depending on the soil, the practices used and the conditions of the growing season, especially weather. With urea-based nitrogen fertilizers and manure, ammonia losses into the atmosphere can be considerable if the material is left on the surface, especially when conditions following application are dry and soil pH is high. Several products on the market reduce ammonia losses by suppressing the activity of the urease enzyme. These ***urease inhibitors*** reduce the production of ammonia by naturally occurring soil enzymes, lessening N losses as well as concerns about air pollution and unwanted nitrogen deposition in nearby areas. ***Nitrification inhibitors*** are another type of products for use with N fertilizers. These suppress conversion of ammonium to nitrate by naturally occurring soil microorganisms. Ammonium is strongly held by negative charges on soil particles (the cation exchange complex) and does not leach from soils, while the negatively charged nitrate ion can wash through the soil when a lot of rain occurs. This is especially a concern with sandy soils. Also, in finer-textured soils, nitrate can be lost during wet periods through denitrification and volatilization of N_2 and

N_2O into the air. Of course, the leaching and gaseous losses are detrimental to farm profitability as well as to the environment. The role of the nitrification inhibitor is to maintain nitrogen in the ammonium form for longer periods, slowly making nitrate available as the growing crop develops, thereby increasing use efficiency. A third type of product, similar to nitrification inhibitors, focuses on ***controlled release*** by using a coating on fertilizer material that causes it to slowly dissolve and release the nitrogen fertilizer.

The choice of enhanced efficiency products depends on the fertilization strategy. Urease inhibitors are appropriate when using urea-based fertilizers without incorporation. When applying ammonia/ammonium-based fertilizers well before crop uptake, consider adding a nitrification inhibitor or using coated materials. In some cases, a combination of products is appropriate. In general, the use of these products reduces N losses, but it depends on the production environment in a particular growing season. It may prevent yield losses in some years or allow reductions in overall N fertilizer rates by reducing the need for using higher levels of fertilizer as “insurance.”

Use perennial forages (sod-forming crops) in rotations. As we’ve discussed a number of times, rotations that include a perennial forage crop help reduce runoff and erosion; improve beneficial aggregation; break harmful weed, insect and nematode cycles; and build soil organic matter. Decreasing the emphasis on row crops in a rotation and including perennial forages also helps decrease leaching losses of nitrate. This happens for two main reasons:

1. There is less water leaching under a sod because it uses more water over the entire growing season than does an annual row crop, which has bare soil in the spring and after harvest in the fall.
2. Nitrate concentrations under sod rarely reach anywhere near as high as those under row crops.

So, whether the rotation includes a grass, a legume or a legume-grass mix, the amount of nitrate leaching to groundwater is usually reduced. (A critical step, however, is the conversion from sod to row crop. When a sod crop is plowed, a lot of N is mineralized. If this occurs many months before the row crop takes it up, high nitrate leaching and denitrification losses occur.) Using grass, legume or grass-legume forages in the rotation also helps with P management because of the reduced runoff and erosion, and the effects on soil structure for the following crop.

Use cover (catch) crops to prevent nutrient losses. High levels of soil nitrate may be left at the end of the growing season if drought causes a poor crop year or if excess N fertilizer or manure has been applied. The potential for nitrate leaching and runoff can be significantly reduced if you sow a fast-growing cover crop like cereal rye immediately after the main crop has been harvested. Such cover crops are commonly referred to as “catch crops” because their fast-growing roots can capture the remaining nutrients in the soil and store them in their biomass. One option available to help manage N is to use a combination of a legume and grass. The combination of hairy vetch and cereal rye or triticale works well in cooler temperate regions. When nitrate is scarce, the vetch or crimson clover does much better than the rye, and a large amount of N is fixed for the next crop. Conversely, the rye competes well with the vetch when nitrate is plentiful; less N is fixed (of course, less is needed); and much of the nitrate is tied up in the rye and stored for future use. Crimson clover with either cereal rye or oats works similarly in the South, with the clover growing better and fixing more N when soil nitrate is scarce, and with cereal rye growing faster when nitrate is plentiful.

In general, having any cover crop on the soil during the off-season is helpful for P management. A cover crop that establishes quickly and helps protect the soil against erosion will help reduce P losses.

Reduce tillage. Because most P is lost from fields by sediment erosion, environmentally sound P

TILLAGE, NUTRIENT LOSS AND FERTILIZER APPLICATION METHODS

Reducing tillage usually leads to marked reductions of nitrate leaching loss to groundwater as well as to runoff and, therefore, N and P loss in runoff. But, questions have come up about potential problems with broadcasting N and P fertilizers in reduced tillage systems, especially in no-till. The main attractiveness of broadcast fertilizer is that you can travel faster and cover more land than with injection methods of application—around 500–800 acres in eight hours for broadcast versus about 200 acres for injection. However, there are two complicating factors.

- If intense storms occur soon after application of surface-applied urea, N is more likely to be lost via leaching than if it had been incorporated. Much of the water will flow over the surface of no-till soils, picking up nitrate and urea, before entering wormholes and other channels. It then easily moves deep into the subsoil. It is best not to broadcast N fertilizer and to leave it on the surface with a no-till system. This is particularly true for urea, since surface residues contain higher levels of the urease enzyme, facilitating fast conversion to ammonia, which is rapidly lost as a gas. Fertilizer N may be applied at different stages: before planting, with the seed at planting, or as a sidedress. Using liquid N as a sidedress results in better soil contact than a solid fertilizer would achieve.
- P accumulates on the surface of no-till soils (because there is no incorporation of broadcast fertilizers, manures, crop residues or cover crops). Although there is usually less runoff, fewer sediments and less total P lost with no-till, the concentration of dissolved P in the runoff is often higher than for conventionally tilled soils. Phosphorus should be applied below the surface to reduce such losses.

management should include reduced tillage systems. Leaving residues on the surface and maintaining stable soil aggregation and lots of large pores help water to infiltrate into soils. When runoff does occur, less sediment is carried along with it than when conventional plow-harrow tillage is used. Reduced tillage, by decreasing runoff and erosion, usually decreases both P and N losses from fields. Recent studies have also shown that reduced tillage results in more effective N cycling. Although N fertilizer needs are generally slightly higher in early transition years, long-term no-till increases organic matter contents over conventional tillage and also, after some years, results in 30 pounds (or more) per acre greater N mineralization, which is a significant economic benefit to the farm.

Working Toward Balancing Nutrient Imports and Exports

In addition to being contained in the products sold off the farm, nitrogen and phosphorus are lost from soils in many unintended ways, including runoff that takes both N and P, nitrate leaching (and in some situations, P as well), denitrification, and volatilization of ammonia from surface-applied urea and manures. Even if you take all precautions to reduce unnecessary losses, some N and P loss will occur. While you can easily overdo it with fertilizers, using more N and P than is needed also occurs on many livestock farms that import a significant proportion of their feeds. If a forage legume, such as alfalfa, is an important part of the rotation, the combination of biological N fixation plus imported N in feeds may exceed the farm's needs. A reasonable goal for farms with a large net inflow of N and P through feed would be to try to reduce imports of these nutrients onto the farm (including legume N), or to increase exports, to a point closer to balance.

On crop farms, as well as on livestock-based farms with low numbers of animals per acre, it's fairly easy to bring inflows and outflows into balance by properly crediting N from the previous crop, and N and P in manure. But it is a more challenging problem when there are a large number of animals for a fixed land base and a large percentage of the feed must be imported. This happens frequently on factory-type animal production facilities, but it can also happen on smaller, family-sized farms. At some point, thought needs to be given to either expanding the farm's land base or exporting some of the manure to other farms. In the Netherlands, nutrient accumulation on livestock farms became a national problem and generated legislation that limits animal units on farms. One option is to compost the manure, which makes it easier to transport or sell. It causes some N losses during the composting process, but stabilizes the remaining N before application. On the other hand, the availability of P in manure is not greatly affected by composting. That's why using compost to supply a particular amount of "available" N usually results in applications of larger total amounts of P than plants need.

Using Organic Sources of Phosphorus and Potassium

Manures and other organic amendments are frequently applied to soils at rates estimated to satisfy a crop's N need. This commonly adds more P and potassium than the crop needs. After many years of continuous application of these sources to meet N needs, soil test levels for P and potassium may be in the excessive range. Although there are a number of ways to deal with this issue, all solutions require reduced applications of fertilizer P and P-containing organic amendments. If it's a farm-wide problem, some manure may need to be exported and N fertilizer or legumes relied on to provide N to grain crops. Sometimes, it's just a question of better distribution of manure around the various fields: getting to those fields far from the barn more regularly. Changing the rotation to include crops such as alfalfa, for which no manure N is needed, can help. However, if you're raising livestock on a limited land base, you should make arrangements to have the manure used on a neighboring farm or sell the manure to a composting facility.

Managing High-P Soils

High-P soils occur because of a history of either excessive applications of P fertilizers or, more commonly, application of lots of manure. This is a problem on livestock farms with limited land and where a medium-to-high percentage of feed is imported. The nutrients imported in feeds may greatly exceed the nutrients exported in animal products. In addition, where manures or composts are used at recommended rates for providing sufficient N to crops, more P than needed usually is added. It's probably a good idea to reduce the potential for P loss from all high-P soils. However, it is especially important to reduce the risk of environmental harm from those high-P soils that are also likely to produce significant runoff (because of slope, fine texture, poor structure or poor drainage). Therefore, the environmental context should be considered. If the farm is near a critical water resource that is impacted by field runoff or tile drainage, aggressive measures are needed to reduce the impact. Conversely, small vegetable operations or urban farms on flat ground where fields are surrounded by grass berms or alleyways pose much lower risk, and high soil-P levels are generally more acceptable.

There are a number of practices that should be followed with high-P soils.

- First, deal with the "front end" and reduce animal P intake to the lowest levels needed. Not that long ago a survey found that the average dairy herd in the United States was fed about 25% more P than recommended by the standard authority (the National Research Council, or NRC). Using so much extra can cost dairy farmers thousands of dollars to feed a 100-cow herd supplemental P that the animals don't need and that ends up as a potential pollutant.

- Second, reduce or eliminate applications of extra P. For a livestock farm, this may mean obtaining the use of more land to grow crops, to spread manure over a larger land area, or to swap fields with nearby farms that don't have high-P problems. For a crop farm, this may mean using legume cover crops and forages in rotations to supply N without adding P. The cover crops and forage rotation crops are also helpful to build up and maintain good organic matter levels in the absence of importing manures or composts, or other organic material from off the farm. The lack of imported organic sources of nutrients (to try to reduce P imports) means that a crop farmer will need to be more creative using crop residues, rotations and cover crops to maintain good organic matter levels. Also, don't use a high-P source to meet N demands. Compost has many benefits, but if used to provide N fertility, it will build up P over the long term.
- Third, reduce runoff and erosion to minimal levels. P is usually a problem only if it gets into surface waters. Anything that helps water infiltration or impedes water and sediments from leaving the field—reduced tillage, strip cropping along the contour, cover crops, grassed waterways, riparian buffer strips, etc.—decreases problems caused by high-P soils. (Note: Significant P losses in tile drainage water have been observed, especially from fields where large amounts of liquid manure are applied.)
- Fourth, continue to monitor soil P levels. Soil-test P will slowly decrease over the years once P imports, in the form of fertilizers, organic amendments or feeds, are reduced or eliminated. Soils should be tested every two to three years for other reasons, anyway. So just remember to keep track of soil-test P to confirm that levels are decreasing. Phosphorus accumulates especially rapidly in the surface of no-till soils that have received large applications of manure or fertilizer over the years. One management option in these cases is a one-time tillage of the soil to incorporate the high-P soil layer. If this is done, use practices that don't result in building up surface soil P once again, such as applying P as starter near the seed and injection (especially liquid manure) instead of broadcast applications.

SUMMARY

Both N and P are needed by plants in large amounts, but when soils are too rich in these nutrients, they are environmental hazards. And although N and P behave somewhat differently in soils, most sound management practices for one are also sound for the other. Using soil tests, comprehensive nutrient management planning and recommendation tools that account for all sources, such as soil organic matter, manures, cover crops and decomposing sods, can help better manage these nutrients. Reduced tillage, cover crops and rotation with sod crops decrease runoff and erosion and help in many other ways, including better N and P management. In addition, following the 4R-Plus principles and using technologies like N stabilizers/inhibitors as well as sensors and models can increase the use efficiency of N and P, and can reduce detrimental environmental impacts.

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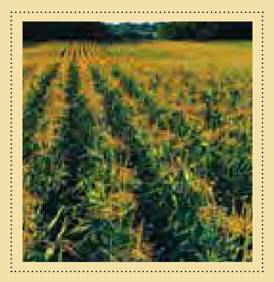
Chapter 20

OTHER FERTILITY ISSUES: NUTRIENTS, CEC, ACIDITY, ALKALINITY



> *The potential available nutrients in a soil, whether natural or added in manures or fertilizer, are only in part utilized by plants …*
>
> —T.L. LYON AND E.O. FIPPIN, 1909

OTHER NUTRIENTS

Additional nutrient and soil chemical issues remain important, although farmers understandably focus on nitrogen and phosphorus, because additions of these nutrients are commonly needed in order to maintain crop productivity, large quantities are normally used, and both have potential for environmental problems, additional nutrient and soil chemical issues remain important. While K deficiency is also fairly common, most other nutrients are not normally deficient. Micronutrient fertilizers generally are required in cases where the micronutrients are naturally unavailable in the soil, or when many years of intensive crop production has reduced much of the natural soil supply. We focus here mostly on the mineral nutrients that are critical for healthy plants, but some trace elements are also important for animal and human health, including zinc, iron, iodine, calcium, magnesium, selenium and fluorine, which need to be supplied through the food chain (soil-plant-animal/human) or added as nutritional supplements.

Overuse of fertilizers and amendments other than N and P seldom causes problems for the environment, but it may waste money and reduce yields. There are also animal health considerations with excess amounts. For example, excess potassium in feeds for dry cows (cows that are between lactations) results in metabolic problems, and low magnesium availability to dairy or beef cows in early lactation can cause grass tetany. As with most other issues we have discussed, focusing on the management practices that build up and maintain soil organic matter will help eliminate many problems, or at least make them easier to manage.

As of the writing of this edition, there are discussions around how glyphosate-based herbicides affect micronutrient availability. Glyphosate is the most frequently applied herbicide worldwide and, like soil organic matter, has chelating abilities. It is still an open debate

Photo by Dennis Nolan

> The risk for sulfur deficiency varies with the soil type, the crops grown on the soil, the manure history and the level of organic matter in the soil. A deficiency is more likely to occur on acidic, sandy soils; soils with low organic matter levels and high nitrogen inputs; and soils that are cold and dry in the spring, which decreases sulfur mineralization from soil organic matter. Manure is a significant supplier of sulfur, and manured fields are not likely to be S deficient; however, sulfur content in manure can vary.
>
> —S. PLACE ET AL. (2007)

whether this has a significant impact on plant micronutrient availability or affects soil, plant health or human health. However, there is no conclusive evidence that it is overall more harmful than the chemicals it replaces.

Potassium (K) is one of the N-P-K "big three" primary nutrients needed in large amounts, and in humid regions it is frequently not present in sufficient quantities for optimum crop yields. Deficiencies occur more readily when the entire crop is harvested and removed versus the grain only. Unlike N and P, K is more concentrated in stalks and stems that remain in the field as stover/straw if only the grain is harvested, thereby recycling most of the K for the next crop. K is generally available to plants as a cation, and the soil's cation exchange capacity (CEC) is the main storehouse for this element for a given year's crop. Potassium availability to plants is sometimes decreased when a soil is limed to increase its pH by one or two units. The extra calcium, as well as the "pull" on K exerted by the new cation exchange sites (see the next section, "Cation Exchange Capacity Management"), contributes to lower K availability. Problems with low K levels are usually easily dealt with by applying muriate of potash (potassium chloride), potassium sulfate or K-mag (potassium magnesium sulfate, also sold as Sul-Po-Mag or Trio).
Manures also usually contain large quantities of K. Some soils have low amounts of CEC, such as sandy and sandy loams low in both organic matter and clay. But if the *type of clay* has low CEC, such as kaolinitic clays found in the Southeast, low CEC may make it impossible to store large amounts of readily K for plants to use. If a lot of fertilizer K is added at one time—an amount that may be reasonable for another soil—a significant portion may be leached below the root zone before plants can use it. In these situations, split applications of K may be needed. Since most complete organic fertilizers are low in K, organic growers with low CEC soils need to pay special attention to maintaining the K status of their soils.

Magnesium deficiency is easily corrected, if the soil is acidic, by using a magnesium (dolomitic) lime to raise the soil pH (see "Soil Acidity"). If K is also low and the soil does not need liming, potassium magnesium sulfate is one of the best choices for correcting a magnesium deficiency. For a soil that has sufficient K and is at a satisfactory pH, a straight magnesium source such as magnesium sulfate (Epsom salts) would be a good choice.

Calcium deficiencies are generally associated with low pH soils and soils with a low CEC. The best remedy is usually to lime and build up the soil's organic matter. However, some important crops, such as peanuts, potatoes and apples, commonly need added calcium. Calcium additions also may be needed to help alleviate soil structure and nutrition problems of sodic soils or soils that have been flooded by seawater (see "Remediation of Sodic [Alkali] and Saline Soils"). In general, there will be no advantage to adding a calcium source, such as gypsum, if the soil does not have too much sodium, is properly limed and has a reasonable amount of organic matter. However, soils with very low aggregate stability may sometimes benefit from the extra salt concentration and calcium associated with surface gypsum applications. This is not a calcium nutrition effect but is a stabilizing effect of the dissolving gypsum salt. Higher soil organic matter and surface residues should do as well as gypsum to alleviate this problem.

Sulfur deficiency is common on coarse texture soils with low organic matter, in part because it is subject to leaching in the oxidized sulfate form (similar to nitrate). Some soil testing labs around the country offer a sulfur soil test. (Those of you who grow garlic should know that a good supply of sulfur is important for the full development of garlic's pungent flavor.) Much of the sulfur in soils occurs as organic matter, so building up and maintaining organic matter should result in sufficient sulfur nutrition for plants. Sulfur deficiency is becoming more common in certain regions now that there is less sulfur air pollution, which previously originated from combustion of high-sulfur forms of coal. (Now it is captured in power plant exhaust scrubbers, and the residue is sold as gypsum.) In the Great Plains, on the other hand, irrigation water may contain sufficient quantities of sulfur to supply crop needs even though the soils are deficient in sulfur. And some fertilizers used for other purposes, such as potassium sulfate, potassium magnesium sulfate and ammonium sulfate, contain sulfur. Calcium sulfate (gypsum) also can be applied to remedy low soil sulfur. The amount used on sulfur-deficient soils is typically 15–25 pounds of sulfur per acre.

Zinc deficiencies occur with certain crops on soils low in organic matter, and in sandy soils or soils with a pH at or above neutral. Zinc problems are sometimes noted on silage corn when manure hasn't been applied for a while. Zinc also can be deficient following topsoil removal from parts of fields as land is leveled for furrow irrigation. Cool and wet conditions may cause zinc to be deficient early in the season. Sometimes crops outgrow the problem as the soil warms up and organic sources become more available to plants. Zinc deficiencies are also common in other regions of the world, especially Sub-Saharan Africa, South and East Asia, and parts of Latin America. Applying about 10 pounds of zinc sulfate per acre (which contains about 3 pounds of zinc) to soils is one method used to correct zinc deficiencies. If the deficiency is due to high pH, or if an orchard crop is zinc deficient, a foliar application is commonly used. If a soil test before planting an orchard reveals low zinc levels, zinc sulfate should be applied.

Boron deficiencies occur most frequently on sandy soils with low organic matter and on alkaline/calcareous soils. It shows up in alfalfa when it grows on eroded knolls where the topsoil and organic matter have been lost. Deficiencies are common in certain regions with naturally low boron, such as in the Northwest maritime area, and in many regions in other parts of the world. Root crops seem to need higher soil boron levels than do many other crops. Cole crops, apples, celery and spinach are also sensitive to low boron levels. The most common fertilizer used to correct a boron deficiency is sodium tetraborate (about 15% boron). Borax (about 11% boron), a compound containing sodium borate, also can be used to correct boron deficiencies. On sandy soils low in organic matter, boron may be needed on a routine basis. Applications for boron deficiency are usually around 1–2 pounds of boron per acre. No more than 3 pounds of actual boron (about 27 pounds of borax) per acre should be applied at any one time; it can be toxic to some plants at higher rates.

Manganese deficiency, usually associated with soybeans and cereals grown on high-pH soils and on vegetables grown on muck soils, is corrected with the use of manganese sulfate (about 27% manganese). About 10 pounds of water-soluble manganese per acre should satisfy plant needs for a number of years. Up to 25 pounds per acre of manganese is recommended if the fertilizer is broadcast on a very deficient soil. Natural, as well as synthetic, chelates (at about 5% to 10% manganese) usually are applied as a foliar spray.

Iron deficiency occurs in blueberries when they are grown on moderate- to high-pH soils, especially a

ESTIMATING ORGANIC MATTER'S CONTRIBUTION TO A SOIL'S CEC

The CEC of a soil is usually expressed in terms of the number of milliequivalents (me) of negative charge per 100 grams of soil. (The actual number of charges represented by one me is about 6 followed by 20 zeros.) A useful rule of thumb for estimating the CEC due to organic matter is as follows: for every pH unit above pH 4.5, there is 1 me of CEC in 100 grams of soil for every percent of organic matter. (Don't forget that there will also be CEC due to clays.) SOM = soil organic matter.

Example 1: pH = 5 and 3% SOM → (5 – 4.5) x 3 = 1.5 me/100g
Example 2: pH = 6 and 3% SOM → (6 – 4.5) x 3 = 4.5 me/100g
Example 3: pH = 7 and 3% SOM → (7 – 4.5) x 3 = 7.5 me/100g
Example 4: pH = 7 and 4% SOM → (7 – 4.5) x 4 = 10 me/100g

pH of over 6.5. Iron deficiency also sometimes occurs in soybeans, wheat, sorghum and peanuts growing on soil with a pH greater than 7.5. Iron (ferrous) sulfate or chelated iron is used to correct iron deficiency. Reducing plant stressors such as compaction and selecting more tolerant crop varieties are also ways of reducing iron deficiency damage to crops. In addition, research in Minnesota indicates that companion planting a small amount of oats (whose roots are able to mobilize iron) with soybeans reduces iron deficiency symptoms. Manganese and iron deficiencies are frequently corrected by adding inorganic salts in a foliar application.

Copper is another nutrient that is sometimes deficient in high-pH soils. It can also be deficient in organic soils (soils with 10–20% or more organic matter). Some crops—for example, tomatoes, lettuce, beets, onions and spinach—have a relatively high copper need. A number of copper sources, such as copper sulfate and copper chelates, can be used to correct a copper deficiency.

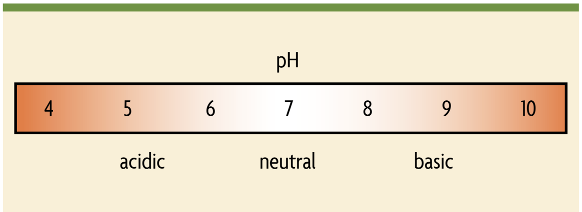


Figure 20.1. Soil pH and acid-base status.
Note: Soils at pH 7.5–8 frequently contain fine particles of lime (calcium carbonate). Soils above pH 8.5–9 usually have excess sodium (sodic, also called alkali, soils).

High-end fertilizer materials have been developed that combine many macro and micronutrients into a single product that can be applied as seed coatings, leaf sprays (foliar), directly to the soil or through fertigation systems, and they are especially of interest for high-value crops.

CATION EXCHANGE CAPACITY (CEC) MANAGEMENT

The CEC in soils is due to well-humified ("very dead") organic matter and clay minerals. The total CEC in a soil is the sum of the CEC due to organic matter and due to clays. In fine-textured soils with medium- to high-CEC clays, much of the CEC may be due to clays. Conversely, in sandy loams with little clay, or in some of the soils of the southeastern United States and of the tropics that contain clays with low CEC, organic matter may account for an overwhelming fraction of the total CEC. There are two practical ways to increase the ability of soils to hold nutrient cations such as potassium, calcium, magnesium and ammonium:

- Add organic matter by using the methods discussed in earlier chapters.
- If the soil is too acidic, use lime (see "pH Manage-

ment") to raise its pH to the high end of the range needed for the crops you grow.

One of the benefits of liming acid soils is increasing soil CEC. As the pH increases, so does the CEC of organic matter as well as some clay minerals. As hydrogen (H^+) on humus is neutralized by liming, the site where it was attached now has a negative charge and can hold Ca^{++}, Mg^{++}, K^+, etc.

