SOILS: A PRACTICAL GUIDE FOR ORGANIC FARMERS AND GARDENERS

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Practical Guide to Soils for Farmers and Gardeners

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This text was compiled on 07/21/2025

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1.1: Introduction

> *"An undiscovered country from whose bourn no traveler returns, puzzles the will."*
>
> *—Hamlet, William Shakespeare*

This may seem like a strange quote with which to begin a book about soil, but I like it. Most people interpret this as Hamlet puzzling over death and what that must be like--a foreign country from which nobody ever comes back to let us know what it is really like. However, I like to think this quote also refers to SOIL, the topic of this book. Soil has been an undiscovered country up until very recently. We didn't know what went on in there, who lived there, or even how much that 'country' impacts our food, our health, our farms, our waters. We took it for granted because it was just 'common ground'. So common, we stand on it, we till it, we eat from it, we build homes on it. We haven't had to think twice about it--soil has just always been there at the foundation, literally, of our lives.

But lately, in the last 50 years, we have begun to examine this undiscovered country. This is especially true as we've started to care about the impact of our farming practices on soil. We've put it under a microscope, we've analyzed its particle sizes and cohesiveness, we puzzle about its mineral nutrient cycles, we are thunderstruck at the life in it, and we watch it wash off our fields and into our waters. This book is a journey about all those things. Come with me as we explore the undiscovered country of soil. I'll be your tour guide along with Fred Magdoff and Harold van Es (who wrote the SARE portions of this book). I will try to pass along what I learned from my guides Henry Foth, Emmett Schulte, Elaine Ingahm, and Rick Adamski. I hope that you will come to see soil as a beautiful, underappreciated country that gives its gifts to all. It is from the soil we were formed - it provides the food that becomes us - it is to the soil that we will return someday. And that return will take us to Shakespeare's version of yet another undiscovered country.

> *"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 flesh, 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 crop plants, 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 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 a rural home's 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 with global warming. 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, homes, industry, and our communities.

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1.2: Thoughts on Soil

The View from This Side of the Fence

After 50 years of digging around in soil, I would like to think I have learned a few things. I want to share with you how I, as a farmer, scientist, and teacher, think about soil. As we begin this soil journey together I share some philosophical thoughts with you rather than the scientific information we will explore later. I want you to get a feel for soil as something you can begin to appreciate and also care about. You will want to know some of the basic things about soil so that you can grow healthy, strong plants, but also, I hope you will learn about soil like you would want to know more about a good friend. I think it is an interesting coincidence that the word “SOIL” and the word “SOUL” are just one keyboard touch away from each other. I often type in Soul instead of Soil; is that an accident or a neat reminder of some quiet kinship?

Definition of Soil

My favorite definition of soil is:

> *"The interface between the living and the dead."*
>
> *—Henry Foth*

I like the definition because it loops us back to both meanings of 'Undiscovered Country', a place where unseen things happen, and a place where the living who die find rest before becoming alive again. The quote describes a hidden, essential role of soil that most people do not consider. Soil is a place, a habitat, for billions of microorganisms. These are the first link in a food chain full of life that transforms non-living materials we call nutrients (like nitrogen, phosphorus, and potassium) into living beings. Its alchemy. Magic. The microbes knit the nutrients together to form their bodies. These are then eaten by bigger and bigger organisms as you will discover in Chapter 10.

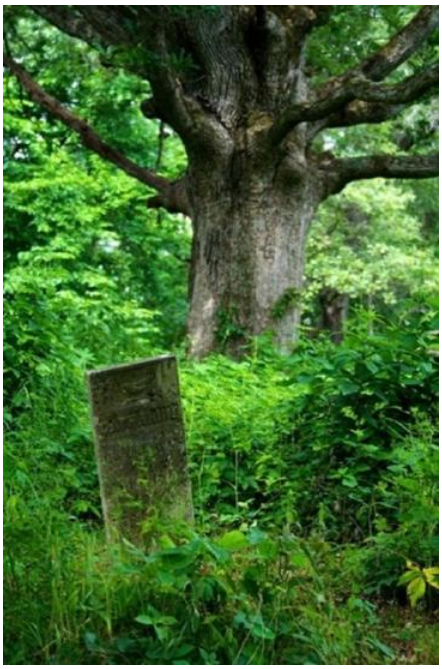

Figure 1.2.1: Depiction of the connection of death to life through the soil.

One body (corpse) decomposes and becomes another body’s life. We truly never remain dead forever, our body’s components are recycled and resurrected and become alive again through the magic of microbes in the soil and plants that grow from them. The plants may be eaten by a cow, the cow eaten by a person, and thus the circle of life continues via the place we call soil. What if the person from the grave in the picture is now living again as an oak tree? Their nutrients are taken up by the roots and sent out to the tree's crown. An acorn from the tree is eaten by a squirrel. The squirrel is eaten by a hawk. The hawk takes wing. The molecules that were you, fly. I, for one, plan to get recycled as soon as possible and get back in the game when I'm done with my corporeal

body and go on to the next journey. This may be too philosophical for most people, but I wanted to give you a glimpse of the awe and respect I have for soil.

Outside - In

When we eat plant or animal material that springs from the soil, we bring the external environment inside ourselves. We have a tube running through us, our guts, our colon, where we allow the external to become internalized and absorbed. Our colon and soil are both places of re-animation, a place where the dead becomes alive again as it is in**corp**orated into our bodies. Remember, "corpse" is just another word for a body. We should colonize our colon with good bacterial life, some of which should come from the soil. “Soil” has been used as a term for what comes out the end of a digestive system.... poop. It is accurate, though in our culture it has a negative connotation. I think the image of “soil-as-poop” is unfortunate because it equates the material with “waste” when rather it is a rich resource. On our farm, cow poop is the base ingredient for compost. Compost is the source of inoculum for organisms that re-cycle the nutrients in our soils and build the base of fertility for our crops.

Figure 1.2.2: Colon. Photo Credit SomkiatFakmee. Getty Images

Our food should be alive, vibrant, and nutrient-dense. Because of my background, with degrees in microbiology and agronomy plus 35 years of farming experience, I know that life starts with the soil. If we do not have vibrant, living, healthy soil our food will be dead. If our food is dead, our guts will be messed up. Pretty simple to comprehend, right? I’ve come to see a connection between the many illnesses associated with the modern, western diet and a lack of good bacteria, good soil, and good farming practices that give us good food. It is simple to understand, but completely unfortunate that many people do not realize that how we practice farming and treat our soil has a profound impact on the quality of our food and our digestion.

Soil Health on Full Circle Farm

At various places in this book, I bring you onto my family farm, Full Circle Organic Farm. We are located just west of Green Bay, Wisconsin, and the farm has been in my husband's family since the land was cleared in the 1890s. Some of the farming practices we use to enhance soil health include; managing animal grazing, composting, crop rotation, planting perennial legumes and cover crops, and plowing a field only every fifth year or so. I think it is very important to have animals on any crop farm because of the manure they produce. The livestock adds manures and beneficial bacteria back into the farm crop system. Composting adds organic matter, that jungle gym-type habitat, back into the soil. Rotating crops keeps non-beneficial pests from gaining a foothold in the system. Using legumes adds nitrogen to the soil, and perennials keep living roots in the soil year-round. Roots exude what soil microbiologist Dr. Elaine Ingham describes as “cakes and cookies” into the soil for microbes to feed on. The perennials and cover crops leaf out very early in spring and have leaves later into the fall. This keeps the soil covered with “many little tents” which prevents raindrop impacts from dislodging soil particles which may then flush them away with the rain. We explore all these soil-healthy farming techniques in the book.

Sustainable farmers understand that soil is alive–it is a biological system. We try to amplify the soil livestock - that is, the microbes and arthropods. There is a complex web of soil life that we have only just begun to explore. Organic farmers foster soil that is fecund with beneficial tiny critters. Organic farmers bank nutrient wealth in the soil for their children’s children. We respect all life, even a bacterium. We cheer on soil life and its magic of resurrection. Welcome to the undiscovered country.

Figure 1.2.3: Organic farmers protect and nourish the soil; letting the soil feed the plant.

A Guide to this Undiscovered Country Called Soil

How can farmers and gardeners do their part to farm better and improve soil health so that we improve plant health, improve our human diet, and as a bonus the environment? The journey takes us, chapter by chapter through that territory. 'Territory' is a word of Latin origin meaning 'Earth', in the sense of soil. Throughout this book, I will occasionally point out the many words in our vocabulary that are 'grounded' in soil-like terms. *Terroir* is an example of a soil-related word. It is the French word indicating that the region a food/wine comes from, a certain place with certain soils, will give it special characteristics.

Let's get going on the path:

- Our first step on the journey is to get this philosophical 'feel' for soil as more than just dirt - in **Chapter One**.
- **Chapter Two** helps us understand the physical nature of the soil. Of what material is it made? It is part air, water, and minerals. How is it formed? What makes some areas of the world so productive that they are called breadbaskets?
- Next, in **Chapter Three**, we explore the chemistry of soil--yes, chemistry, pH, and electric charges--to understand how nutrients behave in the soil.
- **Chapter Four** explores Organic Matter, what it is, how it matters, and how we have been losing it rapidly with modern farming methods. In this chapter, we also examine what it means to have healthy soil. There are some tests that help us understand if our soil is as functional as good soil should be.
- **Chapter Five** is perhaps the territory most people are familiar with--nutrients. That is because we have been taught we can just apply them from a box or a bag and all will be well with the crops we grow. In fact, good organic farmers can grow their most important nutrient, Nitrogen, right on the farm, with no need to buy it as an input. We will also see what fertilizers are available, both synthetic and organic.
- **Chapter Six** is about carbon flows and large-scale movement of nutrients and cycling. The movement of nutrients in an ecosystem provides plants with goodies that do not harm soil life nor exploit and extract nutrients from one place and haul them to our farms and gardens. Interestingly, we are mining some areas of the earth and seas and depositing those nutrients on our crop fields, then shipping them to the coasts and urban areas and into the bodies of the eight billion humans on the planet. We are digging a metaphorical canyon in America's Midwestern belly, a 'metabolic rift'.
- **Chapter Seven** delves into soil sampling, soil tests, and reading test results. I am not a big fan of soil testing, I would rather let the plant health and yield tell me if I have got things right. But, as humans, we like to measure things, so we will put some numbers on our soils and see how we stack up.
- After we've got our soil test results or a guess about our soil's fertility, we move on to **Chapter Eight** to take a look at both organic and conventional fertilizers. What makes them so different from each other? Why do they have such a large impact on the environment if applied incorrectly? What can we do differently to be better stewards of the land and acres we tend? Fertilizers are nutrients we add to the soil to get better crop yields.
- **Chapter Nine** is all about compost. That great, under-appreciated amendment we add to soil to increase organic matter and fluff up the all-important habitat for soil microbiology.
- In **Chapter Ten,** we dig into the unexplored territory of the life beneath our feet. It is a fascinating jungle down there. We get a glimpse of soil life and the critters that dwell there.
- **Chapter Eleven** takes us to livestock and manure. There are two things we need to consider if we want healthy soils. We need livestock for their poop and for how they recycle nutrients and organic matter back to our fields. Plus, watch out, manure can be a pollutant.
- **Chapter Twelve** is all about soil loss and the practices farmers and gardeners can use to stop it. Are we losing a thousand years of soil in just 100 years? Not just focused on problems, this chapter explores how we can help the soil, improve it, and perhaps even fix it if it has been damaged. We explore making better choices in our farm's soil management. We specifically review cover cropping, tillage, and compaction. We explore some soil conservation practices our best farmers are doing to ensure we have healthy soils for the next generations to farm.
- **Chapter Thirteen** brings us to the 'so what' of this book. Does it matter how we farm? Can't the earth and land just cleanse themselves as they have always done and keep giving us the gifts of food? Does the way we farm affect carbon and climate change? The answer to all these questions is 'Yes'. We leave you with some thoughts on who our next farmers will be and how land tenure and care look going into the future.
- **Chapter Fourteen** is about managing soils in urban settings and will be helpful to those new farmers reclaiming that land.

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1.3: Naturally-Made Soil

Before we consider what makes the 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. However, 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 nutrients, which allows soil to continue supporting life. Plant 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 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 1.3.1).

Figure 1.3.1: 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.*

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. 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 change in organic matter cycling. It caused more organic matter to be lost each year than was returned to the soil. In addition, a related break 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 over the millennium has been 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. However, the need to replace the organic matter (carbon) was mostly ignored until recently. The organic matter in the soil is more complex and plays many important roles in soils. 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 space 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*.

This book is a continuation of the story of how soil was formed, then farmed and 'mined' of its nutrients and organic matter. Only now are we understanding that to be sustainable for future generations we have to keep replenishing what we take from soil.

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1.4: Good Soil Characteristics

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 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 healthy soil than on poor, compacted soils. But there are other characteristics that we'd like soil to have. These can be condensed into seven desirable attributes of healthy soils:

1. **Fertility**. Soil should have a sufficient supply of nutrients throughout the growing season.
2. **Structure**. We want a soil with good tilth so 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 soil with sufficient depth before a compact soil layer or bedrock is reached.
4. **Drainage and aeration**. We want the 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 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, high-quality soil should resist being degraded. It should also be resilient, recovering quickly after unfavorable changes like compaction.

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.

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1.5: Balanced Soil

Approaching agriculture and garden 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, gardens and farms. Finally, we'll briefly discuss practices that contribute to creating vital and strong agricultural systems (discussed in more detail in later chapters).

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 beneficial insects 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.

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 above ground and below ground. 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, farm and garden 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 Systems

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 in turn fed upon by other organisms, which are themselves fed upon by others higher up the food web. Natural 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 Systems

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. Competition for resources and specific antagonisms (such as antibiotic production) from the multitude of soil organisms usually keep soilborne plant pathogens from causing diseases in a natural grassland or forest.

Self-Sufficient Systems

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 Systems

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 beneficial insects 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 beneficial insects, and suppress pests, thereby minimizing the extent of *reactive management* (which responds to unanticipated occurrences).** The discussion in the rest of this book focuses on ways to maintain soil health and enhance habitat in order to promote one or more of the three strategies listed above.

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1.6: Bread baskets

We've just reviewed what balanced, healthy soils look like. Where are these soils found? There are many regions around the world where climate and geology are very favorable and therefore fertile, balanced soils result from the natural weathering processes. See the map below.

In some regions, the soil is good but other factors prevent them from becoming bread baskets. Many areas are suitable for small farms but are not good for large-scale machinery because they are too steep, rocky, or wet. Some regions have fertile soil but they also have very high human populations and therefore don't export food to other countries. West Africa, India, and China are examples. Some regions, like the American West (Rockies), the interior of Asia (Himalayas), or the coast of South America (Andes) are too mountainous to farm easily. The northern and southern latitudes do not have long enough growing seasons to support much agriculture, but that is changing as our global climate changes. For example, we never used to grow soybeans on the 44th parallel but now it has warmed up just enough to grow them (newly bred varieties also help too).

Bread basket areas are precious resources, they have enough nutrients to feed their own regional populations, and also in many cases can export and feed the world. They are indicated by green on the map. The map is a composite of several crops, soy, corn, wheat, and rice, but it also adds sorghum and millet, which is why West Africa, China, and India look like bread baskets. White-colored map areas are either too mountainous, cold, or dry to support large-scale production agriculture.

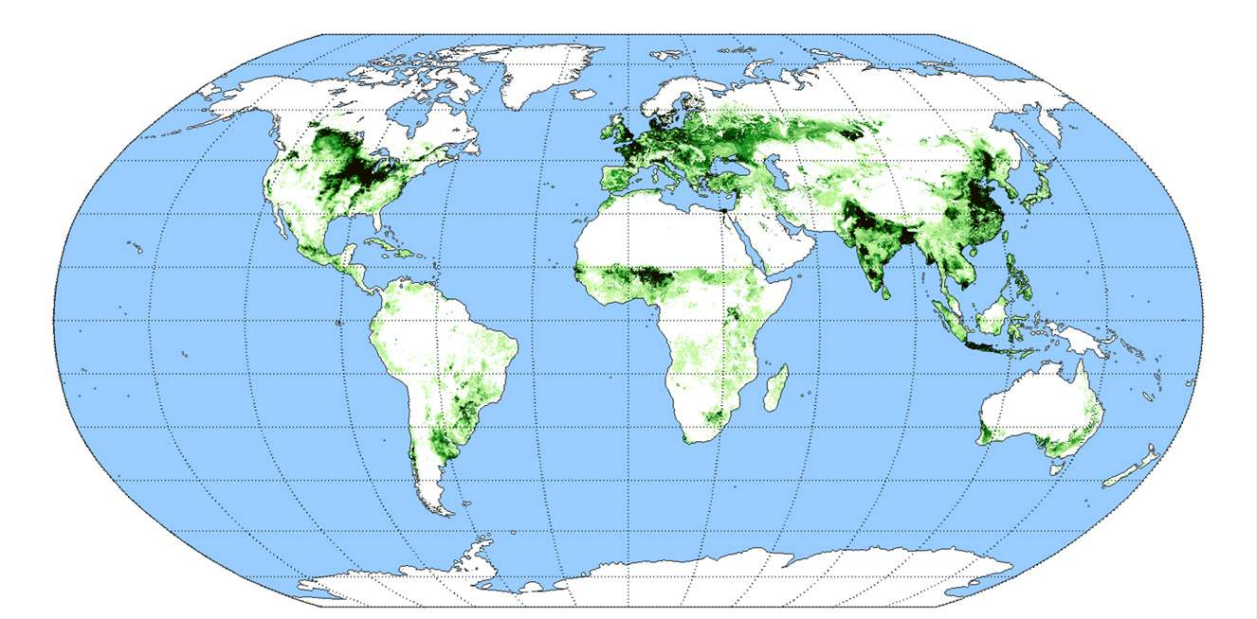

Figure 1.6.1: Composite cultivation world map of Rice, Wheat, Millet, Oats and Maize. Nithyan and Kota.

Another important reason lands with good soils don't grow a lot of food is because of moisture. Some areas, like deserts, never have enough moisture or rainfall to grow many crops. Some other areas that were once productive, like North Africa and the Middle East, used the land in ways that allowed the desert to spread, and now these areas can barely support their own populations. Central Africa and the Amazon Basin in South America have too much rain. Rain brings humidity, pests, and diseases that interfere with cropping systems.

Another factor in the 'moisture regime' is the timing of rains. Favorable global wind patterns must bring adequate rains during the growing season for crops to thrive. Some areas have wet and dry seasonal rainfall and farmers have learned how to work in those systems. The large bread basket regions of the world are the American Midwest, Argentinian and Brazilian pampas, Russia and Ukraine, Poland, and much of Europe. What do all the bread baskets have in common? They have winds that blow onto the land, not away from the land. That is a lucky accident of location.

Look at the map below. When the wind blows across the landscape, you will get rain. When it generally blows away from land, your climate will be dry. Most of our high-producing agricultural regions require, ideally, an inch of precipitation every week during the growing season. In the American Midwest, we get a convergence of air sweeping in across the western mountains and Canada meeting up with warm Gulf air full of moisture. Rain is the result, beautiful rain. Look at the Midwest United States, Brazil, Europe, China, Poland, Ukraine, and Eastern Russia; these are flat lands with enough moisture to feed resident populations and export to other countries. These are the areas we also need to pay attention to and farm responsibly. We have only been on some of these soils for about 100 years and they are already showing signs of wear and tear. Will they last another hundred years? Yes, but we must learn how to take care of these precious soils that have taken millennia to form.

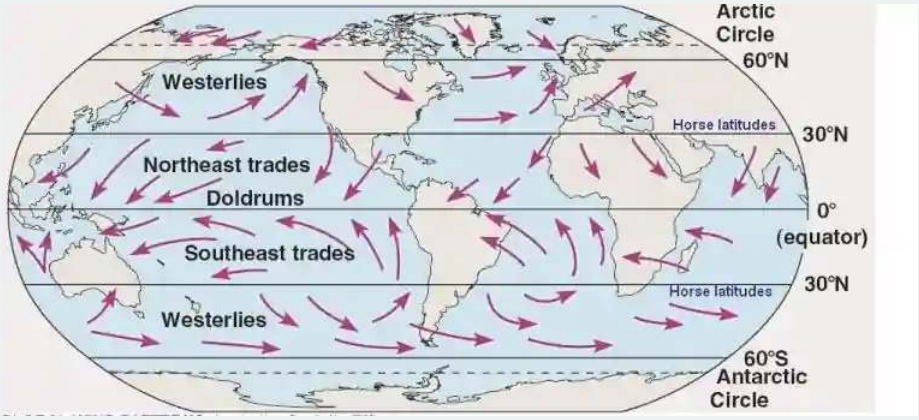

Figure 1.6.2: Global Wind Map.

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CHAPTER OVERVIEW

2: Physical Properties of Soil

2.1: Soil Physical Properties - Texture, Structure, Tilth

2.2: Water, Pore Space, Compaction

2.3: Soil Tilth

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2.1: Soil Physical Properties - Texture, Structure, Tilth

Why do we care about the physical properties of soil? Because these properties help determine how well a soil will grow good crops. Understanding our farm or garden soil texture and structure will help us make good decisions about how (or if) we can amend the soil to make it better, and at what cost. Soil's physical properties affect plant growth in many ways including:

1. Root penetration
2. Root aeration
3. Retention of nutrients, and
4. Water availability.

Soil's physical properties include its structure, texture, consistency (weight, pore space, and air), and color. The properties we will examine most closely are soil **structure and texture**. We will also define soil **tilth** and what that means for farmers and gardeners.

What is Soil's Physical Structure?

Soil's physical structure is important because if soil life cannot breathe and grow, it will die. The physical structure should be like a playground, a jungle gym for microbes, bugs, and plant roots so that they can move and wiggle and branch out and play hide and seek from predators. There should be equal parts open space for air and open space for water and the mineral scaffold of the monkey bars. The scaffold is delicate, almost lacy, almost as fragile as grapes. The scaffold of soil structure, like the bunch of grapes, is called an aggregate. We will look at structure again in more detail in a short bit after we define 'organic' soil and review what texture is.

Figure 2.1.1: The optimal soil structure is like a jungle gym or a bunch of grapes with open spaces. Images created by Microsoft Copilot, March 2025.

The physical nature of soil is intricately related to how soil behaves as a habitat for microorganisms. The better the structure, the better the habitat. Organic farmers want a lot of habitat.

Organic Soils (A Technical Definition)

There is a bit of confusion about what “organic” means. The name of the course I teach at Northeast Wisconsin Technical College is “Organic Soils, Nutrients, and Composting”. To be more precise, the course should have been named “Organically Managed Soils”. That is because there is another older, technical, definition of “organic” soil. This definition has nothing to do with whether or not synthetic chemicals or fertilizers have been used on the soil. Rather, it depends on how much decomposing carbon material (organic material) from plants is present in the soil. Mucks and peats are classic organic soils. Peat still contains some plant tissue structure (that is why it can be burned). Muck’s plant material is nearly completely decomposed. In these two true organic soils, peat and muck, plant material (organic matter) makes up about 20% of the weight soil, depending on how water-saturated the soil is. These soils are very thick and very deep. They store tremendous amounts of carbon.

For purposes of this book, however, unless specifically noted, “Organic soil” should be understood to mean “organically managed” soil, not muck or peat soils.

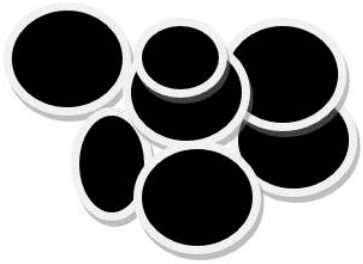
Soil texture

The texture of the soil is what we can feel when we rub the soil between our fingers. This depends on the size of the soil particles. The size of the particles in soils influences how productive the soil will be for growing plants. In mineral soils where the parent material is rock, there are three textures as seen in the table below.

Clay soils, because they have so many more tiny particles, have much, much more surface area than silt or sand. This large amount of surface area creates a huge reservoir of available area for nutrients and water films around each particle. Most soils are not ideal in texture. Areas that are very good for farming have a good balance of sand, silt, and clay. These loamy soils have good water-holding and nutrient-holding capabilities.

Figure 2.1.2: Soil aggregates from a dark clayey soil. Photo courtesy of Pepe Álvarez (Technical University of Cartagena, Spain).

Table 2.1.1. Soil textures. The dots are depictions of relative particle size, not actual size.

Sand	Silt	Clay
Large particles	Medium	Small
2.00-0.05 Size (millimeters)	0.05-0.002	0.002 and lower
		---------- clay particle size They are flat rather than rounded like silt or sand. When wetted, clay soils get slippery/sticky.
Water drains right through the large pores between particles. Sand is not weathered enough to release many nutrients.	The silt feels like powder and does not stick together well. It does contain mineral nutrients that are readily available to plants.	Clay mineral particles are so small they carry a slight charge that attracts water and nutrients in a film around each particle

In northeast Wisconsin, for example, we have some soil that contains relatively large amounts of clay. These soils stay wet longer than loams, and when they do dry out, they “shrink-bake” into a very hard surface. In some areas, the soils are very sandy (perhaps old lake shores). These soils do not hold water well at all. Farmers can plant sandy fields earlier in the spring because they dry out sooner than other soils, but by mid-summer, if the rainfall is scarce, then the moisture is gone and the plants will go dormant or die. When particles are larger than sand, and there are significant amounts of larger rock fragments, soils are said to be gravelly. Gravelly soils are typically not suitable for farming.

In our region, there are some small farms that had the misfortune of having all three types of soil running across their land in 'benches' or waves. It was impossible to farm these fields successfully because when the sandy areas were ready for planting, the wet areas were not. The wet areas did fine in dry conditions but the crops in sandy parts died. Consistent soil textures across a field help farmers manage them effectively.

Besides water-holding capacity, soil texture is important in the role of the nutrient reservoir. Nutrients will be discussed elsewhere, but the reader should be aware that soil texture is an important factor in relation to soil nutrients. Sand is the least “nutritious” soil and silt is a more fertile soil. Clay is actually a mineral formed by the recombination of weathered ions. It has a great amount of surface area and loads of nutrient ions.

Soil texture can be determined by several methods including the use of a hydrometer (a bulb) which floats in a standardized chemical solution. This texture test is performed in a laboratory. This is not a practical test for the average person. However, an average person can with some practice wet a small quantity of soil and ribbon it out between their fingers. Obviously, sandy soils cannot form a ribbon. Clays and silts do form ribbons with clay soils sticking together better than silt soils. If a child can make a clay pot out of the soil then the texture is definitely clay. If a ribbon feels gritty, then it is either a sandy clay loam or a sandy loam.

Texture Types

Various combinations of sand, silt, and clay form texture classes or types like those found on the triangle diagram. The ideal soil texture is classified as loam. A loamy soil has a combination of textures somewhere between 30-50% sand, 30-50% silt, and about 10-30% clay. A soil's textural class, such as 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 soil. Soil texture changes little over time, no matter how the soil is managed, although we can have success in small ways in gardens.

Soils are classified by how much sand, silt, or clay they contain. The texture triangles shown in the diagram are a commonly used way to depict soil classifications based on texture. In the first triangle, each colored line represents 33% of a texture, you can see how soil is classified as a clay loam if it has equal amounts of clay (green line), silt (red line), and sand (blue line).

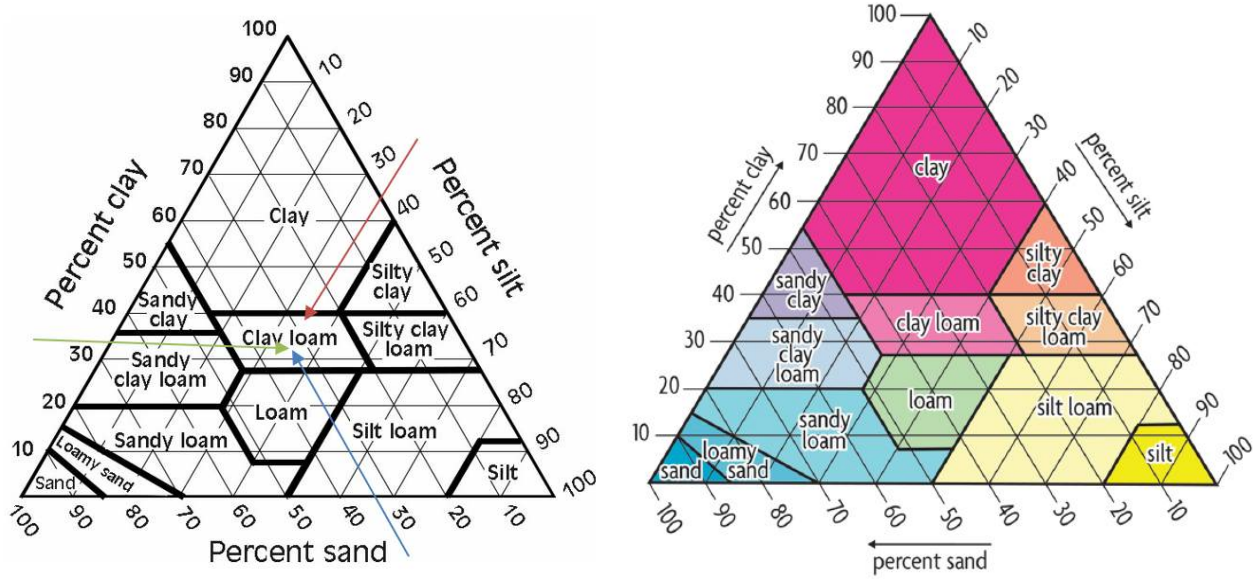


Figure 2.1.3. The percentages of sand, silt, and clay in the soil textural classes.

The textural class of soil (Figure 2.1.3) 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 Structure

Soil mineral 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).

Can a person improve soil texture to improve crop yields? Well, no.

Soil texture cannot be readily changed by farming practices. It is just a function of the parent rock material. There are some cases where sandy soils can be mixed with organic matter and improved to retain moisture and improve plant viability. Also, clay soils can be amended with a lot of work and expense (adding sand and organic matter). Both of these changes are impractical on a farm field scale of more than a couple of acres, but they do work on garden-scale fields. Increasing organic matter in all soil texture

types can improve the soil structure, but it cannot overcome the basic original soil texture. We increase organic matter through additions of compost and perennial plant roots to improve a soil's *structure* rather than its texture.

> *"Structure modifies the influence of texture with regard to water and air relationships and the ease of root penetration."*
>
> *– Henry Foth*

Figure 2.1.4: A loam-textured soil has a crumb-like structure. Photo AI generated by Google. March 2025

The pore sizes are affected not only by the relative amounts of sand, silt, and clay in the 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.

The clusters or aggregates or "peds" are described using various terms like; columnar, blocky, platy, crumb-like, or granular (Henry Foth). The terms are relatively descriptive. The preferred soil structure is crumb-like or granular mainly because the peds are roundish and don't fit snuggly together–and that is a good thing. This creates more pores. Platy or plate-like soils, on the other hand, are considered "tight" because of the flat, overlapping nature of the peds. We want soils light and airy, not dense and flat.

Sandy soils are considered to have no structure at all because each particle functions as its own ped since it is unattached to any other particle. If a clay loam is tilled or trampled when it is wet, the clay particles may slip down and form a layer of very fine particles. This is how plow layers form. When clay soil pores are collapsed, that soil is said to be puddled. Puddled soil or soils with plow layers are difficult to farm because when they dry out, they form huge peds (aggregates) called clods. I can walk my organic plowed fields in spring, but when I walk my neighbor's field that has been continuous corn or soybeans for 15 years, the clay sticks to my feet. His soil produces "cement feet"–the puddled clay sticks tightly to my shoes making it nearly impossible to continue walking.

> The physical nature of soil is intricately related to how soil behaves as a habitat for microorganisms. The better the structure, the better the habitat. And good farmers want a lot of habitat.

As previously mentioned, soil structure and how it forms aggregates can mitigate the influence of soil texture. Clay soils, if managed well, can form aggregates that are more favorable to pore space and therefore air exchange, root penetration, water retention, and nutrient cycling. Let me repeat this point, agricultural practices can influence soil structure by altering aggregation, sometimes for worse, but hopefully for better, as we will discover in further chapters. In organic agriculture, this is mostly accomplished by increasing the soil's biological activity. The gums and sticky substances produced by living organisms help particles aggregate and give soil better structure. Conversely, many conventional agricultural practices tend to cause soil structure to become less crumbly and more flat. Sandy soils amended with organic matter have improved structure.

Tilth

Good soil structure and till-ability are sometimes referred to as good soil **Tilth.**

To illustrate the idea that agricultural practices can affect soil structure, and thus crop yields, Foth cites studies showing that cropping systems that include a legume in rotation with corn create “marked increases in aggregation” over continuous annual cropping. Cover crops or continuous well-managed pastures can also be expected to increase aggregation because they reduce the impact of raindrops, which break soil aggregates apart. A University of Wisconsin study that has been measuring the impact of farming practices for the last 25 years on plots near Madison finds the same results.

Organic farming practices can improve crop yields because we improve soil structure and function.

> This point is an overlooked benefit of organic and sustainable agriculture…..the point that the way we farm, the tillage and cropping practices we use, can alone alter the nature of the physical properties of soils! Changing the physical structure of the soil aggregation quality will change our success as farmers and gardeners mostly because we increase the habitat for beneficial soil life.

Forget about the effects of synthetic fertilizers and herbicides, if we just tilled and rotated crops or used cover crops we can have a huge, beneficial impact on improving rather than degrading the quality of our soil. I’ll also repeat again, the **easiest way to change soil structure is to increase the biological activity of our soil fauna**. Increasing soil biology is exactly the opposite of the effect that conventional agriculture has. Organic and sustainable methods can have the same yields as conventional agriculture because we work to improve soil biology, thereby improving soil physical properties, and then plant growth – this is our alternative to adding synthetic fertilizers.

> *"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 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 the 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.

Soil usually contains about 50% solid particles on a volume basis, with the spaces in between, pores, accounting for the remaining volume. Most solid particles are minerals, and organic matter is a small, but very important, component of the soil. The soil’s mineral particles are a mixture of variously sized minerals that define its texture.

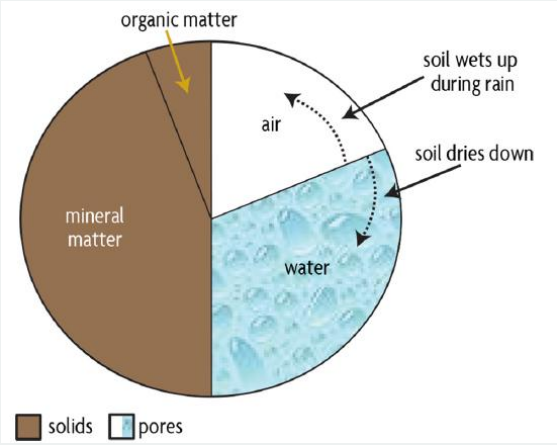


Figure 2.1.5: Distribution of solids and pores in soil.

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 or to reduce 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.

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2.2: Water, Pore Space, Compaction

Soil pore spaces are generally filled with water, air, and biota. Their relative amounts change as the soil wets and dries. 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 oxygen can't enter, leading to undesirable anaerobic (no oxygen) conditions. On the other extreme, soil with little water may have good gas exchange but may be unable to supply sufficient water to plants and soil organisms.

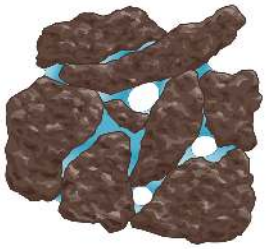

Figure 2.2.1. A moist sand with pores between grains that contain water and air. The larger pores have partially drained and allowed air entry, while the narrower ones are still filled with water. *Illustration by Vic Kulihin.*

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 because of closer contact with solids.

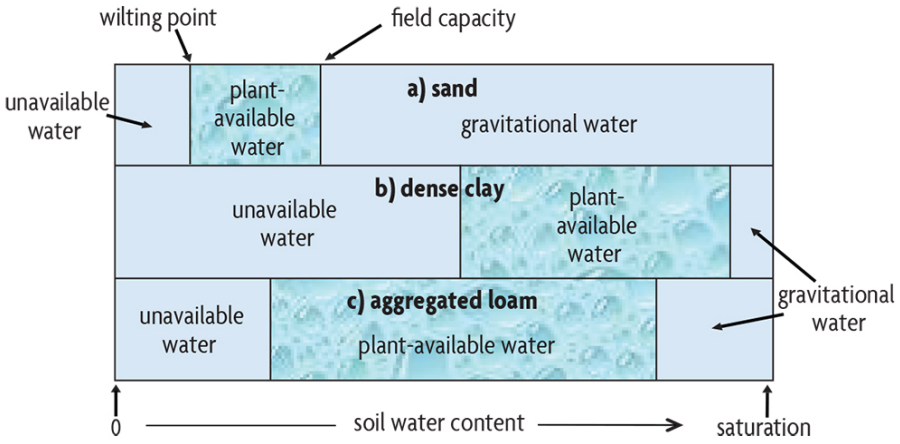

Figure 2.2.2. Water storage for three soils.