Many soil testing labs will run CEC if asked. However, there are a number of possible ways to do the test. Some labs determine what the CEC would be if the soil's pH was 7 or higher. They do this by adding the acidity that would be neutralized if the soil was limed to the current soil CEC. This is the CEC the soil *would* have at the higher pH but is not the soil's current CEC. For this reason, some labs total the major cations actually held on the CEC ($Ca^{++} + K^+ + Mg^{++}$) and call it *effective CEC*. It is more useful to know the effective CEC—the actual current CEC of the soil—than CEC determined at a higher pH.

SOIL ACIDITY

Background

A soil's pH (or acidity status) is critical information because it influences nutrient chemistry and availability, and directly influences plant growth. Many soils, especially in humid regions, were acidic before they were ever farmed. Leaching of bases from soils and the acids produced during organic matter decomposition combined to make these soils naturally acidic. As soils were brought into production and organic matter decomposed (mineralized), more acids were formed. In

SOIL ACIDITY

Background

- pH 7 is neutral.
- Soils with pH levels above 7 are alkaline; those of less than 7 are acidic.
- The lower the pH, the more acidic is the soil.
- Soils in humid regions tend to be acidic; those in semiarid and arid regions tend to be around neutral or alkaline.
- Acidification is a natural process.
- Most commercial nitrogen fertilizers are acid forming, but many manures are not.
- Crops have different pH needs, probably related to nutrient availability or susceptibility to aluminum toxicity at low pH.
- Organic acids on humus and aluminum on the CEC account for most of the acid in soils.

Management

- Test soils regularly, every other year if possible, to track soil acidity changes and to make timely adjustments if needed.
- Use limestone to raise the soil pH. (If magnesium is also low, use dolomitic lime, which contains magnesium in addition to calcium.)
- Mix lime thoroughly into the plow layer.
- Spread lime well in advance of planting sensitive crops, if at all possible.
- If the lime requirement is high—some labs say greater than 2 tons, others say greater than 4 tons—consider splitting the application over two years.
- Reducing soil pH (making soil more acid) for acid-loving crops is best done using elemental sulfur (S).

addition, the most commonly used N fertilizers acidify soil as their ammonium is either converted to nitrate or is taken up by plants. Generally 4–7 pounds of lime are required to neutralize the acid formed from each pound of N applied to soils. Fertilizers that supply all their N in the form of nitrate, however, do not acidify the soil. In fact, applying calcium nitrate or potassium nitrate can slightly raise soil pH.

Plants have evolved in specific environments, which in turn influence their needs as agricultural crops. For example, alfalfa originated in a semiarid region where soil pH was high; alfalfa requires a pH in the range of 6.5–6.8 or higher (see Figure 20.1 for common soil pH levels). But blueberries, which evolved under acidic conditions, require a low pH to provide needed iron (iron is more soluble at low pH). Other crops, such as peanuts, watermelons and sweet potatoes, do best in moderately acid soils in the range of pH 5–6. Most other agricultural plants do best in the range of pH 6–7.5.

Several problems may cause poor growth of acid-sensitive plants in low pH soils. Three common problems:

- aluminum and manganese are more soluble and can be toxic to plants;
- calcium, magnesium, potassium, phosphorus or molybdenum (especially needed for nitrogen fixation by legumes) may be deficient; and
- decomposition of soil organic matter is slowed and causes decreased mineralization of nitrogen.

The problems caused by soil acidity are usually less severe, and the optimum pH is lower, if the soil is well supplied with organic matter. Organic matter helps to make aluminum less toxic, and, of course, humus increases the soil's CEC. Also, soil pH will not change as rapidly in soils that are high in organic matter. Soil acidification is a natural process that is accelerated by acids produced in soil by most nitrogen fertilizers. Soil organic matter slows down acidification and buffers the soil's pH because it holds the acid hydrogen tightly. Therefore, more acid is needed to decrease the pH by a given amount when a lot of organic matter is present. Of course, the reverse is also true: more lime is needed to raise the pH of high-organic-matter soils by a given amount (see "Soil Acidity" box).

Limestone application helps create a more hospitable soil for acid-sensitive plants in many ways:

- by neutralizing acids
- by adding calcium in large quantities (because limestone is calcium carbonate, $CaCO_3$)
- by adding magnesium in large quantities if dolomitic limestone is used (containing carbonates of both calcium and magnesium)
- by making molybdenum and phosphorus more available
- by helping to maintain added phosphorus in an available form
- by enhancing bacterial activity, including the rhizobia that fix nitrogen in legumes
- by making aluminum and manganese less soluble

SOIL SAMPLING FOR pH

Traditionally soils have been sampled to 6 inches or deeper, depending on the depth of plowing. But for farmers using conservation tillage, especially no-till, the top few inches can become acidic while the zone below is largely unaffected. Over time, acidity will work its way deeper. But it is important to catch a significant pH decline early, when it's easy to correct. Therefore, in no-till fields it's best to follow pH changes in the top 2 or 3 inches. Conversely, old soils in tropical regions often have high acidity in the lower soil regions, and a sample from deeper depths may be warranted.

Soil testing labs usually use the information you provide about your cropping intentions and integrate the three issues when recommending limestone application rates. (See the discussion under "pH Management" on the three pieces of information needed.) Laws govern the quality of limestone sold in each state. The limestone recommendations given by soil testing labs meet the minimum state standard.

Almost all the acid in acidic soils is held in reserve on the solids, with an extremely small amount active in the soil water. If all that we needed to neutralize was the acid in the soil water, a few handfuls of lime per acre would be enough to do the job, even in a very acid soil. However, tons of lime per acre are needed to raise the pH. The explanation for this is that almost all of the acid that must be neutralized in soils is "reserve acidity" associated with either organic matter or aluminum. And as the acid (H^+) is removed from organic matter, new CEC sites are created, increasing the soil's ability to hold cations such as calcium and potassium. (It also works in reverse as soils are acidified: H^+ strongly attaches to what had been CEC sites, removing their ability to hold onto calcium, magnesium, potassium and ammonium.)

pH Management

Increasing the pH of acidic soils is usually accomplished by adding ground or crushed limestone. Three pieces of information are used to determine the amount of lime that's needed.

1. What is the soil pH? Knowing this and the needs of the crops you are growing will tell you whether lime is needed and what target pH you are shooting for. You need to use lime if the soil pH is much lower than the pH needs of the crop. But the pH value doesn't tell you how much lime is needed.
2. What is the lime requirement needed to change the pH to the desired level? (The lime requirement is the amount of lime needed to neutralize the hydrogen, as well as the reactive aluminum, associated with organic matter as well as clays.) Soil testing laboratories use a number of different tests to estimate soil lime requirements. Most give the results in terms of tons per acre of agricultural grade limestone to reach the desired pH.
3. Is the limestone you use very different from the one assumed in the soil test report? The fineness and the amount of carbonate present govern the effectiveness of limestone, or, how much it will raise the soil's pH. If the lime you will be using has an effective calcium carbonate equivalent that's very different from the one used as the base in the report, the amount applied may need to be adjusted upward (if the lime is very coarse or has a high level of impurities) or downward (if the lime is very fine, is high in magnesium, and contains few impurities).

Soils with more clay and more organic matter need more lime to change their pH (see Figure 20.2). Although organic matter and clays buffer the soil against pH decreases, they also buffer against pH increases when you are trying to raise the pH with limestone. Most states recommend a soil pH of around 6.8 only for the most sensitive crops, such as alfalfa, and of about 6.2–6.5 for many of the clovers. As pointed out above, most of the commonly grown crops do well in the range of pH 6–7.5.

There are other liming materials in addition to limestone. One commonly used in some parts of the United States is wood ash. Ash from a modern airtight wood-burning stove may have a fairly high calcium carbonate content (80% or higher). However, ash that is mainly black—indicating incompletely burned wood—may have as little as 40% effective calcium carbonate equivalent. On the other hand, the char may

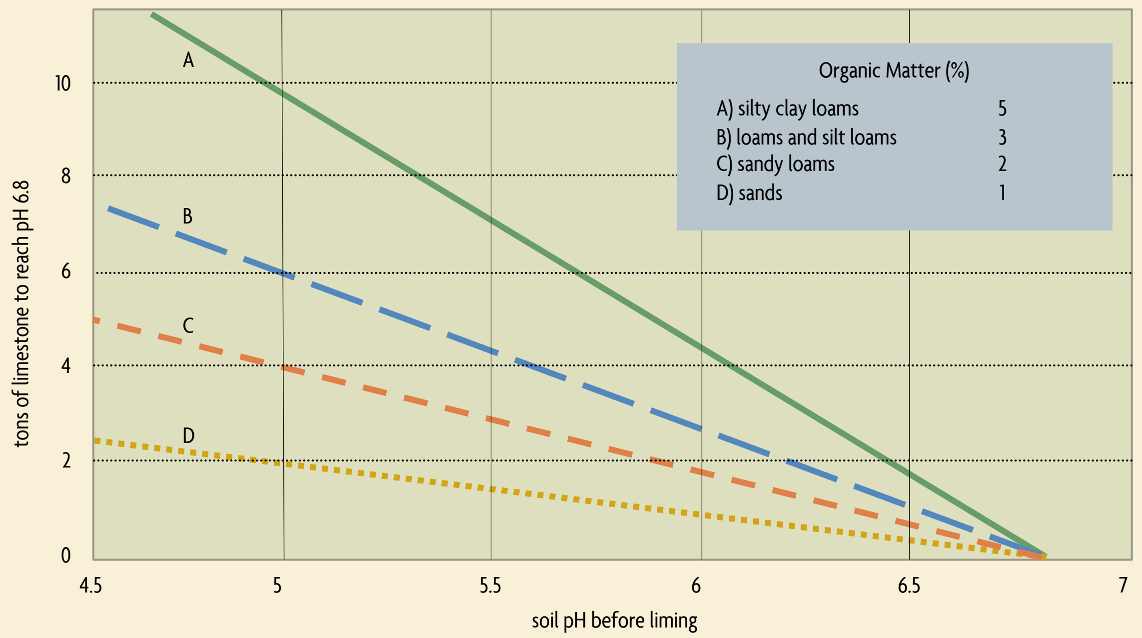


Figure 20.2. Examples of approximate lime needed to reach pH 6.8. Modified from Peech (1961).

provide other benefits to soil (see biochar discussion in Chapter 2). Lime sludge from wastewater treatment plants and fly ash sources may be available in some locations. Normally, minor sources like these are not locally available in sufficient quantities to put much of a dent in the lime needs of a region. Because they might carry unwanted contaminants to the farm, be sure that you test any new byproduct source of lime through an accredited laboratory for trace elements as well as metals and other potential toxins.

Liming and soil structure. Soil aggregation may show some improvements when applying calcium carbonate to soils that are relatively high in magnesium. The higher ionic strength of calcium pulls clay particles together better than magnesium. Conversely, when using dolomitic limestone, magnesium is added and may have the reverse effect (although the magnesium may be beneficial to the crop if it is deficient).

But liming is causing concerns when combined with no-till in the acidic cerrado (savanna) soils in Brazil, a productive region that has become a major global exporter of soybeans, beef and poultry. In these deeply weathered and highly oxidized soils, the structural degradation can be especially pronounced because the formation of aggregates under the naturally low pH of these soils results from high concentrations of Al^{3+} (which has high ionic strength) and dispersed organic matter. The negative charges on organic matter bind to the positive charges of oxides, and Al ions form bridges between organic matter and the minerals. However, liming raises the soil pH, which results in negative charges on soil particles and repulsion between them. In addition, high concentrations of calcium salts remove Al^{3+} from negatively charged sites within the soil, which reduces plant toxicity but also results in further dispersion of the clays and loss of aggregation. Under no-till, the dispersed clay can move with water to lower layers and cause dense and hard soils.

"Overliming" injury. Sometimes problems are created when soils are limed, especially when a very acidic soil has been quickly raised to high pH levels. Decreased crop growth because of "overliming" injury is usually associated with a lowered availability of phosphorus, potassium or boron, although zinc, copper and manganese deficiencies can be produced by liming acidic sandy soils. If there is a long history of the use of triazine herbicides, such as atrazine, liming may release these chemicals and kill sensitive crops.

Need to lower the soil's pH? You may want to add acidity to the soil when growing plants that require a low pH. This is probably only economically possible for blueberries and is most easily done with elemental sulfur, which is converted into sulfuric acid by soil microorganisms over a few months to years (depending on the fineness of the material applied). For the examples in Figure 20.2, the amount of sulfur needed to drop the pH by one unit would be approximately 3/4 ton per acre for silty clay loams, 1/2 ton per acre for loams and silt loams, 600 pounds per acre for sandy loams, and 300 pounds per acre for sands. Sulfur should be applied the year before planting blueberries. Alum (aluminum sulfate) may also be used to acidify soils. About six times more alum than elemental sulfur is needed to achieve the same pH change. If your soil is calcareous—usually with a pH over 7.5 and naturally containing calcium carbonate—don't even try to decrease the pH. Acidifying material will have no lasting effect on the pH because it will be fully neutralized by the soil's lime.

REMEDIATION OF SODIC (ALKALI) AND SALINE SOILS

The origin and characteristics of saline and sodic soils were discussed at the end of Chapter 6. There are a number of ways to deal with saline soils that don't have shallow salty groundwater. One is to keep the soil continually moist. For example, if you use drip irrigation with low-salt water plus a surface mulch, the salt content will not get as high as it would if allowed to concentrate when the soil dries. Another way is to grow crops or varieties of crops that are more tolerant of soil salinity. Saline-tolerant plants include barley, bermuda grass, oak, rosemary and willow. However, the only way to get rid of the salt is to add sufficient water to wash it below the root zone. If the subsoil does not drain well, drainage tiles might need to be installed to lower the water table and remove the salty water leached from the soil. (However, this means that a high-salt water is being discharged into a ditch and may harm downstream water quality. See also Chapter 17.) The amount of water needed to do this is related to the salt content of the *irrigation water*, expressed as electrical conductivity (ECw), and the salt content desired in the *drainage water*, expressed as electrical conductivity (ECdw). The amount of water needed can be calculated using the following equation:

Water needed = (amount of water needed to saturate soil) x (ECw/ECdw)

The amount of extra irrigation water needed to leach salts is also related to the sensitivity of the plants that you're growing. For example, sensitive crops like onions and strawberries may have twice the leaching requirement of moderately sensitive broccoli or tomatoes. Drip irrigation uses relatively low amounts of water, so lack of leaching may cause salt buildup even for moderately saline irrigation sources. This means that the leaching may need to occur during the growing season, but care is needed to prevent nitrate leaching below the root zone.

For sodic soils, a calcium source is added, usually gypsum (calcium sulfate). The calcium replaces sodium held by the CEC. The soil is then irrigated so that the sodium can be leached deep into the soil. Because the calcium in gypsum easily replaces the sodium on the CEC, the amount of gypsum needed can be estimated as follows: for every milliequivalent of sodium that needs to be replaced to 1 foot, about 2 tons of agricultural-grade gypsum is needed per acre. Gypsum is not a liming source and may actually decrease the high pH of sodic soils (commonly pH 8.4 or higher). Adding gypsum to non-sodic soils doesn't help physical properties if the soil is properly limed, except for those soils that contain easily dispersible clay and that are also low in organic matter. Sodic soils can also occur after major coastal flooding events, as the seawater washes a lot of sodium chloride through the flooded soil. This is especially of concern after hurricanes (typhoons), tsunamis or other unusual storm surges. The same remediation method, adding gypsum (or lime when the soil is naturally acidic), helps restore the soils in those cases.

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Chapter 21

GETTING THE MOST FROM ANALYZING YOUR SOIL AND CROP

… the popular mind is still fixed on the idea that a fertilizer is the panacea.

—J.L. HILLS, C.H, JONES AND C. CUTLER, 1908

Although fertilizers and other amendments purchased from off the farm are not a panacea to cure all soil problems, they play an important role in maintaining soil productivity. Soil testing is the farmer's best means for determining which amendments or fertilizers are needed and how much should be used.

The soil test report provides the soil's nutrient and pH levels, organic matter content, cation exchange capacity (CEC) and, in arid climates, the salt and sodium levels. Recommendations for application of nutrients and amendments accompany most reports. They are based on soil nutrient levels, past cropping and manure management, and should be a customized recommendation based on the crop you plan to grow.

Soil tests, and proper interpretation of results, are an important tool for developing a farm nutrient management program. However, deciding how much fertilizer to apply—or the total amount of nutrients needed from various sources—is part science, part philosophy and part art. Understanding soil tests and how to interpret them can help farmers better customize the test's recommendations. In this chapter, we'll go over sources of confusion about soil tests; discuss N, P, other nutrients and organic matter soil tests; and then examine a number of sample soil tests to see how the information they provide can help you make decisions about fertilizer application.

TAKING SOIL SAMPLES

The usual time to take soil samples for general fertility evaluation is in the fall or the spring, before the growing season has begun. These samples are analyzed for pH and lime requirements as well as for phosphorus, potassium, calcium and magnesium. Some labs also routinely analyze for organic matter and other selected nutrients, such as boron, zinc, sulfur and manganese, while others offer these as part of a menu you can select from. Whether you sample a particular field in the fall or in the early spring, stay consistent and repeat samples at approximately the same time of the year and use the same laboratory for analysis. Keep in mind that soils are usually sampled differently (timing and depth) for

Photo by Dena Leibman

evaluating N needs (see below). As you will see below, this allows you to make better year-to-year comparisons.

ACCURACY OF RECOMMENDATIONS BASED ON SOIL TESTS

Soil tests and their recommendations, although a critical component of fertility management, are not 100% accurate. Soil tests are an important tool, but they need to be used by farmers and farm advisors along with other information to make the best decision regarding amounts of fertilizers or amendments to apply.

Soil tests are an estimate of a limited number of

GUIDELINES FOR TAKING SOIL SAMPLES

1. Care and consistency when taking samples are critical to obtaining accurate information. Plan when and how you are going to sample, and be sure there is sufficient time to do it correctly.
2. Don't wait until the last minute. The best time to sample for a general soil test is usually in the fall. Spring samples should be taken early enough to have the results in time to properly plan nutrient management for the crop season.
3. Take cores from at least 15–20 spots randomly selected over the field (or a zone in a field) to obtain a representative sample. Taking many cores for a single sample is critical for obtaining meaningful soil test results, independent of the size of the field or zone. One sample should not represent more than 10–20 acres. For precision zone or grid fertility management, consider a sample for every 1–5 acres.
4. Sample between rows. Avoid old fence rows, dead furrows and other spots that are not representative of the whole field.
5. Take separate samples from problem areas if they can be treated separately.
6. Soils are not homogeneous: nutrient levels can vary widely with different crop histories or topographic settings. Sometimes different colors are a clue to different nutrient contents. Consider sampling some areas separately, even if yields are not noticeably different from the rest of the field.
7. For diversified vegetable farms that use blocks for grouping crops (by plant family, periods of growth, type of crop), sample by management zone block in addition to visibly different portions of fields, like strips or other portions of fields that form the basis of the rotation.
8. In cultivated fields, sample to plow depth.
9. Take two samples from no-till fields: one to a 6-inch depth for lime and fertilizer recommendations, and one to a 2-inch depth to monitor surface acidity.
10. Sample permanent pastures to a 3- or 4-inch depth.
11. Collect the samples in a clean container.
12. Mix the core samplings, remove roots and stones, and allow the mixed sample to air dry.
13. Fill the soil-test mailing container.
14. Complete the information sheet, giving all of the information requested. Remember, the recommendations are only as good as the information supplied.
15. Sample fields at least every three years and at the same season of the year each time. Annual soil tests on higher-value crops will allow you to fine-tune nutrient management and may allow you to cut down on fertilizer use.

—MODIFIED FROM THE PENN STATE AGRONOMY GUIDE (2019–2020)

ASKING THE PLANT WHAT IT THINKS

There are all sorts of liquid chemicals—actually, an almost unlimited number—that you can put a soil sample into, shake, filter and analyze to determine how much of a nutrient is in the liquid. But how can we have confidence that a certain soil test level means that you will probably increase yield by applying that nutrient? And that after a critical test level is passed, there is little chance of increasing yield by applying that nutrient?

Researchers ask the plants. They do this by running experiments over a number of years on many different fields around the state or region. This is done by first taking a soil sample and then laying out plots and applying a few different levels of the nutrient (let's say P) to the different plots, always including plots that received no added P. When crops are harvested in each plot, it is possible to determine what the plant "thought" about the soil test level. If the plant was not able to get enough of the nutrient in the control plots, there will be a yield increase between those and the plots receiving P application.

Without running these experiments—evaluating yield increases with added fertilizer at different soil test levels—there is no way to know what is considered a "good" soil test. Sometimes people come up with new soil tests that make a splash in the farm press. But until the multi-year effort of correlating a proposed test with plant response is made on a variety of soil and under various weather conditions, it is not possible to know if the test is useful or not. The ultimate word about the quality of a test is whether a crop will respond to added fertilizer the way a test value indicates it should.

Also, this type of research is often first done on small plots on research farms and needs to be validated in fields of commercial farms.

plant nutrients based on a small sample, which is supposed to represent many acres in a field. With soil testing, the answers aren't as certain as we might like them to be. A soil test that reveals a low level of a particular nutrient suggests that you will probably increase yield by adding the nutrient. However, adding it may not always increase crop yields. This could happen if the soil test is not well calibrated for the particular soil in question (and because the soil had sufficient availability of the nutrient *for the crop* despite the low test level) or because of harm caused by poor drainage or compaction. Occasionally, using extra nutrients on a high-testing soil increases crop yields. Weather conditions may have made the nutrient less available than indicated by the soil test. So it's important to use common sense when interpreting soil test results.

SOURCES OF CONFUSION ABOUT SOIL TESTS

People may be easily confused about the details of soil tests, especially if they have seen results from more than one soil testing laboratory. There are a number of reasons for this, including:

- laboratories use a variety of procedures;
- labs report results differently; and
- different approaches are used to make recommendations based on soil test results.

Varied Laboratory Procedures

One of the complications with using soil tests to help determine nutrient needs is that testing labs across the world use a wide range of procedures. The main difference among labs is the solutions they use to extract the soil nutrients. Some use one solution for all nutrients, while others will use one solution to extract potassium, magnesium and calcium; another for phosphorus; and yet another for micronutrients. The various extracting solutions have different chemical compositions, so the amount of a particular nutrient that lab A extracts may be different from the amount extracted by lab B. Labs frequently have a good reason for using a particular solution, however. For example, the Olsen test for phosphorus (see Table 21.1) is more accurate for high-pH soils in arid and semiarid regions than the various acid-extracting solutions commonly used in more humid regions. Whatever procedure the lab uses, soil test levels must be calibrated with the crop's response to added nutrients. For example, do yields increase when you add phosphorus to a soil that tested low in P? In general, university and state labs in a given region use the same or similar procedures that have been calibrated for local soils and climate.

Reporting Soil Test Levels Differently

Soil testing reports are unfortunately not standardized and labs may report their results in different ways. Some use parts per million (10,000 ppm = 1%); some use pounds per acre (usually by using parts per two million, which is twice the ppm level, because 1 acre of soil to 6 inch depth weighs approximately two million pounds) or kilograms per hectare; and some use an index (for example, all nutrients are expressed on a scale of 1–100). Some report Ca, Mg and K in milliequivalents (me) per 100 grams. In addition, some labs report phosphorus and potassium in the elemental form, while others use the oxide forms: P_2O_5 and K_2O.

Most testing labs report results as both a number and a category such as *low*, *medium*, *optimum*, *high* and *very high*. This is perhaps a more appropriate way to report the results as the relationship between soil test levels and yield response is affected by soil variability and seasonal growing conditions, and these broader categories provide a more realistic sense of the probability that fertilizer applications will increase yields. Most labs consider *high* to be above the amount needed (the optimum), but some labs use *optimum* and *high* interchangeably. (High, and even very high, does not mean that the nutrient is present in toxic amounts; these categories only indicate that there is a very slim chance of getting a yield increase if that nutrient is applied. With regard to P, very high indicates the potential for greater amounts lost in runoff waters, causing environmental problems in surface waters.) If the significance of the various categories is not clear on your report, be sure to ask. Labs should be able to furnish you with the probability of getting a response to added fertilizer for each soil test category.

Different Recommendation Systems

Even when labs use the same procedures, as is the case in most of the Midwest, different approaches to making recommendations lead to different amounts of recommended fertilizer. Three different systems are used to make fertilizer recommendations based on soil tests: 1) the sufficiency level system, 2) the buildup and maintenance system, and 3) the basic cation saturation ratio system (only used for Ca, Mg and K).

The ***sufficiency level system*** suggests that there is a point, the sufficiency or critical soil test value, above which there is little likelihood of crop response to an added nutrient. Its goal is not to produce the highest yield every year but rather to produce the highest average return over time from using fertilizers. Experiments that relate yield increases with added fertilizer to soil test levels provide much of the evidence supporting this approach. When applying fertilizers when soil tests indicate a need (see Figure 21.1 for K applications to a soil with a very low K test), yields increase up to a maximum yield, with no further increases as more fertilizer is added beyond this so-called *agronomic optimum rate*. Farmers should be aiming not for maximum yield but for the maximum *economic* yields and the *economic*

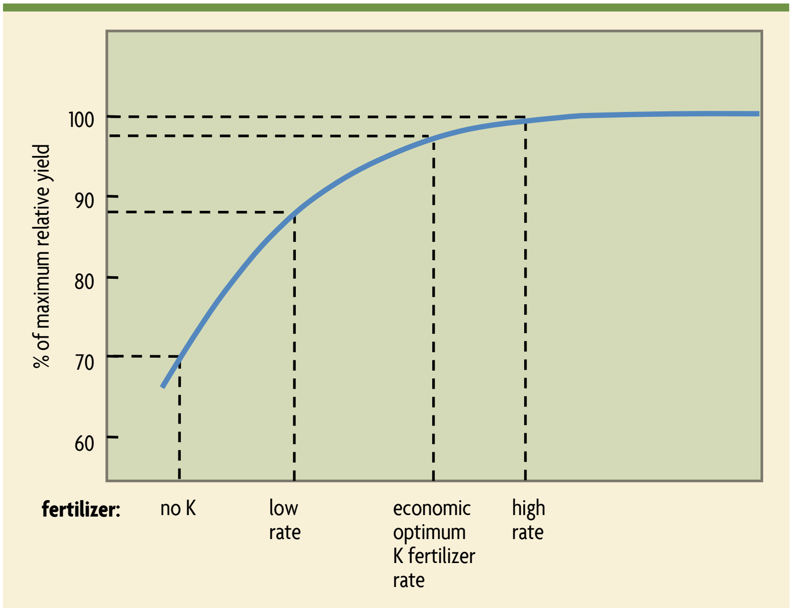

Figure 21.1. Percent of maximum yield obtained with different amounts of fertilizer K applied to a soil with a very low soil test.

optimum rate, which are slightly below the highest *possible* yields obtained with the agronomic optimum rate. With a higher testing soil than shown in Figure 21.1, let's say low instead of very low K, there would be less of a yield increase from added K and smaller amounts of fertilizer would be recommended.

The ***buildup and maintenance system*** calls for building up soils to high levels of fertility and then keeping them there by applying enough fertilizer to replace nutrients removed in harvested crops. As levels are built up, this approach frequently recommends more fertilizer than the sufficiency system. It is used mainly for phosphorus, potassium and magnesium recommendations; it can also be used for calcium when high-value vegetables are being grown on low-CEC soils. However, there may be a justification for using the buildup and maintenance approach for phosphorus and potassium—in addition to using it for calcium—on high-value crops because 1) the extra costs are such a small percent of total costs and 2) when weather is suboptimal (cool and damp, for example), this approach may occasionally produce a higher yield that would more than cover the extra expense of the fertilizer. Farmers may also want to build up their fertility levels during years of good prices to have a buffer against economic headwinds in future years. If you use this approach, you should pay attention to levels of phosphorus: adding more P when levels are already optimum can pose an environmental risk.

The basic cation saturation ratio system (BCSR—also called the base ratio system), a method for estimating calcium, magnesium and potassium needs, is based on the belief that crops yield best when calcium, magnesium and potassium—usually the dominant cations on the CEC—are in a particular balance. It grew out of work in the 1940s and 1950s by Firman E. Bear and coworkers in New Jersey, and later by William A. Albrecht in Missouri.

This system has become accepted by many farmers despite a lack of modern research supporting it (see "The Basic Cation Saturation Ratio System" at the end of this chapter). Few university testing laboratories use this system, but a number of private labs do continue to use it. It calls for calcium to occupy about 60–80% of the CEC, magnesium to be 10–20%, and potassium 2–5%. This is based on the notion that if the percent saturation of the CEC is good, there will be enough of each of these nutrients to support optimum crop growth. When using the BCSR, it is important to recognize its practical as well as theoretical flaws. For one, even when the ratios of the nutrients are within the recommended crop guidelines, there may be such a low CEC (such as in a sandy soil that is very low in organic matter) that

WANT TO LEARN MORE ABOUT BSCR?

The preponderance of research indicates that there is no "ideal" ratio of cations held on the CEC with which farmers should try to bring their soils into conformity. It also indicates that the percent base saturation has no practical usefulness for farmers. If you would like to delve further into this issue, there is a more detailed discussion of BSCR and how it perpetuates a misunderstanding of both CEC and base saturation in the appendix at the end of this chapter.

the amounts present are insufficient for crops. If the soil has a CEC of only 2 milliequivalents per 100 grams of soil, for example, it can have a "perfect" balance of Ca (70%), Mg (12.5%) and K (3.5%) but contain only 560 pounds of Ca, 60 pounds of Mg and 53 pounds of K per acre to a depth of 6 inches. Thus, while these elements are in a supposedly good ratio to one another, there isn't enough of any of them. The main problem with this soil is a low CEC; the remedy would be to add a lot of organic matter over a period of years and, if the pH is low, it should be limed.

The opposite situation also needs attention. When there is a high CEC and satisfactory pH for the crops being grown, even though there is plenty of a particular nutrient, the cation ratio system may call for adding more. This can be a problem with soils that are naturally high in magnesium, because the recommendations may call for high amounts of calcium and potassium to be added when none are really needed, thus wasting the farmer's time and money.

Research indicates that plants do well over a broad range of cation ratios, as long as there are sufficient supplies of potassium, calcium and magnesium. But still, the ratios sometimes matter for a different reason. For example, liming sometimes results in decreased potassium availability and this would be apparent with the BSCR system, but the sufficiency system would also call for adding potassium, because of the low potassium levels in these limed soils. Also, when magnesium occupies more than 50% of the CEC in soils with low organic matter and low aggregate stability, using gypsum (calcium sulfate) may help restore aggregation because of the extra calcium as well as the higher level of dissolved salts. However, this does not relate to crop nutrition, but results from the higher charge density of Ca promoting better aggregation.

Plant Tissue Tests

Soil tests are the most common means of assessing fertility needs of crops, but plant tissue tests are especially useful for nutrient management of perennial crops, such as apples, blueberries, peaches, citrus and vineyards. For most annuals, including agronomic and vegetable crops, tissue testing, though not widely used, can help diagnose problems. However, because a large amount of needed fertilizers (aside from nitrogen) can't usually be delivered to the crop during the season, tissue nutrient tests are best used in combination with soil tests. The small sampling window available for most annuals and an inability to effectively fertilize them once they are well established, except for nitrogen during early growth stages, limit the usefulness of tissue analysis for annual crops. However, leaf petiole nitrate tests are sometimes done on potatoes and sugar beets to help fine-tune in-season nitrogen fertilization. Petiole nitrate is also helpful for nitrogen management of cotton and for managing irrigated vegetables, especially during the transition from vegetative to reproductive growth. With irrigated crops, particularly when the drip system is used, fertilizer can be effectively delivered to the rooting zone during crop growth.

What Should You Do?

After reading the discussion above you may be somewhat confused by the different procedures and ways of expressing results, as well as by the different recommendation approaches. It is bewildering. Our general suggestions for how to deal with these complex issues are as follows:

1. Send your soil samples to a lab that uses tests that have been evaluated for the soils and crops of your state or region. Continue using the same lab or another that uses the same system.
2. If you're growing low value-per-acre crops (wheat, corn, soybeans, etc.), be sure that the recommendation system used is based on the sufficiency approach. This system usually results in lower fertilizer rates and higher economic returns for low-value crops. (It is not easy to find out what system a lab uses. Be persistent, and you will get to a person who can answer your question.)
3. Dividing a sample in two and sending it to two labs may result in confusion. You will probably get different recommendations, and it won't be easy to figure out which is better for you, unless you are willing to do a comparison of the recommendations. In most cases you are better off staying with the same trusted lab and learning how to fine-tune the recommendations for your farm. If you are willing to experiment, however, you can send duplicate samples to two different labs, with one going to your state-testing laboratory. In general, the recommendations from state labs call for less, but enough, fertilizer. If you are growing crops over a large acreage, set up a demonstration or experiment in one field by applying the fertilizer recommended by each lab over long strips and see if there is any yield difference. A yield monitor for grain crops would be very useful for this purpose. If you've never set up a field experiment before, you should ask your Extension agent for help. You might also find SARE's publication *How to Conduct Research on Your Farm or Ranch* of use (download or order in print at www.sare.org/research).
4. Keep a record of the soil tests for each field, so that you can track changes over the years (Figure 21.2). (But, again, make sure you use the same lab to keep results comparable). If records show a buildup of nutrients to high levels, reduce nutrient applications. If you're drawing nutrient levels down too low, start applying fertilizers or off-farm organic nutrient sources. In some rotations, such as the corn-corn-four years of hay shown at the bottom of Figure 21.2, it makes sense to build up nutrient levels during the corn phase and draw them down during the hay phase.

SOIL TESTING FOR NITROGEN

As we discussed in Chapter 19, nitrogen management poses exceptional challenges because gains and losses

To estimate the percentages of the various cations on the CEC, the amounts need to be expressed in terms of quantity of charge. Some labs give concentration by both weight (parts per million, ppm) and charge (milliequivalents per 100 grams, me/100g). If you want to convert from ppm to me/100g, you can do it as follows:

(Ca in ppm)/200 = Ca in me/100g
(Mg in ppm)/120 = Mg in me/100g
(K in ppm)/390 = K in me/100g

As discussed in Chapter 20, adding up the amount of charge due to calcium, magnesium and potassium gives a very good estimate of the CEC for most soils above pH 5.5.

RECOMMENDATION SYSTEM COMPARISON

Most university testing laboratories use the sufficiency level system, but some make potassium or magnesium recommendations by modifying the sufficiency system to take into account the portion of the CEC occupied by the nutrient. The buildup and maintenance system is used by some state university labs and many commercial labs. An extensive evaluation of different approaches to fertilizer recommendations for agronomic crops in Nebraska found that the sufficiency level system resulted in using less fertilizer and gave higher economic returns than the buildup and maintenance system. Studies in Kentucky, Ohio and Wisconsin have indicated that the sufficiency system is superior to both the buildup and maintenance and cation ratio systems.

of this nutrient are affected by its complex interactions in soil, crop management decisions and weather factors. The highly dynamic nature of nitrogen availability makes it difficult to estimate how much of the N that crops need can come from the soil. Soil samples for nitrogen tests are therefore usually taken at a different time using a different method than samples for the other nutrients (which are typically sampled to plow depth in the fall or spring).

In the humid regions of the United States there was no reliable soil test for N availability before the mid-1980s. The nitrate test commonly used for corn in humid regions was developed during the 1980s in Vermont. It is usually called the pre-sidedress nitrate test (PSNT) but is also called the late spring nitrate test (LSNT) in parts of the Midwest. In this test a soil sample is taken to a depth of 1 foot when corn is between 6 inches and 1 foot tall. The original idea behind the test was to wait as long as possible before sampling because soil and weather conditions in the early growing season may reduce or increase N availability for the crop later in the season. After the corn is 1 foot tall, it is difficult to get samples to a lab and back in time to apply any needed sidedress N fertilizer. The PSNT is now used on field corn, sweet corn, pumpkins and cabbage. Although it is widely used, it is not very accurate in some situations, such as the sandy coastal plains soils of the southeastern United States.

Different approaches to using the PSNT work for different farms. In general, using the soil test allows a farmer to avoid adding excess amounts of “insurance fertilizer.” Two contrasting examples:

- **For farms using rotations with legume forages and applying animal manures regularly (so there’s a lot of active soil organic matter)**, the best way to use the test is to apply only the amount of manure necessary to provide sufficient N to the plant. The PSNT will indicate whether the farmer needs to side dress any additional N fertilizer. It will also indicate whether the farmer has done a good job of estimating N availability from manures.
- **For farms growing cash grains without using legume cover crops**, it’s best to apply a conservative amount of fertilizer N before planting and then use the test to see if more is needed. This is especially important in regions where rainfall cannot always be relied upon to quickly bring fertilizer into contact with roots. The PSNT provides a backup and allows the farmer to be more conservative with preplant applications, knowing that there is a way to make up any possible deficit. Be aware that if the field receives a lot of banded fertilizer before planting (like inject-

ed anhydrous ammonia), test results may be very variable depending on whether cores are collected from the injection band or not.

Other Nitrogen Soil Tests

In humid regions there is no other widely used soil test for N availability. A few states in the upper Midwest offer a pre-plant nitrate test, which calls for sampling to 2 feet in the spring. For a number of years there was considerable interest in the Illinois Soil Nitrogen Test (ISNT). The ISNT, which measures the amino-sugar portion of soil N, has unfortunately been found to be an inconsistent predictor of whether the plant needs extra N. An evaluation in six Midwestern states concluded that it is not sufficiently precise for making N fertilizer recommendations. Another proposed test involves combining soluble organic N and carbon together with the amount of CO_2 that is evolved when the soil is rewetted. These tests, individually or in combination, have not yet been widely evaluated for predicting N needs under field conditions.

In the drier parts of the country, in the absence of a soil test, many land grant university laboratories use organic matter content to help adjust a fertilizer recommendation for N. But there is also a soil nitrate soil test used in some drier states that requires samples to 2 feet or more, and it has been used with success since the 1960s. The deep-soil samples can be taken in the fall or early spring, before the growing season, because of low leaching and denitrification losses and low levels of active organic matter (so hardly any nitrate is mineralized from organic matter). Soil samples can be taken at the same time for analysis for other nutrients and pH.

Sensing and Modeling Nitrogen Deficiencies

Since nitrogen management is a challenge for many of the common crops (corn, wheat, rice, oilseed rape, etc.) and is also an expensive input, there has been a significant amount of research into new technologies that allow a farmer or consultant to assess a crop's N status during the season. Generally four types of approaches are used:

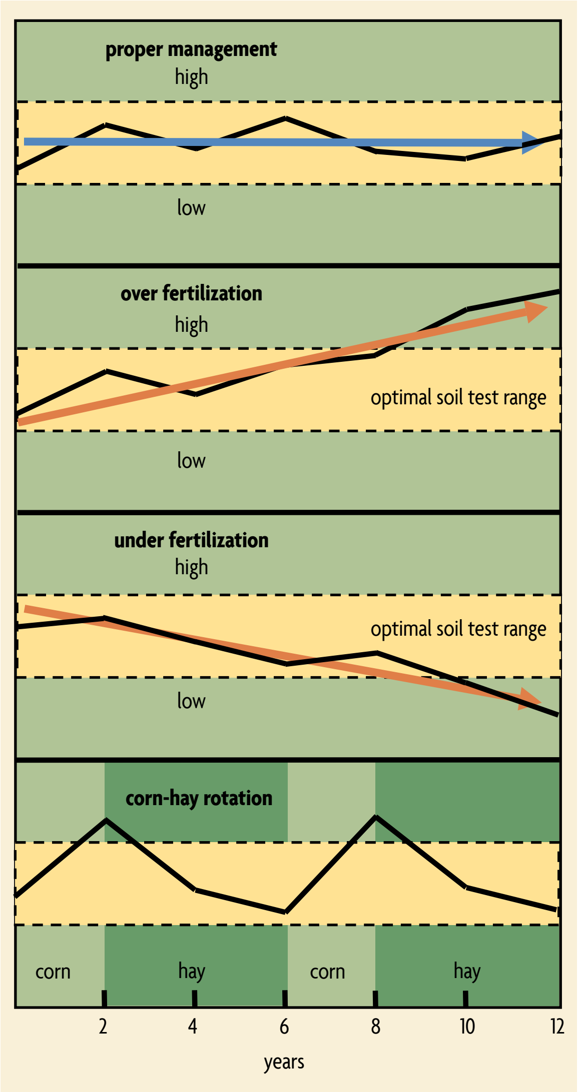

Figure 21.2. Soil test phosphorus and potassium trends under different fertility management regimes. Modified from *The Penn State Agronomy Guide* (2019–2020).

- ***Chlorophyll meters*** are handheld devices that indirectly estimate chlorophyll content in a crop leaf, which is an indicator of its N status (Figure

Table 21.1
Phosphorus Soil Tests Used in Different Regions

Region	Soil Test Solutions Used for P
Arid and semiarid Midwest, west, and northwest	Olsen AB-DTPA
Humid Midwest, mid-Atlantic, Southeast, and eastern Canada	Mehlich 3 Bray 1 (also called Bray P-1 or Bray-Kurtz P)
North central and Midwest	Bray 1 (also called Bray P-1 or Bray-Kurtz P)
Washington and Oregon	Bray 1 for acidic soils Olsen for alkaline soils
Southeast and mid-Atlantic	Mehlich 1
Northeast (New York and parts of New England), some labs in Idaho and Washington	Morgan or modified Morgan Mehlich 3

Source: Modified from Allen, Johnson and Unruh et al. (1994)

Table 21.2
Interpretation Ranges for Different P Soil Tests*

	Low and Medium	Optimum	High
Olsen	0–11	11–16**	>16
Morgan	0–4	4–10	>10
Bray 1 (Bray P-1)	0–25	25–45	>45
Mehlich 1	0–20	20–40	>40
Mehlich 3	0–30	30–50	>50
AB-DTPA (for irrigated crops)	0–8	8–11	>12

*Individual laboratories may use somewhat different ranges for these categories or use different category names.
Also note: Units are in parts per million phosphorus (ppm P), and ranges used for recommendations may vary from state to state; **Low and Medium** indicates a high to moderate probability to increase yield by adding P fertilizer; **Optimum** indicates that there is a low probability for increasing yield with added P fertilizer; **High** soil test levels indicate increasing potential for P pollution in runoff. Some labs also have a Very High category.
**If the soil is calcareous (has free calcium carbonate in the soil), the Olsen soil test “optimum” range would be higher, with over 25 ppm soil test P for a zero P fertilizer recommendation.

21.3, left). It requires field visits and adequate leaf sampling to represent different zones in the field. They are primarily used for final fertilizer applications in cereals, especially when aiming for certain protein contents.

- ***Canopy reflectance sensors*** can be handheld or equipment-mounted devices that measure reflectance without contacting the leaf (Figure 21.3, right). Both sense the light reflectance properties of a crop canopy in the near infrared and red (or red-edge) bands, which can be related to crop growth and N uptake. When equipment mounted, it allows for on-the-go adjustment of N rates throughout a field, which in most cases also requires the establishment of a high-N reference strip in the field for use in calibrating the sensor. These sensors are not imaging; in other words, they don’t create pixel maps, but they can be linked with GPS signals to chart patterns in a field.
- ***Satellite, aircraft or drone imagery*** can be used to extract reflectance information that can be related to a crop’s N status (Figure 21.4, left), usually also using near infrared and red/red-edge bands, with resolutions in the 30–90 foot (10–30 meter) range.
- ***Computer models*** simulate a field’s N dynamics and allow for daily estimation of the soil and crop N status (Figure 21.4, right).

These tools are actively being advanced as part of the drive towards digital technologies in crop production. Each technology has its strengths and weaknesses, and has proven different levels of precision. Use of computer models is relatively inexpensive and scalable. It allows for daily monitoring and is good at integrating other data sources into recommendations, but it does not involve direct field observations. The satellite-derived images are generally available every few days but are highly impacted by cloud cover, which can obstruct fields during critical decision times. Aircraft and drone imaging can avoid cloud issues but are more expensive. The chlorophyll meter is an in-field measurement that is, like the PSNT, relatively labor intensive and costly to repeat for large fields (but more attractive with smaller fields with high-value crops). Canopy reflectance sensors

Figure 21.3. In-field sensors used to measure nitrogen status of leaves and canopies. Left: leaf chlorophyll (SPAD) sensor. Photo by Konica Minolta. Right: proximal canopy sensors. Photo by Trimble Agriculture.

are also generally used once or twice during the season when N fertilizer is applied, but they are not used for continuous monitoring.

SOIL TESTING FOR P

Soil test procedures for phosphorus are different than those for nitrogen. When testing for phosphorus, the soil is usually sampled to plow depth in the fall or in the early spring before tillage, and the sample is usually analyzed for phosphorus, potassium, sometimes other nutrients (such as calcium, magnesium and micronutrients) and pH. The methods used to estimate available P vary from region to region and sometimes from state to state within a region (Table 21.1). Although the relative test value for a given soil is usually similar according to different soil tests (for example, a soil testing high in P by one procedure is generally also high by another procedure), the actual numbers can be different (Table 21.2).

The various soil tests for P take into account a large portion of the available P contained in recently applied manures and the amount that will become available from the soil minerals. However, if there is a large amount of active organic matter in your soils from crop residues or manure additions in previous years, there may well be more available P for plants than indicated by the soil test. (While there is no comparable in-season test for P, the PSNT reflects the amount of N that may become available from decomposing organic matter.)

TESTING SOILS FOR ORGANIC MATTER

A word of caution when comparing your soil test organic matter levels with those discussed in this book. If your laboratory reports organic matter as “weight loss” at high temperature, the numbers may be higher than if the lab uses the original wet chemistry method. A soil with 3% organic matter by wet chemistry might have a weight-loss value of between 4% and 5%. Most labs use a correction factor to approximate the value you would get by using the wet chemistry procedure. Although either method can be used to follow changes in your soil, when you compare soil organic matter of samples run in different laboratories, it’s best to make sure the same method was used. Unfortunately, despite its importance, organic matter assessment is still poorly standardized and lab-to-lab variability remains high. It is therefore best to use the same lab year after year if you want to evaluate trends in your fields.

There is now a laboratory that will determine various forms of living organisms in your soil. Although it costs

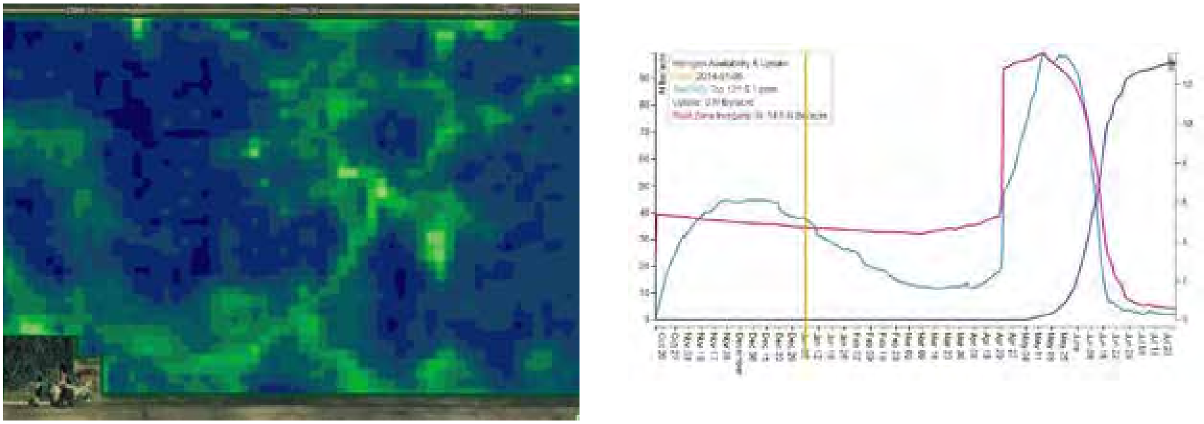

Figure 21.4. Left: satellite-based sensing of crop nitrogen status (green areas require more nitrogen than blue areas in wet season); Right: monitoring soil N status using a model. Images by Yara International.

quite a bit more than traditional testing for nutrients or organic matter, you can find out the amount (weight) of fungi and bacteria in a soil, as well as obtain an analysis for other organisms. (See the “Resources” section for laboratories that run tests in addition to basic soil fertility analysis.)

TESTING SOILS FOR pH, LIME NEEDS

Soil pH and how to change it was discussed in Chapter 20. If a soil’s pH is low, indicating that it is acid, one of the common ways to determine the amount of lime to be applied is to place a sample of soil in a chemical buffer and measure the amount the acid soil is able to depress the buffer’s pH. Keep in mind that this is different from the soil’s pH, which indicates *whether* liming is needed. The degree of change of the buffer’s pH is an indication of *how much* lime needs to be applied to raise the soil pH to the desired level.

INTERPRETING SOIL TEST RESULTS

Below are four soil test examples, including discussion about what they tell us and what types of practices farmers should follow to satisfy plant nutrient needs on these soils. Suggestions are provided for conventional farmers and for organic producers. These are just suggestions; there are other satisfactory ways to meet the needs of crops growing on the soils sampled.

The soil tests were run by different procedures to provide examples from around the United States. Interpretations of a number of commonly used soil tests—relating test levels to general fertility categories—are given later in the chapter (see tables 21.3 and 21.4). Many labs estimate the CEC that would exist at pH 7 (or even higher). Because we feel that the soil’s current CEC is of most interest (see Chapter 20), the CEC is estimated by summing the exchangeable bases. The more acidic a soil, the greater the difference between its current CEC and the CEC it would have near pH 7.

Four soil tests are presented next. Following them is a section on modifying recommendations for particular situations.