Soils are thus a lot like sponges in the way they hold and release water. 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 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.

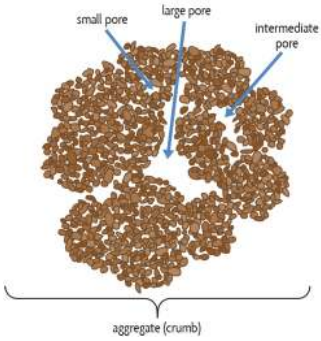

Figure 2.2.3. A well-aggregated soil has a range of pore sizes. This medium-sized soil crumb is made up of many smaller ones. Very large pores occur between the medium-sized aggregates. *Illustration by Vic Kulihin.*

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. 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.

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

Figure 2.2.4. Corn roots in compacted soil cannot access water and nutrients from most of the soil volume.

Figure 2.2.5. Dense rooting allows for full exploration of soil water and nutrients.

Figure 2.2.6. 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.

There is an additional dimension to the 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 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 are able to fully explore the soil volume with many roots, fine laterals, root hairs, and mycorrhizal fungi (not shown) allowing for better water and nutrient uptake.

Similarly, the depth of rooting can be limited by compaction. The figure shows 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.

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.

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2.3: Soil Tilth

We revisit soil tilth here to get a little more detail about what it means. We also want to explore how tillage and compaction affect tilth. All these concepts will come into play towards the end of the book as we uncover solutions to our soil problems. This chapter presents a basic understanding of how farm and garden operations affect soil tilth.

When the soil has a favorable physical condition for growing plants, it is said to have good *tilth*. Such soil is porous and allows water to enter easily, instead of running off the surface (Figure 2.3.1). 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 structure 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.

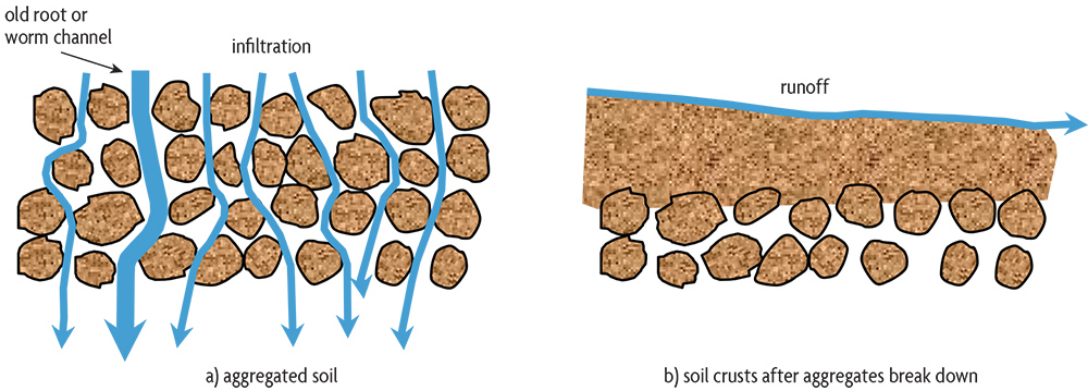

Figure 2.3.1: Changes in the soil surface and water-flow pattern when seals and crusts develop.

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. 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 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 good tilth. 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.

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

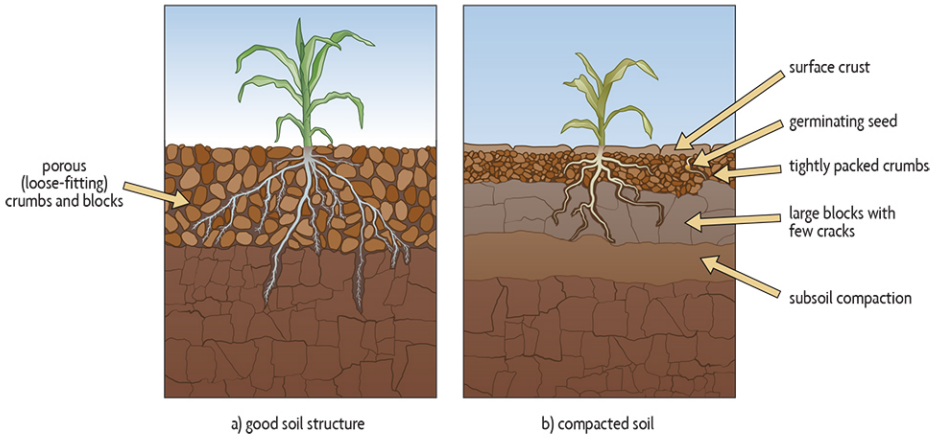

Figure 2.3.2: Plants growing in (a) soil with good tilth and (b) soil with all three types of compaction. Illustration by Vic Kulihin.

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 content, the soil may behave like a liquid because it has little internal cohesion. 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, the soil has somewhat more cohesion, but it can still be easily molded and is said to be *plastic*. Upon further drying, the soil will become *friable*: it will break apart rather than mold under pressure.

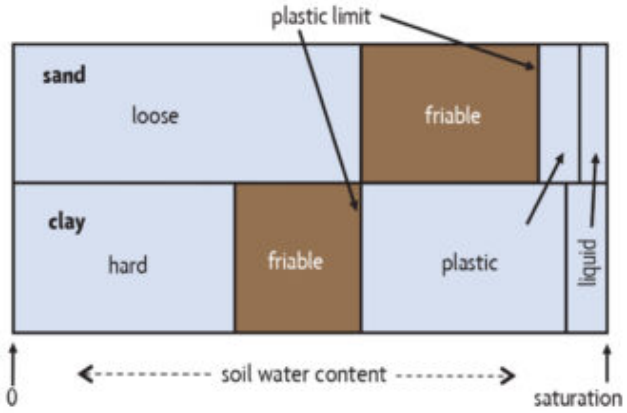

Figure 2.3.3: Soil consistency states for sand soil and for clay soil (friable soil is best for tillage).

The point between plastic and friable soil, the *plastic limit*, has important agricultural implications. When 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. 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 consistency is strongly affected by its texture. 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.

Figure 2.3.4: Deep tire ruts in a hay field following harvest when soil was wet and plastic.

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 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 compacted soil tills up very cloddy and then requires extensive secondary tillage and packing trips to create a satisfactory seedbed. 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 because few sturdy aggregates are present to prevent the soil from dispersing. The result may be 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. The 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 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. 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.

Check Before Tilling

To be sure that the 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.

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).

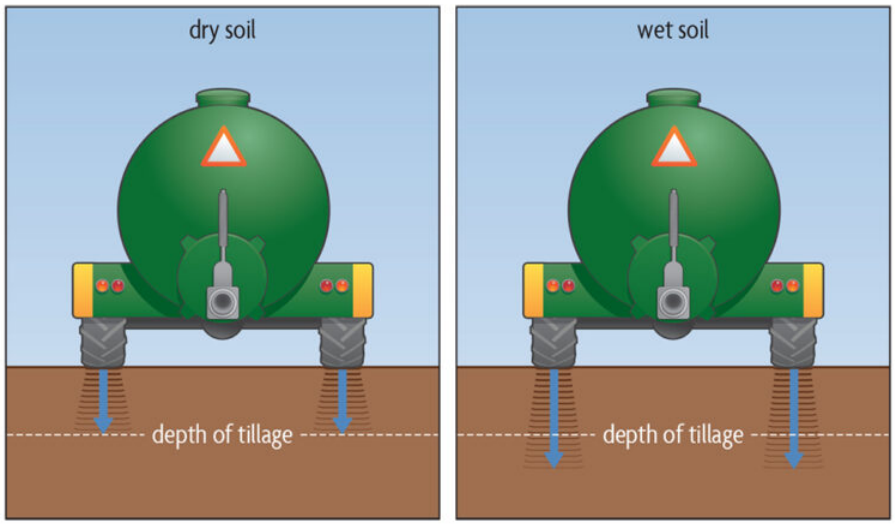

Figure 2.3.5: Forces of heavy tillage loads are transferred deep into the soil, especially when the soil is wet. Illustration by Vic Kulihin.

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.

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

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CHAPTER OVERVIEW

3: Soil Chemistry

3.1: Linking Physical Properties To Nutrient Availability
3.2: Soil pH and Liming
3.3: Relationship of pH to Nutrient Availability
3.4: Cation Exchange Capacity
3.5: Percent Base Saturation

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3.1: Linking Physical Properties To Nutrient Availability

There is just no way around soil chemistry. It is important to understand so you can connect the dots between:

Soil Physical Properties →	Soil Structure →	Nutrient Availability →	Nutrient Uptake →	Plant Growth
Texture: Sand, Silt, Clay →	Aggregates →	Nutrient Cations →	Uptake →	Plant Growth

Maybe we should not call it “chemistry” since that term can frighten some people. Here is a dictionary definition of chemistry that I prefer:

Definition: Chemistry

The transformation of matter - the structure, composition, properties, and reactive characteristics of substances, especially at the atomic and molecular levels.

I like the “alchemy” or transformation aspect in the definition, but that could also be difficult for some to understand.

A more relatable definition, also from a dictionary, gives a picture of the “chemistry” of love. In that sense, chemistry is “a spontaneous reaction between two people, especially a mutual sense of attraction or understanding.” Therefore, for our purposes here, think of chemistry as “attraction”.

If we think of chemistry in human terms, we see that we are talking about relationships and reactions between two things. In soil chemistry, we will be examining a few relationships too. We will look at changes, transformations, and shape-shifting of nutrients in soil depending on the conditions in the soil.

We will stick to three basic terms:

1. the pH of the soil
2. cation exchange capacity
3. base saturation

Once you understand these terms, you will begin to understand how soil works to either hold nutrients or release nutrients to the plants. Once you know that, you will know how to add nutrients as fertilizers or other soil amendments.

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3.2: Soil pH and Liming

pH

This term is pronounced simply like the two letters p and h. The lowercase “p” is actually a *mathematical symbol* for “inverse logarithm”. The capital H is the symbol for the molar concentration of **Hydrogen** ions in a liter of a liquid, like water.

There is an analogy made by Henry Foth that “the pH of a soil is like the temperature of an animal. Both tests are easily made and provide basic information useful in diagnosing what is likely to be the disease or the problem”. I go further and suggest that knowing a soil’s pH, C.E.C, and % base saturation are all tools used by the organic and sustainable agriculturalist to manage soils well, apply nutrients conscientiously, and increase the health of soils and the bottom line of the farm or garden. It is important to know about soil pH because it affects all the nutrients in the soil and how well the plant can use them or take them up.

If you remember high school chemistry, water is made up of two **H**ydrogen atoms and one **O**xygen atom. Because of this, water is commonly known as H_2O. It is also depicted as H--O--H where the “--“dashes are weak (ionic) bonds that hold the whole water molecule together.

pH in Soil Solutions

In almost all solutions, some water molecules break apart and result in ions of hydrogen floating around footloose and free. These are atoms that have a slight electrical charge because one of the hydrogen ions has generously lent an electron (it has a little negative or minus sign charge) to the other hydrogen ion so that it could stay bonded with the Oxygen atom. Now the arrangement looks like this: OH- is now separate from an H+

The **H+ is called a hydrogen ion**. (Occasionally, it is referred to as a proton)

The **OH- is called a hydroxyl ion**. The name tells you exactly what it is; **hydro**gen and **oxy**gen = hydro-oxy ion.

> When the pH of a soil solution is 7, it means that equal numbers of OH- (hydroxyl) and H+ (hydrogen) ions are present. This is a neutral solution. Specifically, there is one hydrogen ion (H+) in every 10,000,000 (ten million) moles per liter of water (note the seven zeroes). There is also one hydroxyl ion (OH-) in every 10,000,000 moles per liter of water. This is considered pure or neutral water.
>
> A pH of 6 means there are 10 times more hydrogen (H+) ions than a pH of 7 (one in every 1,000,000) (note the six zeros). There are also, then 10 times fewer OH- (hydroxyl) ions in this solution. This is called an “acidic” solution. **Whenever there are more H+s than OH-s, then the solution is acidic**.
>
> A pH of 8 is just the opposite; it means there are 10x more OH- ions than a neutral state and 10x fewer H+ ions. There is only one H+ in every 100,000,000 moles/liter (note 8 zeros). This is considered a “base” solution. **Whenever there are more OH-s than H+s in a solution, it is considered “basic”.**

When there is a pH of 9 there would be one H+ ion in a solution with nine zeros.

? Exercise

If the pH is 5, how many zeros follow the 1 in the number of moles/liter of water?

Answer

5. There is one H+ for every 100,000 moles/litter of water in a pH 5 solution.

Cations

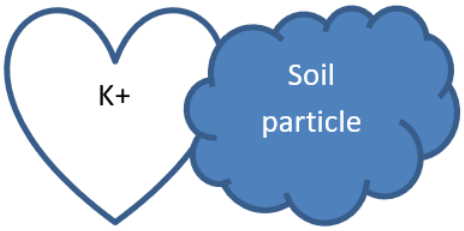
What does it matter if there are a lot of H+ ions in a soil solution compared to OH- ions?

The range of soil pH is usually 4 to 10 (the entire scale goes from 0 to 14). In the United States, farm regions' soils are typically in the 5.5 to 8.5 range. A pH between 6.0 and 6.8 is considered ideal for most crops. At this slightly acidic pH, there are enough free nutrient cations in the solution on which the plant can feed.

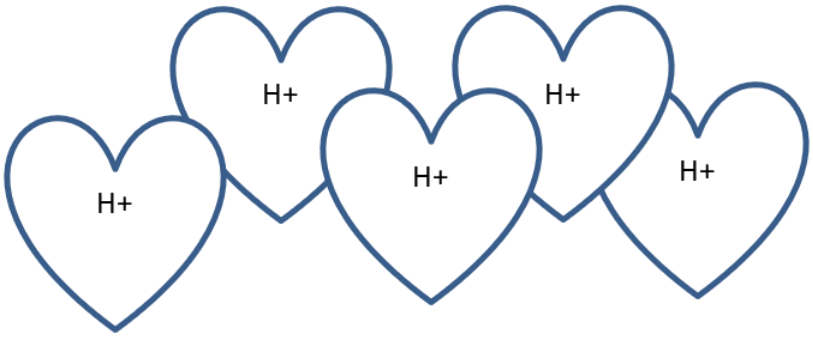
What is a cation (pronounced as cat – eye – on)?

Cations are ions that carry a positive charge, just like the hydrogen ion (H+). The typical nutrient cations needed by the plant are calcium (Ca ++), magnesium (Mg ++), and potassium (K+).

In acidic soils, for those with lots of H+ ions, the hydrogen ion may replace the other positively charged nutrient ions on the soil particle surfaces. This means the positively charged nutrient ions (cations) are bumped off the soil particle and are floating around, free, in the soil solution, ready to be absorbed by the plant cells. This is explained below.

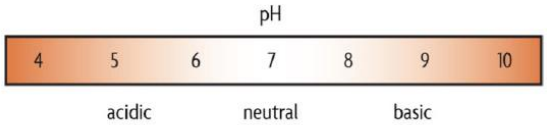


To help explain this better, look at chemistry in terms of relationships. In the illustration above, the soil particle is perfectly happy in its relationship with potassium (K). There are a few H+ ions floating around the water film surrounding the soil particle, but the soil does not notice and is not interested. Then, the soil becomes a bit more acidic, meaning there are significantly more H+ ions flirting with the soil. The soil just cannot keep its eyes off all those handsome H+ ions. Finally, the soil lets go of K+ and instead bonds with an H+. A sad, but true story. But there is a happy ending. Now K+ is free to fulfill its true purpose; K+ is taken up by a plant root to become used as a nutrient. Just think, if the soil had not been slightly acidic, the K+ would have remained unavailable to the plant.



A soil with a pH of 6.9 is like soil with hardly any free H+ ions floating around. But a soil with a pH of 6.5 has significantly more H+ ions that attract the attention of the soil particle and prompt it to let go of its bond with the cation ion it is currently dating. Everyone is happy in the end, the plant gets the cation and the soil gets its hydrogen ion.

Soil Acidity Background



Note: Soils at pH 7.5 to 8 frequently contain fine particles of lime (calcium carbonate).Soils above pH 8.5 to 9 usually have excess sodium (sodic, also called alkali, soils).

Figure 3.2.2: Soil pH and acid-base status.

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. The 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 addition, the most

commonly used N fertilizers acidify soil as their ammonium is either converted to nitrate or 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. 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 3.2.2 for common soil pH levels). 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

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 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. 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 is needed.

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 is easy to correct. Therefore, in no-till fields, it is 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.

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. However, the pH value does not 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 is 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. 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.

Note

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.

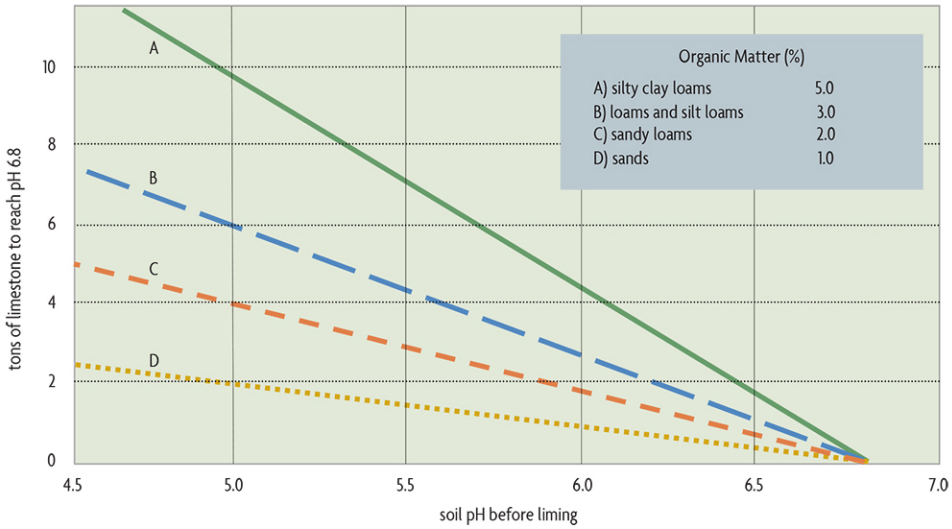


Figure 3.2.3: Examples of approximate lime needed to reach pH 6.8. Modified from Peech (1961).

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 provide other benefits to soil. 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 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 above, 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.

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3.3: Relationship of pH to Nutrient Availability

There are many charts that show the relationship of nutrient availability to the pH of soils. The picture below illustrates more acid pH < 7.0 on the left and more basic pH > 7.0 on the right.

The availability of an element is depicted by the width of the black band. The narrower the band, the less available the element is at a given pH.

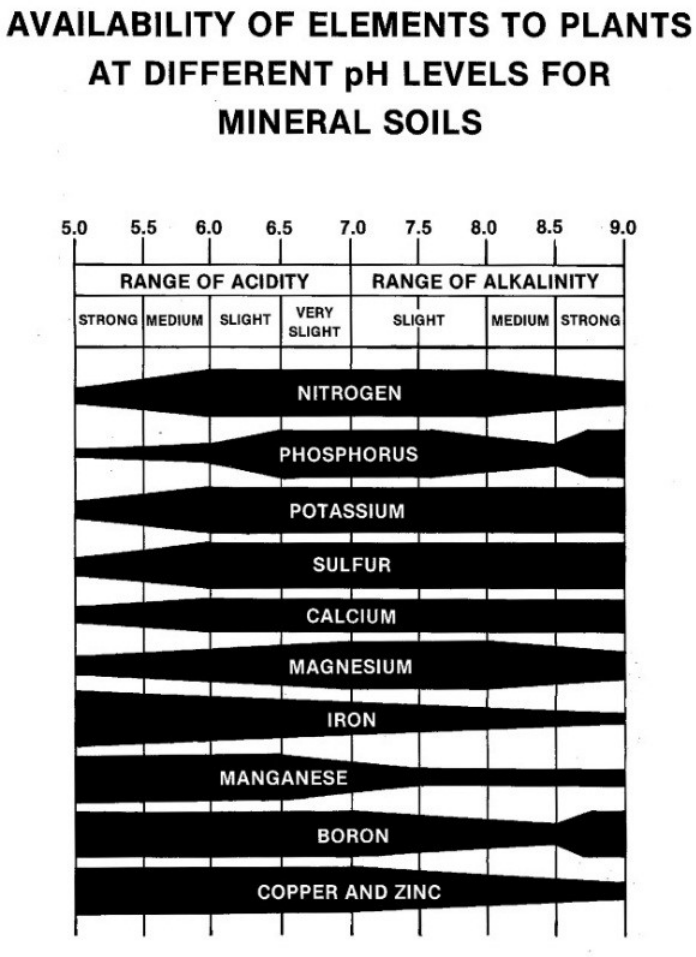

Figure 3.3.1: Availability of elements to plants at different pH levels for mineral soils.

Nitrogen has good availability at a pH down to about 6.0 on the acid (left) and up to about 8.0 (right). Notice how Phosphorus is most available between 6.5 and 7.5. Look at how iron and manganese become unavailable at a pH much above a neutral 7.0. Again, this has to do with the chemistry and attraction of H+ and OH- ions to particular atoms and nutrient compounds.

The pH of a soil also has biological effects. Some soil organisms thrive at lower pH than others. Fungi, for example, “prefer” more acid soils than bacteria. More about that when we talk about soil biology.

The soil tests, liming and nutrient levels, and fertilizers for good crops will be explored in a later chapter. This chapter reviewed some of the “chemistry” background needed as a foundation for exploring nutrients and fertilizers.

These soil chemistry concepts apply to conventional, sustainable, and organic fields and soils. However, because organic farmers need to use their brains and their knowledge to replace synthetic fertilizers, it is especially important to learn these concepts in an organic management system.

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3.4: Cation Exchange Capacity

CEC

This stands for Cation Exchange Capacity. Cation is pronounced CAT-EYE-0N. A **cation** is a positively charged element. We are specifically interested in cation elements that are plant nutrients: Calcium (Ca++), Potassium (K+), and Magnesium (Mg ++).

Exchange Capacity tells us how many spaces or sites there are in soil where exchanges can take place. Soil with a high CEC has a lot of exchange sites while soil with a low CEC does not have much capacity or ability to exchange cations.

CEC is a measurement that tells us whether or not a particular soil has few or many sites or spaces that can exchange, catch, hold, and release nutrients. The CEC tells us if the cations can readily **exchange** places with hydrogen ions and become available for absorption by the plant. A soil with high CEC is potentially quite good soil for growing crops compared to a soil with low CEC This value cannot be readily changed; it is a function of the soil's parent material and texture.

A soil's CEC can be compared to a bank. A large bank has a lot of money available for exchange. Some is in the vault, locked away, and some is in circulation. Similarly, soils with C.E.C's measuring 20 (milliequivalents/100grams) have a larger reserve of cation sites (or vault space) than soils with a CEC of 10 meq/100g. The units of measure are a bit too complex to go into here, but it can be said that high CEC soils can hold perhaps thousands of pounds of cation nutrients per acre at any given time.

The CEC depends on the soil's physical properties (its texture) and on the amount of organic matter present. As discussed previously, soils with fine textures like clay have a lot of surface area compared to sandy soils. They have a large "vault". Clays hold nutrients better than sandy soils. Sandy soils need to be fertilized more often because any free cations not taken up by the plant are readily leached, or washed, out of the soil by rainfall. Nitrates are positively charged nitrogen molecules that cause problems on sandy soils, leaching through them and into rural well water, for example.

Sometimes clay soils hold the nutrient ions too tightly, they do not let enough cations out of the vault and out into circulation. When this happens there may be plenty of calcium for example in the soil bank, but not enough in circulation to feed the plant. This is where pH comes into the picture and, as we'll read in the next section, % Base Saturation. When pH is slightly acidic, plenty of H+ ions are available to bump cations off clay sites and they are put into soil-water solution and thus become available to the plant.

All things being equal, sandy soils typically have C.E.C s of less than 5 meq/100g, and heavy clays have CEC s over 20. Silt loams have more desirable CECs in between.

Sand	Silt Loam (meq/100g)	Heavy Clay
<5	In between	>20

Caption Exchange Capacity Management

The CEC in soils is due to well-humified ("very dead") organic matter and clay minerals. The total CEC in the 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 other chapters.
- If the soil is too acidic, use lime (see "pH Management") 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 the CEC determined at a higher pH.

Estimating Organic Matter's Contribution To A Soil's CEC

The CEC of 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

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).

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3.5: Percent Base Saturation

Percent Base Saturation

The Percent Base Saturation is a measure of how much of the CEC is filled up, or saturated. It measures what % of the available sites are full, either with a H+ or a nutrient cation.

> The term “base” saturation is somewhat confusing because bases are technically molecules that have a negative charge so that they can accept a proton with a + positive charge. It turns out that the cations mentioned above, Ca++, Mg++ , K+ as well as sodium (Na++) all are associated with compound molecules in the soil, for example, $CaCO_3$ (calcium carbonate), Mg CO_3, K CO_3 and Na CO_3 . Each of these compounds acts slightly more negative (-) “basic” than positive (+) “acid”. So, they act as “bases” in this saturation measurement.

There are ideal levels of each nutrient saturating the soil particle (CEC) sites to produce the best plant growth. Returning to the bank analogy, pretend we can have $100,000 in total in the bank (the CEC). In order to have the highest levels of productive economic activity, experts have determined that we should have the money in the following denominations: $1.00 bills = 70-80%; $10 bills = 12-15%; and $100 bills = 3-5%.

Similarly, experts have determined that the plant nutrient requirements for an ideal soil will have the following saturation levels in its nutrient bank (CEC) in the following ratios:

- Calcium base compounds occupy 70-80% of the soil bank,
- Magnesium base compounds occupy 12-15% of the soil bank,
- Potassium (K) base compounds occupy 3-5% of the soil bank,
- Sodium (Na) base compounds occupy 0% of the soil bank.

Ca	Mg	K	Na
$1.00 bank bills	$10.00 bank bills	$100.00 bank bills	pennies
(Georges)	(Alexanders)	(Benjamin’s)	(person's face on the denomination)
Ca compounds	Mg base compounds	K base compounds	Na (sodium) compounds
70 - 80%	12% - 15%	3% - 5%	0 %
55 – 60%	**25 - 40 %**	**5 - 8%**	**Most typical soils**

Unfortunately, these are not the % base saturation levels found in most soils in the temperate climate of the United States. More typically, levels of base saturation are a bit too high in potassium, moderately too high in magnesium, and moderately too low in calcium. This means that the plant may be getting adequate nutrients, but it could, if the base saturation numbers were improved, get great levels of just the right nutrients to produce a bumper crop.

Sometimes, the total of base compounds does not reach 100% saturation. In other words, our bank may have enough room for $100,000 in total currency, but only $75,000 dollars are available. The economy is only using 75% of its “power”. Likewise, we may only see 60% Ca compounds, 25% Mg compounds, and 5% K compounds. This only adds up to 90% base saturation when we could have had 100% under the right conditions. An extra 10% of nutrients would have helped our crops grow that much better.

There is a strong relationship between pH and % base saturation. If the % base saturation is less than 100% (like the 90% in the example above) then increasing the pH can increase the amount of calcium and magnesium in the soil solution and the amount of base compounds saturating the sites.

This is good news because according to Henry Foth “many studies have been conducted that relate increases in plant growth with increases in the percentage of calcium in plants and with increasing pH or % base saturation”.

There is a strong, continuing debate between University researchers and the organic and sustainable farm community on calcium and whether it is a nutrient that limits plant growth because of its availability. It has yet to be resolved; the university says that calcium is not a limiting factor while farmers claim they have good results when balancing their soil calcium levels with pH and magnesium levels. This debate will likely go on for a few more years until soils, CEC, and % base saturation are better understood.

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CHAPTER OVERVIEW

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  - 4.1.2: Organic Matter And Natural Cycles
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4.1: What is Organic Matter?

> *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*

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

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. 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 a 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 resists

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

Identifiable fragments of un-decomposed 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 they are 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-sized 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.

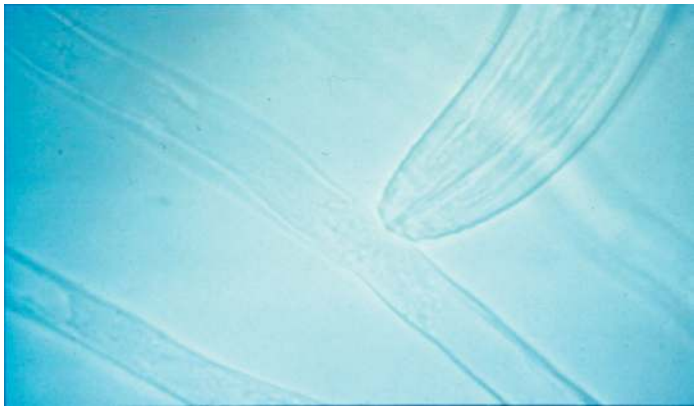

Figure 4.1.1: A nematode feeds on a fungus, part of a living system of checks and balances. *Photo by Harold Jensen.*

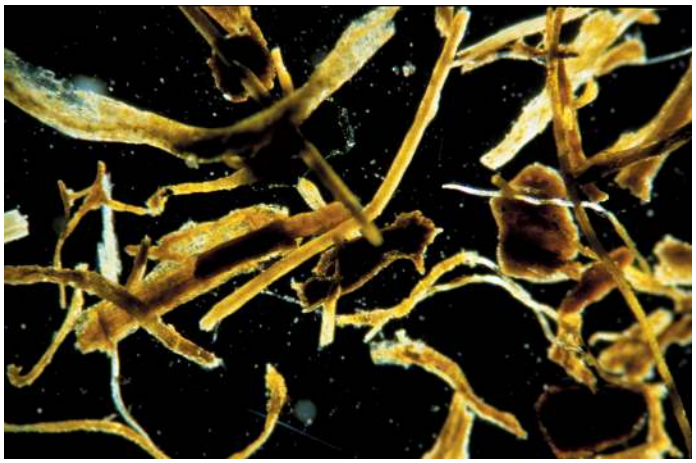

Figure 4.1.2: Partially decomposed fresh residues removed from the soil. Fragments of stems, roots, and fungal hyphae are all readily used by soil organisms.

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 a relatively high cation exchange capacity and supports biological activity by providing a 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 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 seed. Also, benefits from adding biochar should be considered 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.

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.

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 the 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.

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4.1.1: Why Soil Organic Matter is So Important

A fertile and healthy soil is the basis for healthy plants, animals, and humans. Soil organic matter is the very foundation for healthy and productive soils. Understanding the role of organic matter in maintaining 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 so much of the book to discussing 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 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 several global and regional cycles.

In this section of the book, we give you a lot of terms and concepts. It is probably the first time you are learning this vocabulary and coming across these soil principles. We will fully explain more concepts as we work our way through the book. We will start with an introduction through the lens of organic matter, exploring cation exchange and soil microbiology.

You can indeed grow plants on soils with little organic matter. 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. 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–volume ratio means that the 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.

On Full Circle Organic Farm, which practices managed grazing, soil organic matter values are about 3.5%. Other regional farms that have cropped corn and soybeans annually for 25 years have lost organic matter and now have levels of only 1.5%. Corn yields on the organic farm match yields on the conventional farms while using only 1/3 of the nitrogen fertilizer. This is due to the extra boost in soil health and available nitrogen in the extra 2% organic matter in the soil.

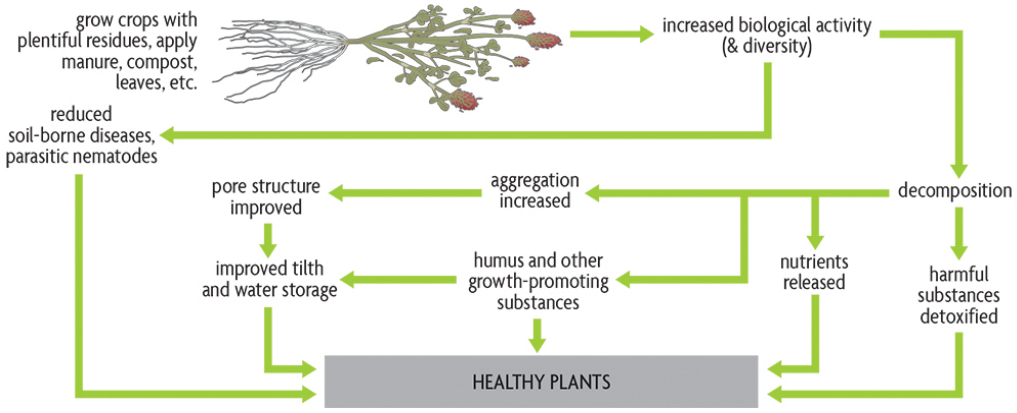

Figure 4.1.1.1: Adding organic matter results in many changes. Modified from Oshins and Drinkwater (1999).

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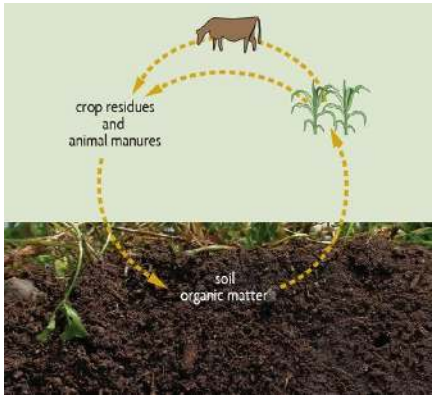

Figure 4.1.1.2: The cycle of plant nutrients.

Plants need 17 chemical elements for their growth (these will be discussed in later chapters). For now, understand that 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.

Nutrients from Decomposing Organic Matter

Most of the nutrients in soil organic matter cannot 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, as well as most of the micronutrients. This release of nutrients from organic matter by mineralization is part of a larger agricultural nutrient cycle. Mineralization is a very important concept as we discuss the form nutrients must be in so that they can be taken into the plants via root hairs.

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.

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^{++}). 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.

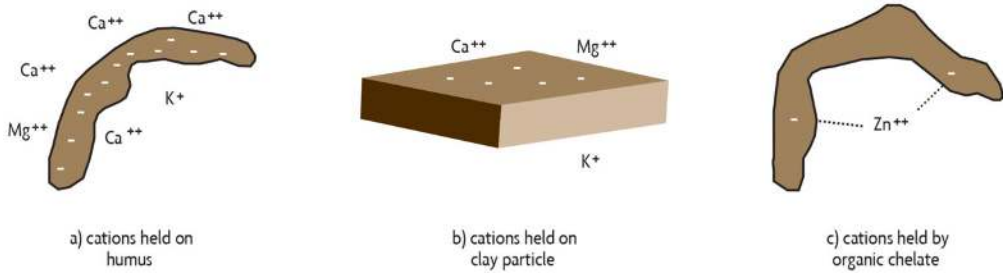

Figure 4.1.1.3: Cations held on negatively charged organic matter and clay.

Clay particles also have negative charges on their surfaces, 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 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. 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 sub-soils 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 several 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.

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
2. their relative populations (referred to as evenness).

It is 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 do not just want a small population of beneficial organisms present; the soil is biologically richer if there is also a moderate population of beneficial organisms. Good populations of diverse organisms help ensure that fewer potentially harmful organisms will be able to develop sufficient numbers to reduce crop yields.

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 cannot infiltrate into the soil runs off the field, carrying away valuable topsoil.

Protection of the Soil Against Rapid Changes in Acidity

Figure 4.1.1.4: 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 is grown in nutrient solution with (right) and without (left) chelating agents (extracted from the soil). *Photo by R. Bartlett*

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 soil at pH 4 is very acidic and its solution is 10 times more acidic than 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 acidic 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 out of solution as acids are produced or by giving off hydrogen as bases are produced.

Stimulation of Root Development

Humic substances in soil may stimulate root growth and development by both increasing the availability of micronutrients and by changing the expression of a number of genes. 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 the 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.

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.

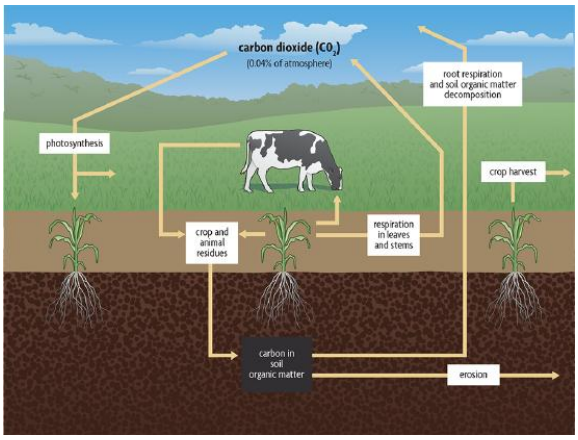

Figure 4.1.1.5: The role of soil organic matter in the carbon cycle. Illustration by Vic Kulihin.