SOIL TEST #1
(New England)
Soil Test #1 Report Summary*

Field name: North

Sample date: September (PSNT sample taken the following June)

Soil type: loamy sand

Manure added: none

Cropping history: mixed vegetables

Crop to be grown: mixed vegetables

Measurement	lbs/acre**	PPM**	Soil Test Category	Recommendation Summary
P	4	2	low	50–70 lbs P_2O_5/acre
K	100	50	low	150–200 lbs K_2O/acre
Mg	60	30	low	lime (see below)
Ca	400	200	low	lime (see below)
pH	5.4			liming material needed
buffer pH***	6			2 tons dolomitic limestone/acre
CEC****	1.4 me/100g			
OM	1%			add organic matter: compost, cover crops, animal manures
PSNT		5	low	side dress 80–100 lbs N/acre

*Nutrients were extracted by modified Morgan's solution (see Table 21.3A for interpretations).
**Some labs report results in pounds per acre while others report results as ppm.
***The pH of a soil sample added to a buffered solution; the lower the pH, the more lime is needed.
****CEC by sum of bases. The estimated CEC would probably double if "exchange acidity" were determined and added to the sum of bases.
Note: ppm = parts per million; P = phosphorus; K = potassium; Mg = magnesium; Ca = calcium; OM = organic matter; me = milliequivalent; PSNT = pre-sidedress nitrate test; N = nitrogen.

What can we tell about soil #1 based on the soil test?

- The pH indicates that the soil is too acidic for most agricultural crops, so lime is needed. The buffer pH indicates that around 2 tons per acre is needed to raise pH to 6.5.
- Phosphorus is low, as are potassium, magnesium and calcium. All should be applied.
- This low-organic-matter soil is probably also low in active organic matter (indicated by the low PSNT test, see Table 21.4A) and will need an application of nitrogen. (The PSNT is done during crop growth, so it is difficult to use manure to supply extra N needs indicated by the test.)
- The coarse texture of the soil is indicated by the combination of low organic matter and low CEC.

Recommendations for conventional growers

1. Apply dolomitic limestone, if available, in the fall at about 2 tons per acre (work it into the soil, and establish a cover crop if possible). This will take care of the calcium and magnesium needs at the same time as the soil's pH is increased. It will also help make soil phosphorus more available, as well as increase the availability of any added phosphorus.
2. Because no manure is to be used after the test is taken, broadcast significant amounts of phosphate (P_2O_5 —probably around 50–70 pounds per acre) and potash (K_2O—around 150–200 pounds per acre). Some phosphate and potash can also be applied in starter fertilizer (band-applied at planting). Usually, N is also included in starter fertilizer, so it might be reasonable to use about 300 pounds of a 10-10-10 fertilizer, which will apply 30 pounds of N, 30 pounds of phosphate and 30 pounds of potash per acre. If that rate of starter is to be used, broadcast 400 pounds per acre of a 0-10-30 bulk blended fertilizer. The broadcast plus the starter will supply 30 pounds of N, 70 pounds of phosphate and 150 pounds of potash per acre.
3. If only calcitic (low-magnesium) limestone is available, use K-Mag (Sul-Po-Mag) as the potassium source in the bulk blend to help supply magnesium.
4. Nitrogen should be side dressed at around 80–100 (or more) pounds per acre for N-demanding crops such as corn or tomatoes. About 220 pounds of urea per acre will supply 100 pounds of N.
5. Use various medium- to long-term strategies to build up soil organic matter, including the use of cover crops and animal manures. Most of the nutrient needs of crops on this soil could have been met by using about 20 tons wet weight of solid cow manure per acre or its equivalent. It is best to apply it in the spring, before planting. If the manure had been applied, the PSNT test would probably have been quite a bit higher, perhaps around 25 ppm.

Recommendations for organic producers

1. Use dolomitic limestone to increase the pH (as recommended for the conventional farmer, above). It will also help make soil phosphorus more available, as well as increase the availability of any added phosphorus.
2. Apply 2 tons of rock phosphate or a combination of 1 ton rock phosphate and 2.5 tons of poultry manure.
3. If poultry manure is used to raise the phosphorus level without using rock phosphate, add 2 tons of compost per acre to provide some longer lasting nutrients and humus. If rock phosphate is used to supply phosphorus and if no poultry manure is used, use livestock manure and compost (to add N, potassium, magnesium and some humus).
4. Establish a good rotation with soil-building crops and legume cover crops. Use manure with care. Although the application of uncomposted manure is allowed by organic certification agencies, there are restrictions. Under the Food Safety Modernization Act (FSMA), the application of uncomposted manure is now regulated for all farms growing food crops, whether organic or not. For example, four months may be needed between the time you apply uncomposted manure and either harvest crops with edible portions in contact with soil or plant crops that accumulate nitrate, such as leafy greens or beets. A three-month period may be needed between uncomposted manure application and harvest of other food crops. These FSMA rules apply to all farms with annual sales of more than $25,000.

SOIL TEST #2
(Humid Midwest)
Soil Test #2 Report Summary*

Field name: #12	Measurement	lbs/acre**	PPM**	Soil Test Category	Recommendation Summary
Sample date: December (no sample for PSNT will be taken)	P	20	10	very low	30 lbs P_2O_5/acre
	K	58	29	very low	200 lbs K_2O/acre
Soil type: clay (somewhat poorly drained)	Mg	138	69	high	none
	Ca	400	200	high	none
Manure added: none	pH	6.8			no lime needed
Cropping history: continuous corn	CEC	21.1 me/100g			
	OM	4.3%			rotate to forage legume crop
Crop to be grown: corn	N	no N soil test			100–130 lbs N/acre

*All nutrient needs were determined using the Mehlich 3 solution (see Table 21.3C).
**Most university laboratories in the Midwestern United States report results as ppm while private labs may report results in pounds per acre.
Note: ppm = parts per million; P = phosphorus; K = potassium; Mg = magnesium; Ca = calcium; N = nitrogen; OM = organic matter; me = milliequivalent.

What can we tell about soil #2 based on the soil test?

- The high pH indicates that this soil does not need any lime.
- Phosphorus and potassium are low. (Note: 20 pounds of P per acre is low, according to the soil test used, Mehlich 3. If another test, such as Morgan's solution, was used, a result of 20 pounds of P per acre would be considered a high result.)
- The organic matter is relatively high. However, considering that this is a somewhat poorly drained clay, it probably should be even higher.
- About half of the CEC is probably due to the organic matter and the rest probably due to the clay.
- Low potassium indicates that this soil has probably not received high levels of manures recently.
- There was no test done for nitrogen, but given the field's history of continuous corn and little manure, there is probably a need for nitrogen.
- A low amount of active organic matter that could have supplied nitrogen for crops is indicated by the history (the lack of rotation to perennial legume forages and the lack of manure use) and the moderate percent of organic matter (considering that it is a clay soil).

General recommendations

1. This field should probably be rotated to a perennial forage crop.
2. Phosphorus and potassium are needed. If a forage crop is to be grown, probably around 30 pounds of phosphate and 200 or more pounds of potash should be broadcasted pre-planting. If corn will be grown again, all of the phosphate and 30–40 pounds of the potash can be applied as starter fertilizer at planting. Although magnesium, at about 3% of the effective CEC, would be considered low by relying exclusively on a basic cation saturation ratio system recommendation, there is little likelihood of an increase in crop yield or quality by adding magnesium.
3. Nitrogen fertilizer is probably needed in large amounts (100–130 pounds per acre) for high N-demanding crops, such as corn. If no in-season soil test (like the PSNT) is done, some pre-plant N should be applied (around 50 pounds per acre), some in the starter band at planting (about 15 pounds per acre) and some side dressed (about 50 pounds).
4. One way to meet the needs of the crop:
    a. broadcast 500 pounds per acre of an 11-0-44 bulk blended fertilizer;
    b. use 300 pounds per acre of a 5-10-10 starter; and then
    c. side dress with 110 pounds per acre of urea. These amounts will supply approximately 120 pounds of N, 30 pounds of phosphate and 210 pounds of potash.

Recommendations for organic producers

1. Apply 2 tons per acre of rock phosphate (to meet P needs) or a combination of 1 ton rock phosphate and 3–4 tons of poultry manure.
2. Apply 400 pounds of potassium sulfate per acre broadcast pre-plant if a combination of rock phosphate and poultry manure is applied to meet P needs.
3. Use manure with care. Although the application of uncomposted manure is allowed by organic certification agencies, there are restrictions. Under the Food Safety Modernization Act (FSMA), the application of uncomposted manure is now regulated for all farms growing food crops, whether organic or not. For example, four months may be needed between the time you apply uncomposted manure and either harvest crops with edible portions in contact with soil or plant crops that accumulate nitrate, such as leafy greens or beets. A three-month period may be needed between uncomposted manure application and harvest of other food crops. These FSMA rules apply to all farms with annual sales of more than $25,000.

SOIL TEST #3
(Alabama)
Soil Test #3 Report Summary*

Field name: River A
Sample date: October
Soil type: sandy loam
Manure added: poultry manure in previous years
Cropping history: continuous cotton
Crop to be grown: cotton

Measurement	lbs/acre**	PPM**	Soil Test Category	Recommendation Summary
P	60	30	high	none
K	166	83	high	none
Mg	264	132	high	none
Ca	1,158	579		none
pH	6.5			no lime needed
CEC	4.2 me/100g			
OM	not requested			use legume cover crops, consider crop rotation
N	no N soil test			70–100 lbs N/acre

*All nutrient needs were determined using the Mehlich 1 solution (seeTable 21.3B).
**Alabama reports nutrients in lbs/acre.
Note: P = phosphorus; K = potassium; Mg = magnesium; Ca = calcium; N = nitrogen; OM = organic matter; me = milliequivalent.

What can we tell about soil #3 based on the soil test?

- With a pH of 6.5, this soil does not need any lime.
- Phosphorus, potassium and magnesium are sufficient.
- Magnesium is high, compared with calcium (Mg occupies over 26% of the CEC).
- The low CEC at pH 6.5 indicates that the organic matter content is probably around 1–1.5%.

General recommendations

1. No phosphate, potash, magnesium or lime is needed.
2. Nitrogen should be applied, probably in a split application totaling about 70–100 pounds N per acre.
3. This field should be in a rotation such as cotton-corn-peanuts with winter cover crops.

Recommendations for organic producers

1. Although poultry or dairy manure can meet the crop's needs, that means applying phosphorus on a soil already high in P. If there is no possibility of growing an overwinter legume cover crop (see recommendation #2), about 15–20 tons of bedded dairy manure (wet weight) should be sufficient. Another option for supplying some of the crop's need for N without adding more P is to use Chilean nitrate until good rotations with legume cover crops are established.
2. If time permits, plant a high-N-producing legume cover crop, such as crimson clover (or a crimson clover/oat mix), to provide nitrogen to cash crops.
3. Develop a good rotation so that all the needed nitrogen will be supplied to nonlegumes between the rotation crops and cover crops.
4. Use manure with care. Although the application of uncomposted manure is allowed by organic certification agencies, there are restrictions. Under the Food Safety Modernization Act (FSMA), the application of uncomposted manure is now regulated for all farms growing food crops, whether organic or not. For example, four months may be needed between the time you apply uncomposted manure and either harvest crops with edible portions in contact with soil or plant crops that accumulate nitrate, such as leafy greens or beets. A three-month period may be needed between uncomposted manure application and harvest of other food crops. These FSMA rules apply to all farms with annual sales of more than $25,000.

SOIL TEST #4
(Semiarid Great Plains)
Soil Test #4 Report Summary*

Field name: Hill
Sample date: April
Soil type: silt loam
Manure added: none indicated
Cropping history: not indicated
Crop to be grown: corn

Measurement	lbs/acre**	PPM**	Soil Test Category	Recommendation Summary
P	14	7	low	20–40 lbs P_2O_5
K	716	358	very high	none
Mg	340	170	high	none
Ca	not determined			none
pH	8.1			no lime needed
CEC	not determined			
OM	1.8%			use legume cover crops, consider rotation to other crops that produce large amounts of residues
N	5.8 ppm			170 lbs N/acre

*K and Mg are extracted by neutral ammonium acetate, P by the Olsen solution (see Table 21.3D).
Note: ppm = parts per million; P = phosphorus; K = potassium; Mg = magnesium; Ca = calcium; OM = organic matter; me = milliequivalent; N = nitrogen, with residual nitrate determined in a surface to 2-foot sample.

What can we tell about soil #4 based on the soil test?

- The pH of 8.1 indicates that this soil is most likely calcareous.
- Phosphorus is low, there is sufficient magnesium and potassium is very high.
- Although calcium was not determined, there will be plenty in a calcareous soil.
- The organic matter at 1.8% is low for a silt loam soil.
- The nitrogen test indicates a low amount of residual nitrate (Table 21.4B) and, given the low organic matter level, a low amount of N mineralization is expected.

General recommendations

1. No potash, magnesium or lime is needed.
2. About 150 pounds of N per acre should be applied. Because of the low amount of leaching in this region, most can be applied preplant, with perhaps 30 pounds as a starter (applied at planting). Using 300 pounds per acre of a 10-10-0 starter would supply all P needs (see recommendation #3) as well as provide some N near the developing seedling. Broadcasting and incorporating 260 pounds of urea (or applying subsurface using a liquid formulation) will provide 120 pounds of N.
3. About 20–40 pounds of phosphate is needed per acre. Apply the lower rate as a starter because localized placement results in more efficient use by the plant. If phosphate is broadcast, apply at the 40-pound rate.
4. The organic matter level of this soil should be increased. This field should be rotated to other crops, and cover crops should be used regularly.

Recommendations for organic producers

1. Because rock phosphate is so insoluble in high-pH soils, it would be a poor choice for adding P. Poultry manure (about 6 tons per acre) or dairy manure (about 25 tons wet weight per acre) can be used to meet the crop's needs for both N and P. However, that means applying more P than is needed, plus a lot of potash (which is already at very high levels). Fish meal might be a good source of N and P without adding K.
2. A long-term strategy needs to be developed to build soil organic matter, including better rotations, use of cover crops and importing organic residues onto the farm.
3. Use manure with care. Although the application of uncomposted manure is allowed by organic certification agencies, there are restrictions. Under the Food Safety Modernization Act (FSMA), the application of uncomposted manure is now regulated for all farms growing food crops, whether organic or not. For example, four months may be needed between the time you apply uncomposted manure and either harvest crops with edible portions in contact with soil or plant crops that accumulate nitrate, such as leafy greens or beets. A three-month period may be needed between uncomposted manure application and harvest of other food crops. These FSMA rules apply to all farms with annual sales of more than $25,000.

ADJUSTING A SOIL TEST RECOMMENDATION

Specific recommendations must be tailored to the crops you want to grow, as well as to other characteristics of the particular soil, climate and cropping system. Most soil test reports use information that you supply about manure use and previous crops to adapt a general recommendation to your situation. However, once you feel comfortable with interpreting soil tests, you may also want to adjust the recommendations for a particular need. What happens if you decide to apply manure after you sent in the form along with the soil sample? Also, you usually don't get credit for the nitrogen produced by legume cover crops because most forms don't even ask about their use. The amount of available nutrients from legume cover crops and from manures is indicated in Table 21.5. If you don't test your soil annually, and the recommendations you receive are only for the current year, you need to figure out what to apply the next year or two, until the soil is tested again.

No single recommendation, based only on the soil test, makes sense for all situations. For example, your gut might tell you that a test is too low (and fertilizer

Table 21.3
Soil Test Categories for Various Extracting Solutions

A. Modified Morgan's Solution (Vermont)

Category	Very Low	Low	Optimum	High	Excessive
Probability of Response to Added Nutrient	Very High	High	Low	Very Low	
Available P (ppm)	0–2	2.1–4.0	4.1–7	7.1–20	
K (ppm)	0–50	51–100	101–130	131–160	>160
Mg (ppm)	0–35	36–50	51–100	>100	

B. Mehlich 1 Solution (Alabama)*

Category	Very Low	Low	Optimum	High	Excessive
Probability of Response to Added Nutrient	Very High	High	Low	Very Low	
Available P (lbs/A)**	0–6	7–12	50	26–50	>50
K (lbs/A)**	0–22	23–45	160–90	>90	
Mg (lbs/A)**		0–25	>50		
Ca for tomatoes (lbs/A)***	0–150	151–250	>500		

*For loam soils (with CEC values of 4.6–9), from: Alabama Agricultural Experiment Station. 2012. *Nutrient Recommendation Tables for Alabama Crops*. Agronomy and Soils Departmental Series No. 324B.
**For corn, legumes and vegetables on soils with CECs greater than 4.6 me/100g.
***For corn, legumes and vegetables on soils with CECs from 4.6–9 me/100g.

C. Mehlich 3 Solution (North Carolina)*

Category	Very Low	Low	Optimum	High	Excessive
Probability of Response to Added Nutrient	Very High	High	Low	Very Low	
Available P (ppm)	0–12	13–25	26–50	51–125	>125
K (ppm)	0–43	44–87	88–174	>174	
Mg (ppm)**	0–25		>25		

**Source*: From Hanlon (1998).
**Percent of CEC is also a consideration.

D. Neutral Ammonium Acetate Solution for K and Mg and Olsen or Bray-1 for P (Nebraska [P and K], Minnesota [Mg])

Category	Very Low	Low	Optimum	High	Excessive
Probability of Response to Added Nutrient	Very High	High	Low	Very Low	
P (Olson, ppm)	0–3	4–10	11–16	17–20	>20
P (Bray-1, ppm)	0–5	6–15	16–24	25–30	>30
K (ppm)	0–40	41–74	75–124	125–150	>150
Mg (ppm)	0–50		51–100	>101	

Table 21.4
Soil Test Categories for Nitrogen Tests

A. Pre-Sidedress Nitrate Test (PSNT)*

Category	Very Low	Low	Optimum	High	Excessive
Probability of Response to Added Nutrient	Very High	High	Low	Very Low	
Nitrate-N (ppm)	0–10	11–22	23–28	29–35	>35

*Soil sample taken to 1 foot when corn is 6–12 inches tall.

B. Deep (4-ft) Nitrate Test (Nebraska)

Category	Very Low	Low	Optimum	High	Excessive
Probability of Response to Added Nutrient	Very High	High	Low	Very Low	
Nitrate-N (ppm)	0–6	7–15	15–18	19–25	>25

recommendations are too high). Let's say that although you broadcast 100 pounds N per acre before planting, a high rate of N fertilizer is recommended by the in-season nitrate test (PSNT), even though there wasn't enough rainfall to leach out nitrate or cause much loss by denitrification. In that case, you might not want to apply the full amount recommended. Another example: A low potassium level in a soil test—let's say around 40 ppm (or 80 pounds per acre)—will certainly mean that you should apply potassium. But how much should you use? When and how should you apply it? The answer to these two questions might be quite different on a low organic matter, sandy soil where high amounts of rainfall normally occur during the growing season (in which case, potassium may leach out if applied the previous fall or early spring) versus a high organic matter, clay loam soil that has a higher CEC and will hold on to potassium added in the fall. This is the type of situation that dictates using reputable labs whose recommendations are developed for soils and cropping systems in your home state or region. It also is an indication that you may need to modify a recommendation for your specific situation.

MAKING ADJUSTMENTS TO FERTILIZER APPLICATION RATES

If information about cropping history, cover crops and manure use is not provided to the soil testing laboratory, the report containing the fertilizer recommendation cannot take those factors into account. The "Worksheet for Adjusting Fertilizer Recommendations" is an example of how you can modify the report's recommendations. New computer models have been developed that integrate this type of information—soil test results, manure applications, previous rotation and cover crops, and enhanced efficiency products—with other soil, management and weather data to better estimate the combined dynamic impacts of various N sources and to fine-tune fertilizer applications.

MANAGING FIELD NUTRIENT VARIABILITY

Many large fields have considerable variation in soil types and fertility levels. Site-specific application of crop

Table 21.5
Amounts of Available Nutrients from Manures and Legume Cover Crops

Legume Cover Crops*	N (lbs/acre)		
Hairy vetch	70–140		
Crimson clover	40–90		
Red and white clovers	40–90		
Medics	30–80		
	N	P_2O_5	K_2O
Manures**	(lbs per ton manure)		
Dairy	6	4	10
Poultry	20	15	10
Hog	6	3	9

*Amount of available N varies with amount of growth.
**Amount of nutrients varies with diet, storage and application method.
Note: Quantities given in this table are somewhat less than for the total amounts given in Table 12.1.

Worksheet for Adjusting Fertilizer Recommendations*

	N	P_2O_5	K_2O
Soil Test Recommendation (lbs/acre)	**120**	**40**	**140**
Accounts for contributions from the soil. Accounts for nutrients contributed from manure and previous crop only if information is included on form sent with soil sample.			
Credits			
(Use only if not taken into account in recommendation received from lab.)			
Previous crop (already taken into account)	0		
Manure (10 tons @ 6 lbs N, 2.4 lbs P_2O_5, 9 lbs K_2O per ton, assuming that 60% of the nitrogen, 80% of the phosphorus and 100% of the potassium in the manure will be available this year)	-60	-24	-90
Cover crop (medium-growth crimson clover)	-50		
Total Nutrients Needed from Fertilizer	**10**	**16**	**50**

*This sample worksheet is based on the following scenario: Past crop = corn; Cover crop = crimson clover, but small to medium amount of growth; Manure = 10 tons of dairy manure that tested at 10 pounds of N, 3 pounds of P_2O_5 and 9 pounds of K_2O per ton. (A decision to apply manure was made after the soil sample was sent, so the recommendation could not take those nutrients into account.)

nutrients and lime using variable-rate technology may be economically and environmentally advantageous for these situations. Soil pH levels, P and K often show considerable variability across a large field because of non-uniform application of fertilizers and manures, natural variability and differing crop yields. Soil N levels may also show some variation due to variable organic matter levels and drainage in a field. It has become easier to accurately apply different amounts of N fertilizer to separate parts of fields using the variable fertilizer application technology now available. And, as mentioned above, on-the-go sensors, models and satellite imagery may be used to guide variable application tools (figures 21.3 and 21.4).

Aside from when automated sensors and models are used to determine nitrogen fertilizer needs, site-specific management requires the collection of multiple soil samples within the field, which are then analyzed separately. This is most useful when the sampling and application are performed using precision agriculture technologies such as GPS, geographic information systems and variable-rate applicators. However, conventional application technology can also be effective (rates can be simply varied by adjusting the travel speed of the applicator.)

The general recommendation is for 2.5- to 5-acre grid sampling, especially for fields that have received variable manure and fertilizer rates. In some areas, one-acre grids are sampled. The suggested sampling procedure is called unaligned because in order to get a better picture of the field as a whole, grid points should not follow a straight line because you may unknowingly pick up a past applicator malfunction. Grid points can be designed with the use of precision agriculture software packages or by ensuring that sampling points are taken by moving a few feet off the regular grid in random directions (Figure 21.5). Grid sampling still requires 10–15 individual cores to be taken within about a 30-foot area around each grid point. Sampling units within fields may also be defined by soil type (from soil survey maps) and landscape position.

Grid soil testing may not be needed every time you sample the field—it is an expensive and time-consuming effort—but it is recommended to evaluate site-specific nutrient levels in larger fields at least once in a rotation, each time lime may be needed, or every five to eight years. Sometimes, sampling is done based on mapping units from a soil survey, but in many cases the fertility patterns don't follow the soil maps. It is better to use grids first and then assess whether mapped soil zones can be used in the future.

TESTING HIGH TUNNEL SOILS

Growing vegetables in high tunnels has become popular as a way of improving crop quality and yield, and extending the growing season. These non-permanent structures provide superior growing conditions compared to the field by offering protection from low temperature, high temperature (with shading added and vents open) and rainfall, as well as the ability to optimize soil moisture and nutrients. Tunnels vary in size but typically are 20–30 feet wide, 100–200 feet long, with a quonset or gothic shape peaking at 10–15 feet. They are covered in greenhouse plastic and either passively or mechanically heated and vented. Drip irrigation is the standard, but surface mulches vary widely. Conventional growers may use synthetic rooting media such as rock wool, peat-lite mixes or other materials suitable for container culture. Organic growers must grow crops in the soil, so tunnels are usually placed over high-quality field soil, significantly amended to achieve the fertility levels needed to realize the high yield potential in tunnels. Tunnel tomatoes are frequently grafted onto greenhouse tomato rootstock to avoid soilborne diseases and to enhance plant vigor.

With a longer growing season, good cultural practices, pest management and sufficient nutrients, tomatoes can yield many times what is achievable outdoors, reaching the equivalent of 60–80 tons per acre. The amount of nutrients needed by such large yields is impressive: equivalent to 200–300 pounds of N, 300–400 pounds of phosphate (P_2O_5) and 700–900 pounds of potash (K_2O) per acre. Many vegetable farmers follow their summer crops (most commonly tomatoes) with

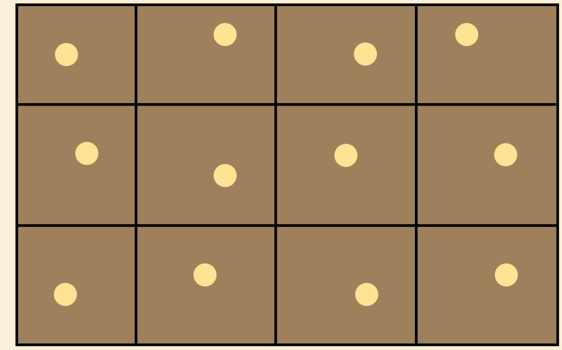

Figure 21.5. Unaligned sampling grid for variable-rate management. Squares indicate 3- to 5-acre management units, and circles are sampling areas for 10–15 soil cores.

UNUSUAL SOIL TESTS

We've come across unusual soil test results from time to time. A few examples and their typical causes:

- Very high phosphorus levels: high poultry or other manure application over many years.
- Very high salt concentration in humid regions: recent application of large amounts of poultry manure in high tunnel greenhouses where rainfall is not able to leach salts, or located immediately adjacent to a road where deicing salt was used.
- Very high pH and high calcium levels relative to potassium and magnesium: large amounts of lime-stabilized sewage sludge used.
- Very high calcium levels given the soil's texture and organic matter content: the soil test used an acid solution, such as the Morgan, Mehlich 1 or Mehlich 3, to extract soils containing free limestone, causing some of the lime to dissolve.
- Soil pH >7 and very low P: the soil test used an acid such as found in Mehlich I, Bray or Mehlich 3 on an alkaline, calcareous soil. (In this case, the soil neutralizes much of the acid, so little P is extracted.)

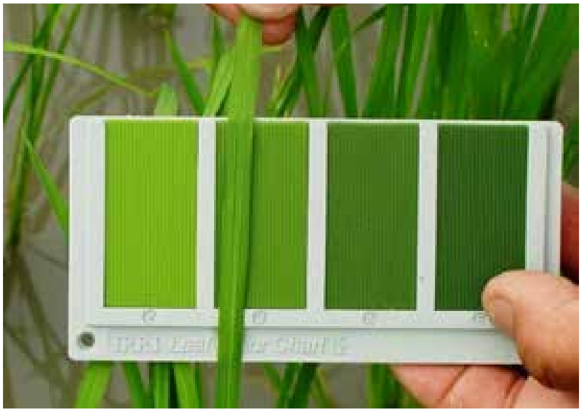

Figure 21.6. International Rice Research Institute (IRRI) leaf color chart for nitrogen evaluation with rice. Photo by IPNI.

greens such as spinach, kale, lettuce and mustards, which allows for harvest of fresh greens throughout the cold winter months and straight through the spring until the subsequent summer crop is planted. Because of the high nutrient levels that are needed in tunnels, fertilizer recommendations based on routine "field soil tests" (using extracts to estimate availability of reserve nutrients) must be adjusted upwards. In addition, because transplants are expected to start growing immediately after being set in the tunnels, and because rainfall does not leach salts from the soil, a "potting soil test" such as the saturated media extract is also useful. That test measures water-soluble nutrient levels (immediately available nutrients), including nitrate-N and ammonium-N, as well as salinity (total salt) levels.

NUTRIENT RECOMMENDATIONS WITHOUT SOIL ANALYSES

As much as soil and tissue testing is now routine in countries with advanced agriculture, there are many places where soil testing and tissue analysis are either too expensive or logistically challenging. Looking at leaf discoloration patterns can be a good diagnostic approach for many crop deficiencies (see the discussion on nutrient deficiency symptoms in Chapter 23), but symptoms generally are apparent only when the nutrient is already severely deficient. A simple approach for nitrogen is the use of *leaf color charts* (available in printed format or as a mobile app; Figure 21.6), which are in use for rice, wheat and corn.

The remaining option without soil testing is to estimate fertilizer needs based on crop removal as we discussed in the "buildup and maintenance approach." With this, the yield is multiplied by a crop nutrient removal factor to derive a recommendation and to prevent long-term depletion. In many other cases, farmers with limited access to credit or other resources simply apply what they can afford, which is often below the optimum amount.

SUMMARY

Routine soil tests for acidity and nutrient availability provide extremely valuable information for managing soil fertility. Soil test results provide a way to make rational decisions about applications of fertilizers and various amendments such as lime, manures and composts. This is the way to find out if a soil is too acid and, if it is, how much liming material will be needed to raise it to the pH range desired for the crops you grow (occasionally acidic material is applied to reduce pH). Testing soils on a regular basis, at least once every three years, should be part of the farm management system on all farms that grow crops. This allows you to follow changes that occur in your fields and may indicate an early warning of some action that needs to be taken.

Use a soil test laboratory that utilizes procedures shown to be appropriate for your region and state. Keep in mind that soil tests are not 100% perfect. Recommendations indicate the probability of improving crop nutrition: whether there is a high, medium or low probability of increasing crop yield or quality by adding a particular fertilizer. But while soil testing isn't perfect, it's one of the basic tools we have to guide decisions on the need to use fertilizers and amendments. With nitrogen, crop availability and fertilizer recommendations should be approached in a timely manner. Soil or tissue tests need to be done right before the major crop uptake phase, and models and sensors can be used to improve precision. Since nitrogen is a highly dynamic nutrient that is strongly impacted by weather events, new data-driven technologies offer great opportunities. When soil health practices like organic matter additions, reduced tillage, cover cropping and better rotations are implemented, they also change how N processes interact with weather, and the complexity of the system increases. Therefore, true 4R-Plus management requires better tools than simple static equations that are still the standard for crop N management promoted by most institutions.

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CHAPTER APPENDIX: THE BASIC CATION SATURATION RATIO SYSTEM

The basic cation ratio system was discussed earlier in this chapter. This appendix is intended to clarify the

With very little data, Firman Bear and his coworkers decided that the "ideal" soil—that is, an "ideal" New Jersey soil—was one in which the CEC was 10 me/100g; the pH was 6.5; and the CEC was occupied by 20% H, 65% Ca, 10% Mg and 5% K. And the truth is, for most crops, that's not a bad soil test. It would mean that it contains 2,600 pounds of Ca, 240 pounds of Mg and 390 pounds of K per acre to a 6-inch depth in forms that are available to plants. While there is nothing wrong with that particular ratio (although to call it "ideal" was a mistake), the main reason the soil test is a good one is that the CEC is 10 me/100g (the effective CEC—the CEC the soil actually has—is 8 me/100g) and the amounts of Ca, Mg and K are all sufficient.

issues for those interested in soil chemistry and in a more in-depth look at the BCSR (or base ratio) system.

Background

The basic cation saturation ratio system attempts to balance the amount of Ca, Mg and K in soils according to certain ratios. The early concern of researchers was with the luxury consumption of K by alfalfa—that is, if K is present in very high levels, alfalfa will continue to take up much more K than it needs and, to a certain extent, it does so at the expense of Ca and Mg. When looking with the hindsight of today's standards, the original experiments were neither well designed nor well interpreted and the system is therefore actually of little value. But its continued use perpetuates a basic misunderstanding of what CEC and base saturation are all about.

Problems with the System

When the cations are in the ratios usually found in soils, there is nothing to be gained by trying to make them conform to an "ideal" and fairly narrow range. In addition to the practical problems and the increased fertilizer it frequently calls for above the amount that will increase yields or crop quality, there is another issue: The system is based on a faulty understanding of CEC and soil acids, as well as on a misunderstanding and misuse of the term *percent base saturation* (%BS). When it is defined, you usually see something like the following:

$$\%BS = 100 \times \text{sum of exchangeable cations} / CEC$$
$$= 100 \times (Ca^{++} + Mg^{++} + K^{+} + Na^{+}) / CEC$$

First off, what does CEC mean? It is the capacity of the soil to hold onto cations because of the presence of negative charges on the organic matter and clays, but also to exchange these cations for other cations. For example, a cation such as Mg, when added to soils in large quantities, can take the place of (that is, exchange for) a Ca or two K ions that were on the CEC. Thus, a cation held on the CEC can be removed relatively easily as another cation takes its place. But how is CEC estimated or determined? The only CEC that is of significance to a farmer is the one that the soil currently has. Once soils are much above pH 5.5 (and almost all agricultural soils are above this pH, making them moderately acid to neutral to alkaline), the entire CEC is occupied by Ca, Mg and K (as well as some Na and ammonium). There are essentially no truly exchangeable acids (hydrogen or aluminum) in these soils. This means that the actual CEC of the soils in this normal pH range is just the sum of the exchangeable bases. The CEC is therefore 100% saturated with bases when the pH is over 5.5 because *there are no exchangeable acids*. Are you still with us?

As we discussed earlier in the chapter, liming a soil creates new cation exchange sites as the pH increases (see the section "Cation Exchange Capacity Management"). Laboratories using the BCSR system either determine the CEC at a higher pH or use other methods to estimate the so-called exchangeable hydrogen, which, of course, is not really exchangeable. Originally, the amount of hydrogen that could be neutralized at pH 8.2 was used to estimate exchangeable hydrogen. But when your soil has a pH of 6.5, what does a CEC determined at pH 8.2 (or pH 7 or some other relatively high pH) mean to you? In other words, the percent base saturation determined in this way has no relevance whatsoever to the practical issues facing farmers as they manage the fertility of their soils. Why then even determine and report a percent base saturation and the percentages of the fictitious CEC (one higher than the soil actually has) occupied by Ca, Mg and K?

If you would like to delve into this issue in more detail, see the articles listed in the appendix sources. We specifically note the 2007 review article that concluded: "Our examination of data from numerous studies [...]

would suggest that, within the ranges commonly found in soils, the chemical, physical and biological fertility of a soil is generally not influenced by the ratios of Ca, Mg and K. The data do not support the claims of the BCSR, and continued promotion of the BCSR will result in the inefficient use of resources in agriculture."

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Chapter 22

SOILS FOR URBAN FARMS, GARDENS AND GREEN SPACES

From New York City to Chicago, Venezuela to Lima, …
rooftop gardens and urban vegetable patches are growing fresh food close to the people.

—NATIONAL GEOGRAPHIC

When most people think about where food is grown, their vision is usually of farms, large and small, in rural regions. The majority of these farms have been in agriculture for decades or longer, and they have never been used for significant residential, commercial or industrial purposes in their past. But in towns and cities around the country, there is a rapidly growing interest in urban food production, from school and community gardens to nonprofit and commercial urban farms. Similarly, urban green spaces, street trees and backyard gardens provide important relief from dense urbanized environments and have proven to be important to city dwellers' overall wellbeing.

Managing soils on urban farms and green spaces is in some ways similar to managing them on rural farms. For example, there is a need to provide adequate water and nutrients to the soil, and to ensure that the pH is balanced, just as with rural agricultural soils. Another similarity is that a main source of soil degradation in urban areas is compaction from lost organic matter and traffic (construction activities, vehicles, pedestrians, etc.).

However, in other ways, managing urban soils is quite different. Urban lands often have gone through any number of residential, commercial or industrial uses in the past, and this land-use history presents unique challenges to the aspiring urban farmer or gardener. Because of their history, urban soils intended for food production often start off in poor shape: they are usually compacted and with low organic matter content, low nutrient availability, and low biological activity and diversity. But unlike soils on rural farms, contamination by toxic compounds is one of the greatest challenges facing urban food growers, and it must be addressed before food can be safely grown and marketed in local communities. This chapter explores the primary challenges you are likely to encounter when preparing urban soils for food production, and it outlines strategies for making these soils both productive and safe to human health.

Photo by Preston Keres

Also, we will discuss challenges with establishing and maintaining urban green infrastructure like parks, street trees and ornamental gardens.

COMMON CHALLENGES WITH URBAN SOILS

Typically, the first challenges you are likely to find with urban soils are compaction, the presence of concrete, construction materials and other trash, and the presence of toxic compounds. The basic causes of compaction in urban settings are very similar to those discussed in Chapter 6, such as traffic from heavy vehicles. However, in urban settings, it is oftentimes construction activity rather than the use of farm equipment that causes compaction and soil degradation. Because construction jobs are often done on tight schedules, the compaction potential of working on wet soils is likely to be ignored. Also, construction regularly involves either removing topsoil or adding fill to build up the ground level, along with the use of very heavy equipment (Figure 22.1). All of this results in disturbed, compacted soils low in organic matter and biological activity (Figure 22.2) In addition, construction debris and chemical waste materials left behind in many cases become part of the soil matrix, frequently raising the pH (because concrete contains lime).

Figure 22.1. A history of construction activity at an urban site oftentimes results in compacted soil that contains both debris and contaminants. Photo by Francisco Andreotti.

There are many kinds of toxic compounds that can be present in urban soils, and they can come from a variety of sources depending on the location and land-use history of a property (Figure 22.3). Addressing the presence of toxic compounds is critical not only because urban farms and gardens produce food for human consumption, but also because urban operations tend to emphasize educational programming. If members of the community are going to visit an urban farm on a regular basis, especially children, it is essential to resolve any problems related to toxic compounds in the soil.

While all of these problems are solvable, their solutions might prove time consuming and expensive, depending on their severity. For example, the opportunity to use forms of tillage to reduce compaction may be limited in urban settings due to unique aspects of urban farming, such as the presence of underground utilities, a lack of space for heavy equipment or the cost. Therefore, if you are thinking about growing food or developing green spaces on an urban property, you should carefully evaluate the condition of its soils first and develop a plan for resolving any problems you identify.

Soil Contamination

Soil contamination is much more prevalent in urban areas than in agricultural ones. In urban soils, lead is the most common contaminant to pay attention to. It is prevalent due to its long-time use in gasoline (banned since 1989 in the United States) and paint (banned since 1978 for residential use). But there is a wide range of

Figure 22.2. Construction activities cause bare compacted soil with potential for water and wind erosion, and challenges with revegetation.

Figure 22.3. This former storage site in Portland, OR, was contaminated with volatile organic compounds. Photo courtesy the U.S. Environmental Protection Agency.

other contaminants from current and past land uses that could pose problems, such as petroleum products and legacy pesticides (lead arsenate, copper sulfate, etc.) (Table 22.1). Cases that are of special concerns include former industrial sites, areas along major roads, recent construction sites, waste disposal sites and junkyards. In some cases, contaminants can end up on a property from distant sources through atmospheric deposition (the process by which particles and gases in the air, such as those that come from tailpipe emissions, settle on the ground or in bodies of water).

People are exposed to soil contaminants through different possible pathways:

- **Ingesting soil**. The risk is greatest when the soil is left bare, especially with chemicals that are concentrated at the soil surface. This is especially of concern with children because they like to play in soil and may put dirty hands in their mouths.
- **Breathing volatiles and dust**. When winds or human activity sweep up bare contaminated soil, contaminants may enter the lungs and become absorbed into the body. Chemicals that stay at the surface are most susceptible to wind erosion. Fine soil particles themselves can also damage the respiratory system. Again, children are at greater risk of inhaling contaminated dust because of their behavior.
- **Eating food grown on contaminated soil**. The food that is grown at a contaminated site can expose people to toxic compounds in two ways: either contaminated soil finds its way onto a vegetable that is eaten without being properly washed or peeled, or the crop absorbs contaminants through its roots. Also, food crops grown using pesticides may contain residues of these chemicals and can expose people when they are eaten.
- **Exposure through the skin**. Skin is generally an effective barrier against contaminants, but in extreme cases a person may be impacted through rashes or blisters. Pesticide contaminants can also pass through the skin.

Some contaminants are highly adsorbed by soil particles, especially when the soil is around neutral pH. These contaminants typically remain close to the soil surface, although over time they may mix slightly into the soil due to biological activity or any form of digging or tilling. In the case of lead, the risk of exposure from contact with contaminated soil is significantly higher than from a crop that has absorbed the metal from the

Table 22.1
Common Contaminants in Urban Soils Based on Previous Land Use

Land Use	Common Contaminants
Agriculture, green space	Nitrate, pesticides/herbicides
Car wash, parking lots, road and maintenance depots, vehicle services	Metals, PAHs*, petroleum products, lead paint, PCB* caulks, solvents
Dry cleaning	Solvents
Existing commercial or industrial building structures	Asbestos, petroleum products, lead paint, PCB caulks, solvents
Junkyards	Metals, petroleum products, solvents, sulfate
Machine shops and metal works	Metals, petroleum products, solvents, surfactants
Residential areas; streets; buildings with lead-based paint; where coal, oil, gas or garbage was burned	Metals, including lead, PAHs, petroleum products, creosote, salt
Stormwater drains and retention basins	Metals, pathogens, pesticides/herbicides, petroleum products, sodium, solvents
Underground and aboveground storage tanks	Pesticides/herbicides, petroleum products, solvents
Wood preserving	Metals, petroleum products, phenols, solvents, sulfate
Chemical manufacture, clandestine dumping, hazardous material storage and transfer, industrial lagoons and pits, railroad tracks and yards, research labs	Fluoride, metals, nitrate, pathogens, petroleum products, phenols, radioactivity, sodium, solvents, sulfate

*Polycyclic aromatic hydrocarbons (PAHs) are a class of toxic chemicals produced when coal, oil, gas, wood and garbage are burned. Caulks containing harmful polychlorinated biphenyls (PCB) were used in schools and other buildings that were renovated or constructed from approximately 1950–1979.
Source: Boulding and Ginn (2004)

soil. This is because plants absorb minimal amounts of lead, especially when pH is neutral. You are much more likely to expose yourself to lead from dirty hands, breathing in dust, or from produce that isn't adequately cleaned. However, lead can accumulate in roots, so growing root crops in lead-contaminated soils should be avoided.

Other contaminants include organic compounds like industrial solvents, pesticides and petroleum products. Industrial solvents like trichloroethylene (TCE) move readily through the soil and can reach groundwater. Some pesticides can remain in the soil for many years and slowly percolate into groundwater. Over time, certain organic compounds are degraded by microorganisms in the soil. Petroleum products tend to stay near the surface.

Obviously, contaminants that stay at the surface pose a larger risk of human exposure, especially if they also suppress vegetation and are therefore more prone to wind and water erosion (Table 22.2). But in that case the contaminants can also be more readily removed by scraping the top layer of soil (and replacing it with good topsoil or compost). Contaminants that readily leach to groundwater may pose a problem through drinking water. Again, the highest risks are with children. They are also more sensitive to toxic contaminants than adults.

TESTING FOR SOIL CONTAMINANTS

When evaluating a plot of land for its suitability for urban farming or gardening, the first step is to research its history. Try talking to the property owner, and use the internet, public library, city hall or tax assessor's office to seek records that would reveal past uses. Useful records include old aerial photos, maps, permits and tax records. Also, visit the site to see whether potential sources of contamination are nearby, such as old houses with peeling paint or a highway. Both cases could mean a high level of lead in the soil. Generally, a site that has a long history as a green space or residential property

Table 22.2
Health and Environmental Effects of Common Soil Contaminants in Urban and Industrial Areas

Contaminant Type	Examples	Comments
Metals	Cadmium, zinc, nickel, lead, arsenic, mercury	Adsorbed by soil at the surface unless physically incorporated. Sometimes a gas. Affect the central nervous system and mental capacity with long-term effects.
Radioactive materials	Radon, uranium, plutonium, cesium, strontium	Mostly soil adsorbed or gaseous. Degrade over long time periods. Acute toxicity in high doses; cancer.
Industrial solvents	Chlorinated organics like PCE, TCE, DCE	Can leach to groundwater or be volatile. Slowly decompose in soil. Affect the central nervous system and mental capacity.
Petroleum products	Benzene, toluene, ethylbenzene, xylene, kerosene, gasoline, diesel	Risk from drinking water and inhalation from volatilized product. Irritation; affect the central nervous system and mental capacity.
Salts	Sodium chloride	Cause sodic soil conditions, aggregate breakdown and compaction.
Agricultural inputs	Nitrates, pesticides/herbicides	Impaire water quality. Irritation; affect the central nervous system and are associated with cancer.
Other organic and inorganic pollutants	PCB, asbestos, drugs and antibiotics	Associated with cancer; sometimes acute toxicity and central nervous system. Affect aquatic biology and drug resistance.

will have fewer problems than one with a commercial or industrial past (Table 22.1).

After you learn what you can about the property's history, consult with your state environmental agency, local health department or local Cooperative Extension office to determine the kinds of tests you should perform to accurately assess the condition of the soil. Also, while there are interim guidelines published by the U.S. Environmental Protection Agency (EPA, *Brownfields and Urban Agriculture: Interim Guidelines for Safe Gardening Practices*, 2011), there are no established federal rules for what soil contaminant levels are considered safe for urban agriculture, so you should work with these qualified professionals to interpret the results of tests and make a plan to recondition the soil. At a minimum, the EPA recommends that urban soils be tested for pH, percent organic matter, nutrients, micronutrients and metals, including lead. Soil testing is described in detail in Chapter 21.

When testing for potential contaminants, you may need to collect samples separately for each contaminant you want to test for, and your sampling procedure for each may vary. For example, you may collect samples at different depths depending on the suspected contaminant (a heavy metal near the surface versus a solvent that may have leached into the soil), or the intended use of different sections of the property (a play area versus a growing area). In addition, contaminants may have been buried in the past.

The distribution of contaminants can be unpredictable, so testing in many locations in the plot may be required. Sections of a property that have obvious signs of potential problems may require separate testing procedures. These can include areas next to old buildings with peeling paint (a higher risk of lead), patches of bare ground where vegetation would otherwise be expected (a sign of compaction or concentrations of toxic compounds), or near stormwater drainage features (which could be bringing petroleum-based compounds, pesticides or other chemicals onto the property from the surrounding neighborhood). Note that the presence of lead in the soil rarely causes physical damage to plants. On the other hand, other metals, such as copper, zinc and nickel can be phytotoxic at high concentrations.

A thorough site assessment of a property should also take into account other conditions that could affect its viability for urban farming or gardening, such as slope and drainage patterns, the presence of aboveground and belowground utility lines, or existing unwanted structures, including possibly the buried foundations of previous buildings. (In the United States, visit www.call811.com, or call 811 to get information on buried utility lines before starting any digging project.)

SOIL RECONDITIONING STRATEGIES

Once you have an understanding of the specific problems associated with a particular urban property, decide on the most appropriate reconditioning (improvement) strategies (Table 22.3). Most make the decision to pursue mitigation (coping) versus removal strategies at this point. Using excavators and trucks to remove contaminated soil is an expensive and extreme option that may be required for highly contaminated sites, and regulations on excavated soil with contaminants make the whole process difficult as well as costly.

Again, improving the soil so that it is safe for food production and for the community will take time and could prove costly. Before you begin, you should have a plan in place that accounts for this time and cost.

Practices to improve urban soils fall into physical, chemical and biological categories, just as they do in any agricultural setting. In urban situations, the strategies outlined here should generally be considered and used in that order, from physical to chemical to biological.

Physical practices can provide immediate solutions to compaction, poor drainage or the presence of toxic materials in the soil, but they're not necessarily easy. If contaminant levels are modest or concentrated near the surface, scraping only the top layer of soil and

SEEK OUT ADDITIONAL RESOURCES

Due to the potential risk to human health of farming on contaminated soils, it is advised to work with environmental consultants and local Extension specialists with expertise in urban soils when assessing whether to use a site. Depending on the severity of its problems, it can be expensive to assess and clean up a site. The EPA Brownfields Program (www.epa.gov/brownfields) offers grants to state, local and tribal governments, as well as to nonprofits, for these purposes, and might be an option when one or more urban farms seek to partner with a local municipality to clean multiple sites at once. The USDA's *Urban Agriculture Toolkit* provides information on how to start an urban farming operation and identifies technical and financial resources that might be available to help with each step.

Further reading on the risks and recommended approaches to site assessment, soil testing and soil management is readily available through state Extension offices and federal agencies, such as:

- *Brownfields and Urban Agriculture: Interim Guidelines for Safe Gardening Practices* (EPA)
- *Evaluation of Urban Soils: Suitability for Green Infrastructure or Urban Agriculture* (EPA)
- *Gardening on Brownfields* series (www.gardeningonbrownfields.org, Kansas State University)
- *Gardening on Lead Contaminated Soils* (Kansas State University)
- *Soils in Urban Agriculture: Testing, Remediation and Best Management Practices* ... (University of California)
- *Minimizing Risks of Soil Contaminants in Urban Gardens* (North Carolina State University)
- *Urban Agriculture and Soil Contamination: An Introduction to Urban Gardening* (University of Louisville)

Table 22.3
Typical Reconditioning Techniques for Degraded Soils

Technique	Physical	Chemical	Biological
Soil removal	X		
Raking	X		
Tillage and subsoiling	X		
Drainage	X		
Soil amendments and additives*	X	X	X
Recyclers			X
Cover crops			X
Mulch	X	X	X

*Examples can include manufactured additives to improve soil structure (physical), commercial fertilizers and composts.

replacing it with quality topsoil might be more feasible. Additionally, a thin layer of contaminated topsoil can be diluted by using tillage or subsoiling to mix it with soil deeper down. This will also alleviate existing compaction problems. If compaction is the primary concern with an urban soil as opposed to contamination, removal is not a recommended approach but amelioration in place makes more sense. Other physical practices include removing old structures and trash, and raking the soil to either level it or to remove old construction debris and trash near the soil surface.