Organic matter is the single most important soil property that reduces pesticide leaching. It holds tightly onto a number of pesticides. This prevents or reduces the 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.

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4.1.2: 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.

In the natural carbon cycle (that leaves out industrial sources) 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 into the atmosphere when fuels, such as gas, oil, coal, and wood are burned.

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.

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, 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 the soil through the rapid depletion of soil organic matter following the conversion of forests to agricultural practices. There is as much carbon in seven inches of soil with 1% organic matter as there is in the atmosphere above a field. If organic matter 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.)

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 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 in 2020, 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* (this link opens a new window).

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 4.1.2.1shows 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 percent organic matter in 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. We will revisit the Nitrogen cycle again, but in this section the focus is on its role in organic matter.

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.

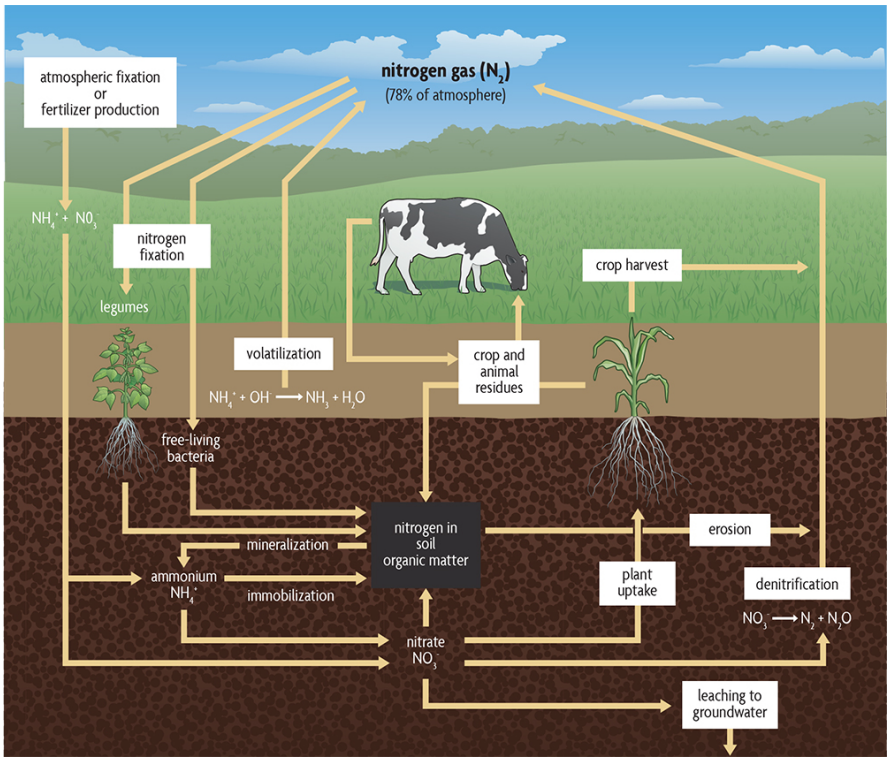

Figure 4.1.2.1: The role of organic matter in the nitrogen cycle. Illustration by Vic Kulihin.

Losses

Nitrogen can be lost from 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 un-composted 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 need 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 the storage of water in the soil. When we look at the increasing 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.

Note

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 of 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 of 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.

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4.1.3: 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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4.2: 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. However, 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 soil is the result of all the additions and losses of organic materials that have occurred over the years. In this section, we 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 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.

Figure 4.2.1: Additions and losses of organic matter from soils.

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

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.

If additions are greater than losses, organic matter increases, which happens naturally when soils are formed over many years. When additions are less than losses, there is a depletion of soil organic matter, which generally happens when soils are put into crop production. Think of plowing as a practice that 'burns' the organic matter out of the soil. When the system is in balance and additions equal losses, the quantity of soil organic matter doesn't change over the years.

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4.2.1: Natural Factors Affecting Soil Organic Matter

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. However, 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

The 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

Figure 4.2.1.1: 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.*

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 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. 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 immediately below typically contain less than 2% organic matter.

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.

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 the 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.

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4.2.2: 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. 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 4.2.2.1, indicate that erosion greatly affects both organic matter levels and water-holding ability. Greater amounts of erosion decreased the organic matter content of these 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 the soil, accelerated mineralization of organic matter because of plowing, and erosion.

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.

Table 4.2.2.1: Effects of Erosion on Soil Organic Matter and Water

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

Source: Schertz et al. (1985)

The more 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 allows 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 a 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

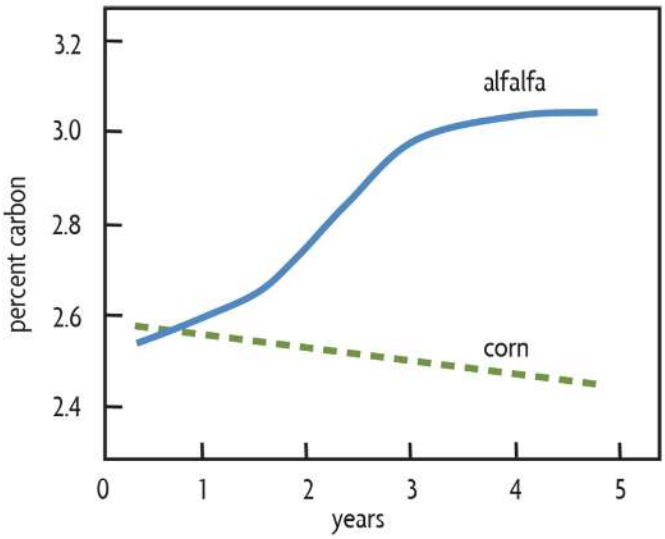

Figure 4.2.2.1: Organic carbon changes when growing corn silage or alfalfa. Redrawn from Angers (1992).

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. 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. 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.

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 the 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 the soil. However, 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.

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 were 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.

Figure 4.2.2.2: Soil surface after harvest of corn silage or corn grain. *Photos by Bill Jokela and Doug Karlen.*

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4.2.3: Organic Matter Distribution Within Soil

Depth

In general, more organic matter is present near the surface than deeper in the soil. 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. 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.

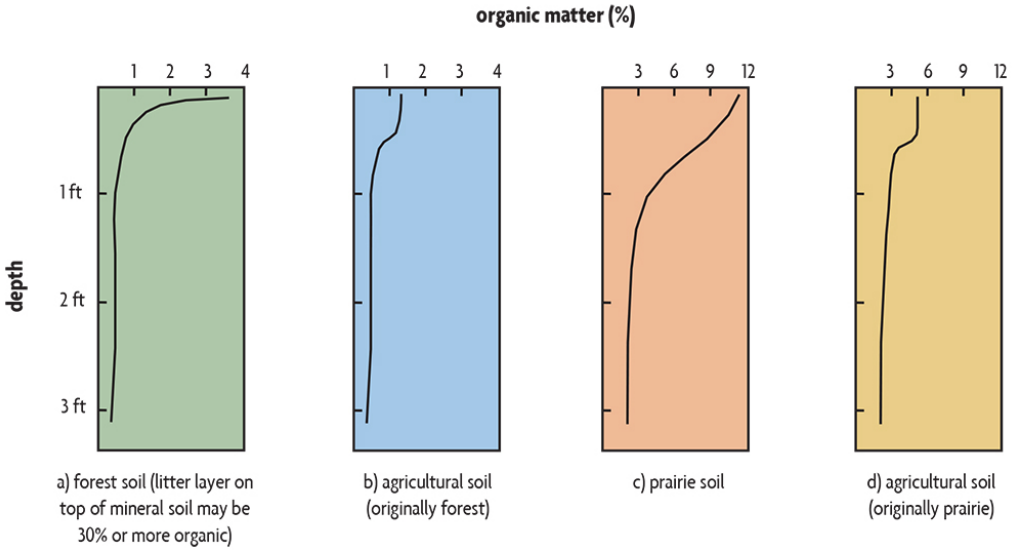

Figure 4.2.3.1: Examples of soil organic matter content with depth (note different scales for forest and prairie soils). Modified from Brady and Weil (2008).

Litter layers that commonly develop on the surface of forest soils may have very high organic matter contents. Plowing forest soils after the removal of the trees incorporates the litter layers into the mineral soil. The incorporated litter decomposes rapidly, and an agricultural soil derived from sandy forest soil in the North or a silt loam in the South would likely have a distribution of organic matter. Soils of the tall-grass prairies have a deeper distribution of organic matter. After cultivation of these soils for 50 years, far less organic matter remains. 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 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, soil with 50% clay may need twice as much organic matter as soil with 10% clay.

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4.2.4: 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 4.2.4.1). 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 4.2.4.1: 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.

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4.2.5: Amounts of Living Organic Matter

In future chapters, we will discuss the various types of organisms that live in soils. Here, we want to emphasize how much of two kinds of soil organisms are present in different general 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. 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 millimeters (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. For this reason, **agriculturally tilled soils have more bacteria** than fungi. This has implications for the soil food web, as you will read in Chapter 10.

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 the 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 large spaces in which to live.

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4.2.6: 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 sandy soil is very good and difficult to reach, but in clay soil, 2% indicates a greatly depleted situation. The complexity of soil organic matter composition, including the 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 on 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 clay 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 importantly, 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.

> *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*

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4.2.7: 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 from 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 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. However, 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 4.2.7.1). 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 4.2.7.1).

Table 4.2.7.1: 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

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4.2.8: 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 the 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.

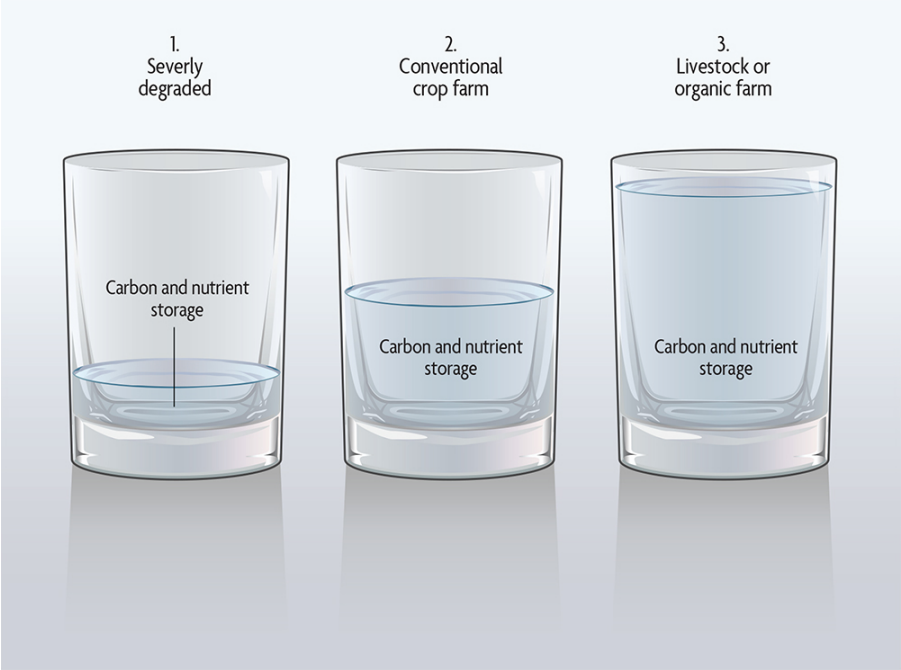

Figure 4.2.8.1: Soil organic matter (carbon) levels vary in different soils and cropping systems, analogous to glasses filled with variable amounts of water. *Illustration by Vic Kulihin.*

Starting Point

It is good to consider the soil's current status when you build up organic matter in the soil. A useful analogy is the three glasses of water in Figure 4.2.8.1that 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, you may imagine a larger glass for fine soil than a coarse soil, and the fullness of the glass is similarly proportional.

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 of 6

inches weighs about 2 million pounds. One percent of 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.

Adding Organic Matter

When you change practices on a soil depleted in organic matter, perhaps one that has been intensively row-cropped for years and has lost a lot of its original aggregation, organic matter will increase slowly, as diagrammed in Figure 4.2.8.2 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 free particles of organic matter, they tend to decompose relatively rapidly under normal (oxidized) conditions.

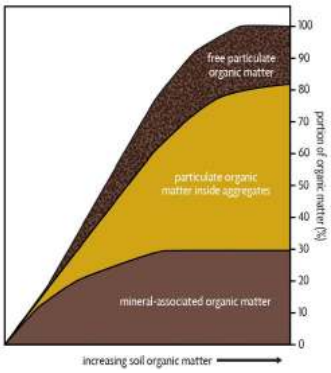

Figure 4.2.8.2: Organic matter changes in the soil as practices favoring buildup are implemented. Redrawn and modified from Angers (1992).

The reverse of what is depicted in Figure 4.2.8.2 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, the estimated percent of organic matter in soils for various combinations of addition and decomposition rates indicates some dramatic differences (Table 4.2.8.1). 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.

Table 4.2.8.1: 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 organic material additions**	**Added to soil if 20% remains after one year**	**Annual rate of organic matter decomposition**				
		1%	2%	3%	4%	5%
----pounds per acre per year----		---equilibrium % organic matter in soil ---				
2,500 5,000 7,500 10,000	500 1,000 1,500 2,000	2.5 5 7.5 10	1.3 2.5 3.8 5	0.8 1.7 2.5 3.3	0.6 1.3 1.9 2.5	0.5 1 1.5 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.

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, mean that it usually takes years to detect changes in the total amount of organic matter in soil.

In addition to the final amount of organic matter in soil, the same simple equation used to calculate the information in (Table 4.2.8.1) 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 4.2.8.3). 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 4.2.8.3).

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 4.2.8.3), 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 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.

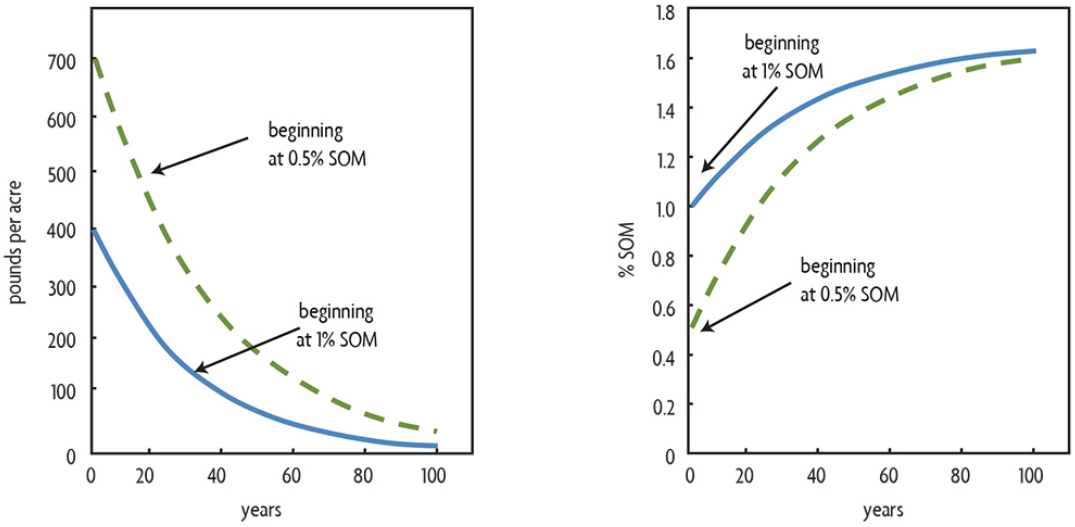

Figure 4.2.8.3: Net organic matter additions and changes in % organic matter content for soils. Estimated for soil starts at 0.5% or 1% organic matter, receiving a total of 5,000 pounds of residue per acre per year; 20% remains after one year, and soil organic matter decomposes at the rate of 3% a year.

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).

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4.3: Amendments - Physical Fixes

> *A soil amendment is not a fertilizer – at least not in my book - Valerie Dantoin.*

Amendments basically amend, change, and correct things–for the better. They usually have an effect on a soil's physical structure or biology.

One can argue that fertilizers change things for the better–but not in the sense of actually changing the soil quality itself. A fertilizer's primary “job” is to add nutrients to the system that will be taken up by the plant, while an amendment’s job is to alter the physical, biological, chemical, or structural nature of the soil. This in turn will increase nutrient availability for the crop or plant. A later chapter is devoted to fertilizers.

This is why I think of compost as an amendment rather than a fertilizer. Compost primarily changes soil by adding organic matter, microbial life, and humic acids rather than NPK nutrients. A compost-amended soil is a higher quality soil than it was before the amendment. Therefore, when a person does add fertilizers to soil with compost, the response may be more amplified than if fertilizing unchanged soil.

There are many books and articles that examine organic soil amendments. There are workshops and conferences devoted to the topic, but in my opinion, they get amendments confused with fertilizers. They also confuse “organic” with “carbon-based”. Most amendments are organic in the sense of using carbon building materials, but they are not certified organic.

In my experience, there are very few worthwhile soil amendments, especially commercially available, decently priced, and that give repeatable results. Just about any commercial organic grower should make their own amendments rather than buying them. This is actually a key to profitability in organic enterprises.

Humic acids are worthwhile soil amendments, but they are expensive to buy. Make your own by further refining your composting techniques. Adding soil conditioners as amendments - like peat moss or sawdust is OK, but they need to be from organic approved sources. Also, they are not practical on a large scale. Figure 4.3.1 summarizes some great organic soil amendments as well as some manures. We will discuss manure further in Chapter 10. The publication from which Figure 4.3.1 came is from a 1998 University of Wisconsin extension bulletin. Notice that it calls these materials 'wastes'. It is never a waste to put organic matter into soils! That publication also lists other soil conditioners like leaves, food wastes, grass clippings, fruit wastes, peat, cornstalks, straw, sewage sludge, and even wood as materials to add to your soil--albeit more easily done in a garden situation than on farm fields. Most of the time we add these as composted materials rather than putting them directly into our soils. We will discuss composting further in Chapter 9.

Remember that other bulky amendments may act both as soil conditioners and fertilizers. Examples include green manure crop and cover crop plow-downs, and crop residues.

Compositions of miscellaneous wastes

Material	Moisture %	Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)
		% "as is"		
Alfalfa hay	15	2.0–3.0	0.2–0.6	2.0–3.2
Brewer's waste	6–94	0.9–3.2	0.1–0.4	0.5–2.0
Cattle manure	85	0.5–0.7	0.2–0.4	0.5–0.8
Coffee grounds	42–70	0.7–3.1	0.1–12.0	0.01–0.9
Horse manure	80	0.4–0.7	0.2–0.5	0.5–0.8
Leather dust	19–68	0.4–7.5	0.1–0.4	0.02–0.3
Malt fiber	7	0.6–5.7	0.2–3.4	1.1–2.2
Poultry manure	70	1.1–1.7	1.0–1.3	0.5–1.0
Rabbit manure	—	1.0–2.0	0.6–1.0	0.3–1.5
Sawdust	4–66	0.1–0.9	0.01–0.5	0.04–1.4
Sheep manure	70	1.0–2.0	0.7–1.0	0.5–2.0
Spent hops	9–87	0.6–5.7	0.2–3.4	0.01–2.6
Tannery waste	6–85	0.1–14.1	—	—
		% dry weight		
Bone meal		0.2–1.0	12–14	—
Dried blood		13	1.5–2.0	1
Fish meal		9–11	5–8	0–3
Fresh leaves		0.5–1.0	0.05–0.08	0.3–0.6
Grass clippings		2–5	1–2	1–3
Sewage sludge		2–6	2–3	0–1
Wood ashes		0.5–1.0	0.8–10	2.0–3.5

Figure 4.3.1: Compositions of Miscellaneous Wastes. E.E. Schulte & K.A. Kelling, UW Extension. Organic Soil Conditioners

In general, you will find true organic soil amendments good, but too expensive to buy for commercial field-scale use. Avoid "sexy" products in eye-catching spray bottles. The best way to fix your soil is to harness your own microbial workforce. The compost you make yourself is your best bet. It is not as fun as buying products, but it will make you a true organic matter, soil-building farmer. Build your soil tilth through methods like fallowing, green manures, cover cropping, and composting.

You will want to check with any company you are thinking of buying a product from to make sure that their product is certified organic. Some companies mistakenly (or not) use the term "Organic" in their advertising yet they are not actually organic. It is buyer beware, as evidenced by the following email exchange with the makers of Aerify Plus, which used to use the term "organic soil conditioner" (see below).

The bottom line is that you should look for the USDA organic or OMRI-certified label on any fertilizers or amendments you plan to use on your organic land. Also look for a statement like this: "Product certified by_____X_____", the name of the certifying agency such as MOSA, Oregon Tilth, OCIA, or any one of probably 50 other certifiers. Below are three examples of marketing claims that are misleading about whether or not they are certified organic.

✔ Organic Soil Conditioner Marketing Examples - To be Organic or Not to be?

This is an email exchange with a company called Aerify Plus explaining if their product is in fact certified for use in organic operations.

From: Dantoin, Valerie L. Sent: Tuesday, October 12, 2024 4:45 PM

To: Stuart Franklin

Subject: Aerify Plus Question

I checked your FAQs and my question was not answered. Your product is advertised as Certified Organic.

Is this product Ok to use on certified organic soil?

What is the surfactant? That will probably determine if it qualifies as organic or not.

Thank you

From: Stuart Franklin [Email: Stuart Franklin] Sent: Tuesday, October 12, 2024 3:50 PM

To: Dantoin, Valerie L.

Subject: RE: Aerify Plus Question

The Aerify products are not certified for organic farms. The Surfactant is ammonium laureth sulfate. It does break down completely in the soil and a lot of organic gardeners have no problem using it, but none that are certified.

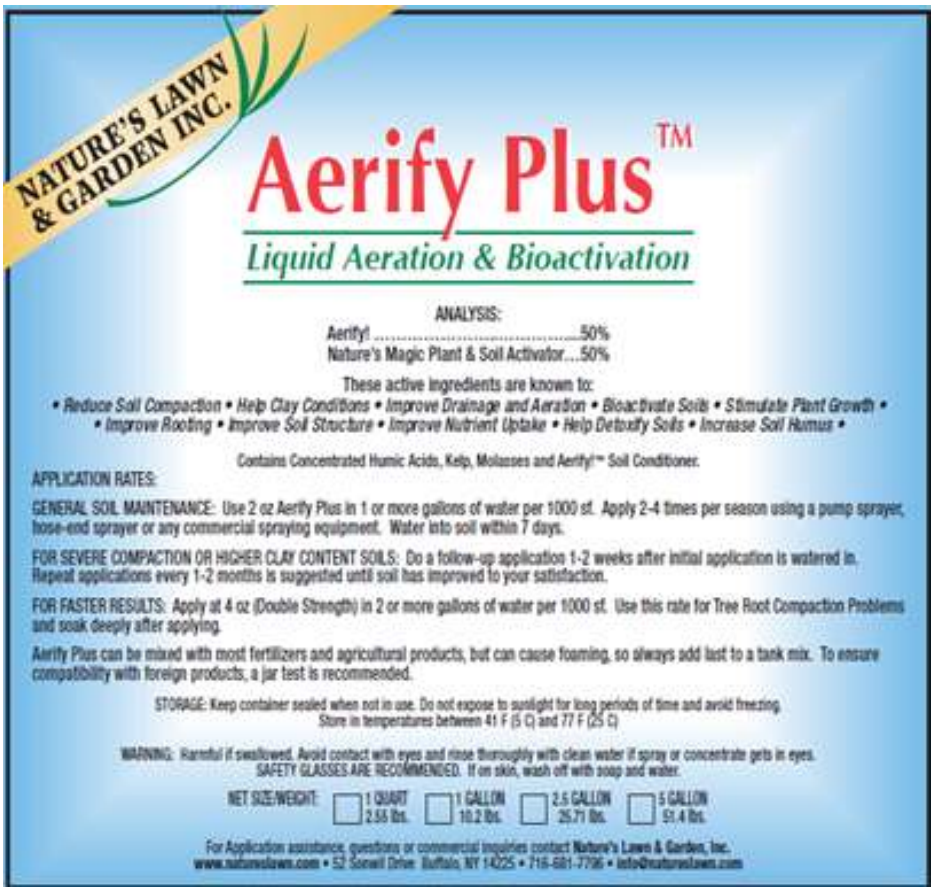

Figure 4.3.2: Aerify Plus label.

The old label called this an organic product. I revisited their website and saw that they have changed it to reflect that it is not organic. However, the website literature still says “organic gardeners know…..” You can see humic acids and kelp on the label– these are certainly organic ingredients if not sourced from an organic vendor, but probably are not certified organic. Find a label, examine it closely, and ask your certifier if you have questions about the product. Do not trust the salespeople – they do not know better and they may naively claim the product is organic.

Another example of a not-truly-organic amendment is Milorganite. This one even has “organic” built into its name. And I believe they say “organic” on the bag. It is bio-digested sewer solids from the water from the Milwaukee metropolitan sewage district. The issue here is that sewage sludge may contain trace heavy metals. Here is the website advertising for the soil amendment Milorganite. It is not certified organic. You cannot use this on organic farms or gardens. It is a cool, eco-friendly, recycled product as they claim, but still, it’s not organic.

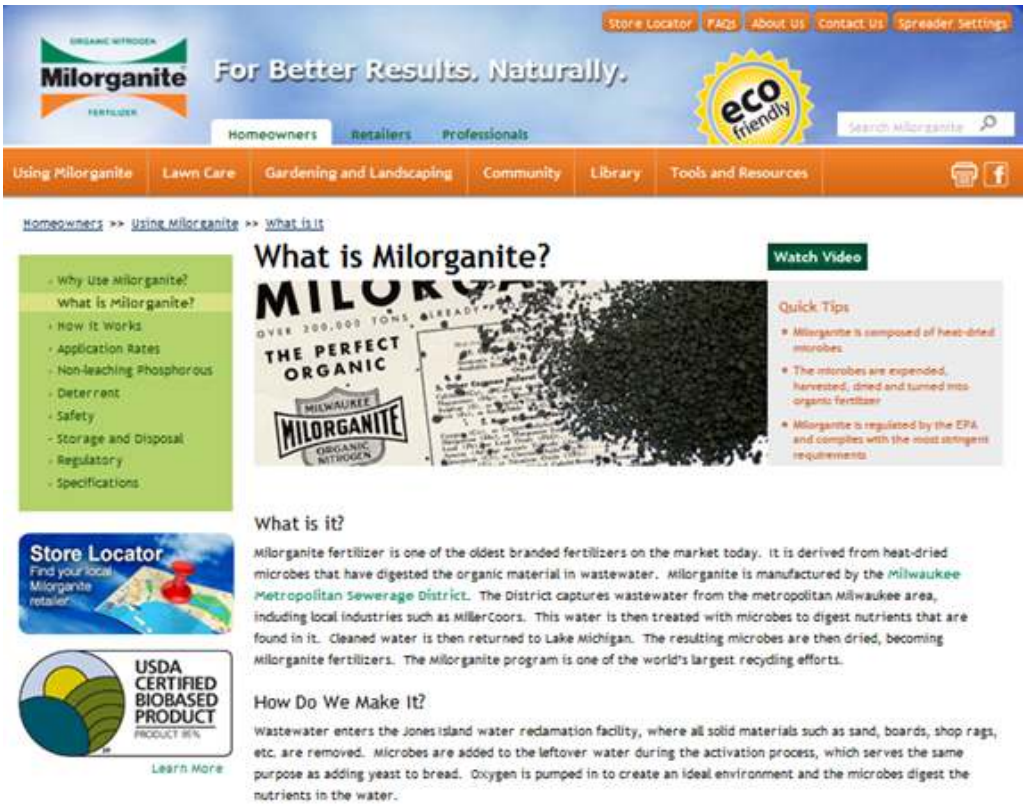

Figure 4.3.3: The soil amendment Milorganite is made of bio-digested sewer solids, but it is not certified organic.

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SECTION OVERVIEW

4.4: Soil Health Tests

4.4.1: Introduction

4.4.2: General Field Observations

4.4.3: Field Indicators

4.4.4: Laboratory Soil Health Testing

4.4.5: Sources

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4.4.1: Introduction

> *... 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*

Good soil has a lot of organic matter. We can test soil for the amount of organic matter it contains, and that is sometimes a good indicator of soil health. However, there are also other ways to test for soil health. Now this is different than most 'regular' soil tests you may have heard about, like testing for N-P-K and pH. And we will discuss soil sampling and those tests in an upcoming chapter. But while we are focused on soil organic matter, let's focus here on soil health tests.

First, ask yourself why you would do a soil health assessment (test).

- The most obvious reason is that it allows you to identify specific problems, such as surface compaction, and then change 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?
- A good soil health assessment done over several years allows you to see whether your farming efforts are going in the right direction. While the goal of building soil health is to prevent problems from developing, it also helps to correct previous problems you might have had.
- 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, 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.

✔ An Example from the Author's Farm 4.4.1.1

On my Full Circle Farm, we have 'banked' some wealth in the soil by adding organic matter and nutrients appropriately. Our soil tests generally show 3.5% organic matter. We rented 35 acres from a neighbor and that field has about 2% organic matter. It is a poor field that has been rented to negligent farmers for 20 years. We get 1/3 less hay yield from that land compared to our fields with the same soil type, seed, and management practices. We are trying to bring the rented land up to our field health levels, but it is slow going.

Similarly, an adjacent 15 acres we bought from a neighbor 25 years ago is finally returning to health after receiving no manure and only synthetic fertilizer inputs in previous years.

A final example is the shortcut walk I took across another neighbor's field a couple of years ago when I realized I was running late for a meeting. It had rained the day before. I walked off my plowed field and my feet sank in the mud on his plowed field. My field could support me and I had no trouble walking it. His field was so 'puddled' that my shoes got stuck in cement-like soil and I had to walk through it barefoot. His soil management of continuous plowing for 25 years of corn and soybeans had destroyed the soil's health. Any crop yield he had came from a bag of fertilizer or a barrel of herbicide spray.

To paraphrase Eliot Coleman..... I fed the soil and it fed my crops, he had to feed the crops from his pocketbook with artificial inputs.

We explore soil health assessment at three levels of detail in the next sections:

1. General field observations
2. Field assessments using qualitative indicators
3. Quantitative soil health tests

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4.4.2: General Field Observations

Making 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 is similar to checking in about your own health when someone asks how you are feeling: Do you have less energy than usual? Do you have a temperature? Do you look pale? This might be an indication that something is not 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?
- Do you notice increased problems with diseases or nutrient stress?
- How does the soil smell? sweet or sour?

These questions ponder problems with soil health, and any affirmative answers should prompt you to consider further action.

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4.4.3: Field Indicators

Field Indicators

The next approach involves addressing the same kinds of questions used to make field observations but in a more detailed manner. In several states, farmers and researchers have developed “soil health scorecards” based on observations made in the field. The Natural Resources Conservation Service (NRCS) has developed a somewhat different visual evaluation system, the "Cropland In-Field Soil Health Assessment Worksheet" (Table 4.4.3.1is 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. Most soil health issues are a result of low soil organic matter. That is why we are discussing soil health in the 'organic matter' chapter.

Figure 4.4.3.1: A soil penetrometer is a useful tool to assess soil compaction. Measurements are best made when soils are moist and friable (around field capacity).

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 4.4.3.1) 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 tends to go deeper into the soil during dry periods, although you may still observe the wormholes and casts (Figure 4.4.3.2). 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 4.4.3.2: 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 conditions. However, soil health problems are better *observed* during wet or dry periods when you might see runoff or crop drought stress symptoms.

Table 4.4.3.1. Cropland Soil Health Assessment Worksheet.

Indicator	Soil Health Concern	Best Time and Use	Observation Benchmarks

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 the 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 a 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 the darker range using a 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 were 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)

Table 4.4.3.1 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.

Types of Field Indicators

Soil Color

Soil color is the result of a combination of the soil's mineralogy, oxidation status, and organic matter content. Some soils are naturally redder (highly oxidized iron), brown (less oxidized iron), grey (poor drainage), or whitish (high lime content), but organic matter makes them dark. 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

Crusting, ponding, runoff, and erosion can be observed from the soil surface. 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. 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.

Stability of Soil Aggregates

You also can easily get an idea about the stability of soil aggregates, especially those near the surface. 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 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

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 a friable state). Make sure the penetrometer is pushed slowly into the soil. 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.

Figure 4.4.3.3: A healthy corn root system with many fine laterals (roots shaken to remove aggregates and make them more visible).

Soil Organisms

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 4.4.3.1). 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, 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. 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 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

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 4.4.3.3), 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, and 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

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 poor soils may show problems when heavy rainfall, causing soil settling after tillage, is followed by a long drying period. Soils may temporarily hard set and stop crop growth altogether under these circumstances.

Field Images

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 4.4.3.4). 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.

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.

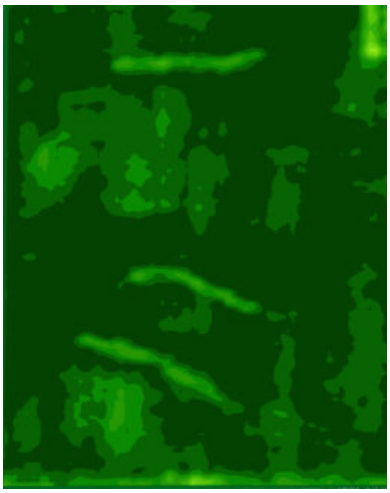

Figure 4.4.3.4: A normalized difference vegetation index (NDVI) map of a field shows areas of lower and higher vegetation density (darker areas have more vegetation), and can guide soil health examinations. Source: Yara International.

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4.4.4: Laboratory Soil Health Testing

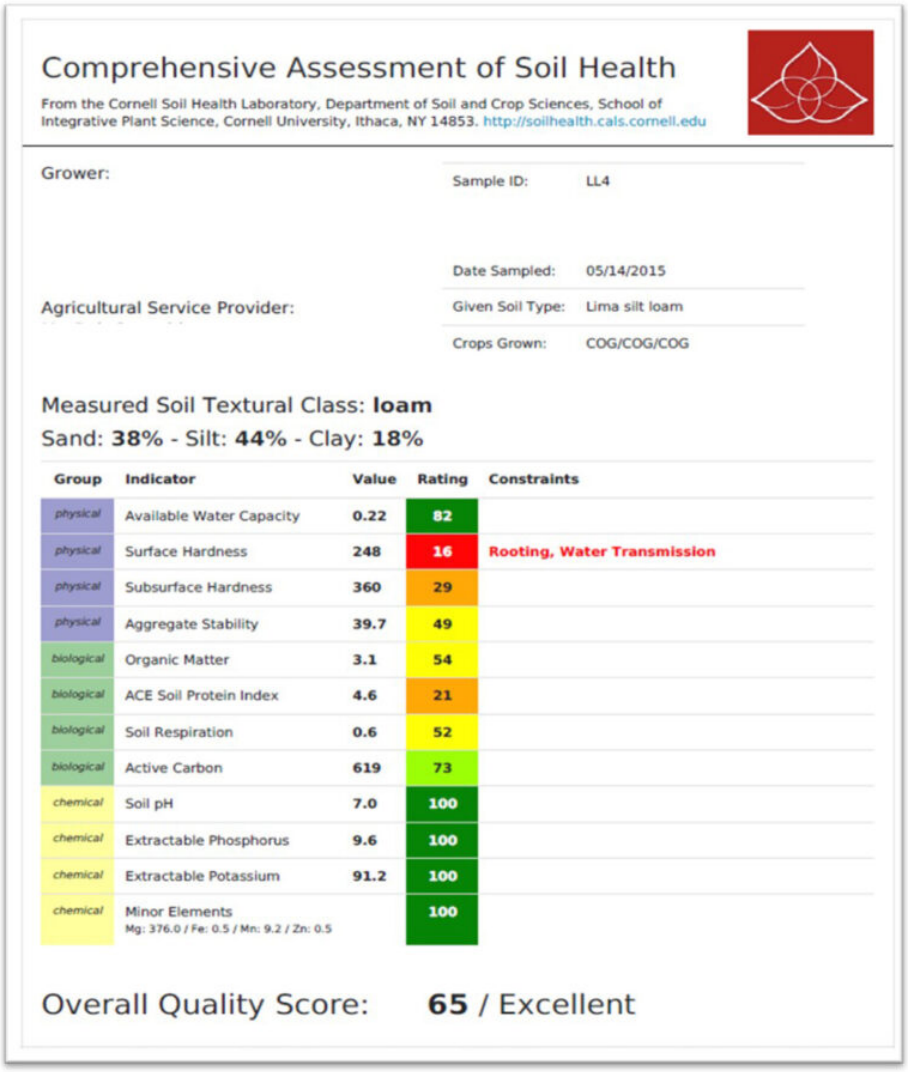
Soil Health Tests: Chemical, Physical and Biological

Chemical Soil Tests

Growers routinely take soil samples and have them analyzed for available nutrients (N-P-K), pH, and total organic matter. In arid regions, it is common to also determine whether the soil is saline (too much salt) or sodic (too much sodium). This provides information on the soil's **chemical/nutrient** health and potential imbalances. As mentioned, you get the most benefit from soil tests with regularly scheduled analyses (at least every two years) and good records. If you requested a test on cation exchange capacity (CEC), you should expect it to increase with higher organic matter levels, especially in coarse-textured soils. And, as discussed, soil CEC increases after liming soil, even if there is no increase in organic matter. We devote Chapter 7 to these more familiar tests.

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 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 physical and biological 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 the cost, consistency, and reproducibility of the methodologies, as well as their relevance to soil management.

Pictured below is a different kind of soil test--one for comprehensive SOIL HEALTH that includes physical indicators and biological indicators. This comprehensive soil test shows three categories (left side) of the test--Purple Physical indicators, Green Biological Indicators, and Yellow Chemical indicators. It also flags results (right side). A red box shows a trouble spot--surface hardness. The orange and yellow boxes indicate things can improve, and the green boxes show that all is well for the chemical portions of the soil as well as Available Water Capacity.



Comprehensive Assessment of Soil Health

From the Cornell Soil Health Laboratory, Department of Soil and Crop Sciences, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853. http://soilhealth.cals.cornell.edu

Grower:

Agricultural Service Provider:

Sample ID: LL4

Date Sampled: 05/14/2015

Given Soil Type: Lima silt loam

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	16	Rooting, Water Transmission
physical	Subsurface Hardness	360	29	
physical	Aggregate Stability	39.7	49	
biological	Organic Matter	3.1	54	
biological	ACE Soil Protein Index	4.6	21	
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	91.2	100	
chemical	Minor Elements Mg: 376.0 / Fe: 0.5 / Mn: 9.2 / Zn: 0.5		100	

Overall Quality Score: **65** / Excellent

Figure 4.4.4.1: Example of a soil health test report.

The USDA evaluated a set of indicators and methodologies in an attempt to encourage standardization in soil health testing. The proposed methods 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: physical, biological, and the typical chemical. Also, measured values need to be interpreted based on inherent variation in soils as a result of different climates, soil textures, etc.

Physical Indicators

For physical indicators, ***aggregate stability*** 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. These soil health indicators have become somewhat widely adopted.

Figure 4.4.4.2: Results of an aggregate stability test for silt loam vegetable soils: organic (70% stable, left) and conventional (20% stable, right) management. This is a physical soil indicator test.

Biological Indicators

The most common biological 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 been 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.

Similarly, soil ***protein content*** is an indicator of the soil organic nitrogen potentially available to microorganisms, and it also shows a 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 the 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. 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)*. The pictures below show an example of a bioassay.

Figure 4.4.4.3: Examples of root rot bioassays on bean plants: conventional (left) and organic (right) soil management.*Photos by George Abawi.*

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 of *pseudomonas* bacteria are). Some tests are showing promise in identifying specific pathogens that may help farmers better manage their fields.

Chemical soil health indicators, as previously discussed 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.

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 are 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 a 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.

Below is a table that summarizes many of the soil health measure. We don't go into detail in this book about the methods, but you should know that these tests are available to help you understand the health of your soil.

Table 4.4.4.1: 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 Carbon sequestration	Soil organic matter content	Dry combustion, Wet oxidation, Loss of 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, Microbial biomass C, Soluble carbohydrates, Substrate-induced respiration

[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)

Soil process	Soil health indicator	Method[1]
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)

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CHAPTER OVERVIEW

5: Nutrients from the Soil into the Plant Body

5.1: What is a Nutrient?
5.2: Nutrients in the Plant Body

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5.1: What is a Nutrient?

> *"All the great agricultural systems which have survived have made it their business never to deplete the earth of its fertility without at the same time beginning the process of restoration." — Albert Howard, The Soil and Health: A Study of Organic Agriculture*

A nutrient is the link between soil elements and plant nutrients.

Farmers, gardeners, horticulturalists, crop consultants, soil scientists, and agronomists have differing ideas regarding nutrients. Perhaps that is because the term soil fertility is often conflated with plant nutrition since they are closely related concepts. In this section we define nutrients in terms of the origins and relationship of *elements* to each other, focusing on the nutrients that should be present in soil to grow healthy plants. This is a short summary of the role of the anion nutrients in the life of a plant. Later sections will cover how these nutrients cycle in the soil and how they are added to soils as fertilizers at various points in the cycle. The reader can also find out more about individual nutrients in plant physiology in a course that focuses on crops and plants.

Elements for Growing

Plants, animals, microbes, and other life forms need external sources of ***elements*** in order to grow and reproduce. Elements are "irreducible" constituents, that is, they are materials that cannot be further simplified. The earth is made up of about 90 naturally occurring elements. Elements are shown in Figure 1. It is a table arranged in repetitions or a "periodic" way to show how many protons or neutrons are in the nucleus of each element. (That number of protons coincides with each element's "periodic" number). As most readers probably recall from high school chemistry, each letter(s) in the box is a shorthand name for an element. For example, Oxygen is element #8 and is abbreviated as "O". Oxygen and silicon (Si) (element #14) are the most abundant elements on earth, next are aluminum (Al) (#13) and iron (Fe) (#26). Iron is abbreviated "Fe" because the Latin word for it is "Ferrous".

Some elements are nutrients, while others are not. For example, all plants require iron, but none require aluminum, and very few require silicon. Sodium, which is very abundant in nature, is not required by plants, and though some plants can use it, it is toxic in high concentrations. Animals, on the other hand, do require sodium. To recap – not all elements are nutrients, but all nutrients are composed of elements.

Minerals

Minerals are generally defined as naturally occurring, homogenous, and inorganic. In this sense, inorganic simply means "does not contain carbon". Each mineral has a well-defined color, hardness, crystalline structure, and chemical composition. Some minerals are composed of a single element, as is the case with both gold and silver.

It gets confusing when organic farmers also refer to some things they use, like kelp, as "a mineral" for animal feed. Kelp is a seaweed (actually now it is classified as an animal but that is another story) that is dried down to flakes–it contains trace minerals like iodine, but kelp is not itself a mineral.

The amounts of nutrients naturally occurring in a given soil depend on the parent rock material of the soil as well as the climate that has weathered the rock. **Soil fertility** is defined by Henry Foth as "the quality that enables a soil to provide the proper compounds, in proper amounts, and in the proper balance, for growth of specified plants when temperature and other factors are favorable."

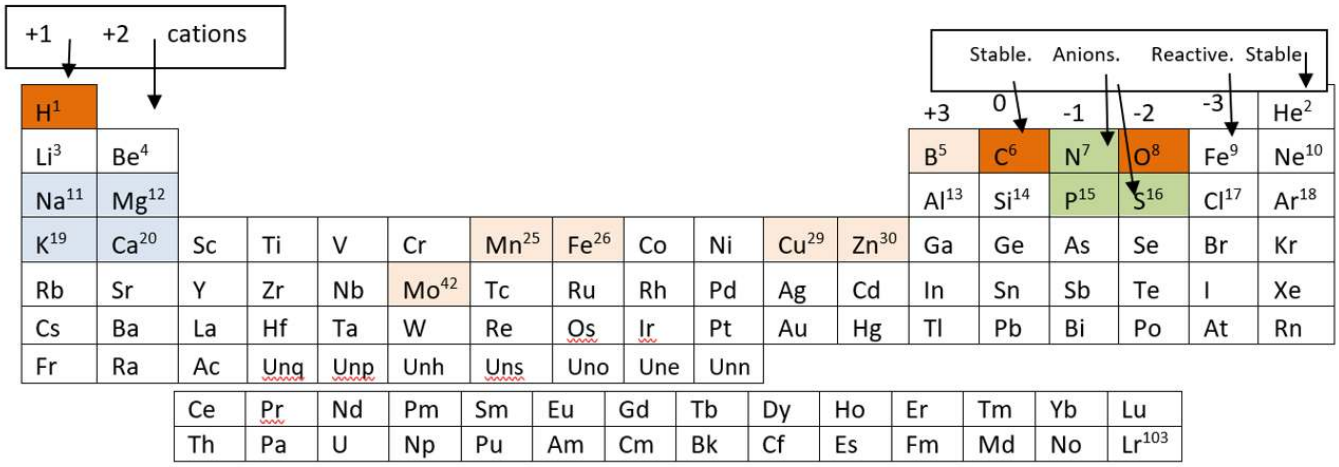

Figure 5.1.1: The sustainable agriculturalist's period table of elements important in plant nutrition. The period table has more than 115 elements, many with higher period numbers are not found in nature. Important nutrient Anions are colored green, Cations are light blue.

Why are we talking about the periodic table of elements in a soil course? It is because we go back to this table to find the foundation of chemical attractions, soil fertility, and plant nutrition. We need to get re-acquainted with the elements just a bit. Many of us have seen the periodic element table, but not in the context of agriculture. It is rewarding to understand the outcome--fertilizers and how to use them in organic agriculture--when one first sees the whole picture of how the elements relate to each other in the table as well as the element's role in the plant.

Let's start by looking at a few "agricultural" elements and their period numbers and how this ends up giving them a slightly positive or negative charge. Remember that electrons have a negative charge, they are symbolized as e-. Protons have a slight positive charge, they are hungry to mate with an e-.

Table 5.1.1: Agricultural Elements

Element	Symbol	Periodic Number	Protons	Electrons	Charge	Outcome	Ionic Form of the Element
hydrogen	H	1	1	0	+1		H+
helium	He	2	2	2	0	stable	
carbon	C	6	6	6	0	Stable	
oxygen	O	8	8	8	0	stable	
nitrogen	N	7	7	7	-1	anion	varies
sodium	Na	11	11	11	+1	cation	Na+
magnesium	Mg	12	12	12	+2	cation	Mg+2
phosphorus	P	15	15	15	-1	anion	varies
sulfur	S	16	16	16	-2	anion	varies
potassium	K	19	19	19	+1	cation	K+
calcium	Ca	20	20	20	+2	cation	Ca+2

Ionic forms

The following representations of the elements show the same information as in Table 5.1.1. Recall that the innermost ring contains just two electrons. The first circle below shows a basic atom and the number of electrons in each orbital ring that would make it stable When the electrons and protons are equal, the element is very stable and unreactive, like helium (He) and carbon (C).

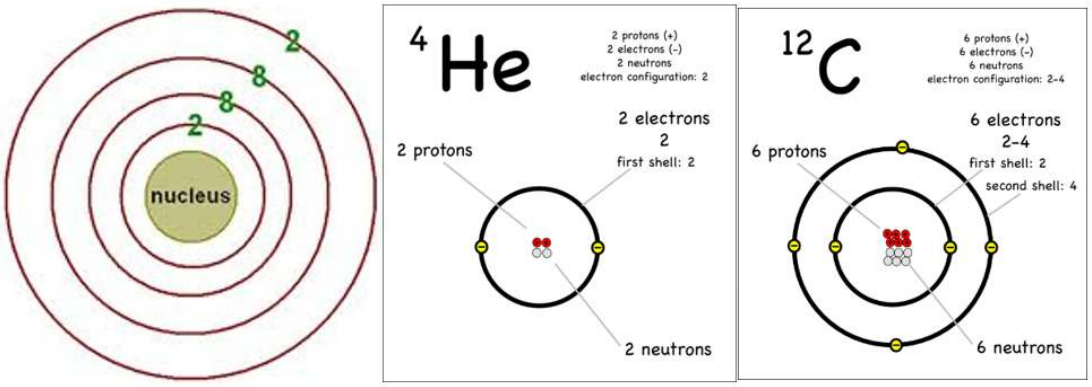

Figure 5.1.2: Helium and Calcium's protons and electrons.

Anions

The nutrient elements are always in some *ionic form* or compound when they are in soil solution and are ready to be taken up by plant roots. You've previously read about cations (cat-eye-ons) and the diagram below really shows what an anion is. Anions can be thought of as elements with a slight negative charge. Anions carry one or more extra electrons. Elemental N and P both carry one more electron in their outermost atomic ring than they have protons to balance with in their nucleus. Sulfur has two extra electrons and thus an ionic charge of -2.

The anions Nitrogen, Phosphorus, and sulfur are more reactive than more stable elements because the negative charges from electrons in their outer orbit want to combine with something positive. You can see that Nitrogen (N) has 2 electrons in the inner orbit and only 5 in the second orbit. It 'looks for' three more electrons to fill its outer shell. Phosphorus and sulfur have 2 electrons in the inner ring, 8 in the next ring, but only 5 and 6 electrons respectively in the third ring. So again, they are not stable and want to combine with other elements and share ionic bonds. Most often the compounds formed by anions are variable and can include oxygen (sharing its electrons) or hydrogen (sharing its proton).

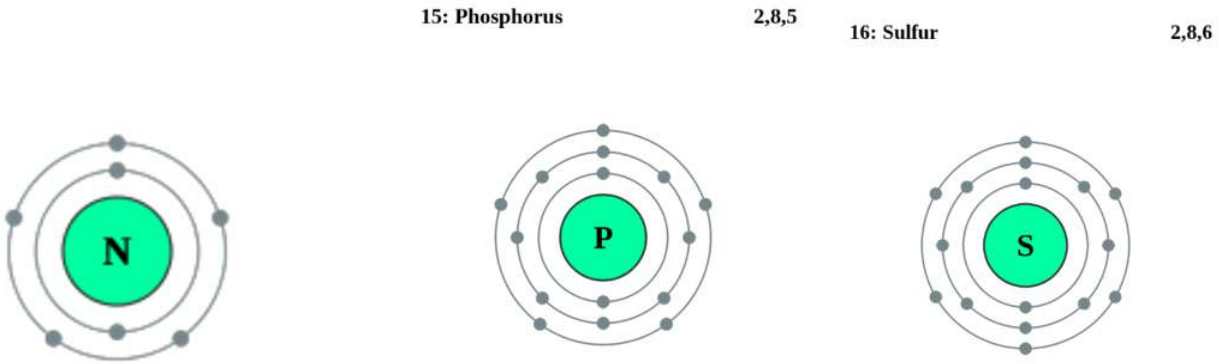

Figure 5.1.3: The anions Nitrogen, Phosphorus and Sulfur.

Cations

The debate over soil balancing and the ratios of Ca^{+2} and Mg^{+2} for example, can be better understood by noting the relationship between the two elements as shown in the period table. Calcium is a "bigger" element than magnesium, that's how it is thought to "open" the soil when it inserts itself into a layer of clay. Organic farmers use knowledge like this as a substitute for synthetic, chemical shortcuts to soil, plant, and animal health. Adding calcium to soil helps soil structure while magnesium, a smaller ion, may 'tighten' soil.

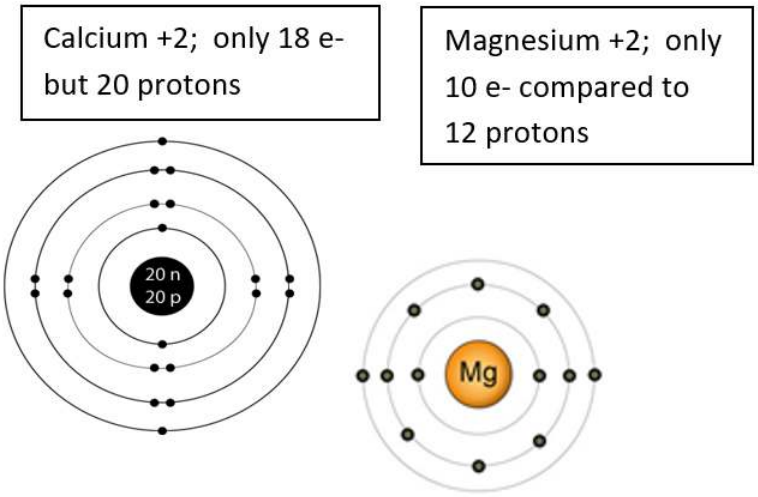

Figure 5.1.4: Calcium takes up more space because it has more electrons than Magnesium. (Copyright; author via source)

Note the Magnesium molecule is smaller because it has one less ring of electrons. Both of these cation molecules have two electrons hanging out in the outer ring.

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5.2: Nutrients in the Plant Body

What Nutrients are in the Plant's Body?

Carbon, hydrogen, oxygen. Although hydrogen (H), oxygen (O), and carbon (C) are elements, they are generally not called "nutrients" because they are usually abundant in water and air. Remember also that the plant body is made up mostly of carbon, hydrogen, and oxygen. These elements are synthesized, or knitted together using energy from the sun to form carbohydrate compounds, often referenced as CH_20. Recall that this is the plant process we call photo (sun) synthesis (knitted).

The table below summarizes the 13-15 elements essential plant for plant growth that are considered nutrients. The table lists the elements in order according to an average concentration in plant tissues. The table below also shows the amount of the element found in a typical soil. It also gives a brief description of the nutrient's role in the plant.

Table 5.2.1: Elements required by plants listed in order of how much of it (%) is in a typical plant's body.

	Macronutrients	Its available form in the soil [A]	% in typical soil	% in typical plant (%DM)[B]	Where is it found in the plant? What role does it play?
N Anions have (–) charges	nitrogen	NO_3^- nitrate or ammonium NH_4^+	0.1	1-3%	Amino acids, proteins, DNA, chlorophyll, enzymes
K Cations have (+) charges	potassium	K^+	1.5	0.3 - 6%	Enzymes, amino acids. Makes proteins. Activates enzymes, opens/closes stomata
Ca Cations have (+) charges	calcium	Ca^{+2}	0.5	0.1-3.5%	Cell walls, enzyme cofactor, cell permeability
P Anions have (–) charges	phosphorus	phosphate H_2PO_4 or HPO_4^{-2}	0.06	0.05-1.0%	Energy compounds i.e. ATP, co-enzymes, Nucleic Acids i.e. DNA. Phospholipids
S Anions have (–) charges	sulfur	sulfate SO_4^{-2}	0.05	0.05-1.5%	Part of some amino acids and proteins and the very important Co-enzyme A molecule
Mg Cations have (+) charges	magnesium	Mg^{+2}	0.4	0.05 - .07%	A part of the chlorophyll molecule. Activates many enzymes.

	Micronutrients	Its available form in the soil [A]	% in typical soil	Parts per million (ppm)	Where is it found in the plant? What role does it play?
Fe	Iron	Fe^{+2} or Fe^{+3}	3.5	10-1500	Synthesis of chlorophyll, cytochrome, and ferredoxin
Mn	Manganese	Mn^{+2}	0.05	5-1500	Activates some enzymes
B	Boron	BO^{-3} or $B_4O_7^{-2}$	0.002	2-75	Influences Ca^{+2} utilization, other unknown functions

	Micronutrients	Its available form in the soil [A]	% in typical soil	Parts per million (ppm)	Where is it found in the plant? What role does it play?
Zn	Zinc	Zn^{+2}	0.001	3-150	Activates some enzymes
Cu	copper	Cu^{+2}	0.0005	2-75	Activates some enzymes
Mo	molybdenum	MoO_4^{-2}	0.0001	0.1-5.0	Nitrogen metabolism
Cl	Chlorine	Cl^-	-	100-10,000	Cell osmosis, O_2 production in photosynthesis

	Essential in some plants	Its available form in the soil [A]	% in typical soil	Parts per million (ppm)	Where is it found in the plant? What role does it play?
Co	Cobalt	Co^{+2}	-	trace	Required by nitrogen-fixing microbes associated with legumes
Na	Sodium	Na^{+2}		trace	Osmotic balance in some desert plants and C_4 plants

Available form. Nitrogen, phosphorus, and sulfur are anions and the form in which the plant takes them up from the soil has always been thought to be in conjunction with oxygen, as shown in the 3rd column. Cationic nutrient elements exist in the soil solution in ionic forms and are taken up by the plant as cations.

Macronutrients. A macronutrient is needed in relatively large amounts by the plant as measured in the "percent of dry matter" of the plant's body. In other words, if you took 100 grams of the plant, dried it, and got rid of all the water, the ashy material that is left may contain about 2.5 grams (g) nitrogen, 2g potassium, 2 g calcium, 0.7g phosphorus, 0.06g sulfur, and 0.06g magnesium – depending on the plant.

> *Primary* macronutrients are nitrogen, phosphorus, and potassium.
>
> *Secondary* macronutrients are calcium magnesium, and sulfur.

Micronutrients are measured in parts per million rather than a percent of dry matter. This tells us that micronutrients, while essential to plant metabolism are needed only in very tiny amounts. The micro-nutrients are not "bodybuilding" components, but rather they are keys or tiny locks in enzymes that allow the plant to function.

For an analogy, envision a car. The bulk of the car is composed of metal in the frame and the body – that is like the CH_2O carbohydrates in a plant body. The primary macronutrients might be rubber, glass, and fiberglass/plastic–much like our N, P, and K. The secondary macronutrients (Ca, S, Mg) may be gas and oil. The micronutrients are the very small things, by volume that are still very critical for function–the sparkplugs, brakes, keys. It's not a perfect analogy but it gives the general idea that a plant's body, like a car, has some components in huge amounts, some in medium, and some in tiny amounts.

Table 5.2.2: Difference between what the soil can provide and what the plant needs

Macronutrients	% in typical soil	% in typical plant (%DM)[B]	Difference	Exchangeable - available
N Nitrogen (anion)	0.1	1-3%	3%	lowest
K Potassium +1 (cation)	1.5	0.3 - 6%	1%	low
Ca Calcium +2 (cation)	0.5	0.1-3.5%	1%	medium
P Phosphorus (anion)	0.06	0.05-1.0%	1%	low
S Sulfur (anion)	0.05	0.05-1.5%	1%	medium
Mg Magnesium +2 (cation)	0.4	0.05 - .07%	abundant	high

Nitrogen: (N). The soil never seems to be able to keep up with the nitrogen demands of plants. Plants need a lot compared to what's in a typical soil. Nitrogen takes many forms when it combines with Oxygen and Hydrogen but it must always be in ionic form when taken in by the plant roots, usually as NH4+ (ammonia). We'll examine the N cycle in other places in the book. We will also go into more detail on nitrogen fertilizers, both organic and synthetic in another chapter.

Farmers & gardeners 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. But both N and P have the potential for environmental problems which we investigate later. While K deficiency is also fairly common, most other nutrients are not normally deficient. 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.

Phosphorus: (P) is needed for many plant functions, just like nitrogen. It tends to be in slightly short supply in most soils unless the farm is a dairy farm. On those farms, phosphorus has built up in the soil over time, more than the plant can use, and then the excess becomes a pollutant. We will discuss phosphorus fertilizers and the phosphorus cycle more in another chapter because they deserve special attention.

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 most often when an entire crop is harvested and removed versus the grain only. Unlike N and P, Potassium 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. However, if the *type of clay* has low CEC, such as kaolinitic clays found in the U.S. Southeast, low CEC may make it impossible to store large amounts of readily available 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.

Secondary Macronutrients

Calcium: Why is Ca considered a secondary macronutrient while it looks like plants have more of that in their body than phosphorus? The answer has to do with the amount of each of those nutrients the soil can provide compared to how much is in the plant body. Review the table's last column "exchangeable–available" to see why calcium and sulfur are considered secondary macronutrients while potassium and phosphorus are primaries. It turns out that there is not much "exchangeable-available" K or P for plants in the soil because of soil chemistry. Clay and other soil particles "grip" the +2 Ca and +2 Mg more than the +1 K. The K slips away via leaching and therefore needs to be replenished by fertilizers. The Ca & Mg are held and "time-released" when they become depleted in the soil solution. On the other hand, the anion -2 Phosphorus can be gripped *too* tightly by adsorption onto soil particles. The phosphorus needed for plant growth may be limited unless fertilizers are added. Sulfur seems to act more like Ca and Mg and is more available than P. That's why it is viewed as a secondary nutrient as well.

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.

Magnesium: At the bottom of Table 5.2.2 is Mg; it is more abundant in soil than what a plant needs. There are a few exceptions, but most farmers do not supply Mg because there is enough in the soil. 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 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.

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 the combustion of high-sulfur forms of coal. (Now it is captured in power plant exhaust scrubbers, and the residue is sold as gypsum.) Organic farmers cannot use gypsum from power plants because of the potential contaminants in that product. 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. 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.

> *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)*

Micronutrients

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.

As of the writing of this edition, there are discussions about how glyphosate-based herbicides affect micronutrient availability. Glyphosate is the most frequently applied herbicide worldwide and, like soil organic matter, has chelating abilities. Remember, chelation in this context means 'grabbing' and hanging onto a nutrient so it becomes unavailable for the plant. It is still an open debate 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.

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 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 with a 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.

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 soi,l or through fertigation systems, and they are especially of interest for high-value crops.

Nutrient Deficiencies

Nutrient deficiency symptoms can appear on plant leaves when soils are low in a particular nutrient (Table 5.2.3). (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 were all nice and green at the end of the season, there was more N than the plant needed. Potassium deficiencies in 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).

Table 5.2.3: Examples of Nutrient Deficiency Symptoms

Nutrient	Deficiency symptoms
Calcium (Ca)	New leaves (at the top of the plant) are distorted or irregularly shaped. Causes blossom-end rot.
Nitrogen (N)	General yellowing of older leaves (at the bottom of the plant). The rest of the plant is often light green.
Magnesium (Mg)	Older leaves turn yellow at the 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.

Nutrient	Deficiency symptoms
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; the plant is stunted.
Copper (Cu)	Leaves are dark green; the plant is stunted.
Iron (Fe)	Yellowing occurs between the veins of young leaves. The area between veins may also appear white.
Manganese (Mn)	Yellowing occurs between the veins of young leaves. These areas sometimes appear “puffy.” The 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 the bottom of the 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. The area between veins on corn leaves may appear white.

Source: Modified from Hosier and Bradley (1999)

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CHAPTER OVERVIEW

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6.1: How Carbon 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. However, 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. 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 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.

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6.1.1: 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 6.1.1.1). 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, is supplied by rivers—the Indus, Ganges, and Brahmaputra—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 were settled by tribes, including Native Americans, where they provided fertile soils and nearby sources of fish and land animals

Note

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 mineral particles, organic matter (carbon), and nutrients deposited over long periods of time.

Figure 6.1.1.1: Basin-wide nutrient, carbon, and water flows converge towards productive confluence zones.

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 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 6.1.1.2). 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. 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

Figure 6.1.1.2:. Degraded land in Crete, Greece, with olive trees.

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 they're called Anthrosols. One example is the so-called *plaggen* soil of northwestern Europe (Figure 6.1.1.3). 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.

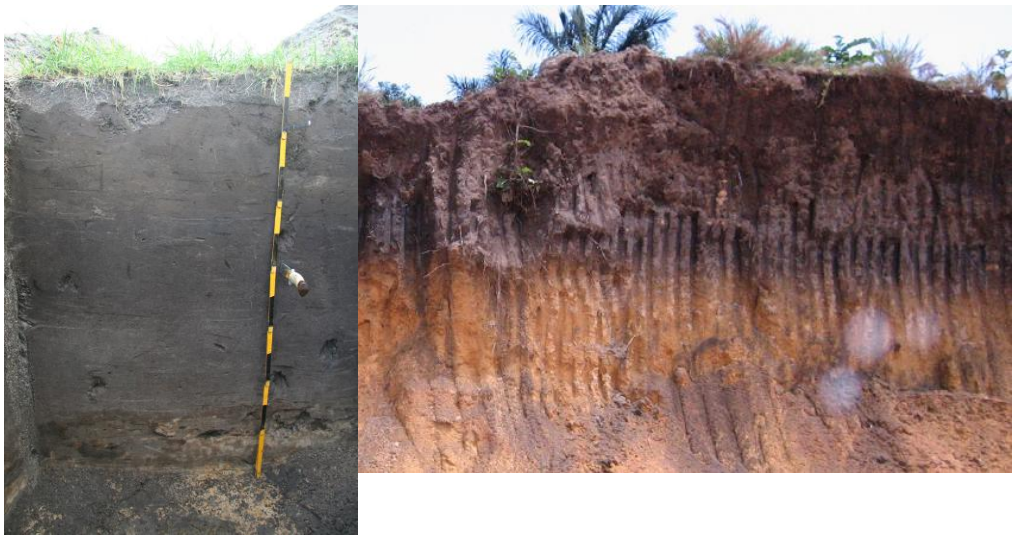

Figure 6.1.1.3: Two cases of soils enhanced through human activity, producing anthropogenic soil (from left): Plaggen soil in Belgium (photo by Karen Vancampenhout) and Terra Preta del Indio soil in Brazil (photo by Biqing Liang).

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. 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.

One more example is the Menominee people of Northeastern Wisconsin who used flooded areas along the Wolf River for cropping on long, raised beds supplemented with biochar and fish emulsion. Dr. Frank Kutka explained that the ancient gardens are thought to be 1,000 years old and were actively cultivated until the early 20th century. In the photo below the raised beds are still visible

though now they are overgrown with forests. The Menominee are one of the few Tribes in the United States not forced to move west to a reservation. Tribal oral history says they occupied northeast Wisconsin ever since the last glacier retreated 10,000 years ago. Their ability to grow crops continuously on this land is a true example of sustainable agriculture.

Figure 6.1.1.4: Ancient Menominee garden beds (left) and their archeological excavation (right). Photo by Frank Kutka.

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. Different rotations and integrating cropping and livestock also offer many opportunities to “grow your own” soil organic matter and improve nutrient cycling.

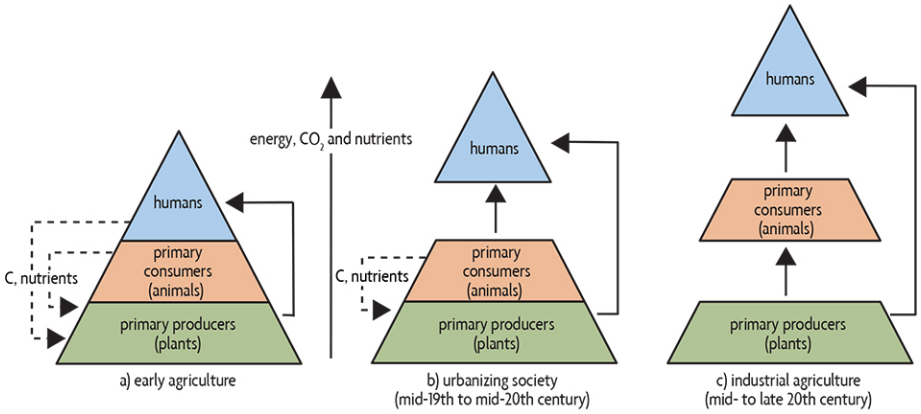

Figure 6.1.1.5: The patterns of nutrient and carbon flows change over time. Modified from Magdoff, Lanyon, and Liebhardt (1997).

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6.1.2: 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 use 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. Thus, nutrients and carbon accumulate 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, 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.

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6.1.3: Flow Patterns at Farm Scale

Definition: Compare Cycling to Flow

Cycling is when nutrients move from soil to plant to animal to soil.

In-Flow is when imported concentrated feed (grains), fertilizers, and minerals move from crops to cows to manure to soil.

Out-Flow is when carbon and nutrients leave a farm moving from soil to crops (to cows?) to markets as grain, hay, milk, or meat, and do not return to soil. Outflow also occurs when nutrients and carbon 'leak' out of the system into the environment.

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 the soil by plants, used, and then returned to the soil. Carbon enters the field as plants take in 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.

Remember, carbon, hydrogen, and oxygen, all of which are the 'bulk' ingredients that build the plant body are provided free from the air and water. They are knit together in the plant body by free sunlight; plants are mini-solar collectors. Farmers are really harvesting the sun, mostly, but they still need rain and nitrogen, phosphorus, and a little potassium - depending on how much of the crop stays on the farm and how much exits.

Three Scenarios

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: a) imports of nutrients are less than exports, b) imports are more significant than exports or c) imports are equal to exports.

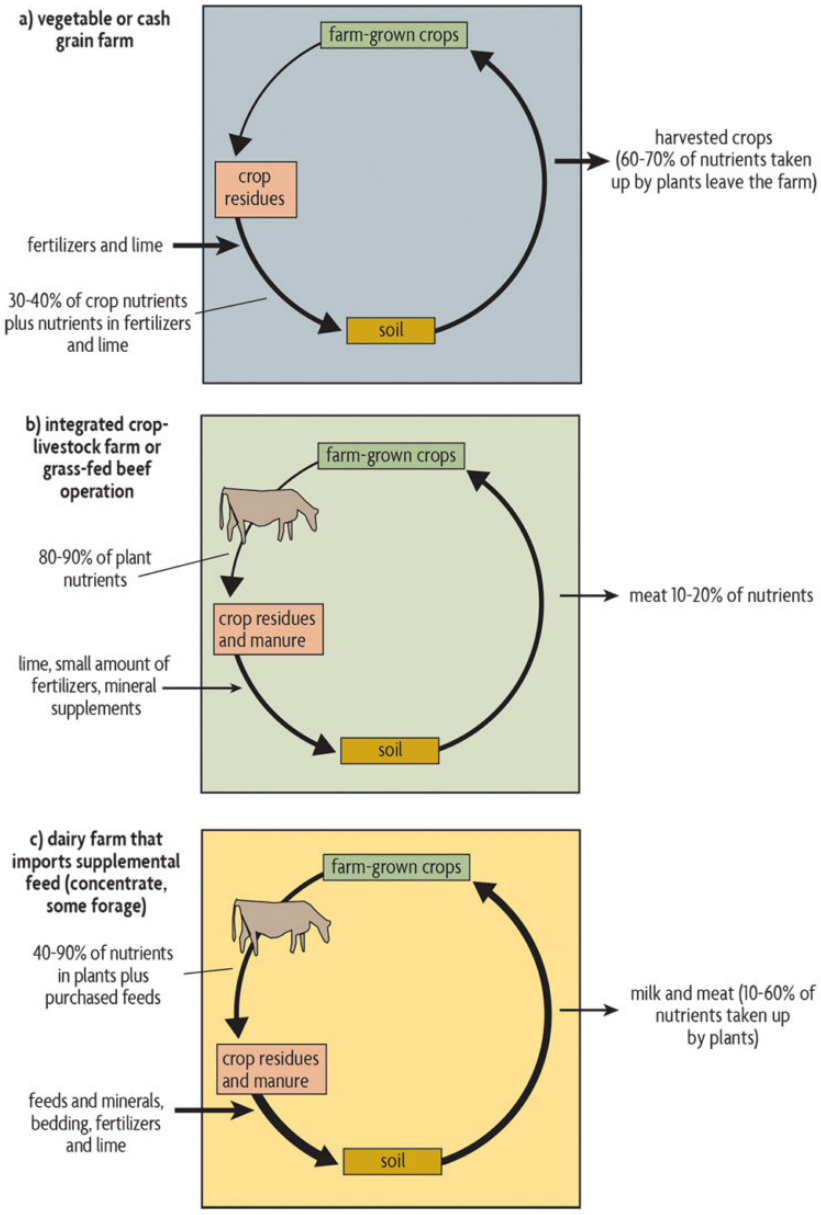

Figure 6.1.3.1: Nutrient flows and cycles on (a) a crop farm, (b) a grass-fed beef or other integrated crop-livestock farm, and (c) a dairy farm.

A. 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.

B. Imports and Exports are Close to Balanced

From the environmental perspective and for the sake of long-term soil health, fertility should be raised 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. 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. 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. However, 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,s 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 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. Most of the nutrients in 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 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.

C. Imports are Larger than Exports

Animal farms with inadequate land bases to produce all needed feed pose a different type of problem. 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 waters 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. That becomes an imbalance, an overload.

Where does this happen? On many farms in Northeast Wisconsin, large concentrations of dairy cows have exceeded the carrying capacity of the land to absorb all the excess nutrients. Some farmers are hauling manure 50 miles away to remove it from the land close to where the cows are confined. The Bay of Green Bay is receiving water for much of the excess nutrients flowing off the land. It is now a hypoxia zone as is the Chesapeake Bay which receives excess nutrients from grain shipped in from Kansas and Nebraska for poultry and swine operations in the watershed. You may wonder why poultry and swine are grown in one place while their grain comes from a thousand miles away. (Good question, the answer lies in the economic realm where cheap immigrant labor is found.)