Depending on soil test results, you will probably need amendments to alter nutrient and mineral levels, or pH. Phosphorus binds to lead, making it less dangerous over time, so be sure to use phosphorus fertilizers if the soil tests indicate a deficiency. Mineral amendments, such as lime or dolomite, may help with poor drainage or to stabilize pH.

Compost, cover crops and other organic amendments are usually required before producing any crops to increase organic matter, improve soil structure and promote soil biological activity, and they should be used each growing season to maintain soil health. Like tillage, mixing in compost will further dilute toxic compounds. Also, organic matter binds some contaminants, making them less available to plants. Compost is readily available in urban areas, but be sure to use only high-quality compost from reliable sources and pay special attention to finding a supply that is itself free of contaminants and weeds. Local restaurants, cafes, arborists and municipal compost piles are common sources (Figure 22.4). The use of cover crops is discussed in Chapter 10, and compost is discussed in Chapter 13.

Mulches, including living mulches, can be used to suppress weeds and reduce erosion. When soil contamination is a concern, mulches have the added benefit of acting as a barrier that reduces contact with contaminated soil. They can also reduce the splashing of soil onto crops.

Rather than try to improve a property's soil, many urban farmers and gardeners opt to build raised beds instead, filling them with a mix of imported topsoil and compost. Again, make sure the topsoil and compost you plan to use is free of toxic materials before buying it. Placing a layer of landscaping fabric on the soil surface before adding the new soil for the raised beds helps to limit roots reaching the original soil. A fabric barrier also lessens soil in the bed mixing over

Figure 22.4. Huerta del Valle, a four-acre urban farm that serves low income communities in Ontario, CA, uses organic waste from a local food distributor to produce compost on site. Photo by Lance Cheung, USDA.

MAINTAINING HEALTHY SOILS

Even after an urban farm or garden has been put into production, good soil management remains critical. Since most urban farms are under continuous, intense production during the growing season, soils can lose fertility quickly and need to be replenished. The best ways to maintain soil health in urban systems are the same as in rural ones. They are described in detail elsewhere in this book, including:

- Cover crops (Chapter 10)
- Crop rotation (Chapter 11)
- Composting (Chapter 13)

time with the buried soil deeper in the ground through biological activity.

URBAN GREEN INFRASTRUCTURE

We have discussed concerns related to urban soils in the context of crops and food production. But natural areas, parks and ornamental gardens are also highly treasured by residents and visitors. Similarly, yards and gardens are small areas of relief from the urban bustle and are cherished by city dwellers. Urban areas also have a lot of food waste, tree leaves and tree trimmings that can be turned into compost or mulch and used to improve the soil—done at the municipal scale or in home backyards. Under ideal conditions even pet waste can be safely composted. (While cities also generate a lot of sewage sludge at wastewater treatment plants, there are often concerns with contamination by industrial and household products that keep it from being used to grow food.)

With the de-industrialization of many cities, urban renewal projects frequently involve the redevelopment of former manufacturing and transportation sites into housing and office developments, or urban parks. Care needs to be taken to study the nature of the previous land uses and the associated possible contamination as we discussed earlier in this chapter.

Remediation

Similar to establishing urban farms, the development of green spaces needs to consider different options. Most green spaces involve perennial plants, and much of the soil health considerations need to be addressed up front. Generally you want the soil to support attractive vegetation at a low maintenance cost. This requires good drainage, high waterholding capacity, good rooting and low weed and disease pressure. This is usually accomplished through the same practices we discussed earlier: loosening compact soil, adding compost and fertilizer, balancing soil pH and mulching.

Except in extreme cases of contamination when the soil may need to be removed, landscaped areas can generally have poor soil buried by trucking in good top soil. Or the soil that is there can simply be *improved* with amendments. Burying soil in place is often sufficient for the remediation of industrial or built sites that contain various debris materials. Building raised beds or berms is a common approach in urban gardens, both to address poor soil quality and to improve drainage. Placing a layer of landscaping fabric on the soil surface before adding the imported soil for the raised beds helps to limit roots reaching the original soil and lessens mixing of the imported material with the surface layer.

When the soil is compacted or has low organic matter, and when there is little chemical contamination or other waste materials in the soil, the best option is probably to improve what is there through mixing and adding organic materials. The physical, chemical and biological quality of the soil can then be improved by applying and incorporating compost using excavators or bucket loaders. The so-called “scoop-and-dump method” works well when there is no existing vegetation on the site (Figure 22.5). If there are trees and other large plants that need to be saved, an air spader (a device that blows soil away with high air pressure) may be used to gradually remove the compacted soil around existing roots and then replace it with healthy soil.

Special Soil Mixes and Street Trees

Plants in pots, planter boxes and green roofs require clean soil mixes that allow for excellent drainage (because of the low gravitational drainage potential due to shallow depth), high water- and nutrient-holding capacity, and low weight. Soil for rooftop gardens needs to be light enough so that it doesn't overburden the roof, and heavy enough that it anchors the plants and won't be dislocated by wind or water. Soil mixes are typically combinations of special minerals like vermiculite clay (treated by heating), perlite (expanded volcanic rock particles) and organic materials like peat moss, compost or biochar. These manufactured soil materials have favorable physical, biological and chemical characteristics with low density, but they generally cost more than traditional soils. Containers for growing plants need to have holes in the bottom to allow for water drainage to avoid saturated conditions when watering.

Street trees are valuable assets to a neighborhood because they moderate the microclimate and improve the aesthetics. Special challenges exist with trees in sidewalks and parking lots. Unlike those in parks, cemeteries or green strips along boulevards, street trees are growing in a paved environment. The pavement substrate (the soil material immediately underneath) is often highly compacted in order to meet the bearing capacity standards to support the sidewalk pavement plus the additional loads from possible emergency vehicles. Oftentimes the tree roots grow big and break or tilt the sidewalks, thereby creating a health hazard and liability for the municipality. They also frequently die prematurely due to the highly constricted rooting environment combined with salt, and heat and moisture stresses.

Street trees therefore create a dilemma between the engineering requirements for a strong pavement that supports high loads (requiring a compacted substrate), and the need for a healthy rooting environment for the trees. One solution is the so-called *gap-graded soils* that can meet both objectives (Figure 22.6). Such materials contain only particles of certain sizes, with some sizes deliberately left out in order to ensure that there will be good amounts of pore space. This soil material commonly uses large, uniform stones as a skeleton matrix that can support high loads from the pavement, while

Figure 22.5. Left: scoop-and-dump method for de-compaction of soil and mixing in compost. Right: Ameliorated soil with plantings and mulch. Photos by Cornell University, Urban Horticulture Institute.

Figure 22.6. Left: Planting hole in gap-graded soil material that supports high loads from the pavement while allowing large pores for tree root protrusion. Pores are partially filled with fine soil particles and organic matter to provide plant growth functions. Right: Healthy street trees in a sidewalk with gap-graded soil. Photos by Cornell University, Urban Horticulture Institute.

allowing large pores for tree root protrusion under the pavement. These pores are partially filled with high quality soil material to support the tree functions. On golf courses and other greens, similar gap-graded soil materials are applied (typically sand, with certain sizes omitted) to better support foot traffic while still maintaining healthy turf growth.

OTHER CONSTRUCTION CONCERNS

Compaction is common with any type of activity that involves soil disturbance, digging and construction equipment, and it affects both rural and urban areas. This is less of a problem if the area is subsequently paved over, like a parking lot in front of a new store. But compaction may have a long-term negative impact if the area will be revegetated or used again for crop production or green infrastructure.

It's important to understand and to pay attention to the ways that construction equipment can cause compaction if such equipment is needed when preparing a site for urban farming or landscaping. Oftentimes construction jobs are done without regard for the high compaction potential with wet soil. Also, when digging work is done (for example when installing a pipeline,

Figure 22.7. Proper pipeline construction: Left: fertile topsoil is first removed and separately stockpiled from the subsoil. Right: After installation the topsoil is restored over subsoil. Photos by Bob Schindelbeck.

Figure 22.8. Retention of urban stormwater. Left: A swale that contains runoff from a parking lot in the distance. Right: Gravel-based swale with subsurface drains (under gravel) that captures roof runoff from a regional airport terminal.

a drain system or a septic system) the fertile topsoil is commonly mixed with subsoil and the site ends up with poor soil at the surface after filling the holes. Therefore, good construction work should follow some principles:

- When construction vehicles are involved near the site, limit traffic patterns to controlled lanes. If possible, cover traffic lanes with metal plates or geotextile fabric under gravel to spread the loads from the vehicles.
- Avoid traffic and construction when the soils are wet and highly susceptible to compaction.
- When digging, first remove the fertile topsoil layer and stockpile it separately before digging deeper into the soil to install the items (cables, pipes, etc.). Then refill the subsoil first and loosen it with rippers. Finally, reapply the topsoil material and avoid further compaction (Figure 22.7).

Generally, urban areas experience increased runoff as a result of sealed surfaces. Roofs, streets, parking lots and other types of development have high potential for runoff and discharge of undesirable contaminants, like oils from leaking cars. Urban stormwater programs aim to contain or slow the direct discharge to water courses through water retention systems. These can often be incorporated into landscaping features of green infrastructure. Notably, swales allow for extended infiltration times and settling of sediment, and gravel covered drain systems (French drains) diverge runoff away from structures (Figure 22.8). Stormwater mitigation practices are generally required by state law for large site developments, and design manuals are available to help developers comply.

SUMMARY

Contamination and compaction of soil are common problems in urban areas and must be addressed before putting urban land into food production. The most significant issue to identify and resolve is the risk of exposing farmworkers and community members to soil that is contaminated with toxic compounds. The most common contaminant in urban and suburban areas is lead, and ingestion of contaminated soil is the most common pathway of exposure. Working with environmental experts to carefully assess the site and its land-use history, along with testing the soil, will help you evaluate the risks and determine if it's feasible to use the site for urban food production. Similarly, green spaces in urban areas may also be impacted by contamination or compaction issues. The strategies for improving degraded, contaminated soils include physical (such as soil removal), chemical (such as altering pH) and biological (such as adding composts) practices. Remediation, or excavating large amounts of contaminated soil and replacing it with clean soil, can be expensive and is usually reserved for only the most contaminated sites. Burying contaminated soils with healthy soil material may be a more economical option. In-place mixing of organic materials and subsequent mulching and use of appropriate plantings are often good options for green spaces and gardens.

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a case study

CITY SLICKER FARMS
OAKLAND, CALIFORNIA

When City Slicker Farms moved into its new location in West Oakland, a 1.4-acre site that was once a paint factory, the nonprofit urban farm faced the challenge of rebuilding the soil from the ground up.

While the soil went through a remediation process, City Slicker still needed to bring in new soil for the entire site. “Because this is topsoil that’s coming in and it’s being brought in big loads, the soil structure was very poor,” says Julie Pavuk, director of urban garden education. It appears that the soil also came from different sources, she adds, as soil textures vary throughout the farm.

Dealing with a new soil wasn’t unfamiliar to the organization, whose mission has been to empower community members to meet the basic need for healthy food by creating organic, sustainable and high-yield urban and backyard farms. Since its founding in 2001, City Slicker Farms has built more than 300 community and backyard gardens out of raised planter boxes. The reason they use raised beds is two-fold: community members who may not be physically able to do in-ground gardening can still participate, and they can install gardens in places where there may not be natural soil, such as parking lots. Over the years, they discovered that not all soil is fit for raised bed production. At times they had to shovel soil back out because it was too compacted, Pavuk says. It took some time to determine that a sandy loam soil called “Local Hero Veggie Mix” from a local company, American Soil and Stone, was the best fit for their planter boxes because of its structure and nutrients.

The main issue they had to address at their new location, the West Oakland Farm Park, was soil compaction. “Some of the initial challenges were just literally being able to dig in and create enough space so that the plant roots could actually grow and go down as far as they needed to be to avoid becoming stunted,” Pavuk says. To prepare the soil for production, City Slicker Farms implemented the biointensive methods of double-digging and layering in a lot of compost—residential green waste provided by Waste Management. The manual labor paid off. “Those methods really work to help us address some of those things like soil structure and make sure we’re adding a lot of nutrients back into the soil,” she says. “Just yesterday, I was out digging in some of the beds, and I was surprised at how easy it was compared to how it had been in that particular space earlier.”

Rebuilding soil was also a better challenge to deal with than the one they faced before: land impermanence. Before purchasing the brownfield that would become the Farm Park, thanks to a $4 million grant from California’s Proposition 84, City Slicker Farms operated on empty sites through temporary arrangements. They were at risk of losing their spaces at any time. Pavuk recalls one day they got the news they had one week to move out from one of their sites. “We salvaged what we could from it, and the food was distributed, but we lost one of our big production spaces, and it happened very quickly,” she says. This made the organization even more aware of the food insecurity the neighborhood faced and kicked off the process of owning their own space.

Designed in partnership with the community, the West Oakland Farm Park is not only an urban farm but also a much-needed green space and community hub where people can visit to relax, learn and play. It features a greenhouse, nursery, orchard, vegetable and herb gardens that the Farm Park staff and volunteers use for food production, a chicken coop, beehives, a demonstration kitchen, an outdoor classroom, a playground, and 28 plots for community members to garden themselves. Like the backyard gardens, the community plots have raised planter boxes to make gardening more accessible to the community, while the rest of the crop production is in-ground.

City Slicker Farms moved into the site in 2016, and it opened to the public that summer. All of the food grown at the Farm Park goes to community members who lack access to healthy food or are experiencing food insecurity. While the farm has been providing food to those participating in their gardens program, they are moving to a "community fridge" model. They'll distribute their food through free refrigerators that an organization called Town Fridge has set up in public spaces around Oakland, allowing anyone to access free food and drinks anytime.

With a better soil structure now in place, the farm is moving away from biointensive methods and is now looking at how they can correct deficiencies to grow even healthier and more nutrient-dense foods. Farm manager Eric Telmer started with soil testing to create a fertilization plan to address some of their plants' stunting and yellowing. He found that the soil is low in calcium and sulfur but very high in magnesium and potassium. To bring the soil into balance, he's been applying an oyster shell flour as a substitute for hi-cal lime, as well as gypsum and CalPhos.

They rely on composting and cover crops for nitrogen. Their compost comes from three sources: compost created onsite from crop residue, such as faba bean cover crops and other organic matter sources, which they usually layer with either manure from their chicken coops or with donated horse manure; worm castings from their worm bins, where they feed the worms food scraps and burlap; and city compost. To kill weed seeds and pathogenic organisms, City Slicker does hot composting. The middle of the compost pile needs to reach at least 130°F for a certain number of days, depending on how big the compost pile is, and they turn it to ensure every part of the pile reaches the center.

For cover cropping, faba beans are the farm's first choice because of their ability to produce nitrogen and to grow quickly. The farm will cut the beans just below the soil level after they've flowered but before they've set seed. This kills the plant while leaving the roots and nodules to continue providing nitrogen. The tops are then either used as mulch, added to compost or served as feed in their chicken coop.

The faba beans also add diversity to their rotation. While the Farm Park grows a variety of crops, including tomatoes, cucumbers, squashes, peppers, beans, radishes, eggplants, bok choy, carrots and peas, its rotation is heavy in brassicas like collard greens, mustards, kale and swiss chard. The faba beans appear to be helping to control pest issues on the brassicas, particularly aphids. Pavuk explains that the aphids will attack the faba beans, but soon after, ladybugs will appear and eat those aphids. This cycle helps keep these beneficial insects in the Farm Park to deal with aphids on brassicas and elsewhere.

Since the West Oakland Farm Park is located in an industrial area, there weren't a lot of plant communities that attracted beneficial insects. To address that, City Slicker built insectary strips filled with plants like chamomile and bachelor buttons at the headrows of their beds to serve as a "beneficial insect oasis," Pavuk says. "We're looking to hopefully prevent some of our pest problems by growing much healthier plants and by increasing the amount of habitat we have for our beneficial insects, so that we'll be able to use more of those biological controls as part of our pest management strategy." The Farm Park also has its beehives to provide the dual benefit of pollination and honey production. In the four years they've been on the site, Pavuk has seen more native bee species and other pollinators show up, like hummingbirds and butterflies.

But one of the biggest indicators that their soil health practices have set them on the right path are earthworms, which they didn't have when they first started production on the site. "Their presence to me is an indicator that our soil is improving, and they're helping to improve it," Pavuk explains. "That first year was so hard, in part because the soil needed so much work, but also we didn't have the diversities of insects and creatures. The next year was amazing because then the other things started to come and the soil was improving; all of it was happening at the same time in concert."

The crops that are crucial to their mission of providing healthy food to the community reflect that change. "The plants are thriving in ways they simply weren't initially," Pavuk says.

PART

4

PUTTING IT ALL TOGETHER

Photo by Olha Sydorovych

Chapter 23

HOW GOOD ARE YOUR SOILS?

FIELD AND LABORATORY EVALUATION OF SOIL HEALTH

... the Garden of Eden, almost literally, lies under our feet almost anywhere on the earth we care to step. We have not begun to tap the actual potentialities of the soil for producing crops.

—E.H. FAULKNER, 1943

An assessment of the current soil health status on your farm is a good way to begin. By now, you should have some ideas about ways to increase soil health on your farm, but how can you identify the specific problems with your soil, and how can you tell if your soil's health is actually getting better? First ask yourself why you would do a soil health assessment. The most obvious reason is that it allows you to identify specific problems, such as P deficiency or surface compaction, and to target your management practices as part of the effort to increase overall soil health. A second reason might be to monitor the health of your soils over time after you have made some management changes. Is your soil improving after you started planting cover crops, began a new rotation or switched to reduced tillage? While the goal of building soil health is to prevent problems from developing, it also helps to correct previous problems you might have had. A good soil health assessment done over a number of years allows you to see whether you are going in the right direction. Another reason might be to better value your soils. If they are in excellent health due to many years of good management, your land should be worth more when sold or rented than fields that have been worn out. After all, a healthy soil produces more and allows for reduced purchased inputs. Being able to effectively appraise soil health may be an additional incentive for farmers to invest in good management and build equity in their land.

We can approach soil health assessment at three levels of detail: 1) general field observations, 2) field assessments using qualitative indicators and 3) quantitative soil health tests. We'll discuss them each in detail.

GENERAL FIELD OBSERVATIONS

A simple but very good place to start assessing a soil's health is to look at its general performance as you go about your normal practices. It's something like wondering about your own performance during the

Photo courtesy Harold van Es

course of a day: do you have less energy than usual? This might be an indication that something isn't quite right. Likewise, there are signs of poor soil health you might notice as part of the normal process of growing crops:

- Are yields declining?
- Do your crops perform less well than those on neighboring farms with similar soils?
- Does your soil delay water from infiltrating during a downpour?
- When you dig up roots, do they look unhealthy or constrained?
- Does the root system lack mycorrhizal fungi that promote healthy crops?
- Do your crops quickly show signs of stress or stunted growth during wet or dry periods?
- Is the soil obviously compacted? If you use tillage, does it plow up cloddy and take a lot of secondary tillage to prepare a fine seedbed?
- Does the soil crust over easily? Do you observe signs of runoff and erosion?
- Does it take more power to run tillage or planting equipment through the soil?

Figure 23.1. A soil penetrometer is a useful tool to assess soil compaction. Measurements are best made when soils are moist and friable (around field capacity).

- Do you notice increased problems with diseases or nutrient stress?

These questions address problems with soil health, and any affirmative answers should prompt you to consider further action.

FIELD INDICATORS

The next approach involves addressing the same kind of questions listed above, but in a more detailed manner. In several states, farmers and researchers have developed "soil health scorecards" that are based on observations made in the field. The NRCS has developed a somewhat different visual evaluation system, the Cropland In-Field Soil Health Assessment Worksheet (Table 23.1 is based on this worksheet). The goal of this type of assessment is to help you understand your soil's health and improve it over time by identifying key limitations or problems.

Whenever you try to become more quantitative, you should be aware that measurements naturally vary within a field or may change over the course of a year. For example, if you decide to evaluate soil hardness with a penetrometer (Figure 23.1) or metal rod, you should perform at least 10 penetrations in different parts of the field and be aware that your results also depend on the soil moisture conditions at the time of measurement. If you do this after a dry spring, you may find the soil quite hard. If you go back the next year following a wet spring, the soil may be much softer. You shouldn't then conclude that your soil's health has dramatically improved, because what you mostly measured was the effect of variable soil moisture on soil strength. Similarly, earthworms will be abundant in the surface 6–9 inch layer when it's moist but tend to go deeper into the soil during dry periods, although you may still observe the wormholes and casts (Figure 23.2). Make sure you select your locations well. Avoid unusual areas (e.g., where machinery turns) and aim to include areas with higher and lower yields.

Figure 23.2. A soil with many wormholes suggests biological activity and improved potential for aeration and water movement.

This type of variability with time of year or climatic conditions should not discourage you from starting to evaluate your soil's health—just keep in mind the limitations of certain measurements. Generally, soil health is best *measured* in the early spring and late fall under moist (but not too wet) soil condition. But soil health problems are better *observed* during wet or dry periods when you might see runoff or crop drought stress symptoms.

Table 23.1 provides guidance on good soil health indicators, sampling times and how to interpret measurements, and in the following paragraphs we further clarify the practical considerations.

Soil color is the result of a combination of the soil's mineralogy, oxidation status and organic matter content. Some soils are naturally more red (highly oxidized iron), brown (less oxidized iron), grey (poor drainage) or whitish (high lime content), but organic matter makes them more dark (see Chapter 2). We therefore associate black soils with high quality, and within the same soil type and texture class you can reasonably conclude that the darker the soil, the better. However, don't expect a dramatic color change when you add organic matter; it may take years to notice a difference.

Crusting, ponding, runoff and erosion can be observed from the soil surface, as we illustrated in Chapter 15. However, their extent depends on whether an intense rainstorm has occurred, or whether a crop canopy or mulch protected the soil. These symptoms are a sign of poor soil health, but the lack of visible signs doesn't necessarily mean that the soil is in good health: it must rain hard for these signs to occur. Try to get out into the field sometime after a heavy rainstorm, especially in the early growing season. Crusting can be recognized by a dense layer at the surface that becomes hard after it dries (Figure 15.1). Ponding can be recognized either directly when the water is still in a field depression, or afterward in small areas where the soil has slaked (that is, aggregates have disintegrated). Areas that were ponded often show cracks after drying. Slaked areas going down the slope are an indication that runoff and early erosion have occurred. When rills and gullies are present, a severe erosion problem is at hand. Another idea: Put on your rain gear and actually go out during a rainstorm (not during lightning, of course), and you may actually see runoff and erosion in action. You might notice that most of the runoff and erosion that occurs comes from a relatively small portion of the field, and this may help in remedying the problem. Compare fields with different crops, management and soil types. This might give you ideas about changes you can make to reduce runoff and erosion.

You also can easily get an idea about ***the stability of soil aggregates***, especially those near the surface (see Figure 15.1). If the soil seals readily, the aggregates are not very stable and break down completely when wet. If the soil doesn't usually form a crust, you might take a sample of aggregates from the top 3–4 inches of soil from fields that seem to have different soil quality (or from a field and an adjacent fencerow area). Gently drop a number of aggregates from each field into

Table 23.1
Cropland Soil Health Assessment Worksheet

Indicator	Soil Health Concern	Best Time and Use	Observation Benchmarks
Soil cover	Organic matter, organism habitat	Anytime	Greater than 75% surface cover from plants, residue or mulch
Residue breakdown	Organic matter, organism habitat	Anytime; mostly no-till; farmer interview	Natural decomposition of crop residues as expected; previous year residues partially decomposed and disappearing
Surface crusts	Aggregation	Before tillage; before or early in the growing season	Crusting in no more than 5% of field
Ponding	Compaction, aggregation	After rain or irrigation (not when frozen); farmer interview	No ponding within 24 hours after major rainfall or irrigation
Penetration resistance	Compaction	With adequate soil moisture; before tillage; before, early in or after the growing season	Penetrometer rating <150 psi in surface layer and <300 psi in subsoil layer, OR slight or no resistance with wire flag inserted
Water stable aggregates	Aggregation, organism habitat	Anytime	Water-submerged in glass jar: at least 80% remains intact after 5 minutes with little cloudy water
Soil structure	Compaction, soil organic matter, aggregation, organism habitat	Anytime	Granular structure in surface horizon and no platy structure in surface or subsoil horizons
Soil color	Organic matter	With adequate soil moisture	No color difference between field and fence row samples, OR value is in darker range using color chart
Plant roots	Compaction, organic matter, organism habitat	During growing season	Roots covered in a soil film or part of soil aggregates, OR living roots are healthy (no black/dry roots or lesions), fully branched and extended into subsoil
Biological diversity	Organic matter, organism habitat	With adequate moisture; before tillage	More than three different types of organisms observed without magnification
Biopores	Organic matter, compaction, aggregation, organism habitat	Before tillage; mostly no-till	Presence of root or earthworm channels that extend vertically through the soil, with some connecting to the surface

Source: Modified from USDA (2021)

separate glass jars that are half filled with water (the aggregates should be completely submerged in water). See whether they hold up or break apart (slake). You can swirl the water in the jars to see if that breaks up the aggregates. If the broken-up aggregates also disperse and stay in suspension, you may have an additional problem with high sodium content (a problem that usually occurs only in arid and semiarid regions).