Many dairy farms do not have the land base to grow all their needed feed and tend to emphasize growing subsidized grain crops. 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. However, the portion of nutrients in manure that originally entered the farm as purchased feeds and mineral supplements does *not* participate in a true cycle. These nutrients are completing a flow (not a cycle) 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 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 a 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.

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.

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. 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 and through the use of cover crops to catch excess nitrogen at the end of the season. Better rotations that include crops that leach very low amounts of nitrate will reduce the *average* losses over the period of the rotation.

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* of 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. However, 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.

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 into 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. However, rotations with corn appearing less frequently would also help reduce nitrate pollution of water.

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6.1.4: 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 boatload of grain from the Midwest to the eastern United States, or even from Brazil to Asia, *a lot* of carbon and nutrients flow and don't return. The international trade in agricultural commodities such as corn, soybeans, and wheat means that significant quantities of the basic ingredients 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.) According to the American Farm Bureau Federation in 2023, **$174.9 billion** worth of American agricultural products were exported around the world.

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

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. As previously discussed, climate and topography help shape nutrient-carbon flows. 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 6.1.4.1). 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. The Americas have a lower population density and can feed their own people and have excess food and feed for export.

Economics and politics are intertwined with American farming and global nutrient cycles. Some crops, like corn and soy, are heavily subsidized and heavily dependent on exports. It will be interesting to see if, in 2025 a global re-alignment occurs due to tariffs on imports to America and retaliatory tariffs on American farm exports. Interestingly, imports of cheap American grain since the 1970s have disrupted the *internal* cropping patterns of some nations. For example, Mexican farmers used to grow corn to supply their own markets. However, cheap American corn undercut those markets and was part of the start of mass immigration to the U.S. since many farmers had to come north looking for jobs. Exporting grain led to importing people, in a way.

There are many market forces that drive Midwest farmers toward growing more corn rather than crops like hay that, for example, would return more carbon to the farm's soil. The ethanol market and the high fructose corn syrup/soda industry did not exist in the 1960s but played a big part in increasing corn acreage in the U.S. It is worth mentioning also that the profitability of corn is strongly tied to the price of nitrogen fertilizer. Fracking and cheap fossil fuels are the energy sources driving the Haber-Bosh process that makes synthetic nitrogen fertilizer. However, synthetics, though they can grow corn, contribute nothing to soil organic matter as does manure. The reader should be aware that most farming does not occur in a vacuum but it is definitely influenced by market pressures, input costs, and farm gate commodity prices. Smaller diversified farms that sell locally and grow most of their own inputs are somewhat insulated from those outside pressures.

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.

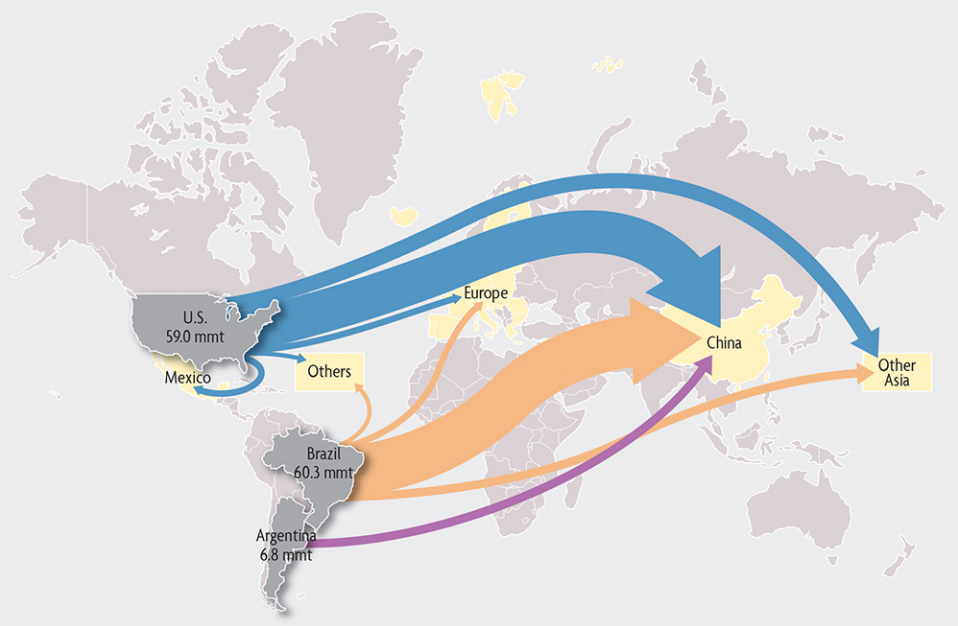

Figure 6.1.4.1: Leading exporters and destinations of soybeans during 2016/2017. Carbon and nutrients are reallocated and impact soils on both sides. Source: USDA-ERS.

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6.1.5: 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., 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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6.2: How Nutrients Flow

> *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, 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 their overuse has potential environmental implications. Other nutrients, cation exchange, soil acidity (low pH) and liming, and arid and semiarid region problems with sodium, alkalinity (high pH), and excess salts are covered later.

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 the 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 the 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 with 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, 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 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 into groundwater or running into surface water.

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.

Organic Matter and Nutrient Availability

The best overall strategy for nutrient management is to enhance the level of organic matter in soils (Figure 6.2.1). 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, 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. A wide diversity of soil organisms helps maintain low populations of plant pathogens.

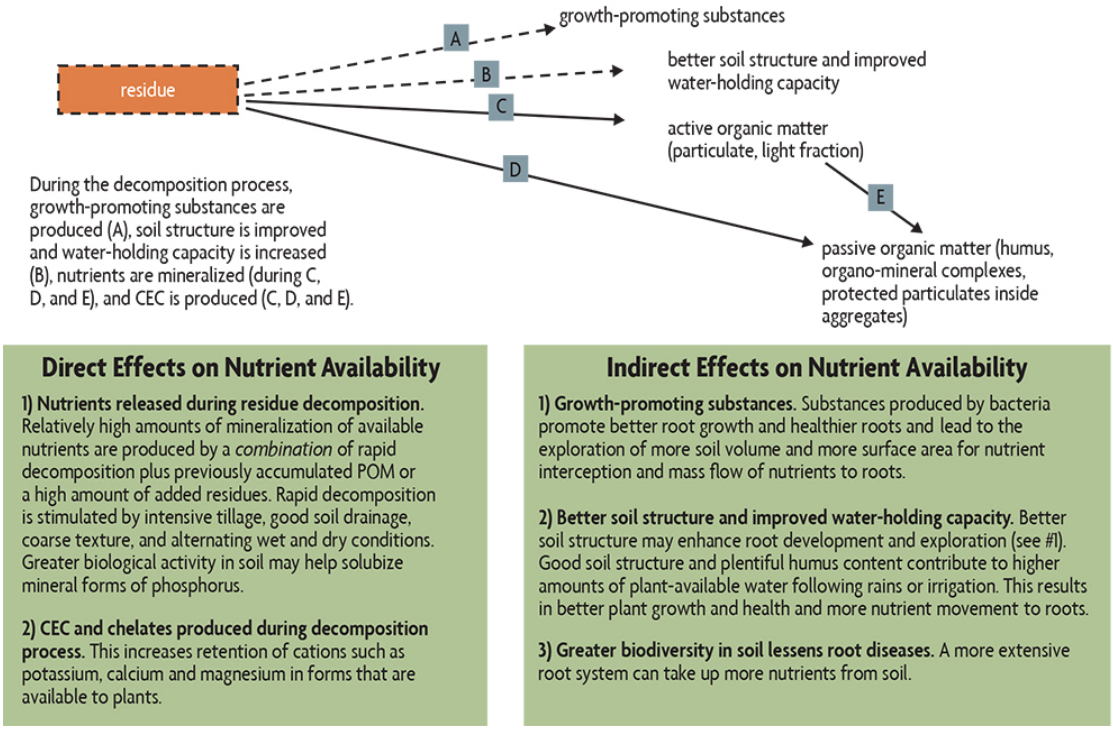

Figure 6.2.1: Influence of residue decomposition on nutrient availability.

Cover crop roots (living soil organic matter) also contribute to nutrient management. They provide energy material that allows soil organisms to 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.

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6.3: Nitrogen Cycling

The Elusive Case of Nitrogen

You have read a little in the previous sections about the cation exchange capacity of soil and how the nutrients K, Ca, and Mg are made available to the plant. Now we explore how the anion nutrients, especially Nitrogen (N), behave in soil and how the plant can access them. Rather than “exchanging” the major anions N, P, and S are considered to “cycle” through the soil in various forms.

Nitrogen (N)

Nitrogen is not very abundant in soil but it is a relatively large component of the plant body. Plants remove nitrogen from the soil and concentrate it in their tissues. Nitrogen needs to be replenished whenever annual crops (except legumes) are grown because they remove nitrogen from the system.

What **role** does nitrogen play in the plant? The presence of nitrogen is the defining characteristic of all proteins. You’ve probably heard of amino acids, these are simply some basic nitrogen-containing molecules that are the building blocks of even more complex molecules called proteins. This is why nitrogen is in such demand by both plants and animals. It is the foundation of all proteins, and thus all life. It is not synthesized from the air (except by bacteria in the nodules of legume plants) or water. Nitrogen is usually not a limiting factor in normal plant growth; but it is often limited in the high production and yield goals of modern agriculture, even sustainable agriculture.

Besides nitrogen, there are two other anionic macronutrients plants require, phosphorus and sulfur. What is the relationship between the presence (or absence) of these anionic elements in the soil and their availability for the plant as nutrients? The availability is considered in the context of how they cycle from one form to another. Nutrient cycling of **anions** is complex compared with the availability of the **cations** which simply “exchange”. We’ll take a look at the nitrogen cycle to see all the forms this nutrient can take and just how complex it is to find out if plants have enough. After that, we’ll review the implications of the cycle for nitrogen fertilizer and farming.

Nitrogen has a lot of options when it comes to forming compounds. It is simply looking for ways to feel stable and balance out that extra electron circling outer orbit. Chemically, relationship-wise, it’s looking to be completed.

Table 6.3.1: Nitrogen Compounds

Shares electron(s) with:	Results in:	We call it:	Comments
Another N	N_2	Nitrogen gas	It’s in the air. It makes up 78% of our atmosphere! Super stable triple bond takes energy to break.
Two oxygens	NO_2	Nitrous oxide	Potent “greenhouse” gas
Three oxygens	NO_3^-	Nitrate – a 'slippery' molecule	If it is not taken up by plant roots it either leaves the soil as NO_2 gas or through leaching.
Four H’s	NH_4^+	ammonium	Yummy form plants can take up via roots
Three H’s	NH_3	ammonia	An intermediate form on the way to NH_4^+

The nitrogen cycle is a picture of the different ways and places that nitrogen exists.

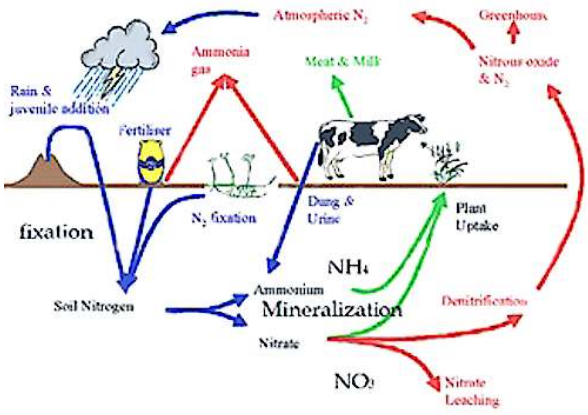

Figure 6.3.1: The Nitrogen Cycle. Design: V. Dantoin

The blue arrows above indicate ways that inert atmospheric nitrogen N_2 enters the biological system. The red arrows indicate ways that biologically available nitrogen leaves the plant/soil system.

Definitions in the Nitrogen Cycle:

Fixation (Getting N into the soil)

The process of converting atmospheric nitrogen (N_2) to forms usable by plants. How? Three ways: a) nodules form with micro-organisms and roots in legumes b) lightening or volcanic eruptions provide enough energy to bind molecules of nitrogen together with oxygen or c) industrial manufacturing process which results in fertilizer. To "fix" nitrogen requires energy and that is why it's an expensive fertilizer. At any one time, 99% of the soil nitrogen is in this fixed, organic form. Fixed nitrogen means it is stuck in, or part of the bodies of soil micro-organisms.

De-nitrification (Losing N from the soil)

Fixed soil nitrogen converts back to N_2. There are a variety of ways denitrification occurs. Both have to do with water. Rainwater can leach the "slippery" nitrate molecules out of the soil and into the groundwater. Nitrogen can also volatilize - becomes a gas; it leaves the soil and re-enters the atmosphere as inert N_2 or as greenhouse gas NO_2. These two processes, fixation and denitrification are always in balance. More sub-cycles occurring in the soil are outlined below:

Mineralization

Fixed, organic nitrogen becomes *available* nitrogen to the plant as Ammonium (NH_4^+), this is mineralization. About 2-3% of organic nitrogen becomes mineralized in a year. One complete "turn over" of soil nitrogen occurs then every 30-50 years. Mineralization is also called ammonification because it first becomes ammonia (NH_3) which then continues its' transformation into ammonium which plants use. Soils high in organic matter can contribute a lot of nitrogen to plants through mineralization.

Nitrification

This is the process by which NH_4^+ produces available nitrogen as the nitrate (NO_3^-) anion. Nitrification results in the production of H^+ ions and can increase soil acidity (lowers pH). Nitrates are stable in well-aerated soil but leach easily out of wet soil because they combine with H_2O and run away together.

Uptake or Immobilization

Plants take up both NH_4^+ and NO_3^- through their roots and incorporate them into their bodies. The nitrogen becomes immobile because it is "stuck" in the body of a plant. This is different than mineralization where N from the atmosphere becomes embodied in soil organisms.

Natural Nitrogen Fixation

Most people don't realize that we are surrounded by an atmosphere full of nitrogen. The air we breathe is 78% nitrogen gas, N_2. This nitrogen gas is very inert because it is triple-bonded to itself. It (N_2) doesn't want to transform into a biologically available form of nitrogen. If only we could get all that nitrogen into something we can use to grow plants then life would be wonderful, right? How does N_2 from the air become bio-available? Well, in a natural system, nitrogen is fixed in one of two ways. One way it

is fixed is by the incredible, tiny, fantastic little bacteria (Rhizobia) associated with root nodules of plants in the legume (and other) families as shown in the image below. There are also some other kinds of free-living bacteria that fix nitrogen. A second (minor) way N enters the biosphere is with a massive injection of lightning energy, or volcanoes. The heat energy in lightning causes the N to combine with oxygen to form compounds that fall to the earth in the rain.

Figure 6.3.2: Roots of soybean plant with root nodules. The interior of the nodule is red showing the nitrogen that is fixed by bacteria. Copyright: Fabian von Beesten, www.gartensoja.de. CC BY 4.0

Synthetic Nitrogen Fixation

The third way nitrogen gets fixed is synthetically, by humans. We use energy from fossil fuels to power the reaction. Here is a short explanation from the website "How Stuff Works". "In this process, heated nitrogen (from the air) and hydrogen are mixed under very high pressure in a vessel where they combine chemically. The vessel contains a catalyst (usually iron with oxides of aluminum and potassium), which speeds up the chemical reaction. The Haber process is the most widely used process for the commercial production of ammonia. Fritz Haber, a German chemist, developed the process in the first decade of the 20th century. Karl Bosch, another German scientist, adapted the process for industrial use." This is the Haber-Bosch process. As a side note, Fritz Haber was also a nazi war criminal - his nitrates were used in bomb-making. Is the Haber-Bosch process a blessing (feeds a lot of people) or a curse (significant degradation of the environment) because it allows nitrogen to break free from its natural moorings and be added anywhere fossil fuel manufacturing can make it available?

Demand by plants (to build proteins) is why synthetic nitrogen fertilizers are the most heavily used type of fertilizer in conventional agriculture. Because plants (and resulting animal milk and meat) are removed from a farm by harvest, nitrogen is removed and must be replaced. Synthetic nitrogen is quite expensive and energy-intensive to manufacture. It is an "unnatural" addition to a plant-soil-atmosphere system that was balanced at one time. What we've done is take a stable N_2 atmospheric molecule, break it apart, feed some of it to plants as fertilizer, and let the rest escape the soil cycle as either nitrous oxide greenhouse gas or nitrates leached into our waterways.

> **Industrially fixed nitrogen is something new on the earth**. We've doubled the amount of fixed nitrogen previously in the natural cycle taking it from a stable N2 form. Unstable soil nitrogen escapes as a reactive greenhouse gas. We now add over 10 million tons of NO_2 to the atmosphere annually. As non-organic corn production rises so will our synthetic N production and its transformation and escape into the atmosphere and into our groundwater. Humans have become an important factor in the nitrogen cycle.

It is estimated that up to half of the nitrogen conventional farmers apply to their corn crops is lost from the system by leaching or denitrification. In high corn yield areas, it is not uncommon for farmers to add 200 lbs of synthetic nitrogen per acre to a corn field. They add it at somewhat lower or higher levels according to the price of the N fertilizer. Nitrogen fertilizer is relatively cheap because of the fracking boom in natural gas and the cheap energy costs. But if 200/lb/A is added, and only half of that is actually used by the crop, the other 100 lbs/A runs out of the system and into the environment. This is a cost externalized to all of us.

Organic Farming and the Nitrogen Cycle

Organic farms are not allowed to use synthetically produced sources of nitrogen like urea or synthetic ammonium. In fact, this restriction is probably what prevents a majority of regular crop farmers from becoming certified organic. They just can't imagine

cropping without synthetic N.

So how do organic farms get nitrogen into the soil? What are the organic options for nitrogen? There are organic fertilizers that can be purchased, but most organic farmers choose to “grow their own” nitrogen.

A “per acre furrow slice” of soil contains about 1000 lbs. of nitrogen for each 1% of organic matter, but as we have learned, most is in the fixed form. There will be about 20-30 pounds of nitrogen mineralized each year for each 1% organic matter in the soil. A 150 bushels of corn/A contains 235 pounds of nitrogen incorporated into plant tissue itself. The natural sources of nitrogen in many conventional soils is small compared to the needs of industrial corn. Where will the organic farmer get the 200 lbs. of nitrogen needed to grow 150 bushels of corn?

High Amounts of Organic Matter

Soils with high amounts of organic matter may supply almost enough nitrogen for a high-yielding corn crop. For example, soil with organic matter of 3.5 percent may contain 3,500 lbs. of Nitrogen per acre. It will mineralize or make available about 105 pounds of nitrogen per acre. Organic farmers seek to increase soil organic matter as a means of increasing the nitrogen available to their plants.

Mineralization Rates

The nitrogen-supplying power of soil is intimately related to the organic matter and mineralization rates of soil.

Organic farmers tend to supply most of their nitrogen needs by using biological processes rather than synthetic processes. Organic farmers “grow their own” nitrogen in a variety of ways; animal manures, green manures, cultivating the mini-livestock in the soil, the nitrogen-fixing bacteria and the worms, and soil biology. The bottom line, organic farmers grow nitrogen by harvesting it from the atmosphere rather than purchasing nitrogen when possible.

Also, organic farms lose very little nitrogen from the system or soil cycle due to denitrification, leaching, and volatilization. Organic nitrogen is slowly released and steady. It is not lost from the system and is therefore available to the plant.

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6.4: Phosphorus Cycling and Flows

Phosphorus, like nitrogen, is a macronutrient anion. And like N it also cycles in the soil (though not in as complicated a way as nitrogen).

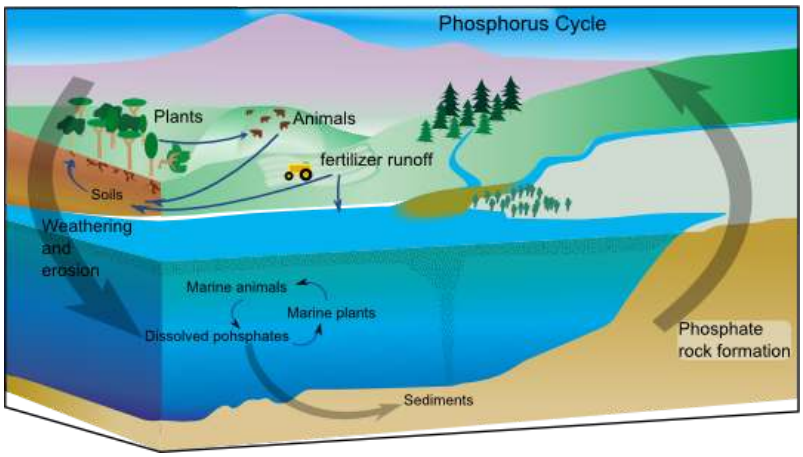

Figure 6.4.1: The 'natural' Phosphorus Cycle: Reworked by Bonniemf from the public domain file. CC - Wikimedia

Figure 6.4.1 shows that **rock weathering** from the earth's crust had been **the only way** geological phosphorus came into the biological realm. For this reason, P has been described as a bottleneck element--a plant or a field is often limited by how much of this nutrient it can lay its roots on. As Julia Rosen writes in her 2021 article in the Atlantic magazine, "Organisms have generally had to wait for geologic forces to crush, dissolve, or otherwise abuse the planet's surface until it weeps phosphorus. This process of weathering can take thousands, even millions, of years. And once phosphorus finally enters the ocean or the soil, where organisms might make use of it, a large fraction reacts into inaccessible chemical forms."

Phosphate ions (H2PO4-) are the forms the plant takes up from soil/water solution and immobilizes in its body.

Phosphorus does not enter into a gaseous state and causes greenhouse gas problems like Nitrogen. It does not often leach through the soil either unless it is quite excessive. So the P cycle is simpler than the N cycle because it does not leak P via gas or leaching.

Phosphorus does, however, cause serious environmental problems because the H2PO4- ion is not stable in soil solution like the nitrate ion. It adsorbs onto clay particles. When the clay topsoil is washed into streams and rivers via rainfall, the phosphate ion goes with it. Then, it "releases" when it is in the water. Algae blooms are fueled by too much phosphorus entering the system. The resultant explosion of algae sucks the oxygen out of the water causing fish and other aquatic organisms to die, the water body becomes hypoxic. The Bay of Green Bay (Wisconsin) has 'always' been green because of the abundant phosphorus released from the clay soils in the watershed. One local stream was named 'glaice' or clay creek by the first French traders to make the area their home.

What the first diagram of the phosphorus cycle does not show, but the diagram below does, is the influence of human activity on the cycle.

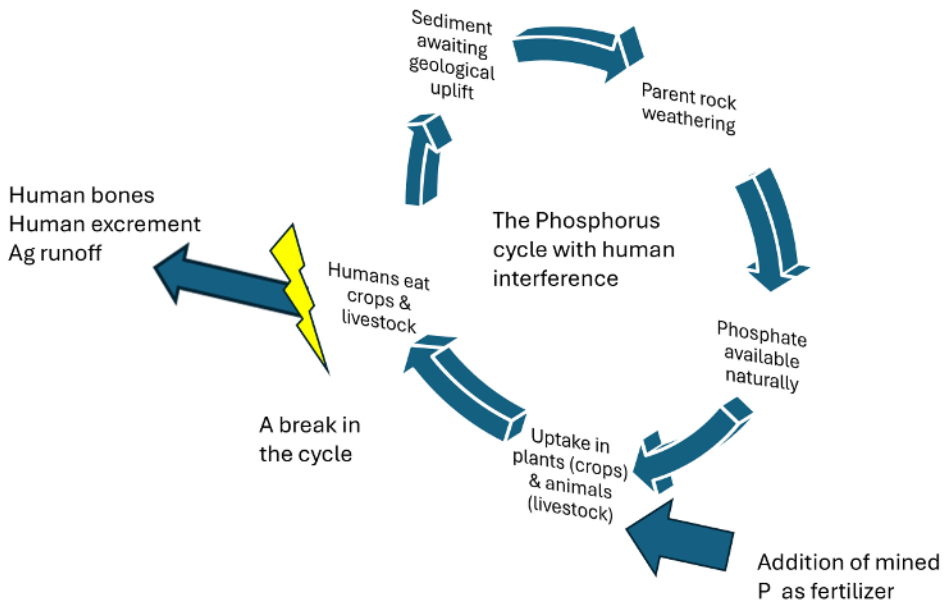

Figure 6.4.2: The Phosphorus Cycle with human interference. Author: Valerie Dantoin 2025

What happens to all the phosphorus that accumulates in cities in the form of human bodies and human excrement? That is where there is a break in the cycle. The phosphorus is not returning to the soil, it is sent into the ground in human bones, but they are locked far away from farm fields. Phosphorus is not removed during sewage treatment and it is discharged into waterways of cities and towns. It flows out into large water bodies and settles at the bottom. In millions of years, as the earth changes and seas rise and fall, the phosphorus may again become available as dried sediment if there are any humans around to mine it. Because there is a finite amount of phosphorus and because we humans are sealing it away in our bones or peeing it into our waterways where it becomes a pollutant - we remove it from the farm cropping system and it will run out.

The Natural P Cycle and Human Activity - Julia Rosen

"Over the course of several weeks in 1669, a German alchemist named Hennig Brand boiled away 1,500 gallons of urine in hopes of finding the mythical philosopher's stone. Instead, he ended up with a glowing white substance that he called *phosphorus*, meaning "light bearer." It became the 15th element in the periodic table, the incendiary material in matches and bombs, and—thanks to the work of Liebig and others—a key element in fertilizer.

Long before phosphorus was discovered, however, humans had invented clever ways of managing their local supplies, says Dana Cordell, who leads the food-systems research group at the University of Technology Sydney, in Australia. There and in the Americas, for example, Indigenous people managed hunting and foraging grounds with fire, which effectively fertilized the landscape with the biologically available phosphorus in ash, among other benefits. In agrarian societies, farmers learned to use compost and manure to maintain the fertility of their fields. Even domestic pigeons played an important role in biblical times; their poop—containing nutrients foraged far and wide—helped sustain the orchards and gardens of desert cities.

By the 1800s, centuries of cultivation had sapped Britain's soils of nutrients, including phosphorus—an essential element for crops. At the time, manure and bones were common sources of phosphorus, and when the country exhausted its domestic reserves, it looked elsewhere for more.

"Great Britain is like a ghoul, searching the continents," wrote Justus von Liebig, the German chemist who first identified the critical role of phosphorus in agriculture. "Already in her eagerness for bones, she has turned up the battlefields of Leipzig, of Waterloo, and of the Crimea; already from the catacombs of Sicily she has carried away the skeletons of many successive generations."

Then, in the 1840s, geologists discovered phosphorus-rich stones buried in the fields around Cambridge (England)" ...

> "Over the ensuing decades, workers extracted 2 million tons of coprolites, transforming the fields and fens of southeast England into a warren of pits and trenches that dwarfed Simon's hole. Coprolites were sorted, washed, and transported by buggy, train, and canal barge to processing facilities, where they were milled and treated with acid to make superphosphate—the world's first chemical fertilizer.
>
> The rocks helped Britain boost its food supply and consummate the so-called Second Agricultural Revolution (the first "revolution" being the rise of agrarian civilization). Coprolites and other geologic deposits of phosphorus also raised the tantalizing possibility that humans had at last broken free of an age-old biological constraint. For billions of years, life on Earth had struggled against a stubborn lack of phosphorus. Finally, that was about to change."

Seabird guano (manure) from islands in the Pacific Ocean was mined by workers (and some slave labor) in the late 1800s. This mining industry sent phosphorus by the ton, in sailing ships to Europe to fertilize fields and uncork the phosphorus bottleneck. Bat guano from caves was also mined by imperial industries until it was all gone. Of course, mining operations disrupted the birds and the bats so no new deposits accrued.

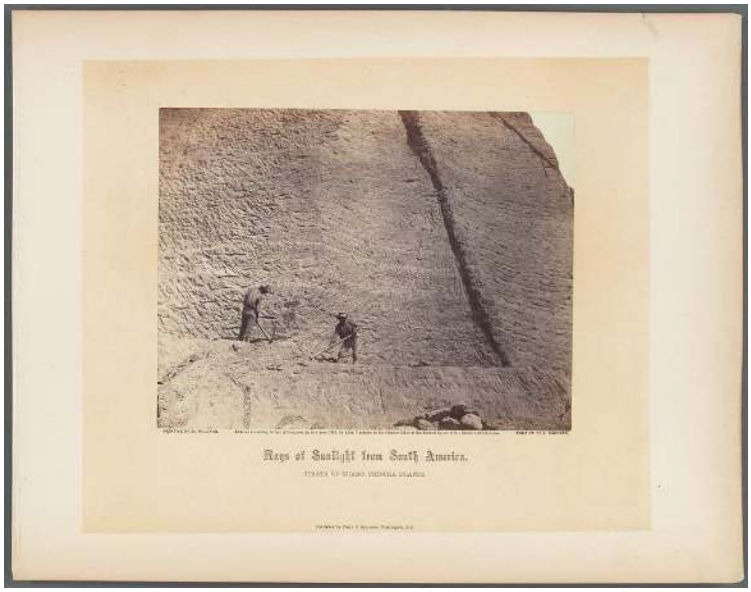

Figure 6.4.3: Mining guano in the South Pacific. CC Public Domain [creativecommons.org]

In the United States, bones of bison slaughtered on the Great Plains were collected and ground for phosphorus fertilizer. In the late 1800s phosphate mines began operations near Charleston South Carolina--digging the rock sediments of long-dead sea life and ocean deposits. Most P now comes from sediments in Florida where problems with mining and evaporation ponds cause their own environmental issues.

Again, Rosen writes: "These deposits became increasingly important in the 20th century, during the Green Revolution (the third revolution in agriculture if you're keeping track). Plant breeders developed more productive crops to feed the world and farmers nourished them with nitrogen fertilizer, which became readily available after scientists discovered a way of making it from the nitrogen in the air (Haber Bosch). Now, the main limit to crop growth was phosphorus—and as long as the phosphate mines hummed, that was no limit at all. Between 1950 and 2000, global phosphate rock production increased sixfold and helped the human population more than double.

But for as long as scientists have understood the importance of phosphorus, people have worried about running out of it. These fears sparked the fertilizer races of the 19th century as well as a series of anxious reports in the 20th century, including one as early as 1939, after President Franklin D. Roosevelt asked Congress to assess the country's phosphate resources so that "continuous and adequate supplies be insured."

Figure 6.4.4: A phosphate mine in Morrocco. Kopalnia piasku Dargocice. Web Archive [web.archive.org] CC BY

If phosphorus is a limiting factor in plant growth, a weak link in the chain, that means we do not have unlimited capacity to continue growing the human population. A 'new' source of phosphorus must be found and perhaps that source is recycling. Not recycling of metal cans or cardboard or plastics.... but of poop and pee.

Julia Rosen writes "... human waste was perhaps the most prized fertilizer of all. Though we too need phosphorus (it accounts for about 1 percent of our body mass), most of the phosphorus we eat passes through us untouched. Depending on diet, about two-thirds of it winds up in urine and the rest in feces. For millennia, people collected these precious substances—often in the wee hours, giving rise to the term *night soil*—and used them to grow food."

There are many examples of civilizations that realized the importance of recycling their 'waste' and using it to continue producing food. Rosen continues "The sewage of the Aztec empire fed its famous floating gardens. Excreta became so valuable that authorities in 17th-century Edo, Japan, outlawed toilets that emptied into waterways. And in China the industry of collecting night soil became known as “the business of the golden juice.” In Shanghai in 1908, a visiting American soil scientist named Franklin Hiram King reported that the “privilege” of gathering 78,000 tons of human by-products cost the equivalent of $31,000."

F.H. King was a soil scientist who wrote the book 'Farmers of Forty Centuries' explaining the way Chinese farmers on terraced hillsides kept their land productive by recycling human waste. The soils department building at the University of Wisconsin Madison is named after him. He understood that our modern way of taking care of our sewage using clean water for flushing, was not, perhaps the best way. It certainly failed to recycle the P in our pee or poop. King wrote that although 'sanitation' was a great achievement because it reduced some biological illnesses found in sewage where large numbers of humans congregate, it failed to recognize the importance of recapturing phosphorus (and nitrogen) in our own manure.

Of course, back in the 1900s it would have been difficult to collect, transport, and spread human waste back onto farm fields. But this break in the P cycle was exactly what early thinkers in economics would describe as a metabolic rift. The rift is a break in the cycle and the change in flows from sources to new sinks. As Rosen pictures it, the loop has become a one-way pipe. It can also be pictured as a map of the U.S. where the Pacific coast and the Atlantic coast are made of mountain ranges, and the ranges are piles of human bones and excrement. On the map, in the middle of the country is a deep valley where the nutrients have been mined and transported to the human population mountains on the coasts. Its an unsettling image, but one that depicts how a source (the American Midwest) is hollowed out to build up the coastal mountains - the final resting place of the continent's phosphorus and other nutrients.

She continues “That single disruption has caused global chaos, you could argue,” Cordell says. For one thing, it forced farmers to find new sources of phosphorus to replace the nutrients lost every year to city sewers. To make matters worse, agricultural research in the late 1800s suggested that plants required even more phosphorus than previously thought. And so began a frantic race for fertilizer. These events raised a terrifying possibility: What if the phosphorus floodgates were to suddenly slam shut, relegating humanity once more to the confines of their parochial phosphorus loops? What if our liberation from the geologic phosphorus cycle is only temporary?

Dan Eagan writes in The Devils Element that 'The potential benefits to better managing manure are staggering, both in protecting water quality and preserving phosphorus rock reserves for future generations'. He is writing about cow manure, but the same applies to human manure. Eagan quotes Jim Elser director of the Sustainable Phosphorus Alliance, "If all manures were recycled and returned for [agricultural] production, I think you could displace half of the mined fertilizer."

We have a strong prohibition against human waste in the U.S. because of potential pathogens. We seem to treat it like it's poisonous. We have crafted laws that regulate any manure, let alone human manure, from touching or contacting our vegetables

and fruits. However, these regulations do take into account that if a raw vegetable is cooked (has a 'kill' step) then it can come in contact with manure used as fertilizer. There are numerous ways to limit pathogens in produce. It is safe to use manures, for example, if they go through a composting process or if there is a waiting period between application and vegetable harvest. We as a society just have to get over the 'ick' factor. Some scientists are experimenting with new toilets that conserve water (up to 7 gallons for every flush according to Eagan) and also collect and concentrate the nutrients. There are companies working on systems that retrieve and concentrate P from municipal sewage plants. Some European countries have passed laws that require P recovery from sewage.

The U.S. used to be an exporter of P but has now become a net importer. Estimates vary on how much P there is left to mine in deposits around the world. The Moroccan deposits in the Western Sahara desert as well as deposits in China may only have a few decades left before they are scraped dry, just like the once mountainous reserves on the Guano islands in the Pacific. Of course, both countries' mines are subject to political instability as well. Other experts in the industry claim there are 350 years worth of P left in global deposits and that we will find more ways to find more supply as we have done with fossil fuels. Perhaps rocks on the floor of the ocean? It will of course take more energy to extract these remote P resources and then we still have the problem that we re-deposit P in our skeletons and excrete P fertilizer inputs out into our waterways via pee.

Eagan notes that it is a bit ironic that it has been about 350 years since Hennig Brandt discovered phosphorus and now we are facing a potential reduction in crop yields as P runs out. However, it is exciting to consider that maybe we are beginning to realize we have to 'do agriculture' and take care of nutrients in the soil in more careful ways. Maybe we are at the bottom of a pit where we have extracted resources and spilled them onto the landscape and into the water without care. Maybe we will understand that to farm sustainably we have to recover and reuse our precious phosphate if we are to dig our way out from the bottom and reach sustainability.

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6.5: 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

Reduce 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, 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.

The ABCs Of Nutrient Management

1. Balance nutrient inflows and removals to maintain optimal levels and allow a little “drawdown” if nutrient levels get too high.
2. 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.
3. Build up and maintain high soil organic matter levels for biodiverse soils and to develop healthy plant roots.
4. Test manures and credit their nutrient content before applying fertilizers or other amendments.
5. If using liquid manure, consider soil injection to reduce N volatilization and potential loss of nutrients in runoff.
6. Test soils regularly to determine the nutrient status and whether or not manures, fertilizers, or lime are needed.
7. Use regionally adapted nutrient recommendation tools.
8. Apply most nitrogen close to the time of crop uptake, and use recommendation tools that account for soil, weather, and management practices.
9. Use forage legumes or legume cover crops to provide N to subsequent crops and to develop good soil structure.
10. 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.
11. Maintain soil pH in the optimal range for the most sensitive crops in your rotation.
12. 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.
13. To get the most efficient use of fertilizer when P and K levels are at or below the medium or lower categories, consider band application at planting, especially in cool climates.

Enhance Nutrient Uptake Efficiency

Enhance the uptake of nutrients by carefully using fertilizers and amendments, as well as irrigation practices. Better placing and synchronizing nutrient applications with plant growth improve the 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

Seek 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). 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 the 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

Support local markets and return local food waste 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

Add 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 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 are discussed later, on integrating livestock and cropping.

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

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.

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. The problem with using more technology to mitigate a nutrient flow problem is that it is not scale-neutral. That means that you have to be a farm of a certain size, usually something like 750 dairy cows, to make it

cost-effective to install any type of nutrient export technology. If public tax dollars are put toward these solutions then they become a type of subsidy to a CAFO farm and make them more competitive at selling milk in volume, thus perpetuating the problem of too many cows on too few acres.

A better solution for large-scale farms, albeit lower-tech, is to move dairy heifers to outlying regions and pasture them there. Put cows back on landscapes that were formerly just supplying crops to the CAFO.

Farmers are finding that composting is an attractive alternative way to handle manure. During the composting process, volume and weight are greatly reduced, 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.

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

> *... 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*

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6.6: N and P Movement in the Environment

As you've previously read, 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 here because we don't want to prioritize the management of one nutrient and neglect the other; it is important to consider a balance. Potassium (K) does not present environmental problems. 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 at once. 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.

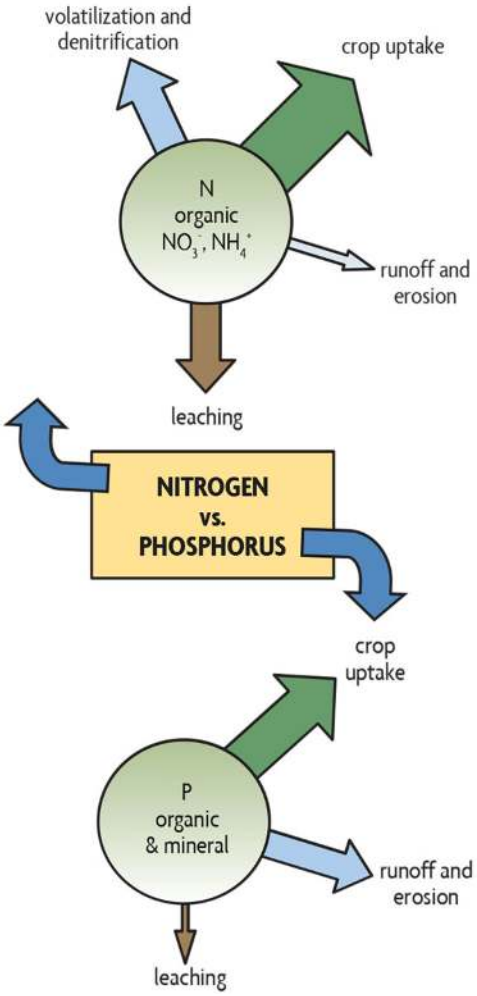

Figure 6.6.1: Different pathways for nitrogen and phosphorus losses from soils (relative amounts indicated by the width of arrows). Based on an unpublished diagram by D. Beegle, Penn State University.

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, block 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 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 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.

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, New York, and Wisconsin 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 and in Lake Michigan's Green Bay.

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 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. Both N and P can, of course, be supplied with 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 6.6.1 for a comparison between relative pathways for N and P losses). But it doesn't take much P to have a 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. 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.

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.

Improving N and P management can help reduce reliance on commercial fertilizers. A more ecologically based system, with good rotations, reduced tillage, and 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.

Table 6.6.1: 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. • 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. • Nitrate can be easily lost in large quantities by leaching to groundwater or by conversion to gases (N_2, N_2O). • 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.	• Phosphorus becomes available from decomposing soil organic matter and minerals. • P is relatively immobile and is only available to plants in small concentrations as dissolved phosphorus in the soil solution, mainly as dihydrogen phosphate ion $[H_2PO_4]^-$ while the removal of two protons gives the hydrogen phosphate ion $[HPO_4]^{-2}$ • 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. • No equivalent reaction can add new P to the 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.

A high percentage of the nutrients in feeds pass right through animals and end up in their manure. 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, 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 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.

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.

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 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.

It is worth noting also that one dairy cow produces as much manure or poop as 18 humans each day. So, a typical CAFO that has 4,000 cows is equivalent to a small town with 72,000 people..... and the farm does not have a sewage treatment system.

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CHAPTER OVERVIEW

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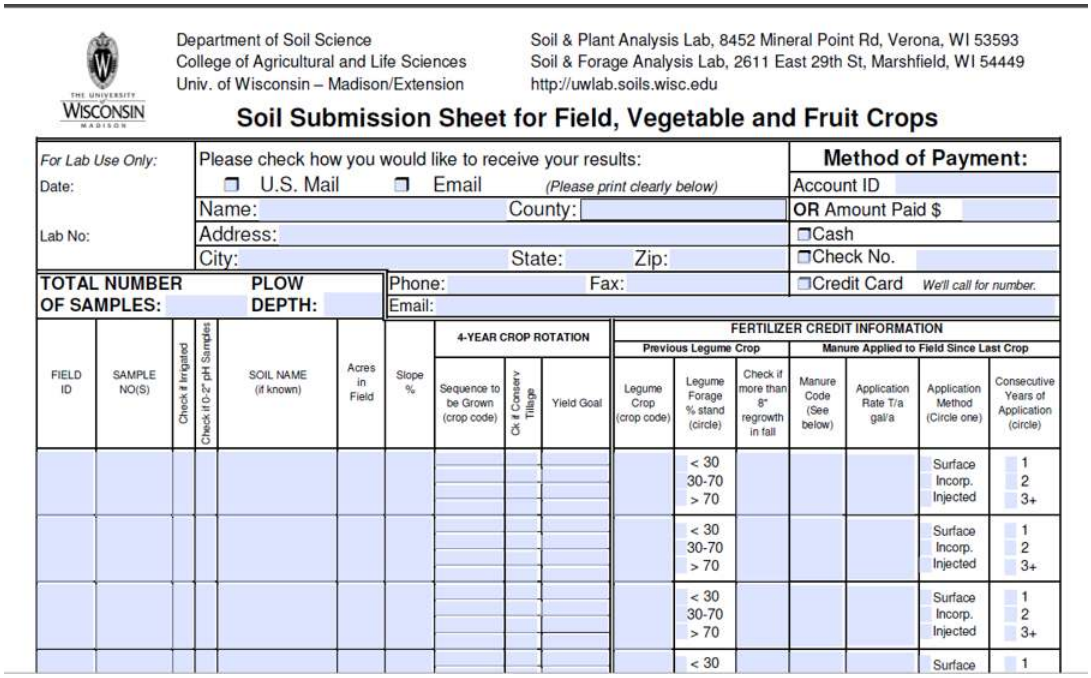
7.1: How to Submit Soil Samples for Testing

Steps for Submitting Soil Samples

1. Find the name of your soil
2. Write down the crop rotation.
3. Indicate the tests you want done.

Here is a picture of a typical soil sample submission form from the University of Wisconsin.



Department of Soil Science
College of Agricultural and Life Sciences
Univ. of Wisconsin – Madison/Extension

Soil & Plant Analysis Lab, 8452 Mineral Point Rd, Verona, WI 53593
Soil & Forage Analysis Lab, 2611 East 29th St, Marshfield, WI 54449
http://uwlab.soils.wisc.edu

Soil Submission Sheet for Field, Vegetable and Fruit Crops

For Lab Use Only: Date: Lab No:

Please check how you would like to receive your results: ❒ U.S. Mail ❒ Email *(Please print clearly below)*
Name: County:
Address:
City: State: Zip:
Phone: Fax:
Email:

Method of Payment:
Account ID
OR Amount Paid $
❒Cash
❒Check No.
❒Credit Card *We'll call for number.*

TOTAL NUMBER OF SAMPLES: **PLOW DEPTH:**

FIELD ID	SAMPLE NO(S)	Check if Irrigated	Check if 0-2" pH Samples	SOIL NAME (if known)	Acres in Field	Slope %	4-YEAR CROP ROTATION: Sequence to be Grown (crop code)	4-YEAR CROP ROTATION: Ck if Conserv Tillage	4-YEAR CROP ROTATION: Yield Goal	FERTILIZER CREDIT INFORMATION: Previous Legume Crop: Legume Crop (crop code)	Previous Legume Crop: Legume Forage % stand (circle)	Previous Legume Crop: Check if more than 8" regrowth in fall	Manure Applied to Field Since Last Crop: Manure Code (See below)	Manure Applied to Field Since Last Crop: Application Rate T/a gal/a	Manure Applied to Field Since Last Crop: Application Method (Circle one)	Manure Applied to Field Since Last Crop: Consecutive Years of Application (circle)
											< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
											< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
											< 30 30-70 > 70				Surface Incorp. Injected	1 2 3+
											< 30				Surface	1

Figure 7.1.1: Soil sample submission form. (Copyright; University of Wisconsin)

One important piece of information you will need to complete the form is the **name of the soil** in your fields. This will ensure that the best recommendations can be made. The university results rely heavily on soil types, so it's important to figure out the soil name.

What Is the Name of My Soil?

In order to get the most accurate information out of a farm or field soil test you need to know what kind of soil you are working with. This is where soil maps come in handy. Or call your USDA NRCS office to get help. List that soil name on your soil test submission form.

For example, our farm is predominantly Onaway sandy loam. It has a corn yield potential code of 3 and an alfalfa yield potential code of 2. On this scale, 1 = very high, 2 = high, 3= medium and 4 = low.

Web Soil Survey - USDA

If you don't know your soil type or name you can go online and discover your soil name by bringing up USDA Natural Resources Conservation soils maps and locating your property. To find a soil name anywhere in the country, click on this link: Web Soil Survey

Read the page then click on the green "Start WSS" button. The next page that opens has a listing of "navigate by" bars on the left. Click the "State and County" bar and then type in the location by state and county that you want to visit. Once you have done that, a map will appear on the right. Place the cursor over the location you want to explore more closely and click. This tool works like Google Maps; click to keep zooming in until you have found the farm or plat of land you are looking for.

Figure 7.1.2: USDA Web Soil Survey site (Copyright; United States Department of Agriculture)

Once you have zoomed in on the acreage you want to view, click on the little AOI (Area Of Interest) button. Use it to draw a rectangle over the acreage you want to more closely examine. Once the rectangle is drawn, go back to the top set of tabs and click on “soil map.” Soon, a new map will be drawn with the soil abbreviations overlaying the entire acreage you have highlighted as an AOI. The left-hand side of the page will give a little description of the soils that appear on your map. You can then click on the “printable version” tab. (If the map will not print, you may have to disable the “cookie protection” in your browser.)

Now that you know your soil's name, you can enter it on the soil sample submission form to get the most accurate fertilizer recommendations possible.

Cropping History and Intentions

One other thing you will have to indicate on the soil submission form is the cropping history and the crop you intend to plant. That is because recommendations are based on crop expectations and how much of each nutrient each crop needs.

Many people make the mistake of submitting a lawn & garden form rather than a field crop form. The tests are the same, but farmers get a cheaper rate, so submit a field crop form to save money. Also, lawn & garden recommendations are based on your county, not the name of the soil itself. Lawn & garden recommendations are less precise than farm & field. I suggest submitting a garden soil on a farm “field” sheet rather than a lawn & garden sheet. It is less expensive ($8.00 vs. $15.00).

Once you’ve submitted a sample you will get results and a recommendation of whether to take corrective actions.

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7.2: Ideal Soil Test Numbers

One of the first steps in understanding how to read and interpret your own soil test report is to know what an “ideal” soil looks like. In this section, we will review averages for soil pH, Nitrogen (N), Organic Matter (OM), Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), Cation Exchange Capacity (CEC), and percent base saturation. If your soils are a lot higher or a lot lower than the ideal numbers shown here, then you will probably consider taking corrective actions by amending the soil and applying appropriate fertilizers or amendments. Recommendations for action are presented in another section; here we concentrate on the ideal or average numbers you are looking for in a soil test report. In the remainder of this chapter, we discuss in more detail testing methods, how to read the results, and what the numbers mean. Use this section as a more simple 'cheat sheet' for appropriate soil test values.

pH

This should generally be between 5.8 to 6.8. If your results are lower, your soils are probably too acidic and will require liming. Here is a list of the target pH for several crops important in the upper Midwest of the U.S. according to University of Wisconsin recommendations. More crops are listed in Publication A3030.

Table 7.2.1: Target pH for Crops in the Upper Midwest

Crop	Ideal pH	Crop	Ideal pH
Corn, silage, or grain	6.0	Pasture; grass or legume/ grass mix	6.0
Soybeans	6.3	Wheat	6.0
Most vegetable crops	5.8 - 6.0	Red Clover	6.3
Blueberry, cranberry	4.5	Alfalfa	6.8

Some soils (in northeastern Wisconsin for example) have a naturally occurring high pH due to underlying parent rock like dolomitic limestone. If you are in a high-pH soil area, do not add lime (calcium carbonate).

A typical university soil test report may show you the actual pH number, or it may just indicate if the soil pH is high, low, or just right in the context of the most pH-sensitive crop you submit on the information sheet.

Nitrogen (N)

Nitrogen is a very expensive input so farmers and gardeners should know what an ideal amount is in the soil, right? Well, it turns out that soil tests don’t measure nitrogen for a variety of reasons. The main reason is that nitrogen is a “changeling” – it exists in a variety of forms that are hard to test for and measure. Also, synthetic N fertilizers can’t be stored in the soil well; they may leach into the groundwater or volatilize or denitrify. Rather, the nitrogen numbers you see on most University soil test reports are simply suggested amounts based on likely crop responses to a standard amount of fertilizer.

Organic Matter

Organic Matter is another way to think about how much nitrogen and carbon an ideal soil should have. Biological and organic farmers should look at the percent **organic matter** (OM) on a soil test to get an indication of the nitrogen potentially available from within the soil itself. The higher the percent organic matter, the better. Though organic matter is a measure of soil carbon, it is also a reflection, generally, of how much soil life your fields or garden have. Soil life (soil livestock) is a source of slow-release nitrogen when their bodies die. Organic matter also increases other nutrient-holding capacity.

Organic matter amounts depend on farming practices and can be increased with good long rotations of hay, pasture, or cover crops and the addition of compost or manures. Negative influences on organic matter include tillage and salt-based synthetic fertilizers. Soils that have been row-cropped for a long time without much attention paid to returning organic matter to the soil will be in the 1.5%-2.0% range. Well-tended organic fields have OM in the 2.5% – 6.0% range. An ideal soil on a farm that has been farmed organically for a long time should have at least 3.5% organic matter. This level may not be possible at all on sandy soils or other similar soil types.

Phosphorus (P) and Potassium (K)

Phosphorus and potassium amounts are reported in parts per million (ppm) on soil tests. According to the University of Wisconsin, the amount of fertilizer needed to increase the ppm of P or K to the desired level is dependent on the subsoil fertility group. Including your soil name on the paperwork you submit with your sample is important for this reason. Most land grant university lab results are reported on a simplified scale of recommendations that tell you if, comparatively, the soil is very low (VL), low (L), optimum (O), high (H), very high (VH) or excessive (Ex).

Here is what optimum P and K levels look like for subsoil fertility group A.

Table 7.2.2: Optimum Phosphorus (P) and Potassium (K) Levels for Subsoil Fertility Group A

Subsoil Fertility Group A (naturally high in P, low in K)	Ideal **P** (ppm)		Ideal **K** (ppm)	
Crop to be grown:	UW	Soil Bal.	UW	Soil Bal
Corn	11-15	50-100	81-100	100-350
Soybeans & low-demand field crops	6-10		81-100	
Alfalfa & low-demand veg crops	16-23		91-120	
Red clover & medium-demand field crops	16-20		71-100	
High-demand vegetable crops	31-45		121-180	
Potato	161-200		121-160	

Remember, to find out your subsoil type you will need to know your soil name (see the last section). Laboratories that use the soil balancing approach tend to give a value for ideal P or K without regard to the subsoil fertility or the crop to be grown. The two labs I know of that use the “Soil Balancing” method are the Midwest BioAg lab and a Neal Kinsey-related lab – their average numbers are listed in the table.

Sulfur (S)

This is another element that, like nitrogen, is “slippery” and moves out of the soil profile as well as changing forms. Sulfur enters the system in applied manure, and (in previous years) as free fertilizer in the form of acid rain. It had been released into the atmosphere as a contaminant from coal-fired power plants--it was free--except it was killing lakes in the northeast U.S. because it was too acidic. Sulfur is present in the subsoil and is also released by organic matter in the soil. All these available forms should total something like 3-40 ppm in an ideal soil according to the UW. Soil balancing proponents suggest 50 ppm as an ideal. Most farmers in Wisconsin do not add S fertilizers. Many organic farmers feel that they do get a crop response so they add some sulfur fertilizers.

In general, if you as a farmer or grower, feel like you get enough of a yield increase to cover the cost of adding a fertilizer, then go ahead and do so. Just be aware that with N and P, if you go over the recommendations, you may inadvertently be adding to environmental pollution.

Calcium (Ca)

This is where the UW ideal and the soil balancing ideal numbers part company. There are conflicting theories about the interactions and relationships between soil calcium, potassium, and magnesium; this influences how much Ca is deemed “adequate” by the two different schools of thought. Suffice it to say for now that the UW staff indicate 400-600 ppm Ca is about right for sandy soils while a value of 600-1000 ppm Ca is ideal on loams, silts, clays, organic soils, and “red” soils. Interestingly, until just recently, the University faculty argued that Ca was almost never a limiting factor in plant growth and therefore was not considered an important nutrient for which to test. Since flue-desulfurized gypsum (a waste product from the coal burning plants’ chimney scrubbing) has become available, more and more farmers are applying that product to boost Ca. It is not allowed in organics.

The Soil Balancing professionals, on the other hand, look for ideal Ca numbers in a wide range between 700-2700 ppm, depending on which lab is checked. Some soil balancers are not as concerned with the actual ppm of Ca as they are with the amount of calcium occupying or saturating the cation exchange sites. Remember that this term is called “base saturation”. For soil balancers,

the percentage of cation sites that should ideally be occupied by calcium is 70-75%. Anything less than that likely means, in their theory, that not enough calcium will be plant available.

Magnesium (Mg)

The ideal amount of Mg, according to the University, is **50-250 ppm on sandy** soils and **100-500 ppm Mg on loams**, silts, clays, organic soils, and "red" soils. One soil balancing source gives a range of **110-190 ppm as ideal**. Once again, balancing advocates prefer to suggest that an ideal % base saturation is 12-15%.

Boron (B), Manganese (Mn), Zinc (Zn), Copper (Cu) and Iron (Fe)

These are all considered micronutrients, and most farmers and gardeners don't test the soil for them. Some organic farmers do test for B, Mn, and Zn, and Cu. The University publication A3030 states that presently there are no soil tests for Cu and Fe calibrated for Wisconsin because deficiencies are just so rare. In any case, here are the "ideal" numbers I found listed in the literature and important to soil-balancing advocates:

Table 7.2.2: Ideal Numbers

B	Mn	Zn	Cu	Fe
1-2 ppm	11-20 ppm on low pH soils	3-20 ppm	2 ppm	20 ppm

Cation Exchange Capacity (CEC)

This is a function of the parent material of your soil, just like texture. There is not a lot that one can do to increase the CEC of soil, except perhaps to add organic matter to sandy soils. I'm not sure if it's possible or desirable to decrease the CEC of soil. In general, expect the following CEC levels. The units are milliequivalents (mEq)/100 grams of soil.

Table 7.2.3: CEC Levels to Expect

Muck to high OM soil	Clay to clay loam	Silt loam to loam	Sandy loam to sand
200 - 30	25 - 20	15 - 10	10 - 5 - 1

Percent Base Saturation

As mentioned earlier, base saturation is a poor name. It is confusing. What it means is "how many cation exchange sites are occupied and by what kind of cations." It is expressed as a percent of the occupied sites. It must total 100%. It is a calculation, not an actual test result number. The University does not report it. Soil balancing theorists suggest the following ideal "occupation":

Table 7.2.4: Ideal Percent Base Saturation

% K	% Ca	% Mg	% H	% Na (sodium)
3-5	70-75	12-15	10	1

If you use a soil testing lab that uses the soil balancing approach, these are your ideal % base saturation numbers.

Summary

Using the values found in this section, you should be able to compare your soil test reports with the numerical values you get from the lab. You'll be able to see if you are too low, or too high. Then, you'll be better equipped to make choices about what fertilizers or amendments to put on your crops. You can work with your crop consultant or agronomist to make sure you both understand your numerical results. The more you know, the smarter you'll be about adding inputs and adding to your bottom line.

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7.3.1: Introduction

> *… 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 the 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 important tools 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.

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7.3.2: 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 evaluating N needs (see below). As you will see below, this allows you to make better year-to-year comparisons.

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)

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7.3.3: 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 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 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.

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 nutrients 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.

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7.3.4: 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 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 in 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

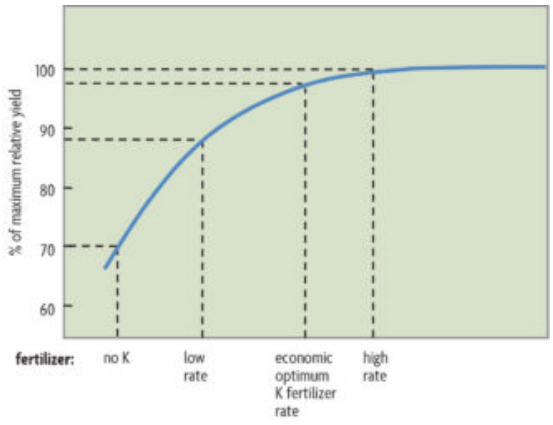

Figure 7.3.4.1: Percent of maximum yield obtained with different amounts of fertilizer K applied to a soil with a very low soil test.

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 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 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 7.3.4.1, 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 from 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 sandy soil that is very low in organic matter) that 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.

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.

Plant Tissue Tests

Soil tests are the most common means of assessing the 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 the 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.

Note

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

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.

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. (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, it makes sense to build up nutrient levels during the corn phase and draw them down during the hay phase.

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.

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7.3.5: Soil Testing for Nitrogen

As we discussed, nitrogen management poses exceptional challenges because gains and losses 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).

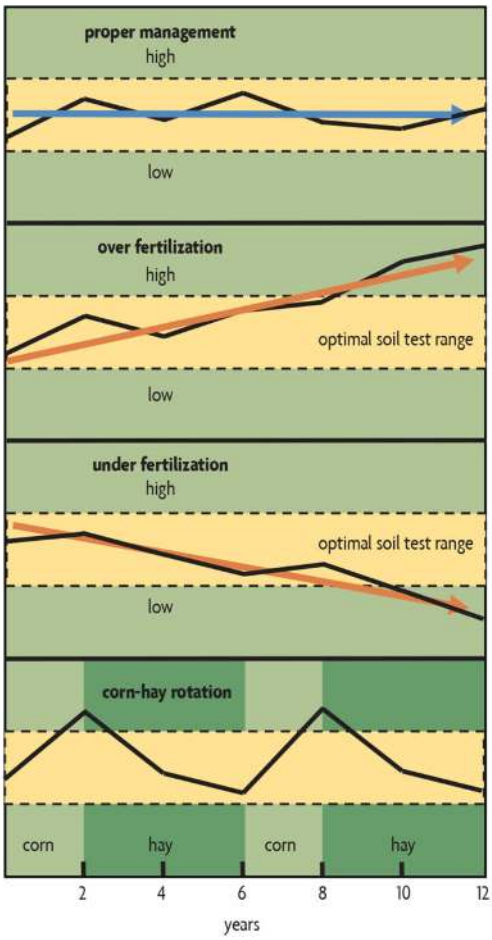

Figure 7.3.5.1: Soil test phosphorus and potassium trends under different fertility management regimes. Modified from The Penn State Agronomy Guide (2019–2020).

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 pre-plant 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 injected anhydrous ammonia), test results may be very variable depending on whether cores are collected from the injection band or not.

Table 7.3.5.1: 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 7.3.5.2: 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.

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 of 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:

- ***Chlorophyll meters*** are handheld devices that indirectly estimate chlorophyll content in a crop leaf, which is an indicator of its N status. 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. 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 is 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, 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.

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. The 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 are also generally used once or twice during the season when N fertilizer is applied, but they are not used for continuous monitoring.

Figure 7.3.5.2: In-field sensors used to measure the nitrogen status of leaves and canopies. Left: leaf chlorophyll (SPAD) sensor. Photo by Konica Minolta. Right: proximal canopy sensors. Photo by Trimble Agriculture.

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7.3.6: 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. Although the relative test value for a given soil is usually similar according to different soil tests (for example, soil testing high in P by one procedure is generally also high by another procedure), the actual numbers can be different.

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.)

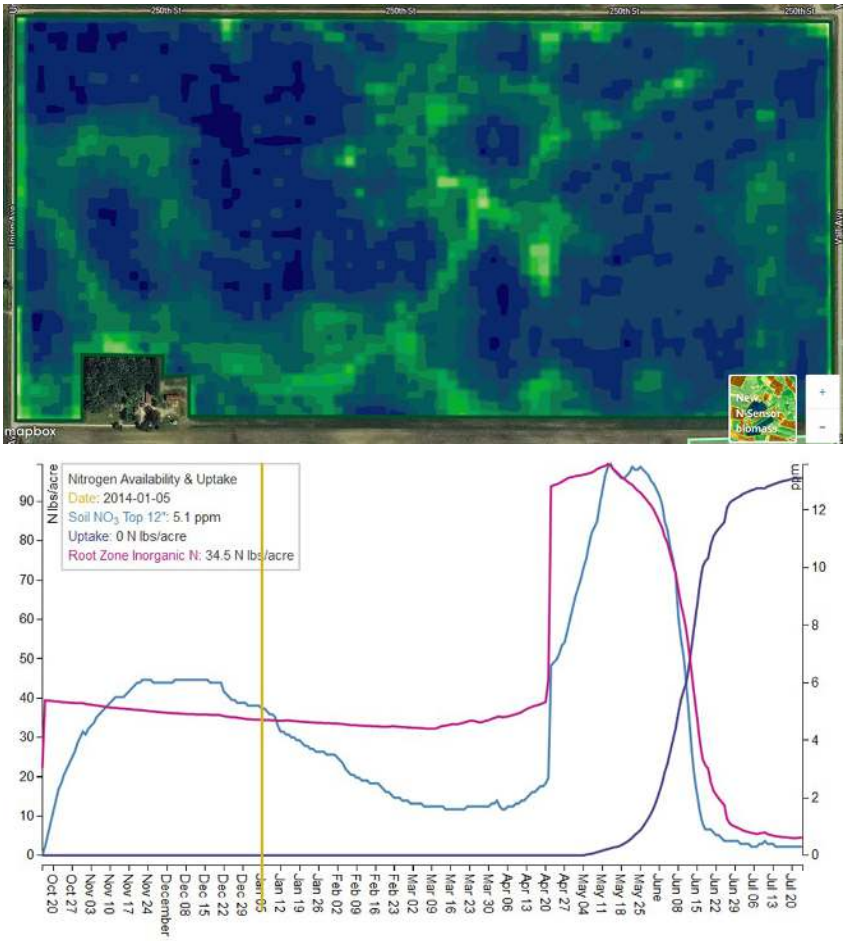

Figure 7.3.6.1: Left: satellite-based sensing of crop nitrogen status (green areas require more nitrogen than blue areas in the wet season); Right: monitoring soil N status using a model. Images by Yara International.

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7.3.7: 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 temperatures, 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 quite a bit more than traditional testing for nutrients or organic matter, you can find out the amount (weight) of fungi and bacteria in the 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.)

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7.3.8: Testing Soils for pH, Lime Needs

Soil pH and how to change it was discussed earlier. 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 in the buffer's pH is an indication of *how much* lime needs to be applied to raise the soil pH to the desired level.

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7.3.9: Interpreting Soil Test Results

Below are four soil test examples, including a 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. 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, the CEC is estimated by summing the exchangeable bases. The more acidic the soil, the greater the difference between its current CEC and the CEC it would have near pH 7.

Following the four soil tests below is a section on modifying recommendations for particular situations.

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 are 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.)

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			

*Nutrients were extracted by modified Morgan's solution **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.

MEASUREMENT	LBS/ACRE**	PPM**	Soil Test CATEGORY	Recommendation SUMMARY
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 **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 of 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 the harvest of other food crops. These FSMA rules apply to all farms with annual sales of more than $25,000.

SOIL TEST #1 (Humid Midwest): Soil Test #1 Report Summary*

- **Field name:** #12
- **Sample date:** December (no sample for PSNT will be taken)
- **Soil type:** clay (somewhat poorly drained)
- **Manure applied:** none
- **Cropping history:** continuous corn
- **Crop to be grown:** corn

Measurement	LBS/ACRE**	PPM**	Soil Test CATEGORY	Recommendation SUMMARY
P	20	10	very low	30 lbs P_2O_5/acre
K	58	29	very low	200 lbs K_2O/acre
Mg	138	69	high	none
Ca	8,168	4,084	high	none
pH	6.8			no lime needed
CEC	21.1 me/100g			
OM	4.3%			rotate to forage legume crop
N	no N soil test			100–130 lbs N/acre

*All nutrient needs were determined using the Mehlich 3 solution **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 is probably due to the clay.
- Low potassium indicates that this soil has probably not received high levels of manure 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 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 is 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:
    1. broadcast 500 pounds per acre of an 11-0-44 bulk blended fertilizer;
    2. use 300 pounds per acre of a 5-10-10 starter; and then
    3. 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 of 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's 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 the 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 #1 Report Summary*

- **Field name:** River A
- **Sample date:** October
- **Soil type:** sandy loam
- **Manure applied:** 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 **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 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 the 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 #1 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. *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 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 pre-plant, 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 the harvest of other food crops. These FSMA rules apply to all farms with annual sales of more than $25,000.

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7.3.10: 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 send 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 7.3.10.1. 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 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.

Table 7.3.10.1: 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	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_: 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 7.3.10.2: 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

Table 7.3.10.3 Amounts of Available Nutrients from Manures and Legume Cover Crops

Legume cover crops*	N lbs/acre	P_2O_5 lbs per ton manure	K_2O

*The amount of available N varies with the amount of growth. **The amount of nutrients varies with diet, storage and application method. *Note*: Quantities given in this table are somewhat less than for the total amounts

Legume cover crops*	N lbs/acre	P_2O_5 lbs per ton manure	K_2O
Hairy vetch	70–140		
Crimson clover	40-90		
Red and white clovers	40–90		
Medics	30–80		
Manures**			
Dairy	6	4	10
Poultry	20	15	10
Hog	6	3	9
*The amount of available N varies with the amount of growth. **The amount of nutrients varies with diet, storage and application method. *Note*: Quantities given in this table are somewhat less than for the total amounts			

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7.3.11: 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, 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.

Worksheet for Adjusting Fertilizer Recommendations

Note: 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.)

	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) 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) Cover crop (medium-growth crimson clover)	0 -60 -50	-24	-90
Total nutrients needed from fertilizer	10	16	50

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7.3.12: Managing Field Nutrient Variability

Many large fields have considerable variation in soil types and fertility levels. Site-specific application of crop 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.

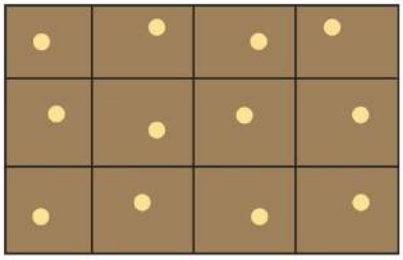

Figure 7.3.12.1: Unaligned sampling grid for variable-rate management. Squares indicate 3- to 5-acre management units, and circles are sampling areas for 10–15 soil cores.

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. 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.

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7.3.13: 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 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.

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7.3.14: 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), 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), which are in use for rice, wheat, and corn.

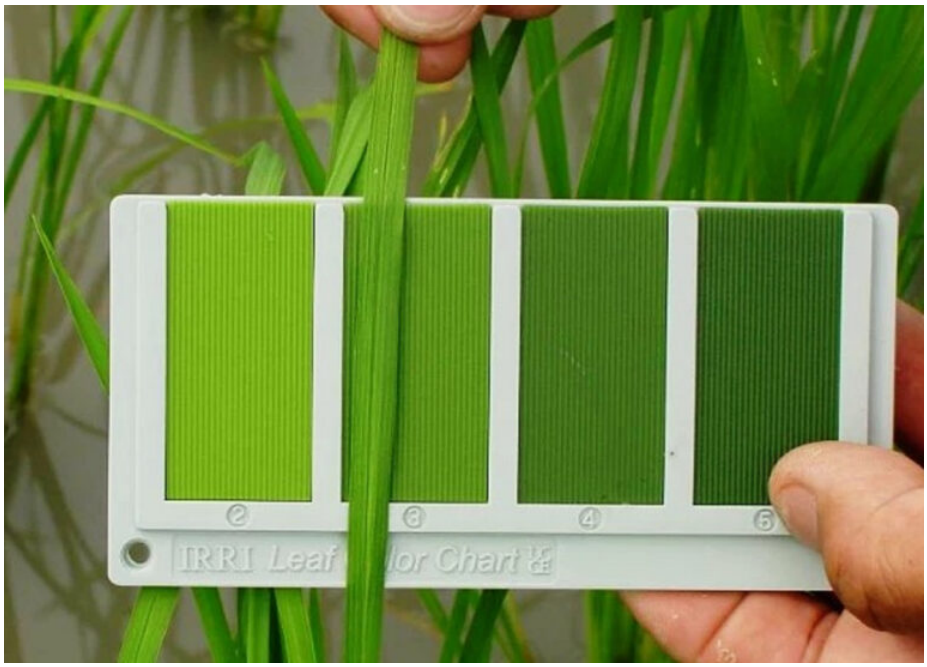

Figure 7.3.14.1: International Rice Research Institute (IRRI) leaf color chart for nitrogen evaluation with rice. *Photo by IPNI.*

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.

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7.3.15: 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 the applications of fertilizers and various amendments such as lime, manures, and composts. This is the way to find out if the soil is too acidic 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. 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 monitor the fields. 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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7.3.17: 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 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 at 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. However, its continued use perpetuates a basic misunderstanding of what CEC and base saturation are all about.

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.

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 x sum of exchangeable cations / CEC

= 100 x (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 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 below. 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 OVERVIEW

8: Fertilizers

8.1: Organic Fertilizers
8.2: Conventional Fertilizers
8.3: Management of Nitrogen and Phosphorus
8.4: OMRI Approved
8.5: How Much Do I Apply?

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8.1: Organic Fertilizers

Organic Approved (Or Not)

A fertilizer is, technically speaking, any substance that is added to soil to provide the nutrient elements that plants need in order to grow. The difference between organic fertilizers and non-organic is mainly that organic fertilizers are naturally occurring substances, while non-organics are either manufactured or synthesized. One could argue whether some fertilizers currently classified as organic meet the organic definitions. For example, though “blood” is a naturally occurring substance, blood meal fertilizer requires collecting and drying large quantities of animal blood from a slaughterhouse–certainly not a naturally occurring phenomenon. The definitions are discussed and debated long and hard in the organic community. Substances are classified as organic (or not) by the National Organic Standards Board (NOSB). This board meets continuously and is informed and influenced by industry, product developers, consumers, and farmers before they come to a decision on “approved for organic use” or “not allowed for organic use”.

Also, remember that another technical definition of organic is that it is a carbon-containing compound. We are not using *that* organic definition here when we talk about fertilizers that supply essential plant elements. Here we mean organically approved fertilizers--since all compounds that do not contain carbon are technically *inorganic*.

Fertilizer Grades or Guaranteed Analysis

Fertilizers that contain three of the macronutrients, N-P-K are said to have a guaranteed amount of these elements in them. Most fertilizer bags or spec sheets will list some analysis like 10-10-10. Although this fertilizer does have 10% elemental nitrogen, it really has 10% phosphorus in the form of P_2O_5 and 10% potassium as k_2O. When soil fertilizer recommendations are made, they are given as lbs. of each combined component needed, not as lbs. of the *element* needed. The fertilizers listed below show the % of P_2O_5 or % k_2O in the material rather than the % of the singular element.

In this section, we explore three macronutrient fertilizers: phosphorus, potassium, and nitrogen. We will not examine sulfur and calcium fertilizers, because there is only one organic source for them, and that is naturally-mined gypsum. Sulfur used to be supplied adequately by recycling animal manure on the land or through precipitation when acid rain was a problem. The University says calcium is not ever needed as a fertilizer. When magnesium is needed, it is simply spread as dolomitic limestone, which, by definition is lime with Mg embedded in it. Both gypsum and dolomitic limestone are approved organic fertilizers.