Soil tilth and hardness can be assessed with an inexpensive penetrometer (the best tool), a tile finder, a spade or a stiff wire (like those that come with wire flags). Tilth characteristics vary greatly during the growing season due to tillage, packing, settling (dependent on rainfall), crop canopy closure and field traffic. It is therefore best to assess soil hardness several times during the growing season. If you do it only once, the best time is when the soil is moist but not too wet (it should be in the friable state). Make sure the penetrometer is pushed slowly into the soil (Figure 23.1). Also, keep in mind that stony soils may give you inaccurate results: the soil may appear hard, but in fact your tool may be hitting a rock fragment.

Soil is generally considered too tough for root growth if penetrometer resistance is greater than 300 psi, but fully unrestricted rooting in the surface layer generally requires soil resistance less than 150 psi. The soil is often harder in the deeper soil layers, and it is common to measure a dramatic increase in resistance when the bottom of the plow layer is reached, typically 6–8 inches into the soil. This indicates subsoil compaction, or a plow pan, which may limit deep root growth. It's difficult to be quantitative with tile finders and wire, but the soil is generally too hard when you cannot push them in. If you use a spade when the soil is not too wet, evaluate how hard the soil is and also pay attention to the structure of the soil. Is the plow layer fluffy, and does it mostly consist of granules of about a quarter inch in size? Or does the soil dig up in large clumps? A good way to evaluate that is by lifting a spade full of soil and dropping it from about waist height. Does the soil break apart into granules, or does it fall into large clumps? When you dig below the plow layer, take a spade full of soil and pull the soil clumps apart. They should generally come apart easily in well-defined aggregates of several inches in size. If the soil is compacted, it does not easily come apart in distinct units.

Soil organisms can be divided into six groups: bacteria, fungi, protozoa, nematodes, arthropods and earthworms. Most are too small to see with the naked eye, but some larger ones like ants, termites and earthworms are easily recognized. These larger soil organisms are also important "ecosystem engineers" that assist the initial organic matter breakdown that allows other, smaller species to thrive. Their general abundance is strongly affected by temperature and moisture levels in the soil. They are best assessed in mid-spring, after considerable soil warming, and in mid-fall during moist, but not excessively wet, conditions. Just take a full spade of soil from the surface layer and sift through it looking for bugs and worms. If the soil is teeming with life, this suggests that the soil is healthy. If few invertebrates are observed, the soil may be a poor environment for soil life, and organic matter processing is probably low. Earthworms are often used as an indicator species of soil biological activity (see Table 23.1). The most common worm types, such as the garden worm and red worm, live in the surface layer when soils are warm and moist, and they feed on organic materials in the soil. The long nightcrawlers dig near-vertical holes that extend well into the subsoil, but they feed on residue at the surface. Look for the worms themselves as well as their casts (on the surface, for nightcrawlers), and holes are evidence of their presence (Figure 23.2), which are typically greatly enhanced in no-till systems. If you dig out a square foot of soil and find 10 worms, the soil has a lot of earthworm activity. After soaking rains, many worms will come to the surface as the channels and burrows become saturated.

With a little more effort, nematodes, arthropods and earthworms can be removed from a soil sample and observed. Since these soil organisms like their environment to be cool, dark and moist, they will crawl away when you add heat and light. With a simple desk lamp shining on soil in an inverted cut-off plastic soda bottle with a small piece of screen at the bottom (what

Figure 23.3. A healthy corn root system with many fine laterals (roots shaken to remove aggregates and make them more visible). Compare with Figure 15.3.

was the lower part of the bottle top) to keep the soil from falling through (called a Berlese funnel), you will see the organisms escape down the funnel, where they can be captured on an alcohol-soaked paper towel (the alcohol keeps them from escaping). Descriptions of how to make and use a Berlese funnel are readily available on the internet.

Root development can be evaluated by digging anytime after the crop has entered its rapid growth phase. Have the roots properly branched, and are they extending in all directions to their fullest potential for the particular crop? Do they show many fine laterals and mycorrhizal fungal filaments (Figure 23.3), and will they hold on to the aggregates when you try to shake them off? Look for obvious signs of problems: short stubby roots, abrupt changes in direction when hitting hard layers, signs of rot or other diseases (dark-colored roots, lesions; fewer fine roots). Make sure to dig deep enough to get a full picture of the rooting environment because many times there is a hardpan present.

General crop performance as affected by soil health is most obvious during extreme conditions. During prolonged wet periods, poor soils remain saturated for an extended time, and lack of aeration stunts crop growth. Leaf yellowing indicates loss of available nitrogen by denitrification. This may even happen with high-quality soils if the rainfall is excessive, but it is certainly aggravated by poor soil conditions. Dense, no-till soil may also show greater effects.

Watch also for the onset of drought stress—leaf curling or sagging (depending on the crop type)—and for stunted crop growth during dry periods. Crops on soils that are in good health generally have delayed signs of drought stress. But with poor soils they may show problems when heavy rainfall, causing soil settling after tillage, is followed by a long drying period. Soils may temporarily hardset and stop crop growth altogether under these circumstances.

Nutrient deficiency symptoms can appear on plant leaves when soils are low in a particular nutrient

Table 23.2
Examples of Nutrient Deficiency Symptoms

Nutrient	Deficiency Symptoms
Calcium (Ca)	New leaves (at top of plant) are distorted or irregularly shaped. Causes blossom-end rot.
Nitrogen (N)	General yellowing of older leaves (at bottom of plant). The rest of the plant is often light green.
Magnesium (Mg)	Older leaves turn yellow at edge, leaving a green arrowhead shape in the center of the leaf.
Phosphorus (P)	Leaf tips look burnt, followed by older leaves turning a dark green or reddish purple.
Potassium (K)	Older leaves may wilt and look scorched. Loss of chlorophyll between veins begins at the base, scorching inward from leaf margins.
Sulfur (S)	Younger leaves turn yellow first, sometimes followed by older leaves.
Boron (B)	Terminal buds die; plant is stunted.
Copper (Cu)	Leaves are dark green; plant is stunted.
Iron (Fe)	Yellowing occurs between the veins of young leaves. Area between veins may also appear white.
Manganese (Mn)	Yellowing occurs between the veins of young leaves. These areas sometimes appear “puffy.” Pattern is not as distinct as with iron deficiency. Reduction in size of plant parts (leaves, shoots, fruit) generally. Dead spots or patches.
Molybdenum (Mo)	General yellowing of older leaves (at bottom of plant). The rest of the plant is often light green.
Zinc (Zn)	Terminal leaves may be rosetted, and yellowing occurs between the veins of the new leaves. Area between veins on corn leaves may appear white.

Source: Modified from Hosier and Bradley (1999)

(Table 23.2). (Note that crop nutrient deficiencies can sometimes result from compaction and poor aeration, even though enough nutrients are present in the soil). Many nutrient deficiency symptoms look similar, and they may also vary from crop to crop. In addition, typical symptoms may not occur if the plant is suffering from other stresses, including more than one nutrient deficiency. However, some symptoms on some crops are easy to pick out. For example, N-deficient plants are frequently a lighter shade of green than plants with sufficient N. Nitrogen deficiency on corn and other grasses appears on the lower leaves first as a yellowing around the central rib of the leaf. Later, the entire leaf yellows, and leaves farther up the stem may become yellow. However, yellowing of the lower leaves near maturity is common with some plants. If the lower leaves of your corn plant are all nice and green at the end of the season, there was more N than the plant needed. Potassium deficiencies on corn also show as yellowing on lower leaves, but in this case around the edges. Phosphorus deficiency is normally noted in young plants as stunted growth and reddish coloration. In corn, this may appear early in the season due to wet and cold weather. When the soil warms up, there may be plenty of phosphorus for the plants. For pictures of nutrient deficiencies on field crops, see Iowa State University's publication *Nutrient Deficiencies and Application Injuries in Field Crops* (IPM 42).

Field images from satellites, aircraft or drones help you see crop performance anomalies and whether certain areas in a field have soil health problems. On a conventional color image, compacted or poorly drained areas show less crop biomass during the early season, i.e., more soil and less crop reflectance in the image. In wet years, areas with poor drainage may exhibit nitrogen deficiencies and appear more yellowish. Vegetation indexes (like NDVI, normalized difference vegetation index) can also help gain insights by showing vegetation density (Figure 23.4). It may not give you a direct cause for the apparent problem, but it will at the least allow you to identify the location and check it out at ground level.

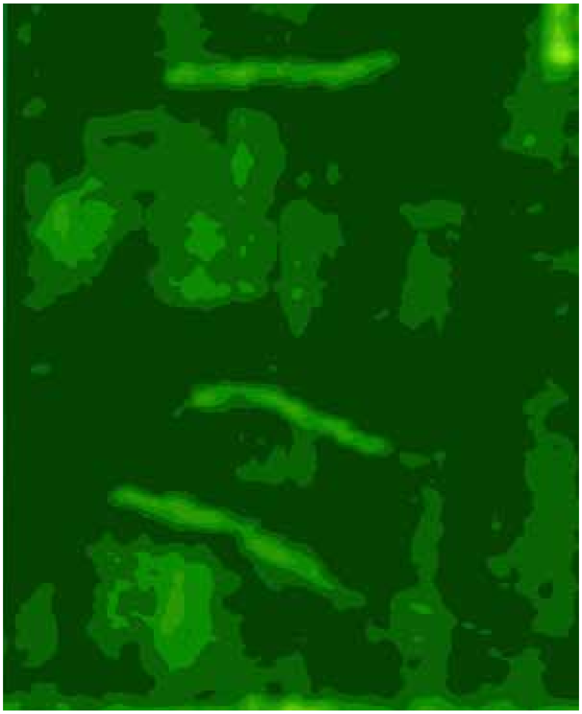


Figure 23.4. A normalized difference vegetation index (NDVI) map of a field shows areas of lower and higher vegetation density (darker areas have more vegetation), and can guide soil health examinations. Source: Yara International.

You can evaluate your soil's health using the simple tools and observations suggested above. Scorecards or assessment worksheets provide a place to record field notes and assessment information to allow you to compare changes over the years.

LABORATORY SOIL HEALTH TESTING

Comprehensive Soil Tests

Growers are used to taking soil samples and having them analyzed for available nutrients, pH and total organic matter by a university, government or commercial lab. In arid regions it is common to also determine whether the soil is saline (too much salt) or sodic (too

Table 23.3
USDA-NRCS-Evaluated Laboratory Soil Health Indicators and Methodologies, and Associated Soil Processes They Measure

Soil Process	Soil Health Indicator	Method[1]
Organic matter cycling and C sequestration	Soil organic matter content	Dry combustion Wet oxidation Loss on ignition
Structural stability	Aggregation	ARS wet aggregate stability NRCS wet aggregation Cornell sprinkle
General microbial activity	Short-term C mineralization	CO_2 respired—4 day CO_2 respired—24 hours
General microbial activity	Enzyme activity	BG NAG Phosphomonoesterases Arylsulfatase
C food source	Readily available pool	POXC POM 28-day mineralization WEOC Soluble carbohydrates Substrate-induced respiration Microbial biomass C
Biological available N	Available organic N pool	ACE protein WEON Correlation with short-term mineralization 7-day anaerobic PMN 28-day PMN Illinois soil N test NAG Protease
Microbial diversity	Community structure	PLFA EL-FAME

[1] Acronyms are: BG = β-Glucosidase; NAG = N-acetyl-β-D-glucosaminidase; POXC = Permanganate oxidizable C; POM = Particulate organic matter; WEOC = Cold/hot water-extractable organic C; ACE = Autoclaved citrate extractable (protein); WEON = Cold water-extractable organic C; PMN = Potentially mineralizable N; PLFA = Phospholipid fatty acid; EL-FAME = Ester-linked fatty acid methyl ester profile.
Source: USDA (2019)

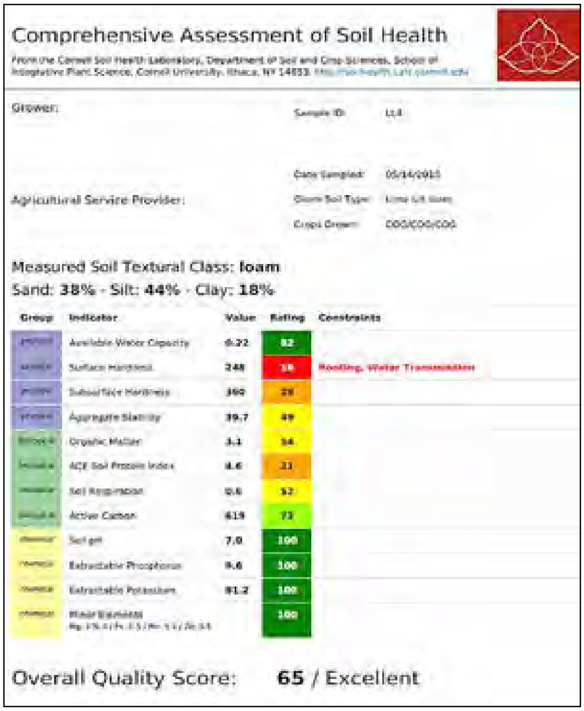
much sodium). This provides information on the soil's chemical health and potential imbalances. As we discussed in Chapter 21, you get the most benefit from soil tests with regularly scheduled analyses (at least every two years) and good records. If your soil test report includes information on cation exchange capacity (CEC), you should expect it to increase with higher organic matter levels, especially in coarse-textured soils. And, as discussed in Chapter 20, soil CEC increases after liming a soil, even if there is no increase in organic matter.

The traditional soil test does not, however, make a comprehensive assessment of soil health, which probably led to the "chemical bias" in soil management. In other words, the widespread availability of good chemical soil tests, although a very useful management tool, may also have encouraged the quick-fix use of chemical fertilizers over the longer-term holistic approach promoted in this book. Several soil health tests have been developed to provide a more comprehensive soil assessment through the inclusion of soil biological and physical indicators in addition to chemical ones. Indicators were selected based on the soil processes that they represent, and thereby the tests provide insights into a soil's ability to provide ecosystem services (like growing healthy crops). They also consider cost, consistency and reproducibility of the methodologies, as well as relevance to soil management.

In this context, the USDA evaluated a set of indicators and methodologies in an attempt to encourage standardization in soil health testing (Table 23.3). The proposed methods have all proven to provide useful insights into aspects of soil health. Currently (in the year 2020) there is no single standard soil health test, but there is universal agreement that a comprehensive soil health test should include indicators that represent all three types of soil processes: biological, physical and chemical (Figure 23.5). Also, measured values need to be interpreted based on inherent variation in soils as a result of different climates, soil textures, etc.

Some soil health indicators have become more widely adopted. For *physical* indicators, ***aggregate stability*** (Figure 23.6) relates to infiltration, crusting and shallow rooting, and represents the "tilth" of the soil. It generally shows a fast response after the introduction of new management practices like reduced tillage, cover cropping or manure or compost additions. ***Available water capacity*** relates to plant-available water and is relevant to drought resistance. It is more sensitive to inherent soil texture differences than to changes in management.

For *biological* indicators, the most common indicator is total ***soil organic matter*** (SOM) content, which affects almost all important soil processes, including water and nutrient retention, and biological activities. It is often the single most important measurement of soil health, but unfortunately it is not very sensitive to management. It takes many years to measure a real change in SOM, and farmers would generally want to know earlier about the benefits of a management change. ***Active carbon*** is an inexpensive test that relates to a small fraction of the organic material that is more actively engaged with biological functions, and it has shown to be very sensitive to changes in soil management. It is therefore a good early indicator of soil health improvements. Active C is assessed as the portion of soil organic matter that is oxidized by potassium permanganate, and the results can be measured with an inexpensive spectrophotometer (Figure 23.7). Similarly, soil ***protein content*** is an indicator of the soil organic nitrogen potentially available to microorganisms, and it also shows strong response to management changes, especially when more legumes are introduced. ***Respiration*** (CO_2 released by soil organisms) is widely measured as an indicator that integrates both abundance and metabolic activity of soil microbes; it is also correlated with nitrogen mineralization potential. ***Ammonia losses*** from amino sugars in the soil is a related measurement.



Comprehensive Assessment of Soil Health

Grower:

Agricultural Service Provider:

Crops Grown: COG/COG/COG

Measured Soil Textural Class: **loam**

Sand: **38%** - Silt: **44%** - Clay: **18%**

Group	Indicator	Value	Rating	Constraints
physical	Available Water Capacity	0.22	82	
physical	Surface Hardness	248	18	Rooting, Water Transmission
physical	Subsurface Hardness	390	29	
physical	Aggregate Stability	39.7	49	
biological	Organic Matter	3.4	54	
biological	ACE Soil Protein Index	4.6	33	
biological	Soil Respiration	0.6	52	
biological	Active Carbon	619	73	
chemical	Soil pH	7.0	100	
chemical	Extractable Phosphorus	9.6	100	
chemical	Extractable Potassium	81.2	100	
chemical	Minor Elements		100	

Overall Quality Score: **65** / Excellent

Figure 23.5. Example of a soil health test report.

Figure 23.6. Results of an aggregate stability test for silt loam vegetable soils: organic (70% stable, left) and conventional (20% stable, right) management.

There are a number of other biological indicators. The bean root rot bioassay provides an effective and inexpensive assessment of root health and overall disease pressure from various sources (plant-parasitic nematodes; the fungi *Fusarium*, *Pythium*, *Rhizoctonia*; Figure 23.8).

Chemical soil health indicators are discussed in Chapter 21 on conventional soil testing and include macro and micronutrients, and soil reaction (pH). Undesirable elements like salts and sodium should be evaluated in arid regions and covered areas, such as inside greenhouses and high tunnels. In urban or industrial environments, toxic elements like heavy metals, salts, radioactive materials, solvents and petroleum products should be considered when assessing soil health, as discussed in Chapter 22.

Interpreting test results is the next step towards identifying specific soil constraints (see Figure 23.5). This particular report (based on the Cornell CASH test) is for a soil that had been under grain production for many years. For each indicator, the report provides a measured value and the associated score (1–100), which is an interpretation of the measured result. If scores are low (less than 20), specific constraints are listed. An overall soil health score, also standardized to a scale of 1–100, is provided at the bottom of the report, which is especially useful for tracking soil health changes over time. The test report in Figure 23.6 is somewhat typical for grain production fields in the northeastern United States. It shows the soil in good shape regarding the chemical indicators but severely underperforming with respect to the physical and biological indicators. Why is that the case? In this situation, the farmer was diligent about using the conventional soil test and keeping nutrients and pH at optimal levels. But intensive cropping caused an unbalanced soil health profile for this field. The test identified these constraints and allows for more targeted management, which we'll discuss in the next chapter.

You might wonder how measured soil health test values are interpreted through scores. In traditional chemical soil tests, the measured values are related to potential crop response (likely yield increase or decline depending on whether it is a nutrient or a toxic element). For biological and physical indicators, scientists have developed normative scoring functions where test results are compared to a larger population of analyzed soil samples in similar soils and cropping systems (similar to how we interpret cholesterol and potassium levels in human blood samples). This approach allows a sample to be scored and interpreted without knowing the precise impact of high or low values. This normative scoring is typically done by calculating mean and

Figure 23.7. Assessment of active carbon using permanganate oxidation and a portable spectrophotometer. Photo by David Wolfe.

standard deviation values for a population group (say, medium-textured soils in grain crop systems in the midwestern United States) and using the cumulative normal distribution function as a fuzzy scoring curve.

Microbial Soil Tests

Soils can also be tested for specific biological characteristics—for potentially harmful organisms relative to beneficial organisms (for example, nematodes that feed on plants versus those that feed on dead soil organic matter) or, more broadly, for macro- and microbiology. Two common tests—the phospholipid fatty acid (***PLFA***) and fatty acid methyl ester (***EL-FAME***) assays—have shown sensitivity to management changes and are offered by some commercial soil testing labs. They produce an estimate of the soil's living biomass. Also, the biomarkers, or signature fatty acids, identify the presence or absence of various groups of interest such as different bacteria, actinomycetes, arbuscular mycorrhizal fungi, rhizobia and protozoa. The relative amounts or activities of each type of microorganism provide insights into the characteristics of the soil ecosystem. Bacterial-dominated soil microbial communities are generally associated with highly disturbed systems with external nutrient additions (organic or inorganic), fast nutrient cycling and annual plants. Fungal-dominated soils are more common with low amounts of disturbance and are characterized by internal, slower nutrient cycling, and high and stable organic matter levels. Thus, the systems with more weight of bacteria than fungi are associated with intensive agricultural production (especially soils that are frequently plowed), while systems with a greater weight of fungi than bacteria are typical of natural and less disturbed systems. The significance of these differences for the purposes of modifying practices is somewhat unclear, but modifying practices causes biological changes to occur. For example, adding organic matter, reducing tillage and growing perennial crops all lead to a greater ratio of fungi to bacteria. Since networks of mycorrhizal fungal filaments help plants absorb water and nutrients, their presence suggests more efficient nutrient and water use. But we generally want to do these practices for many other reasons—improving soil water infiltration and storage, increasing CEC, using less energy, etc.—that may or may not be related to the ratio of bacteria to fungi.

The study of genetic material recovered directly from soil has advanced in recent years. Routinely characterizing the genetic profile of a soil's organic matter to obtain a picture of the organisms present is thus becoming commercially feasible. It is challenging to extract specific genetic material from soils due to the high complexity of soil organic matter, and DNA profiling is mostly used for descriptive purposes (for example, how prevalent different types

Figure 23.8. Examples of root rot bioassays on bean plants: conventional (left) and organic (right) soil management. Photos by George Abawi.

of *pseudomonas* bacteria are). Some tests are showing promise with identifying specific pathogens that may help farmers better manage their fields.

Sensing methods are increasingly considered for soil health assessment. Visible near-infrared and mid-infrared reflectance spectroscopy methods are non-destructive approaches that measure the optical reflectance properties of soil, which is influenced by chemical bonds like O-H (abundant in clay minerals), C-H (abundant in organic matter), etc. They therefore can assess certain soil properties rapidly and at low cost. Such methods appear to be especially efficient when combined with a subset of laboratory-measured properties that can be compared with the spectroscopy results through advanced statistical and machine learning techniques.

SUMMARY

There are many things to be learned by regularly observing soils and plants in your fields. These include being able to evaluate such important aspects as the severity of runoff, erosion and compaction; root development and health; severe nutrient deficiencies; and the presence of earthworms and other easily visible organisms, among other things. Laboratory evaluations of physical and biological indicators as well as comprehensive interpretation frameworks can also be employed. It is, of course, not enough to know whether a particular limitation exists. In the following (and last) chapter we will discuss both how to put together soil and crop management systems for building healthy soils, and how to address particular issues that may arise from field observations or laboratory analyses.

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Chapter 24

PUTTING IT ALL TOGETHER

… generally, the type of soil management that gives the greatest immediate return leads to a deterioration of soil productivity, whereas the type that provides the highest income over the period of a generation leads to the maintenance or improvement of productivity.

—CHARLES KELLOGG, 1936

In this chapter, we'll provide some guidance on promoting high-quality soils through practices that maintain or increase organic matter, develop and maintain optimal physical and biological conditions, and promote top-notch nutrient management. In Part 3, we discussed many different ways to manage soils, crops and residues, but we looked at each one as a separate strategy. In the real world, you need to combine a number of these approaches and use them together. In fact, each practice is related to, or affects, other practices that promote soil health. The key is to modify and combine them in ways that make sense for your farm. In our discussion of the topics, we generally focused on farms, but the same principles apply to gardens large and small.

We hope that you don't feel as confused as the person on the left in Figure 24.1. If the thought of making changes on your farm is overwhelming, you can start with just one or two practices that improve soil health. Not all of the suggestions in this book are meant to be used in every situation. Also, a learning period is probably needed to make new management practices work. Experiment on one or two selected fields and permit yourself to make a few mistakes.

Ultimately your decisions need to support the bottom line. Research shows that the practices that improve soil health generally also improve the economics of the farm, in some cases dramatically. Higher soil health tends to provide higher yields and more yield stability, while allowing for reduced crop inputs. However, you need to consider the fact that the increased returns may not be immediate. After you implement new practices, soil health may improve slowly, and it may take a few years to see improved yields or changes in the soil itself. Similarly for other businesses like landscaping, your initial investments in soil health may be more expensive but will result in better outcomes for your clients in the long run, like more aesthetic parks and gardens that are more resilient and less expensive to maintain.