Phosphorus (P)

Phosphorus enters the plant as $P_2O_4^-$ (phosphate ion). However, because this ion reacts very quickly with other ions, it is delivered in fertilizers in a stable form and standardized as, P_2O_5 (phosphorus pentoxide, more simply called phosphate).

Organic Approved

1. **Rock Phosphate** (Calcium phosphate). The chemical formula of this naturally occurring ore is $3[Ca_3(PO_4)_2]$. It is found in extensive deposits that were formed 10-15 million years ago in the ocean when dissolved phosphorus precipitated out of solution with calcium. In the United States, phosphate rock is mined in Florida, North Carolina, Tennessee, Utah, and Idaho and ground into a fine powder. Some predict that we will run out of this resource in the next 50 years. Hard rock phosphate contains about 33% P_2O while colloidal (contains clay) phosphate contains 22%. Some growers like Tennessee brown rock phosphate because of the other trace minerals it contains. In a few million years, check back on the Bay of Green Bay. It may be a phosphorus mine since we are loading the Bay with it now because of intensive cropping here.
2. **Bone meal.** Bones have a lot of phosphorus in them, but they normally decompose too slowly to be effective fertilizers. In the mid-19th century, entrepreneurs were gathering bones and treating them with sulfuric acid to make superphosphate. Bones became scarce commodities. Today, bones are ground into fine powders and applied as “meal”. It is a relatively high-priced fertilizer. Reasons not to use this are the same as with blood meal--if the source of the animal bones is unknown, the bones are not technically organic. Contains 17-30% P_2O_5.
3. **Poultry Manure.** This fertilizer is discussed more fully in the nitrogen fertilizer section. It is listed here, for reference, as containing about 1% P_2O_5. If your soil test results suggested that you add 30 lbs P per acre, you would have to add about 2 tons of poultry litter, or equivalently, 70 lbs of litter in a 1,000-square-foot garden.

Not Organic Phosphorus

Commercial phosphates. There are several non-organic phosphorus fertilizers including superphosphate, Triple super phosphate (TSP), mono-ammonium phosphate (MAP), and di-ammonium phosphate (DAP). These synthetic, commercial fertilizers are made from rock phosphate that is treated with sulfuric acid or phosphoric acid to extract and concentrate the phosphorus. When the phosphoric acid is then neutralized with ammonium, MAP and DAP are created. These synthetic fertilizers are good sources of both phosphorus and nitrogen with the P being very soluble. They typically contain 45-53% P_2O_5 . They have in the past been relatively cheap to manufacture.

Nitrogen Fertilizers (N)

There are many sources of nitrogen fertilizers. Most commercial nitrogen fertilizers are made with synthetic processes and are therefore not qualified as organic. These synthesized fertilizers have concentrated amounts of nitrogen. They have been made at a relatively inexpensive cost in the past, which made them more attractive to most farmers than organic sources of nitrogen. However, it takes significant energy to manufacture concentrated nitrogen fertilizers and the price has risen quite steeply. In our area, farmers started considering organic nitrogen sources around 2008, even if they are not organic farmers, simply because the cost of manufactured N was getting out of hand and was not cost-effective. Now that fracking has made cheap energy available, the price of N fertilizers has fallen again. Table 8.1.1 shows the relative nitrogen concentrations of various fertilizers.

Blood Meal

This fertilizer supplies nitrogen and iron. It is just what it sounds like, dried animal blood. Most organic people shy away from blood meal because we do not like the source; probably confinement, GMO-corn & soybean-fed pigs and cattle. When they are slaughtered, the blood is collected after stunning, while the animal bleeds out, into a trough on the floor. The blood is collected and dried. The animal does not need to be organic for its blood to be considered organic. Some buyers, like Organic Valley Cooperative, will not buy milk from farmers who use bloodmeal even if it is allowed by the National Organic Program. Growers should check their product buyer as well as OMRI (organic materials review institution) to stay current on whether blood meal is allowed, or not allowed.

Poultry Litter

This has been a favorite source of nitrogen for organic farmers for many years. Especially if a farmer does not have their own livestock to provide manure, poultry litter can be a good choice. Recently, however, there has been some debate over poultry litter. If the chickens producing the manure/litter are fed GMO corn and soybeans, it is likely that their manure contains residual glyphosate (Roundup herbicide's active ingredient). It might just be that the only way to obtain glyphosate-free poultry litter is to source it from poultry farms that do not feed conventional corn & soybeans. Right now, that source is not readily available. Although poultry litter also supplys phosphorus, it is mainly used for its N contribution.

Green Manure

This is not really manure at all. It is living, green plant material that is plowed down into the soil. Many organic farmers grow a green manure cover crop over the winter on bare soil to protect the soil from wind and water erosion. Then, in the springtime, the green manure is plowed down. The decomposing plant material feeds the microbes and soil life. Green manures can cause population explosions of soil micro and macro-biota. These life forms can tie up other nutrients in their bodies and actually set back a seeded crop for a few weeks until they themselves die and the nutrients that were immobilized in their bodies become released or mineralized once again. Most green manures are plowed down at least a month before seeding to give this microbial uptake, growth, and dieback cycle adequate time to take place.

Dairy Cattle Manure

Manure is excrement from cattle. In Wisconsin, manure has been a problem when too many animals are concentrated in too small of a space, and the nutrients in the manure either leach or volatilize. A sustainable goal for livestock farmers is typically to match the land base with appropriate animal numbers so that manure can be used as a fertilizer asset rather than having it become a liability. Cattle manure from dairy farms usually is managed in one of three ways.

1. The first, and previously most typical way most livestock farmers handle manure has been a "**daily haul**" in which farmers run a barn cleaner in a gutter to collect manure behind cows that are tied in stalls. Manure is semi-solid and hauled daily to adjacent fields and spread with a manure spreader. This becomes difficult to accomplish once all the fields have crops growing on them in the summer. It is also difficult in winter when deep snow and frozen ground make access to fields or snow melt and runoff very real possibilities. A daily haul is becoming a thing of the past as manure pits come to dominate the landscape.
2. In order to avoid the problems with spreading at inappropriate times and to deal with the sheer volume of manure, many dairy farmers have gone to **manure pits**. In this system, manure is mixed with water to transport it into a pit. It is typically accumulated for six months and then spread after crops come off in the fall, and again in spring before planting. The trouble with this system is that the nitrogen in liquid manure may volatilize under anaerobic pit conditions. Also, adding water adds to the cost of moving the water/manure slurry out to fields. And lastly, the free N in liquid manure is great for causing a flush of weed seeds to germinate. Conventional farmers then deal with the weed problem they have created by applying herbicides. I do not recommend liquid manure in organic soils because at the volumes it is often applied it overwhelms and "drowns" the aerobic soil micro-organisms. Liquid manure does not add to soil health because it doesn't add the organic matter of a semi-solid manure.
3. Some organic dairy and beef farms **compost** their manure as a way to stabilize and store nitrogen. This is the system we use on our farm. We spread a layer of straw through a bale processor in a three-sided shed and let the cows move about freely in this building. This is called a bedded pack. Each day the manure and straw bedding mix together and accumulate, layer by layer until the bedded pack is several feet high. Every six weeks or so, the bedded pack is hauled out with a skid steer, placed in a long windrow, and then left as either a static pile or composted in place by periodic turning. This system has drawbacks also; it is time and machinery intensive and if not managed well, N can be lost from the compost.

Horse Manure

This can be a good, free source of nitrogen. Some horse owners may actually pay you to haul away this "waste" from their barns and stables. One thing to consider, however, is that most horse owners de-worm their horses with Ivermectin. Residual Ivermectin in horse manure may affect dung beetles and other soil micro-organisms. More information on this is currently needed, especially whether composting the horse manure reduces the Ivermectin.

Fish Emulsions

Fish emulsions are a slurry of ground-up fish, usually an oily ocean fish called menhaden, that is cooked and stabilized and sold in smaller volumes usually only feasible for backyard gardeners. The NPK analysis of fish emulsions is often 5-1-1 or 5-2-2. Check the label of how the emulsion is made. Some phosphoric acid is allowed to reduce the fish odor, but it must not be more than 1% of the final weight to be considered organic. In Northeast Wisconsin, we have a couple of companies that use fish waste from Lake Michigan to manufacture local products, some of which are available in bulk for bigger organic enterprises.

Table 8.1.1: Nitrogen fertilizers and % Nitrogen on a dry matter basis *(other sources list different amounts of nitrogen in these fertilizers – they do vary widely on their content – but this list seems reasonable to me)*

Organic Fertilizers	% N	Synthetic Fertilizers	% N
Cow manure	.5	Fish emulsion	5
Horse manure	.6	Tankage	6.5
Pig manure	.6	Blood meal	13
Sheep manure	1	Chilean nitrate	15
Poultry Layer litter	1.5	Ammonium nitrate	33
Poultry Broiler litter	1.3	Ammonium sulfate	20
Compost	1.2	Urea (synthetic)	43
Fish meal	9		

From R. Parnes, Fertile Soil, published by agAcess, Davis, CA.

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8.2: Conventional Fertilizers

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?

We have detailed 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. 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 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 the 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 hand, when hay is harvested and sold off the farm, P drawdown can happen more rapidly.

Table 8.2.1: Composition of Various Common Amendments and Commercial Fertilizers (%) All those listed are NOT ORGANIC.

	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	

	N	P_2O_5	K_2O	Ca	Mg	S	Cl
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 - some of these materials (below) may be organic, depending on source							
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				

	N	P_2O_5	K_2O	Ca	Mg	S	Cl
Sulfur (elemental S, gypsum, ammonium sulfate)						30–99	
Wood ashes		2	6	23	2		

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, but 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]). The ability of more urban people to 're-learn' gardening so they can feed themselves fresh produce may also play a role.

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.

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 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.

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 8.2.1 are not allowed in organic production because they are synthetically derived. In place of sources such as urea, anhydrous ammonia, di-ammonium 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 8.2.2). Finally, to make matters more confusing, many countries, especially in Europe, label products as "bio" or "biological" when they are grown using organic practices.

Selection of Commercial Fertilizer Sources

There are numerous forms of commercial fertilizers. 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 are 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 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, di-ammonium 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 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 its 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.

An earlier section of the book described some organic fertilizers, here is another sample selection of organic fertilizers from another source. Not all the numbers may agree with the previous table.

Table 8.2.2: 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

Notes: 1. Values of P_2O_5 and K_2O represent total nutrients present. For fertilizers listed, the numbers are the amounts that are readily available. 2. Organic growers also use potassium magnesium sulfate ("sul-po-mag" or "K-mag"), wood ashes, limestone, and gypsum. Although some use only manure that has been composted, others will use aged manures. 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)

	% N	% P_2O_5	% K_2O
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, the numbers are the amounts that are readily available. 2. Organic growers also use potassium magnesium sulfate ("sul-po-mag" or "K-mag"), wood ashes, limestone, and gypsum. Although some use only manure that has been composted, others will use aged manures. 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)

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 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 pre-plant 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 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.

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 to 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.

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 tile lines, and then discharge into waterways.

Soil Tests

Routine soil tests, one of the key nutrient management tools, are discussed elsewhere in this book.

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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8.3: Management of Nitrogen and Phosphorus

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).
   - 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

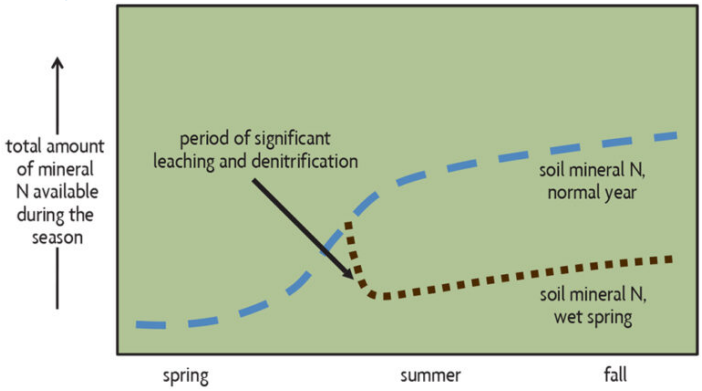

Figure 8.3.1: Available N in soil depends on recent weather. After increasing for a period, mineral N decreases during a wet spring because leaching and denitrification losses are greater than N being converted to mineral forms. More mineral N is available for plants when the spring is drier. (Gains and losses are greater when large amounts of organic applications, for example, manure, are made.)

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. Fertilizers should be used only to supplement the soil's supply in order to provide full plant nutrition. 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.

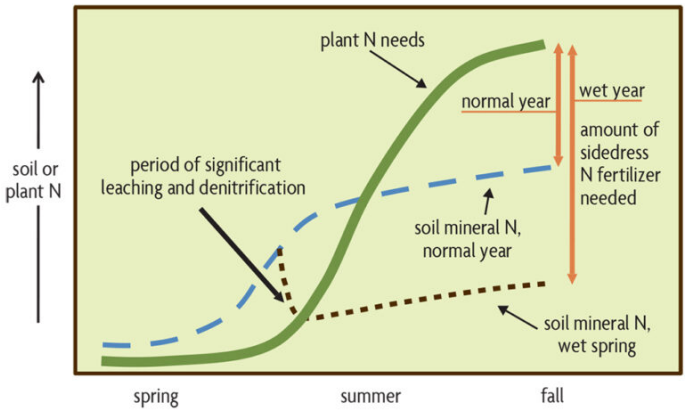

Figure 8.3.2: The need for supplemental N fertilizer depends on early season weather. Note: The amount of mineral N in the soil will actually decrease (not shown) as plants begin to grow. They grow rapidly and take up large quantities of N faster than new N is converted to mineral forms.

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, weather-related factors like soil temperature (higher temperatures increase N mineralization), and soil wetness (saturated soils cause large 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. When plants germinate in the spring, it takes a while until they begin to grow rapidly and take up a lot of N. 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. 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. 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 expectations 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 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 used to provide input information for computer models.

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 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 the 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. The following considerations are important for planning management strategies for N and P.

Table 8.3.1: 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.

Nitrogen	Phosphorus
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, decrease runoff and erosion, and keep the mycorrhizal network intact.
Use sod-type forage crops in rotation to reduce nitrate leaching and runoff, making N more available to the 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 left 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).

Figure 8.3.3: 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.

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. 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.)

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 are 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.

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.

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 8.3.2). 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. Also, some of the adaptive simulation models described above can incorporate such credits into recommendations, while also accounting for variable weather conditions.

Table 8.3.2: Examples of Nitrogen Credits for Previous Crops

Previous crop	N credits (pounds per acre)
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.

Relying on legumes to supply N to the 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.

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.

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.

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 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 in 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 the 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 their way deeper into the soil surface. P can be band applied as a 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 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 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. However, 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 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 the 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 product for use with N fertilizers. These suppress the 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.

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).

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.”

Table 8.3.2: 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

[1]This list is not comprehensive but includes the most widely used products. The 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.

Mode of action	Formulation and use	Common enhanced efficiency products[1]
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. The 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 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, 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).

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 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.

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 the 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.

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 losses 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 in 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.

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. 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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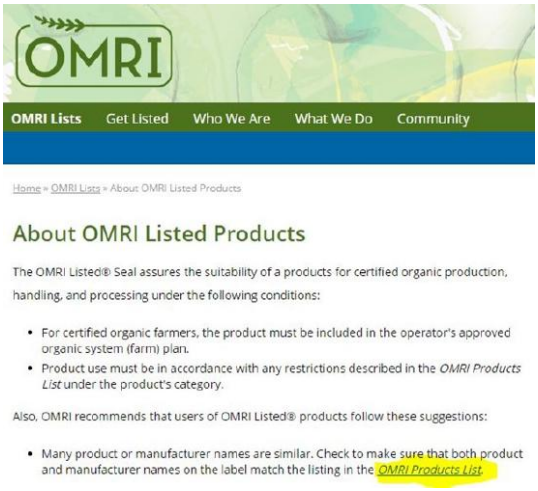
8.4: OMRI Approved

OMRI and Organic Fertilizers

The Organic Materials Review Institute (OMRI) is a web-based site to visit for information about whether or not a product--be it a fertilizer, soil amendment, animal vet product, or cleanser--is “approved for use in organic systems”. OMRI is used and trusted by the organic industry, certifiers, inspectors, and farmers. http://www.omri.org/about-omri-listed-products

Here is what the site looks like on the internet. You can search the site for all kinds of great information.



The OMRI website changes periodically so you may not see a site that looks exactly like what is shown here. As a farmer or commercial gardener, you should be able to explore, navigate, and find products in which you are interested. Most farmers I know do not “subscribe” to OMRI. I recommend that level of involvement only for those who want to sell products or get products certified.

Here is the kind of information you can get from the OMRI website:

- the function of a product
- the status of a product
- exceptions or any restrictions on the use

This is a sampling of a few fertilizers and amendment products that we use on our farm (Full Circle Farm) and those described on the OMRI website. The information includes the purpose of the function and whether or not they are “OMRI approved.” If something is OMRI-approved, you can be confident it is OK to use on your organic farm.

Potassium Fertilizers

Their function is to supply potassium.

- **Potash.** Status: It is OMRI allowed as described in the OMRI information. “Only from mined sources.”
- **Potassium Chloride (KCl).** Status: Allowed with Restrictions. Class: Crop Fertilizers and Soil Amendments. Origin: Non-synthetic. Muriate of potash (potassium chloride) must be applied in a manner that minimizes chloride accumulation in the soil. NOP Rule: 205.203(d)(3) & 205.602(e) A mined substance of high solubility. [Prohibited] unless derived from a mined source and applied in a manner that minimizes chloride accumulation in the soil.

Blood meal

The collected blood of slaughtered animals after it has been dried. The major nutrients supplied are nitrogen and additional trace elements, including iron. It is allowed as described below.

- Status: Allowed. Class: Crop Fertilizers and Soil Amendments. Origin: Non-synthetic.
- Description: Animal material. See website glossary for the definition of "blood meal." NOP Rule: 205.105(a)

Dolomitic Lime

Dolomite does not contain a major nutrient but does serve a primary function in adjusting pH with magnesium carbonate and calcium carbonate (alkaline.) It is allowed, as described:

- Dolomite: naturally mined. Status: Allowed. Class: Crop Fertilizers and Soil Amendments.Origin: must be non-synthetic.
- Description: Magnesium carbonate and calcium carbonate. May cause a build-up of magnesium. See also MINED MINERALS – UNPROCESSED. NOP Rule: 205.203(d)(2) A Mined substance of low solubility.

Gypsum

Gypsum fertilizer is calcium sulfate. It must be mined (synthetic gypsum is about 30% of the market). This fertilizer provides calcium and sulfur, is used in the case of excessive phosphorous, and can be a correction for salinized soil. It is superior to lime because it reaches subsoil and lime does not. The mined form is allowed as described below.

- Status: Allowed. Class: Crop Fertilizers and Soil Amendments. Origin: Non-synthetic.
- Description: Calcium sulfate; only mined forms are acceptable. See also GYPSUM BY-PRODUCTS and MINED MINERALS – UNPROCESSED. NOP Rule: 205.203(d)(2) A mined substance of low solubility.

Tennessee Brown Rock Phosphate

This is non-synthetic and contains total phosphate of 21-25%, calcium 20%, and trace elements. It is allowed as described below.

- Status: Allowed. Class: Livestock Feed Ingredients, Livestock Health Care. Origin: Non-synthetic.
- Description: May be supplied by: calcite, chalk, rock, ground clam shells, gypsiferous shale, ground limestone, dolomitic limestone, oyster shell flour, ground phosphate rock, soft phosphate rock, or shell flour. NOP Rule: 205.237(a)

K2SO4 Potassium Sulfate

This is also non-synthetic with the major nutrient supplied being potassium. It is allowed upon the conditions described below (non-synthetic origin.)

- Status: Allowed. Class: Crop Fertilizers and Soil Amendments. Origin: Non-synthetic.
- Description: Only if from langbeinite or other nonsynthetic sources. See also MINED MINERALS – UNPROCESSED.
- NOP Rule: 205.203(d)(3) A mined substance of low solubility.

Poultry Litter

Poultry is the richest animal manure source of N-P-K, all major nutrients. It is organic allowed when composted, as described below.

- Compost – windrow (plant and animal materials). Status: Allowed. Class: Crop Fertilizers and Soil Amendments. Origin: Non-synthetic.
- Description: Plant and animal materials are composted through a process that establishes an initial C:N ratio of between 25:1 and 40:1 and maintains a temperature of between 131°F and 170°F for 15 days, during which period the composting materials must be turned a minimum of five times. Acceptable feedstocks include, but are not limited to, animal manure, by-products of agricultural commodities processing, and source-separated yard debris or "clean green." Compost must not contain more than $1x10^3$ (1,000) MPN fecal coliform per gram of compost sampled and must not contain more than 3 MPN Salmonella per 4 grams of compost sampled. See also MICROBIAL PRODUCTS for information on compost starters, other COMPOST listings, SEWAGE SLUDGE, and MUSHROOM COMPOST. See the website glossary for the definition of "compost."
- NOP Rule: 205.203(c)(2)(i) & (iii) Composted plant and animal materials.

Compost

Compost provides nitrogen-fixing in many cases, as well as organic matter, and improves microbial activity. Allowed as described below.

- Compost – other (plant and animal materials). Status: Allowed. Origin: Non-synthetic.
- Class: Crop Fertilizers and Soil Amendments
- Description: Compost is acceptable if (i) made from only allowed feedstock materials; (ii) the compost undergoes an increase in temperature to at least 131ºF (55ºC) and remains there for a minimum of 3 days, and (iii) the compost pile is mixed or managed to ensure that all of the feedstock heats to the minimum temperature for the minimum time. Compost must not contain more

than 1x10³ (1,000) MPN fecal coliform per gram of compost sampled and must not contain more than 3 MPN Salmonella per 4 grams of compost sampled. This does not include Compost Tea. See other COMPOST listings. See the website glossary for the definition of "compost."
- NOP Rule: 205.203(c)(2)

Cattle Manure

Provides N-P-K. Allowed as described below.

- Composted – other (plant and animal materials) Status: Allowed. Origin: Non-synthetic.
- Class: Crop Fertilizers and Soil Amendments
- Description: Manure compost is acceptable if (i) made from only allowed feedstock materials; (ii) the compost undergoes an increase in temperature to at least 131ºF (55ºC) and remains there for a minimum of 3 days; and (iii) the compost pile is mixed or managed to ensure that all of the feedstock heats to the minimum temperature for the minimum time. Compost must not contain more than 1x10³ (1,000) MPN fecal coliform per gram of compost sampled and must not contain more than 3 MPN Salmonella per 4 grams of compost sampled. This does not include Compost Tea. See other COMPOST listings. See the website glossary for the definition of "compost."
- NOP Rule: 205.203(c)(2)

References

- Organic Materials Review Institute (OMRI) - http://www.omri.org/about-omri-listed-product
- Elizabeth Moriarity, Door County, WI organic inspector

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8.5: How Much Do I Apply?

In a previous section, we explained how organic fertilizers are different than commercial, synthetic fertilizers. We often struggle with this next logical step, explaining how much commercial fertilizer to actually apply and how to apply it. The main reason for the struggle is that most home gardeners and many large-scale commercial gardens and small farms can “grow their own” fertilizers so you may not need to apply any fertilizer at all. Larger farms, those over 10 acres, will likely need to apply some fertilizer inputs brought in from off the farm. This is especially true if they are just beginning a transition to organic farming or if the farmland has been run conventionally in continuous corn or soybeans for several years without adequate replacement of nutrients.

The way to figure rates, volume, and amounts for lawns, home gardens, commercial gardens, and farm fields is essentially the same and we will review it in this section. We also cover how organic fertilizer rates and costs stack up against conventional.

Lawn fertilizer application rates are easy to figure out because lawns are a monoculture of mostly bluegrass with a little fescue or related grass species. I do not fertilize my lawn, but again I do not hold lawns in high regard. I think the typical home has too much lawn and too much attention and work is focused on it. Personally, I would rather spend my resources growing food. That said, a lawn was more important to my family when our children were young and we played in the lawn space. Thankfully, in Wisconsin, the nutrient phosphorus is no longer included in a bag of fertilizer you can buy for home lawns because of the environmental water pollution problems it can cause. For more information on the ban on phosphorus on lawns go to the Department of Agriculture webpage that explains the law, which took effect in April 2010. http://datcp.wi.gov/uploads/Environment/pdf/TurfFertHomeownerPub194.pdf

Gardens

When gardening and growing food for home use, gardeners do not need to be very precise and can apply store-bought organic fertilizer without going broke. But commercial gardeners cannot afford to over-apply fertilizer, organic or otherwise. Keeping within a budget for fertility inputs can determine whether or not a CSA or Farmer’s Market garden is profitable. Commercial gardeners adjust fertilizer application rates frequently because each plot or area for individual vegetables has different nutrient needs. The good news is that large-scale gardeners can probably manage to apply nutrients only in the crop row (side-dress) for the biggest benefit without encouraging weeds in between rows as would happen if fertilizer was broadcast. Also, the equipment needed to apply garden fertilizer is small enough do-it-yourself scale to not break the bank. Most fertilizers I will discuss here are granular or dry fertilizers. However, I have used fish emulsions and other liquid fertilizers in the garden. They are relatively easy to apply with just a sprinkler can if you only have a half acre to fertilize. Over a half acre? Consider applying liquid fertilizer through an irrigation system. You will likely need irrigation anyway for that inevitable August dry spell. You may as well plan to fertilize at that time too.

Do not use push lawn spreaders that you can buy for $100 at Home Depot. This type of spreader broadcasts the fertilizer. That is great for a lawn, but not good in a garden since you will be promoting weed growth between rows. Use small spreaders that apply fertilizer only in the row, not broadcasting.

Small Farms

Farms over 5 acres will probably need to use a mechanical aid to apply fertilizer. Your local farmer cooperative has small fertilizer spreaders for rent that are pulled behind a tractor. Many times, if you buy fertilizer through the cooperative the use of the spreader is free as a part of the deal.

Figure 8.5.1: Spreading fertilizer with a tractor

> Full Circle Organic Farm explains their fertilization methods:
>
> In our pastures, we often broadcast organic approved composted poultry litter. We spread about 50 pounds per acre in mid-summer to perk up the grasses in their summer slump. We feel like there is a good return on our investment with higher pasture yields through the remainder of the growing season. The nutrient analysis of the fertilizer is 4-3-2. This fertilizer also has 11% calcium added. We buy it in semi-load quantities of 25 tons to spread over 100 acres of pasture. This fertilizer cost is $170/ton delivered (2020 pricing). For the 25 tons we bought that meant a bill of $4,250. That works out to about $42.50 per acre. How much did we pay per pound for the fertilizer? About 8.5 cents per pound of fertilizer.

How Does Our Organic Fertilizer Cost Compare to Conventional Fertilizer Costs?

Since there is 4% nitrogen in the organic fertilizer we bought:

0.04% N x 50lbs/A. = 2 lbs of nitrogen were applied per acre. This cost therefore is $21.25/lb per acre for N.

This is far below the typical rates suggested by universities (50 units N per acre) for grass pastures, but it seems to work for us because we feel N is cycled well and available to our grass pastures without much lost from the system due to volatilization, leaching or runoff. We also use clovers (legumes) to fix nitrogen and feed the grasses. We have about 3.5% organic matter in our pastures compared to our neighbors' fields which run about 1.5% organic matter. As you know from reading a previous paper, this extra two percent organic matter gives us the equivalent of 50 lbs of mineralized nitrogen. We grow our own nitrogen.

Compare this cost with the cost of conventional nitrogen fertilizers. Urea cost about $570/Ton last year (2014). In this scenario, a farmer is paying $570/2000 lbs = about $0.28 cents per pound of fertilizer.

How much nitrogen is that? Urea’s NPK grade is 43% nitrogen. So in a ton (2,000 lbs of urea there is 2,000 x 0.43 = 860 lbs of nitrogen.

A pound of nitrogen from urea costs ($0.28/lb) x (1 lb/0.43 lb) = $0.65/lb of N. Conventional farmers are typically advised to input 50 lbs of synthetic N per acre when they grow pasture or hay. At 0.65 cents per pound, that amounts to about $32.50/A. By the way, because natural gas prices are falling due to fracking technology, N fertilizer costs are also dropping because the energy needed costs less.

You can see why organic farmers have to “grow our own” nitrogen. If we tried applying 50# nitrogen per acre by using organic poultry litter we would have to apply 1250 lbs or a little more than half a ton of poultry litter at a cost of $109/A. Yet our forage yields per acre are equivalent to or higher than conventional farms.

The Cost of Organic Nitrogen Fertilizers is the Biggest Extra Cost in Organic Farming!

The same logic holds true for corn. Our organic corn yields beat the county averages every year. In 2014 our fields yielded about 180 bushels of corn per acre. How is that possible when we only add a few pounds of nitrogen from poultry litter to the corn crop each spring? We take credit for green manure plow down of the previous year’s pasture, we out-winter the dairy cows on the field that will be turned under for corn, thus accumulating manure. We spread composted manure to the field. In all, we likely add close to 100 pounds of nitrogen from organic on-farm sources to our corn field. And almost none of the nitrogen we add to the system is lost like happens in conventional farming. Conventional farms may add 150 lbs N per acre, but they likely lose 1/4 - 1/2 to leaching or volatilization.

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CHAPTER OVERVIEW

9: Compost

9.1: The Dirty Little Secret of Compost
9.2: Making Composts
9.3: Using Composts
9.4: Advantages of Composting
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9.6: Sources

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9.1: The Dirty Little Secret of Compost

> *"Producing quality compost is the most important job on the organic farm. A lot of the problems I see on farms I visit could be solved by making better compost." ~ Eliot Coleman*

Many organic farmers and gardeners know that compost is a good thing. Many people believe they add lots of nutrients to soils when they spread compost. Not exactly true. We are adding some nutrients to our plants, but very little when compared with commercial, conventional fertilizers or even some organic fertilizers. Compost is NOT a fertilizer. The secret of compost is that it makes soil better, and better able to do its job of providing nutrients.

Compost creates a stable home for nutrients and bacteria and fungi to all live, function, and cycle in the system.

In my opinion, compost should be viewed as a soil amendment rather than as a true fertilizer. We should recognize that compost has a whole different way of supplying nutrients to a plant than simply dumping a pile of elements right at the plant's root. Compost has two mechanisms that are very different from this “dump” method of concentrated fertilizers.

In the first mechanism, consider that compost’s job is to create a habitat for the “good” fungal hyphae. The hyphae work with plant roots to make them hundreds of times more capable of foraging for nutrients by helping them cast a wider net. This goes back to the idea of soil tilth. Compost creates good tilth.

The second way compost performs its magic is to create a great habitat for soil bacteria and other soil fauna (animals). Compost feeds soil livestock! Visualize soil bacteria as mini-pacmen. The bacteria scoot around in the soil and chow down nutrient molecules in compost raw material. The bacteria, which are single cells, break down old plant material and manures, take in those released nutrients, and use them as building blocks to grow. They incorporate the free, unbound nutrients into their “bodies”. Thus the nutrient is said to be “immobilized” since it is bound up in that bacterial cell, or the body of the next biggest organism that feeds on the bacteria. The bacteria do not live long, and when they die, the nutrient, say nitrogen, is available to the plant again. However, the nutrient is available in the sticky mess that is the bacterial cell. The nutrient will not simply wash through the soil as it does in the synthetic method of salt-bound mineral fertilization. So the gummy bodies of the minute soil livestock stabilize the nutrients in the soil.

> The **secret** of compost is that we are **amplifying** both bacteria and fungi by giving the little darlings what they need to thrive; a small nitrogen source, a carbon source, air, moisture, and a decent pH. Let them do the work of enhancing soil nutrient availability.

So, consider yourself a baker when it comes to composting. You mix ingredients, cook, and create something great. You can vary your ingredients and your bake times and processes, and you will still make something delicious. The “cake” you make is a great soil amendment. Some of you are already pretty experienced at making compost and some of you are just beginning. We all have more to learn. Don’t forget about temperature and the length of time you are incubating the mix of ingredients. Don't forget you need moisture and air. Be wary as you take advice from others about compost. There are many people trying to make a buck off you by getting you to purchase fancy microbial inoculants. Nature provides what you need, don't buy it.

We inoculate our soils with beneficial organisms when we use compost. We are enlivening our soils. This is akin to adding yeast to flour and water. When bread is allowed to rise under warm conditions, we are really growing the yeast that causes the gas that raises the bread. When we compost, we are fostering bacteria and fungi by providing them with a warm, cozy place to grow and rise. When we spread compost or compost tea, we send our homegrown soil livestock out into the field or garden to do more of the work in the soil food web. That is the secret of compost.

The compost recipe can amplify bacteria by adding more available carbon – like molasses, or they favor fungi by adding more protein to the recipe. The pH level also will favor either bacteria or fungi. Your job as the farmer or gardener is to recognize what you are trying to accomplish, and nudge nature toward those goals.

The decomposition of organic materials takes place naturally in forests, fields, and 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 the 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° 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 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.

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.

Reference

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9.2: Making Composts

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)

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 parts carbon for every part nitrogen. 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 because of the contaminants they contain. 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.

Figure 9.2.1: On-farm composting facility, in which tarps are used to control moisture and temperature. The piles in the background are curing.

One thing to keep in mind is that not all carbon is equally available for microorganisms. Lignin is not easily decomposed. 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 1). For some materials, there is little difference between the C:N calculated with total carbon and calculated with only biodegradable carbon.

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 9.2.1) is a large, natural convective structure, something like a set of chimneys next to each other. Oxygen moves into the pile 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.

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 9.2.2). (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)

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.

Table 9.2.1: 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)

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 the upper reaches of the pile (Figure 9.2.3). 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. 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 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.

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.

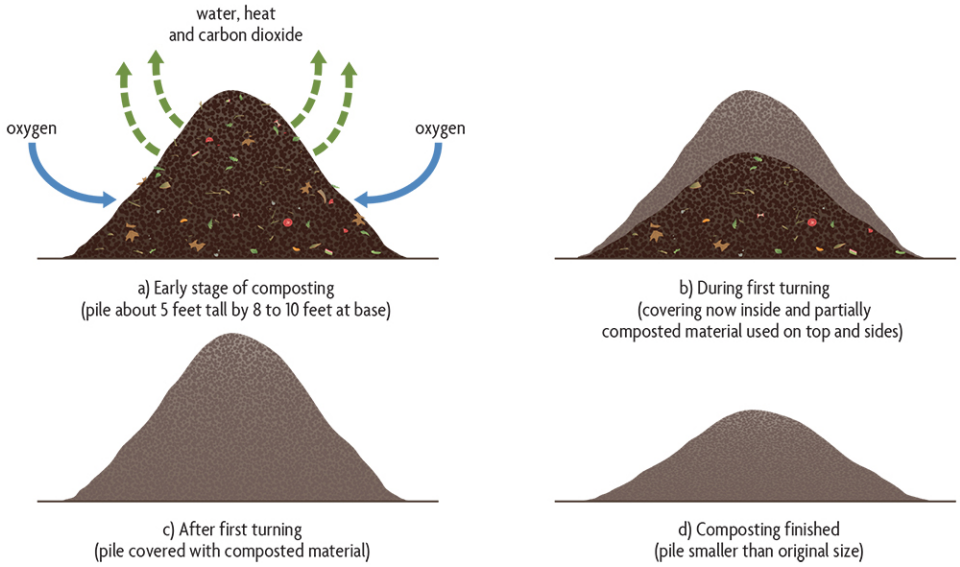

Figure 9.2.2: Compost pile dimensions and turning techniques. Illustration by Vic Kulihin.

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 temperatures between 131°F and 170°F. To comply with 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.

Figure 9.2.3: Turning a compost windrow at a commercial facility.*Photo by Alison Jack.*

Figure 9.2.4: An example of a belowground composting pit, often used by small farmers in tropical countries and when the soil is well-drained.

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 doesn't really finish composting. Determining when compost is finished is sometimes difficult, but if it is reheated, it is not finished. (The Solvita® test measures carbon dioxide losses from compost as a way to determine compost maturity.) Curing the pile furthers the 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.

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, 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. However, 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 windows, 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 the 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 used as topdressing).

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9.3: 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.

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 from 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 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. 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 the 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 the 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 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).

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 to the environment and are not killed by chlorination. Composting of manure, however, is an economical option that kills the pathogen and protects drinking water.

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9.4: 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.

The composting process also helps us address the concerns around nutrient flows. 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 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 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 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).