The bottom line therefore may not improve immediately. Changing management practices may involve an

Photo by Abram Kaplan

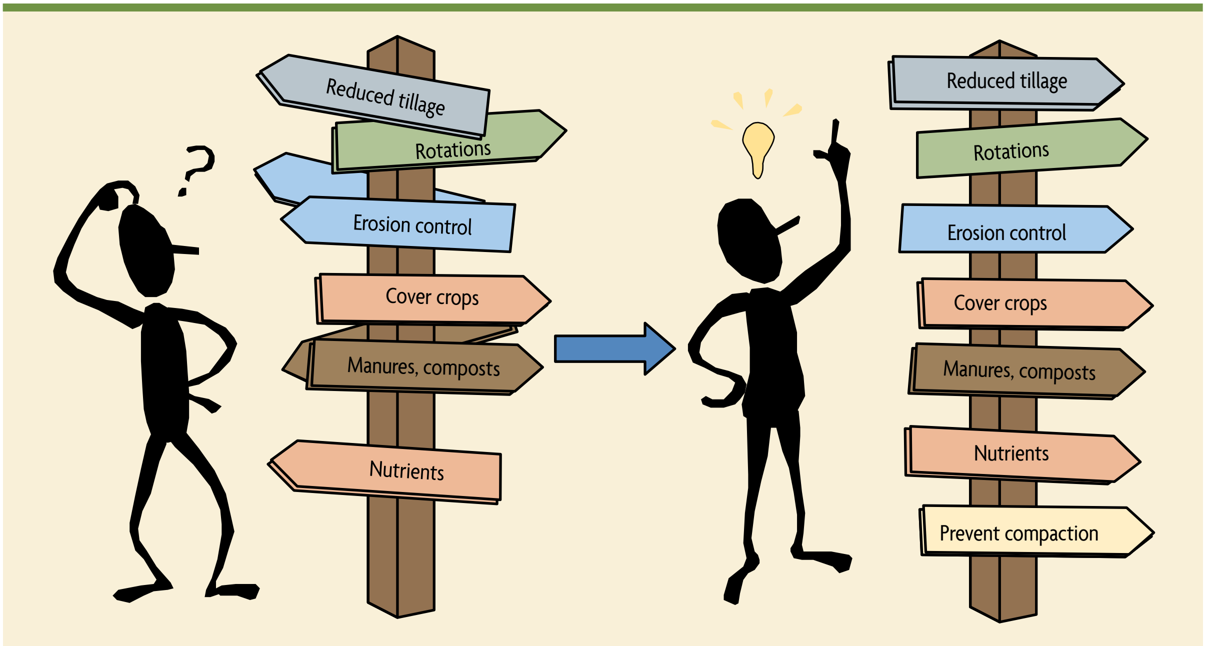

Figure 24.1. Are all the practices discussed in this book just confusing? Solutions can be found by matching them with the needs and opportunities of your farm.

investment in new equipment; for example, changing tillage systems requires new tillage tools and planters. For many farmers, these short-term limitations may keep them from making changes, even though they are hurting the long-term viability of the farm. Big changes are probably best implemented at strategic times. For example, when you are ready to buy a new planter, consider a whole new approach to tillage as well. Also, take advantage of flush times—for example, when you receive high prices for products—to invest in new management approaches. However, don't wait until that time to make decisions. Plan ahead, so you are ready to make the move at the right time. If you establish a new orchard, vineyard or landscaped area, it's best to do whatever is possible to improve the soil before you put your plants into the ground. When switching to no-till it likewise makes sense to try to add extra organic matter, take care of subsoil compaction and correct any nutrient deficiencies. Remember that soil health management is a long-term commitment. There are no silver bullets or snake oils that will work to build soil health; it requires integrating the concepts of physical, biological and chemical processes we have discussed in this book.

GENERAL APPROACHES

The ultimate purpose of ecological soil management is to create a healthy habitat belowground, with good soil structure, thriving and diverse soil organisms, and nutrients in sufficient supply for high crop yields while not in excess and, as a result, causing off-site pollution. When this is combined with healthy above ground habitat, in the field and around its perimeter, plants are provided with optimal conditions for their growth and protection against pests. Soil health can be improved through six main approaches:

- reducing tillage
- avoiding soil compaction
- growing cover crops

- using better crop rotations
- applying organic amendments in appropriate quantities
- applying inorganic amendments in appropriate quantities, timing and locations

There are many options for making soil management changes in different types of farming systems. We have discussed these in the previous chapters with respect to helping remedy specific problems. A good analogy is to think of your soil as a bank account with credits and debits. The credits are management practices that improve soil health, like manure additions, reduced tillage and cover crops. The debits are the ones that degrade the soil, like compaction from field traffic and intensive tillage (Table 24.1). One farming system may result in a different balance sheet than another due to specific constraints. For example, a daily harvest schedule means that you cannot avoid traffic on wet soils, and small-seeded crops require intensive tillage (at least in the planting row) in order to prepare a seedbed. Still, strive to optimize the system: If a "bad" practice, such as harvesting in a wet field that contains spoilable crops, is unavoidable, try to balance it with a "good" practice, thereby making your soil health account flush. Also, you may have options to reduce the impacts of a bad practice, like controlling traffic to certain lanes to reduce unavoidable soil compaction.

If at all possible, use rotations that use grass or legume forage crops (or a combination of the two), or crops with large amounts of residue as important parts of the system. Leave residues from annual crops in the field, or, if you remove them for feed, composting or bedding, return them to the soil as manure or compost. Use cover crops when soils would otherwise be bare to add organic matter and maintain soil biological health, capture residual plant nutrients, keep the soil protected and reduce erosion. Cover crops also help maintain soil organic matter in resource-scarce regions that lack possible substitutes for using crop residues for fuel or building materials.

Raising animals or having access to animal wastes from nearby farms gives you a wider choice of economically sound rotations. Those that include perennial forages make hay or pasture available to dairy and beef cows, sheep and goats—and nowadays even poultry. In addition, on mixed crop-livestock farms, animal manures can be applied to cropland. It's easier to maintain organic matter on a diversified crop-and-livestock farm, where sod crops are fed to animals and manures are returned to the soil. Compared to crop farms, fewer nutrients leave farms when livestock products are the

Table 24.1
Balance Sheet for Soil Health Management*

Practice or Condition	Improves Soil Health	Reduces Soil Health
Tillage		
moldboard plowing		XX
chisel plowing		X
disking		X
harrowing		X
conservation tillage	X	
Compaction		
light		X
severe		XX
Organic matter additions		
bedded manure	XX	
liquid manure	X	
compost	XX	
mulch	XX	
Cover crops		
winter grain	XX	
winter legume	X	
summer grain	XX	
summer legume	XX	
Rotation crops		
3-year sod	XX	
1-year sod	X	

*X = a moderate effect; XX = a greater effect.

main economic output. However, growing crops with high quantities of residues, plus frequent use of green manures and composts, helps maintain soil organic matter and soil health even without animals. In many situations you may have opportunities to bring in organic resources. Perhaps there is a lot of municipal compost available in your area, or maybe a nearby dairy farm sells well-composted manure that can help you grow vegetables or improve an orchard or landscaped area.

You can maintain or increase soil organic matter more easily when you use reduced-tillage systems, especially no-till and strip-till. The decreased soil disturbance keeps biological activity and organic matter decomposition near the surface and helps maintain a soil structure that allows rainfall to infiltrate rapidly. Leaving residue on the surface, or applying mulches, has a dramatic impact on soil biological activity. It encourages the development of earthworm populations, maintains soil moisture and moderates temperature extremes. Adding mulch can be very helpful after you plant perennial trees to control weeds and conserve soil moisture.

Compared with conventional tillage, soil erosion is greatly reduced under minimum-tillage systems, which help keep organic matter and rich topsoil in place. Any other practices that reduce soil erosion, such as contour tillage, strip cropping along the contours and terracing, also help maintain soil organic matter. Even if you use minimum-tillage systems, you also should use sound crop rotations. In fact, it may be more important to rotate crops when large amounts of residue remain on the surface, as they may harbor insect and disease organisms. These problems may be worse in monoculture with no-till practices than with conventional tillage.

WHAT MAKES SENSE FOR *YOUR* SITUATION?

We strongly advocate a holistic management approach designed to prevent problems from developing, as preventive medicine approaches do. And, as with human health, we have the ability to diagnose problems through observations and testing. If problems are identified, the patient and physician develop strategies to address them. This may include a change in diet, exercise, a pill or even surgery. There are often multiple ways and combinations to reach the same goal, depending on personal preferences and circumstances. Similarly for soil health, what makes sense for any individual operation depends on the soils, the climate, the nature of the enterprise, the surrounding region, potential markets and your goals. The tests and observations provide useful guidance to help target constraints, but there is rarely a simple recipe. We wish it was that easy. Holistic soil health management based on ecological principles requires an integrative understanding of the processes, which is basically the purpose behind this book.

Start with regularly testing your soils, preferably using comprehensive soil health analyses, and applying amendments only when they are needed. Testing soils on each field every two to three years is one of the best investments you can make. If you keep the report forms, or record the results, you will be able to follow soil health changes over the years. Monitoring soil test changes will help you fine-tune your practices. Also, maintaining your pest scouting efforts and keeping records of those over the years will allow you to evaluate improvements in that area.

PRACTICES TO HELP REMEDY SPECIFIC CONSTRAINTS

Building soil health can help prevent problems from affecting the environment and plant growth. However, as good a job as you might do, specific problems may arise that require some sort of remedial action. The choice of a practice or combination of practices depends largely on specific soil health problems and possible constraints imposed by the farming system. We discussed in Chapter 21 how traditional (chemical) soil tests are used to provide quantitative nutrient and lime recommendations. As discussed in Chapter 23, newly

Table 24.2
Linking Some Soil Health Measurements to General Management Solutions

	Suggested Management Practices	
Physical Concerns	**Short Term or Intermittent**	**Long Term**
Low aggregate stability	Fresh organic materials (shallow-rooted cover/rotation crops, manure, green clippings)	Reduced tillage, surface mulch, rotation with sod crops
Low available water capacity	Stable organic materials (compost, crop residues high in lignin, biochar)	Reduced tillage, rotation with sod crops
High surface density	Limited mechanical soil loosening (e.g., strip tillage, aerators), shallow-rooted cover crops, bio-drilling cover crops, fresh organic matter	Shallow-rooted cover/rotation crops, avoiding traffic on wet soils, controlled traffic, physical decompaction—loosening
High subsurface density	Targeted deep tillage (zone building, etc.), deep-rooted cover crops	Avoiding plows/disks that create pans, reducing equipment loads and traffic on wet soils, deep tillage
Biological Concerns		
Low organic matter content	Stable organic matter (compost, crop residues with high lignin, biochar), cover and rotation crops	Reduced tillage, rotation with sod crops, mulch
Low active carbon	Fresh organic matter (shallow-rooted cover/rotation crops, manure, green clippings)	Reduced tillage, rotation
Low organic forms of nitrogen	N-rich organic matter (leguminous cover crops, manure, green clippings)	Cover crops, manure, rotations with forage legume crop, reduced tillage
High root-rot rating	Disease-suppressive cover crops, disease-breaking rotations	Disease-suppressive cover crops, disease-breaking rotations, IPM practices
Chemical Concerns		
Low CEC	Stable organic matter (compost, lignaceous/cellulosic crop residues, biochar), cover and rotation crops	Reduced tillage, rotation
Unfavorable pH	Liming materials or acidifier (such as sulfur)	Repeated applications based on soil tests
Low P, K	Fertilizer, manure, compost, P-mining cover crops, mycorrhizae promotion	Repeated application of P, K materials based on soil tests; increased application of sources of organic matter; reduced tillage
High salinity	Subsurface drainage and leaching	Reduced irrigation rates, low-salinity water source, water table management
High sodium	Gypsum, subsurface drainage, leaching	Reduced irrigation rates, water table management

available soil health tests, as well as careful attention to your soils and crops, can help target management practices related to specific limitations. We cannot be quite as precise for making recommendations regarding physical and biological constraints as we can be for nutrient problems because these systems are more complex and we don't have as strong a research base.

General management guidelines for specific constraints that may have been identified from soil health tests or field observations are presented in Table 24.2. They are listed in terms of two timelines: short term or intermittent, and long term. The short-term recommendations provide relatively quick responses to soil health problems, and they may need to be repeated to prevent recurrence of the problem. The long-term approaches focus on management practices that don't provide quick fixes but that address the concern more sustainably. You will probably note that the same practices are often recommended for different constraints because they address multiple concerns at the same time.

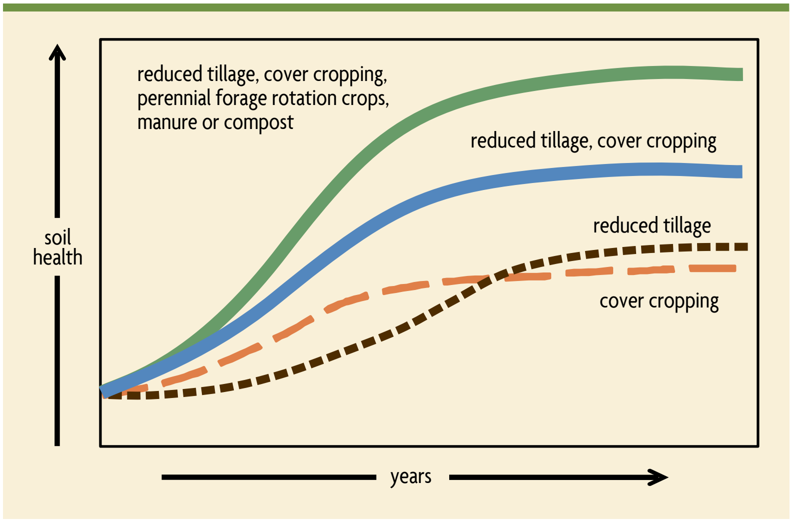

Figure 24.2. Combining practices that promote soil health has an additive effect.

Note that many of the management solutions listed in Table 24.2 involve improving organic matter. As you probably realize at this stage of the book, we believe that improved organic matter management is key to sustainable soil management. But keep in mind that simply bringing in any type of organic material in any amount is not necessarily the solution. For one thing, organic additions that are too large may create problems with nutrient surpluses. Second, some organic materials reduce disease levels, but others can increase them (see Chapter 11 on rotations and Chapter 13 on composting). Third, some constraints like acidity, sodicity and extremely low nutrient levels are often more effectively approached with chemical amendments. Fourth, there are important considerations relating to the type of organic materials that are used. In chapters 9, 10 and 12 we discussed different organic residues and manures, and their effects on soil health. One important distinction is whether the material is mostly "fresh" and easily decomposable or contains more stable compounds. Fresh materials like manure, cover crops and green clippings are high in sugars, cellulose and proteins, and have relatively high N content (low C:N ratios). They immediately stimulate soil biological activity, especially bacteria, and provide a lot of available N for crops. The organic materials that are dominated by stable materials high in lignin, like the residues of mature crops, and those that contain humic material, like composts, are critical to building soil health in the long term. Biochar and other heat-treated organic materials decompose slowly and are much more stable materials, sometimes remaining for hundreds of years. If, for example, aggregate stability or active carbon levels are low, the application of easily decomposable materials will be beneficial in the short term. However, these materials disappear quickly and need to be added regularly to maintain good aggregation. For longer-term effects it is recommended to include more stable organic compounds and use reduced tillage.

What is the role of fertilizers? The emphasis on organic matter should not be interpreted as a complete condemnation of synthetic fertilizers. It is true that the sole dependence on synthetic chemicals without consideration of organic matter and biology in the soil is a primary source of soil health degradation. But not supplying adequate nutrients where they are needed will make matters more dire. There are situations where organic crop production is possible and makes sense, but for better or worse, the current structure of agriculture leaves many areas without adequate options for carbon and nutrient cycling. There the emphasis should be on using conservation practices and supplemental fertilizer to reduce nutrient losses, maintain crop yields and enhance biomass cycling. Otherwise, soil health will deteriorate further and yield reductions will result in food shortages or will necessitate more agricultural expansion into natural areas.

Grain Crop Farms

Most grain crop farms export a lot of nutrients and are managed with a net loss of organic matter. Nevertheless, these farms provide a great deal of flexibility in adopting alternative soil management systems because a wide range of equipment is available for grain production systems. You can promote soil health easily with reduced-tillage systems, especially no-till and strip-till. Well-drained, coarse-textured soils are especially well adapted to no-till systems, and finer-textured soils do well with strip-till or zone-till systems. Regardless of the tillage system that is used, travel on soils only when they're dry enough to resist compaction. However, managing no-till cropping on soils that are easily compacted is quite a challenge because there are few options to relieve compaction once it occurs. Controlled-traffic farming is a very promising approach, especially for such situations, although it may require adjustments of equipment and investment in a GPS guidance system. Incorporating these innovations into a conventional grain farm often requires an investment in new equipment and creatively looking for new markets for your products. There also are many opportunities to use cover crops on grain farms, even in reduced-tillage systems.

Even if you use minimum-tillage systems that leave significant quantities of residue on the surface and decrease the severity of erosion, you also should use sound crop rotations. Consider ones that use grass or legume perennial forage crops, or a combination of the two. Even bringing small grains into a row crop system (like corn and soybeans) can improve soil health and open up opportunities for cover crops. Raising animals on what previously were exclusively crop farms, cooperating on rotations and manure management with a nearby livestock farm, or growing forage crops for sale gives you a wider choice of economically sound rotations and at the same time helps to cycle nutrients better.

Organic grain crop farms do not have the flexibility in soil management that conventional farms have. Their main challenges are providing adequate nitrogen and controlling weeds. Tillage choices are limited because of the reliance on mechanical methods, instead of herbicides, to control weeds. On the positive side, organic farms already rely heavily on organic inputs through green or animal manures and composts to provide adequate nutrients to their crops. So their balance sheet (Table 24.1) is often very good despite the tillage. A well-managed organic farm usually uses many aspects of ecological soil management. However, erosion may remain a concern when you use clean and intensive tillage. It is important to think about reducing tillage intensity; using strips, ridges or beds; controlling traffic; and perhaps investing in a good planter. New mechanical cultivators can generally handle higher residue and mulch levels, and may still provide adequate weed control. Look into ways to increase surface cover, although this is a challenge without the use of chemical weed control. Alternatively, consider more traditional erosion control practices, such as strip cropping, as they work well with rotations involving sod and cover crops.

Crop-Livestock Farms

Diversified crop-and-livestock farms have an inherent advantage for improving soil health. Crops can be fed to animals, and manures can be returned to the soil, thereby providing a continuous supply of organic materials. For many livestock operations, perennial forage crops and management intensive grazing are an integral part of the cropping system, thereby reducing erosion potential and improving soil physical and biological properties. Nevertheless, integrated crop-livestock farms have challenges. Corn silage harvests do not leave much crop residue, which needs to be compensated for with manure applications or cover crops. Minimizing tillage is also important and can be done by injecting the manure or gently incorporating it with aerators, disks or harrows rather than plowing it under. Soil pulverization can be minimized by reducing secondary tillage, using strip or zone tillage, and establishing the crops with no-tillage planters and seeders.

Preventing soil compaction is important on many livestock-based farms. Manure spreaders are typically heavy and frequently go over the land at unfavorable times, doing a lot of compaction damage. Think about ways to minimize this. Livestock farms require special attention to nutrient management, including making sure that organic nutrient sources are optimally used around the farm and that no negative environmental impacts occur. This requires a comprehensive look at all nutrient flows on the farm, finding ways to most efficiently use them, and preventing problems with excesses. Finally, management-intensive grazing systems are very efficient and are similar to how herds of wild animals naturally graze. Harvesting and fertilizing are done by the animals, but be aware that it is important to match stocking rates to the productivity of pastures.

Vegetable Farms

Soil health management is especially challenging on vegetable farms. Many vegetable crops are sensitive to soil compaction and often pose greater challenges in pest management. Vegetable lands have generally been worked hard over many years and have a long way to go toward improved soil health. Most vegetable farms are not integrated with livestock production, and it is difficult to maintain a continuous supply of fresh organic matter. Bringing manure, compost or other locally available sources of organic materials to the farm should be seriously considered. In some cases, vegetable farms can economically use manure from nearby livestock operations or swap land with them in a rotation. Farms near urban areas may benefit from leaves and grass clippings, and municipal or food waste composts, which are increasingly available. In such cases, care should be taken to ensure that the compost does not contain contaminants. Contrary to large commercial vegetable operations, we found that many smaller organic vegetable farms are often on the other end of the spectrum for soil health. They typically use good rotations and cover crops to provide nitrogen and to reduce pest problems, and they import manure or compost to maintain fertility.

FINDING CREATIVE SOLUTIONS

Dairy farmers in Vermont were concerned about soil health on their corn fields. The state's colder continental climate limits the time window for cover crop establishment before winter dormancy sets in. Working together with University of Vermont specialists, the farmers experimented with two shorter-season corn varieties that mature seven to 10 days earlier and increase the time window for cover crop establishment equivalently. They found that their corn yields were generally unaffected by the shorter growing season, but their ability to establish cover crops was greatly enhanced.

Vegetable cropping systems are often well adapted to the use of cover crops because the main cropping season is generally shorter than those for grain and forage crops. There is usually sufficient time for the growth of cover crops in the pre-, mid- or post-season to gain real benefits, even in colder climates, and vegetable growers often have a multitude of cover cropping options. Using them as a mulch (or importing mulch materials from off the farm) appears to be a good system for certain fresh market vegetables, as it keeps the crop from direct contact with the ground, thereby reducing the potential for rot or disease.

But many vegetable crops are highly susceptible to diseases, and selection of the right cover or rotation crop is critical. For example, according to Cornell plant pathologist George Abawi, bean root rot is suppressed by rapeseed, crown vetch, wheat and rye but is actually enhanced by white clover. Sudan grass can effectively remediate compaction, control pathogenic nematodes and allelopathically control weeds, but it requires a long time window for sufficient growth.

The immediate need to harvest crops during a very short period before quality declines, often a concern with vegetables, can result in severe compaction problems on vegetable farms. Controlled-traffic systems, including permanent beds, should be given serious consideration. Limiting compaction to narrow lanes and using other soil-building practices between them is the best way to avoid compaction damage under those conditions.

Fruit Farms and Landscaping

Many fruit crops, such as brambles, citrus, grapes, apples and stone fruits, are perennials that take several years to establish and may be harvested for 20 or more years. Similarly, landscaped areas in parks and gardens are intended to remain attractive for many years with minimal maintenance. This makes it especially important to address soil health concerns up front and to avoid mistakes during the establishment years, which can have negative impacts long into the future. Comprehensive soil health analyses and field surveys are worthwhile investments, considering the already high costs of establishing the crops. For tree and vine crops, these evaluative steps should pay attention to deeper soil layers, especially the presence of hard pans, subsoil acidity and shallow water tables, because the quality of the fruits is often strongly influenced by deep roots. It is often worthwhile to make one-time investments like drainage installation, in-row deep ripping and deep lime and compost incorporations, as these are difficult to perform after planting. For landscaped areas, future maintenance costs and watering are concerns that can be addressed by building up the soil before transplanting. Post-establishment, the emphasis should be on managing the surface layer. Avoiding compaction is important, and maintaining good surface mulches is generally also beneficial, depending on the crop type.

SOME FINAL THOUGHTS

The old folk saying, “The farmer’s footprint is the best fertilizer” could be modified to “The farmer’s footprint is the best path to improved soil health.” If you don’t

MORE IS NOT ALWAYS BETTER WITH GRAPEVINES

A good soil is needed in the early years in order to establish healthy grapevines. But the best wines generally come from soils that are not overly fertile and that allow for some water stress during the season. High organic matter and nitrogen contents in vineyard soils create overly abundant vegetative growth in grapevines, reducing fruit set and requiring repeated pruning. Also, important traits of wines are enhanced by the presence of the grapes’ anthocyanin pigments, which contribute to both the taste and to the color of wine. Mild water stress and reduced root growth during the early summer (between bloom and the beginning of the ripening stage) increase the content of these pigments. Poor drainage and aeration are bad for wine quality. Some of the world’s best wines are grown on soils that allow for deep rooting; are calcareous, sandy or gravelly; and are low in organic matter. The best climates experience water deficits during the growing season, which can be supplemented by irrigation if needed. This complex interaction between soil, climate and vine is referred to as *terroir.*

already do so, begin to regularly observe and record the variability in plant growth and yield across your fields. Take the time to track production from the various sections of your fields that seem different. Compare your observations with the results of your soil tests, so you can be sure that the various areas within a field are receiving optimum management. Each of the farming systems discussed above has its limitations and opportunities for building better soils, although the approaches and details may differ. Whatever crops you grow, when you creatively combine a reasonable number of practices that promote high-quality soils, most of your soil health problems should be solved along the way, and the yield and quality of your crops should improve. By concentrating on the practices that build high-quality soils, you also will leave a legacy of land stewardship for the next generations to inherit and follow.

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BUILDING SOILS FOR BETTER CROPS

ECOLOGICAL MANAGEMENT FOR HEALTHY SOILS

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