Figure 9.4.1: Top: Compacted soil. Bottom: compost application prior mixing and planting.*Photos by Urban Horticulture Institute, Cornell University*

In 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 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.

Remember, compost's benefit is not that it provides great fertilizer value, rather it makes the soil better in numerous ways. Do you see why, now, after reading about all the benefits of compost.....we can say that it is a powerful, secret tool organic farmers and gardeners can harness?

Figure 9.4.2: Three years of tree growth without (top) and with (bottom) compost application. Photos by Urban Horticulture Institute, Cornell University.

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9.5: A Case Study, Cam Tabb

Composting in 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, after years of fine-tuning his operation, he can talk about compost for hours.

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 the 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 a 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 totally 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."

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CHAPTER OVERVIEW

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10.1: Introduction

> *… 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!

Organic farmers want many beneficial soil micro-organisms to thrive in the habitat. These micro-organisms are 'soil livestock'. They may be the most important livestock on the farm. Farmers should do as much as they can to help them multiply and increase. They, in turn, grow and recycle soil nutrients that feed plant crops. Legumes, plants that have a beneficial relationship with soil bacteria, are another important type of livestock. Legumes form nodules, a habitat for the bacteria, that pluck free nitrogen from the air and then fix it into their bacterial and plant bodies – free nitrogen! It doesn't get any better than that.

Figure 10.1.1: Nitrogen-fixing bacteria nodules on a legume plant. USDA-NRCS.

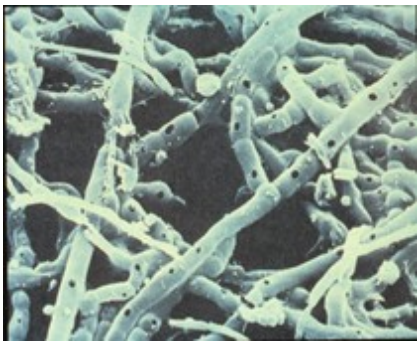

Figure 10.1.2: Fungal hyphae in soil. USDA-NRCS.

Soil worms, fungi, bacteria, and other microbes, much like the soil structure itself, need air space water space, and open space. Soil that is alive with good microbes must not be compacted nor sterilized by salt-based fertilizers, herbicides, pesticides, and heavy tractor traffic. Did you know that 90% of vascular plants typically have a mycchorhizal fungal association that works with roots to reach further and deliver nutrients? – these fungi are killed by plowing, compaction, and herbicides. Organic farmers want a lot of beneficial soil life so that the food we grow uses nutrients produced by natural, biological cycles rather than by synthetic means. We want good organisms to overwhelm and out-compete the pathogens so that we don't need to spray and kill all the soil life. We are not afraid of microbes, we embrace them as mini-colleagues that do their part in the system. We trust the way biology has worked for millennia to grow the gifts of good food from rich soil of which we are stewards at this time.

Some of the farming practices used to enhance soil health include; managed animal grazing, composting, crop rotation, planting perennial legumes, and cover crops, and plowing a field only every fifth year. It is very important (if at all possible) to have animals on any crop farm because of the manure they produce. The livestock adds manures and beneficial bacteria back into the farm crop system. Composting adds organic matter, that jungle gym habitat, back into the soil. Rotating crops keeps non-beneficials from gaining a foothold in the system. Using legumes adds nitrogen to the soil and perennials keep living roots in the soil year-round. Roots exude what Soil Microbiologist Dr. Elaine Ingham describes as "cakes and cookies" into the soil for microbes to feed on. The perennials and cover crops leaf out very early in spring and have leaves later into the fall and this keeps the soil covered with "many little tents" which prevents raindrop impacts from dislodging soil particles which may then flush them away with the rain.

Figure 10.1.3: Water droplet.

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 into the atmosphere. They do not have lungs of course, we are describing cellular respiration. 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 the 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 10.1.4). Many of these break 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, such 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, 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 10.1.4), usually called a food *web* (compared to a food *chain*, which involves only one direction).

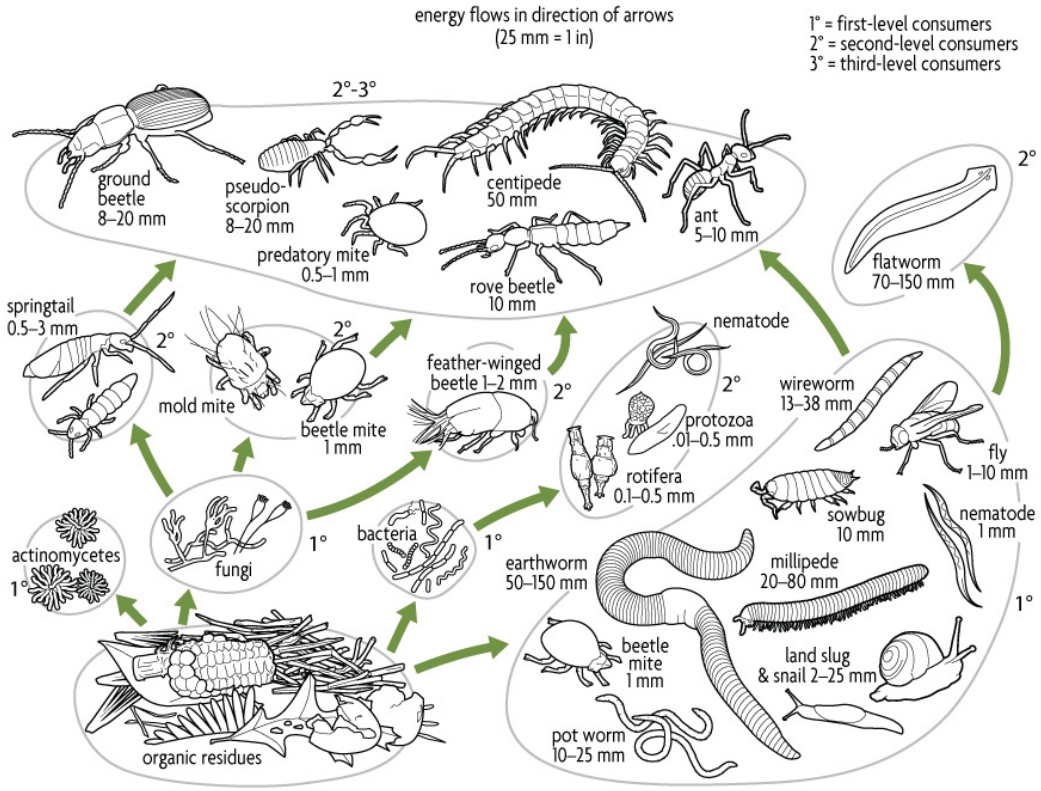

Figure 10.1.4: The soil food web. Modified from D.L. Dindal (1972). Illustration by Vic Kulihin.

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.

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10.2: 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 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 grow 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 ounces) 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, helps 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 are 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 of 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 to 50 pounds per acre.

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.

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 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 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.

Note

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 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 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 10.2.1 and 10.2.2). 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 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 fungi. 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.

Figure 10.2.1: A soybean root heavily colonized with mycorrhizal fungi (Rhiziphagus irregularis). Photo by Yoshihiro Kobae.

Figure 10.2.2: 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.

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 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.

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 well-being.

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. 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.

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10.3: 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, 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 the 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 the 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 nightcrawlers. 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-sized 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.

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10.4: 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.)

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10.5: 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 the 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. 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 helping 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*

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10.6: Biological Diversity, Abundance, Activity and Balance

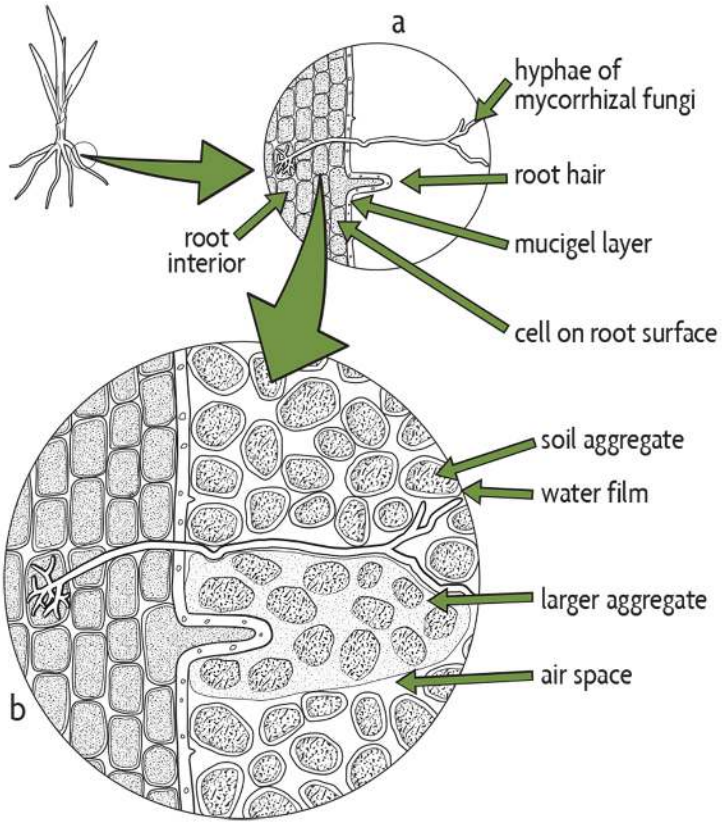

Figure 10.6.1: Close-up view of a plant root: (a) The mucigel layer is shown containing some bacteria and clay particles on the outside of the root. Also shown is a mycorrhizal fungus sending out its rootlike hyphae into the soil. (b) Soil aggregates are surrounded by thin films of water. Plant roots 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.

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 provide 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 soil, 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 to 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 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.

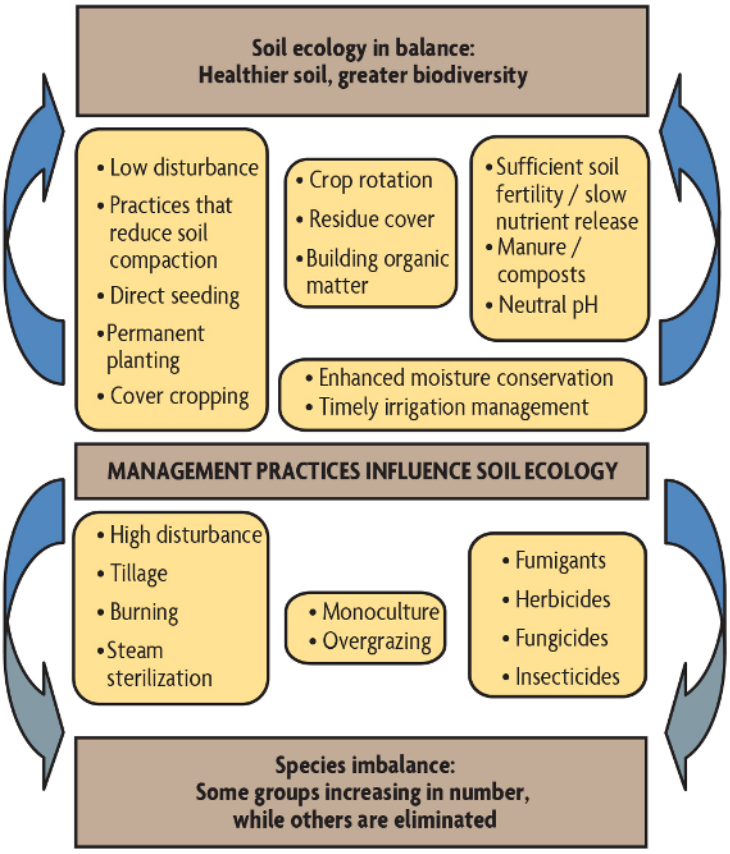

Figure 10.6.2: Management practices that influence soil life. Modified from Kennedy, Stubbs and Schiller (2004).

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)*. Also, the 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 10.6.2 for management effects on organisms). For example, the less 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 healthy soil. Crop rotations of plants from different families are recommended to keep microbial diversity at its maximum and to break up any potentially 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 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.

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10.7: 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 from 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 the 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. Trophic levels are a way of classifying soil organisms based on their role in the soil food web. 'Trophic' just means which level or type of feeding the soil critter does. Some organisms cross over into more than one trophic level. Different authors sometimes assign different trophic levels but a widely used version appears here.

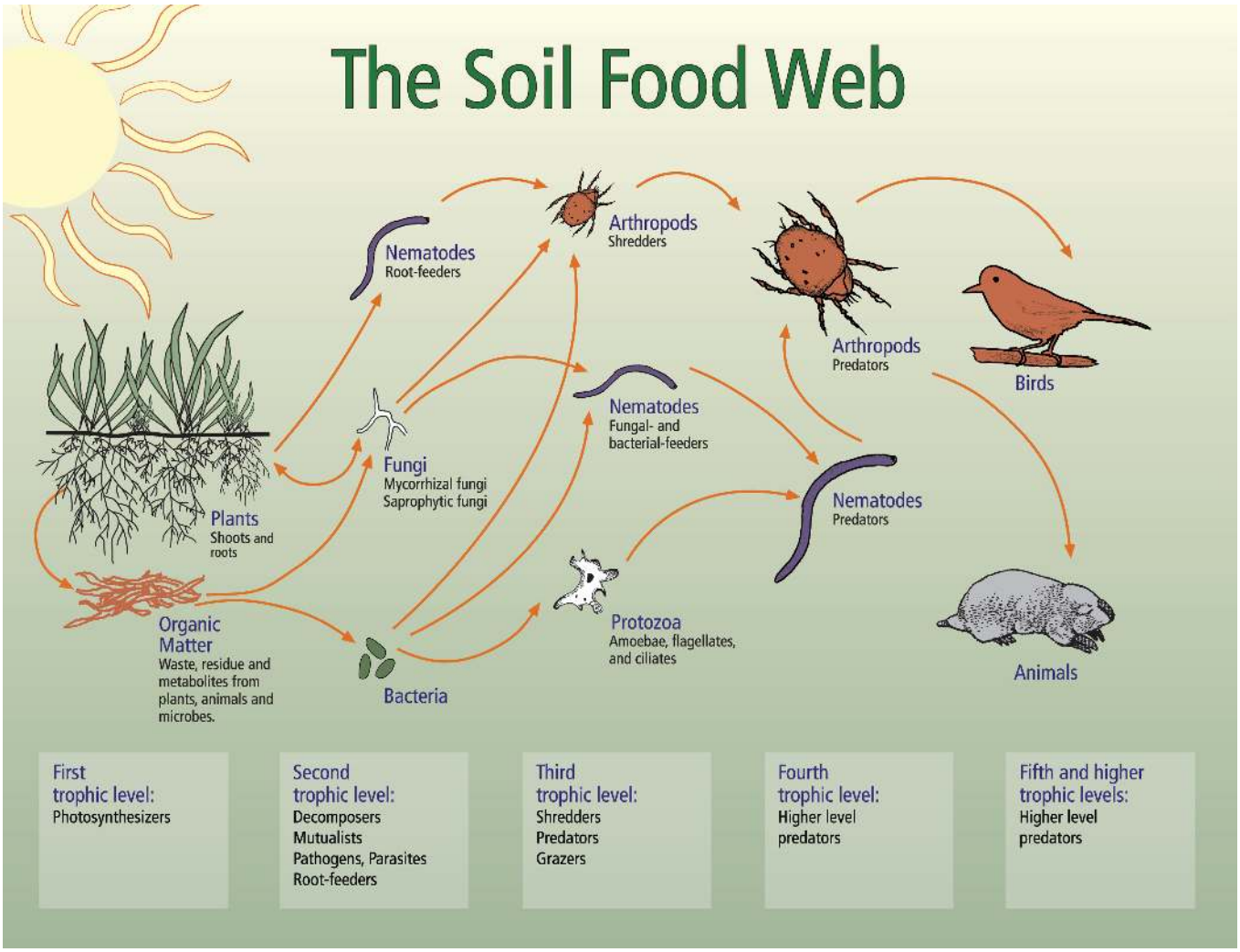

Figure 10.7.1: The Soil Food Web of organisms and trophic levels. USDA -SARE https://creativecommons.org/licenses/by/4.0/

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CHAPTER OVERVIEW

11: Integrating Livestock (and Manure) with Crop Fields

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11.2: Types of Crop-Livestock Farms
11.3: Manure
11.4: Manure Handling Systems
11.5: Effects of Manuring on Soils
11.6: Using Manures
11.7: Estimating Manure Nutrient Availability
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11.10: Summary
11.11: A Case Study, Darrell Parks
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11.1: Introduction

> *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*

Once plants and animals were raised together on the same farm - which therefore neither produced unmanageable surpluses of manure, to be wasted and to pollute the water supply, nor depended on such quantities of commercial fertilizer. The genius of American farm experts is very well demonstrated here: they can take a solution and divide it neatly into two problems.

Wendell Berry (2015). “The Unsettling of America: Culture & Agriculture”, p.54

Wendell Berry's tongue-in-cheek, sarcastic quote about American farmers (above) summarizes how we handle manure in modern agriculture. We fail to see it as a resource. We've separated animals from the land. We let manure become a problem. This system can wreak havoc on our soils and our water.

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 large 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. 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. We previously reviewed the flow of nutrients into high-density animal operations. On the other hand, farms that exclusively produce annual grain crops, such as corn, soybeans, wheat sorghum, or even vegetables, export a lot of nutrients contained in their crops. Another issue is that farms concentrating on the 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 market for it in the wide expanse of regions growing annual crops. Exclusively growing annuals, especially only one or two crops, make 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 make it more complex. If not implemented in the right way it can also increase environmental problems.

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11.2: 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 several 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 in 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 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.

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11.3: 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.

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 are influenced by soil type. In other words, it is impossible to give blanket recommendations for manure application. They need to be tailored for every situation. 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.

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11.4: Manure Handling Systems

Solid, Liquid or Composted

The type of barn on the dairy farm farmstead frequently determines how manure is handled. There are generally three kinds of dairy manure. 1) Solid from regular stall barns, 2) liquid, from large CAFO cow 'sheds', with >200 cows per shed, 3) semi-solid from cows out grazing pasture.

Dairy cow manure containing a fair amount of bedding (straw or sawdust), 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. In dairy country, you might see a farmer pulling a manure spreader out to the field full of cow manure. On some farms, this meant a 'daily haul' chore to keep up with the pile of poop. A cow eats about 40 pounds of feedstock in a day and excretes as much as about 18 people. Winter spreading of manure has become less common as farmers began, in the early 2000s, to value the fertilizer contained in the manure that was lost to winter weather.

Liquid manure-handling systems are common where animals are kept in a free-stall barn. Minimal bedding is added to the manure. Most often the cows lie on sand-filled or rubber mats in stalls that they can freely get up, leave, and walk over to a bunk feeder. Thus the name free-stall barn. Liquid manure is usually very wet, in the range of 2–12% dry matter (88% or more water!). Most large dairy farms automatically flush the concrete barn floors with water every fifteen or twenty minutes. This is followed by a slow-moving scraper that pushes all the cow poop into a receiving trough. Then the liquefied manure is conveyed along the trough to pass through a liquid-solid separator and then sent to a storage lagoon. The lagoons usually have several million gallons of capacity; enough for six months of storage. Sometimes plumbing fails and the liquid spills causing great ecological damage. Liquid manure is trucked by the tanker-load to farm fields miles from the cow barn. Some liquid manure is pumped via pipes or hoses to nearby fields. Once crops start growing, no more manure is applied.

Figure 11.4.1: A lagoon holding millions of gallons of liquid manure. Photo credit: Dan Bertalan.

Pasture cow manure is unmixed with water or bedding and simply falls onto the farm field in its semi-solid form. In well-managed grazing paddocks, the active soil life like dung beetles and earthworms will pull the cow pie into the earth in a matter of a week or two. A natural 'crust' forms on top of the cow pie to keep nitrogen from volatilizing and escaping into the air. Cows have four legs, let them walk out to the pastures, get exercise, eat, and spread their own manure on the fields and return to the ground the valuable nutrients. You have never heard of a manure spill from a pasture, since they do not happen. Manure spills only happen when manure is collected in a big hole in the ground and the man-made system fails.

Figure 11.4.2: A pastured cow herd at Full Circle Farm. Photo by: Valerie Dantoin

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. Composting manures is becoming an increasingly popular option for farmers. Compost stabilizes nutrients (although some Nitrogen as ammonium is usually lost in the process). Other benefits of composting manure are that there is a smaller amount of solid material to spread, and it stinks less than liquid manure 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. We have a composting barn at Full Circle Farm. We shred a large round bale of straw onto the area where the cows are free to come in and lie down. This 'bedded pack' stays warm all winter because it is actively composting. New straw keeps the animals clean and comfortable. The mass of manure and straw is left in place after the cows leave the open barn in spring to spend the next six months completely on pasture. We then compost the manure straw mixture by windrowing it and turning it to meet organic and produce safety standards. We reduce the volume of an entire winter's worth of manure for 100 animals by about two-thirds. When active composting on the cowyard is complete, we work it into the beds of the commercial organic vegetable garden on the farm, or we spread it back on a pasture that needs a boost. Our manure handling method uses about 1/3 of the fossil fuel energy required to start tractors, pump flushing water, run barn cleaner/scrapers, operate conveyors, load and haul tankers, and apply and incorporate the manure. In short, a compost barn uses microbes to handle manure rather than all the energy-intensive, man-made handling activities of CAFO manure systems

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 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 the storage method, it is important to understand how potential losses occur in order to select a storage method and location that minimizes environmental impact.

Anaerobic bio-digesters are sometimes used to process manure on large livestock farms. In these systems, specific bacteria 'eat' the manure and produce methane (and a few other gases) that are captured. The 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 bio-digesters can reduce greenhouse gas emissions, odors, and pathogens, and improve air and water quality. They are a major capital investment for a farm

costing millions of dollars. To make them profitable, farmers typically need to make full use of the energy, carbon credits, tipping fees from external organic wastes, and co-products 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. Some farms re-use the solids from manure as bedding for their cattle.

Table 11.4.1: 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				

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11.5: 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 many 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 forage (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 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 to 30 tons of the solid type of dairy manure per acre is needed to maintain soil organic matter (Table 11.5.1). As discussed above, a nitrogen-demanding crop, such as corn, may be able to use all of the nitrogen in 20 to 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.

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 11.5.1, which contains the results of a long-term experiment in Vermont with continuous corn silage on 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, the 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. The soil in plots receiving manures was better aggregated and less dense and, therefore, had greater amounts of pore space than fields receiving no manure.

Table 11.5.1: 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	5.2
CEC (me/100g)	19.8	15.8	17	17.8	17.8
pH	6.4	6	6.2	6.3	6.3
P (ppm)*	4	6	7	14	14
K (ppm)*	129	121	159	191	191
Total pore space(%)	ND	44	45	47	47

*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)

An example of how a manure addition might balance annual loss is given in Figure 11.5.1. 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 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.

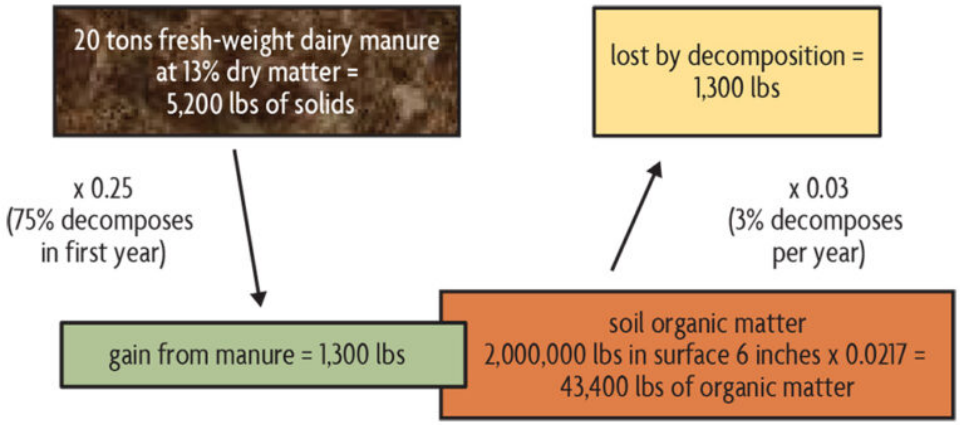

Figure 11.5.1: Example of dairy manure addition just balancing soil organic matter losses.

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).

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11.6: 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 into 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. 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 of 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 are 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). If the manure is surface applied, this allows for rapid incorporation by the 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 for 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.

Figure 11.6.1: Injection of liquid manure into shallow frozen soils, which eliminates compaction concerns and reduces spring application volumes. Photo by Eleanor Jacobs.

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 a 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). 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.

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.

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11.7: 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 11.7.1. 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.
- 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 11.7.1: 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 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. These allow for in-season evaluation of a crop's N status and a more precise determination of the need for corrective N applications.

Table 11.7.1: 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

*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)

		Nitrogen Availability Factor*			
		> 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)

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11.8: 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 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.

Figure 11.8.1: Rotational grazing system for dairy cows with relatively high stocking densities for short durations. (White lines in the background are paddock separation wires.)

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 (or 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 re-grazing early shoot regrowth depletes root reserves, making it harder for the plant to regrow again after grazing. Using what is called *managed grazing* (MG), 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 MG, cows are turned out into a fresh paddock after each milking (Figure 11.8.1). 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 makes 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.

Figure 11.8.2: Grazing allows for productive use of marginal lands (New Zealand).

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 11.8.2). Grazing has gotten a bad reputation

when it is not managed properly, that is, when animals are stocked at too high of densities and pasture plants are not given a chance to rest and recover. Areas can quickly become denuded of vegetation and in some cultures that has been the start of desertification (along with other causes). Grazing must match animal numbers with amount of feed produced and that varies from year to year with rainfall and temperature. Managed grazing is not a one-size-fits-all prescriptive farming tool.

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 nighttime. The carbon, nutrients, and seeds gathered during the day are excreted into the smaller area and provide a significant boost for soil fertility and re-vegetation (as discussed with "plaggen soils"). 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 11.8.3). 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 11.8.4 (This 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 enhances 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. The emergency feed may be required during unusual weather events like drought, high snow, or ice.

Figure 11.8.3: Swath grazing of winter forage in the northern Great Plains. Photo by West-Central Forage Association.

Figure 11.8.4: Mixed winter cover crop used for grazing (Washington State). Photo by Bill Wavrin.

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11.9: Manure as a Pollutant; stewardship farming.

As we all know, there can be too much of a good thing. Excessive manure applications may cause plant growth problems. Here we are mostly referring to raw animal manure (not composted manure) applied to farm fields. It definitely causes problems in the water-rich region we live in, especially since dairy cattle carrying capacity typically exceeds the amount of acreage available to receive the poop as fertilizer. Manure is typically spread across the surface of a crop field. But, manure runs off fields and gets into streams and lakes. Nitrogen in manure can also leach down through the soil profile and seep into groundwater. Both are big pollution problems and are becoming worse in many areas where livestock, (poultry, pigs, or cows) are confined and congregate.

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 solid manure that has been stored for a year or more. Injection of liquid manure by large-scale farms sometimes causes problems when done 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. Loss of readily available nitrate for plants occurs by denitrification when too much water saturates a field.

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 in excess of what a crop needs. It is often mistakenly believed that buildup results from the fact that manure nutrient ratios are out of balance with crop uptake requirements (especially more P). Nutrient ratios for most manures are actually equivalent to a crop's needs (roughly a 2:1 ratio for nitrogen and phosphorus). If farmers are smarter about how they apply manures, most nitrogen can be conserved through good timing and application methods. Apply manure immediately prior to the growing season rather than winter for example. Or inject liquid manure and incorporate it right away. Then the manure rate necessary to meet crop nitrogen requirements can be substantially lowered and the accumulation of P and K in soil reduced!

Erosion of phosphorus-rich topsoil contributes both soil sediments and phosphorus to streams and lakes, polluting surface waters. This is how Green Bay gets its name, alot of P naturally occurs in the clay soils in the watershed. If soil P levels are built up even more with manure applications the problem will only worsen as the 'loose' P feeds algae in the receiving waters. The sediment from plowed fields for annual corn and soybeans also contributes to ecological problems in bays and lakes. Green Bay used to have wild rice growing on its margins but sediment (and the introduction of bottom-feeding carp, and paper mill PCBs) killed this natural wild food. The wild rice was a staple crop of the native people who inhabited the region before European contact. The people were named "Menominee" by French voyagers - it means people of the wild rice. Sadly, the wild rice disappeared completely in about 1950.

When very high P buildup occurs, it may be wise to switch the manure application to other fields or to use strict soil conservation practices to trap sediments before they enter a stream. Crops that do not need manure for N, such as alfalfa (its a legume), allow a "draw-down" of phosphorus that accumulates from manure application to grains. (However, this may mean finding another location to apply manure.) In the last 50 years, our Green Bay region has lost 50% of its former hay crop acreage to corn and soybeans because of the federal subsidies for these crops and the lack of consequences. The manure and sediment from plowing for annual crops have suffocated the Bay waters and created a hypoxia zone.

Figure 11.9.1: Milk wagons in front of the Lessor-Maple Grove Townline Cheese Factory in Wisconsin.

Case study in farm modernization and the resulting nutrient flow on the farm: Full Circle Farm, Seymour WI., Valerie Dantoin-Adamski

This farm has been in my husband's family for over 125 years. The farm has seen a lot of changes over five generations. It started with a homestead of 160 acres carved out of a cedar tree swamp by Poland-born Valentine and Barbara Adamski. My husband Rick Adamski (and I) bought the farm from his parents in 1990 and promptly bumped dairy cow numbers up from 35 to 80. We put in a new milking parlor and bought a new tractor. We were on the path of the 'modern' dairy mantra to get ever-bigger (or get out). But instead, we took a turn to a more sustainable farming system. We chose to use managed grazing and perennial hay fields rather than growing annual crops. We chose to sell organic milk and now organic, grass-fed beef as better choices for the environment. Our son Andrew (and partner Heather) are downsizing even more and growing organic vegetables on just 16 acres. We will likely put the farm in a trust that will allow it to return to its pre-settlement state. The farm has come full circle.

Along the way, farming with five generations, the nutrient concentration on the farm has ebbed and flowed. The land was fresh and full of minerals and nutrients built up after the last glacier retreated from the Green Bay, Wisconsin area ten thousand years ago. The land was home to the Menominee people who moved from one forest area or waterway to new areas every ten years. There was no title to the land back then, before colonization. It belonged to everyone. Then the French, British, and Americans had a little war over who would own the land. The English/American system of government claimed the land, surveyed it and designated townships - six miles by six mile size units of government. The townships were further divided into 40 acre parcels that were then 'titled' so the land could be sold to homesteaders to occupy. The Menominee people were confined to a reservation about 45 miles west of Green Bay, about a 1/10th of the land they formerly occupied for the last several thousand years.

The township of Maple Grove where our farm is located was surveyed and platted in 1853 and the first immigrant farmer/settlers came in the 1880s, cut the cedar and white pine tree, and blew up the stumps with dynamite (some of which we discovered in an old granary as late as 1996). They turned the soil with plows and horses. An acre was just about how much land a man could turn over (plow) in a day. Full Circle was just a homestead in its first generation under the Polish immigrants, Valentine and Barbara. Very few nutrients were imported or exported.

The second generation (Stanley and Tekla) fed their 13 children from a large garden and sold eggs, pork, and a little milk to the corner cheese factory that Stanley helped organize in 1905 (Figure 11.9.1). They hand-milked a dozen cows, keeping milk in cans cooled by groundwater or springs. Electricity and refrigeration came to their farm around 1940. That meant hand-pumping water for livestock could be replaced by an electric pump. Milking machines replaced the children's labor. Herd size tripled to 36 cows. They still kept fertilizer purchases very low because there was still a good supply of natural minerals in the soil.

Two boys stayed on the farm, Frank and Dick (the 3rd generation). They bought a tractor in 1958. The last horse, Prince, left the farm in 1958. They continued to use dairy animals and pigs as a source of manure nutrients. They were considered 'low

input' farmers by the neighbors because they never got on the modernization kick. They bought some fertilizers and started using some chemical herbicides, but not much. They used old-time organic methods of crop rotation and animal manure as ways to retain organic matter and natural soil fertility. The Adamskis were organic before it was a 'thing'. They milked about 36 cows and bought the neighboring 80 acres so Dick and his bride Evelyn could establish their own household in 1953.

When Rick and Val (4th generation) bought the farm, it was not a difficult decision to choose the track of low-input, only organic, fertilizers. The soil tests show the farm didn't need phosphorus because of all the animal manure over the years. Nitrogen was needed, but only about 1/3 of what most farmers would consider the 'right' amount. Corn yields on this farm were above the county average. What started to show depletion was potassium. Naturally mined potassium sulfate (K2SO4) or gypsum was brought in to bring K levels up. The number of dairy cows increase to 80 head. That did not include replacement heifers or steers. This farm is an example of one that buys fertilizer in the form of purchased hay from other organic farmers. The farm quit dairying in 2014 and now 90 beef cattle graze 160 acres of pasture. Sun and rain, hay and pasture, build the beef bodies. They poop out the excess nutrients, and the soil fertility cycle continues, Full Circle.

The fifth generation on the farm, Andrew & Heather, compost the cattle manure and use it to intensively grow 16 acres of organic vegetables which they direct market locally within about a 50 mile radius. This is a net out-flow of nutrients from the farm as vegetable produce leaves the farm, but it is well-balanced by the inflow from the beef cattle operation. Other non-family members of the farm are buying shares and becoming new farmer managers and gaining access to the land so that this 240 acres continues to operate as a farm. About 1/10th of the farm acreage is set aside for perennial plantings, wildlife and wetlands. The farm was named 2024 Organic Farm of the Year by the Midwest's Marbleseed Organic Organization. It was also named the 2024 Leopold Conservation award winner by the Sand County Foundation. The farm is a new model of conservation and productive agriculture that expands the definition of 'family' farm to include new members who share the same values.

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 balance, one of the advantages of integrated farms. 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 remove 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 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.

In Northeast Wisconsin, the number of milk cows in the region greatly exceeds the amount of land available on which to spread manure. Some technologies are being tried out, like making manure bricks and selling them. Many large dairies have bio-digesters which use microbes to digest the manure and release methane. The methane is then used to power electric generators. To move the manure from the large free-stall cow barns, water is flushed across the cement barn floor. It makes a manure slurry that is then scraped from the floors into a slurry pit before being de-watered and then sent to the digester. Seems like a lot of work. If we had right-sized farms more dispersed on the landscape, then the cows would simply walk out to the pasture and deposit their poop. The right amount of cows brings the right amount of manure. Nutrients stay in balance.

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 foot baths 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 end 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, we call these “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. However, because these cow pies are unevenly distributed, they generate small areas with concentrated nutrients while areas in between the “pies” have fewer 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. Most graziers (the farmers who graze their animals) are adept at having just the right number of livestock on each acre so they avoid unbalanced, built-up nutrients.

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11.10: 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.

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. However, some animal-based systems pose great environmental concerns because they do not adequately consider nutrient cycles and the potential 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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11.11: A Case Study, Darrell Parks

Hog Manure in 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 let 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."

For most of their lives, Parks' hogs are raised on half of a 10-acre field. He plants the remaining five acres of 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. 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" manure 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."

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12.1: How We Care for Soil

As farmers and gardeners, we have a responsibility to care for the soil that feeds us and our population. We also understand that it is difficult to grow crops without disturbing the soil. And when soil is disturbed, generally bad things happen. We have already examined how agriculture and gardening impact soil nutrients--we lose them when we remove crops from the field for sale. We have looked at how we have negative impacts on soil structure unless we strive to keep adding organic matter and provide a decent habitat for soil biological organisms. We have considered how manure is both a blessing because it adds organic matter and nutrients to soil, and a curse because it can overload some nutrients and become a pollutant.

In other words, we have seen how we will definitely alter soil's nutrient profile, its biology, or its structure simply by gardening or farming. And now in this chapter, we will explore soil erosion--losing the actual soil itself from a field. We revisit soil structure because we will explore tillage and compaction which have huge impacts on it.

Before we leave this chapter we inject some hope. You will read about the ways farmers and gardeners can blunt the effects of their activities through erosion control methods like cover cropping, buffers, and no-till. We also dive into tillage methods that work to minimize negative changes to soil structure. And we survey compaction and what farmers can do to lessen that in their fields.

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12.2.6: Sources

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12.2.1: Introduction- Wind and Water

The major forces that strip soil from fields are wind and water. Nature buffers these erosive forces by keeping a vegetative cover on the soil year-round. Of course, farming and gardening expose the soil because we have to have a way to get our desired crop seeds in the ground. In this section, we look more closely at erosion and its causes. In upcoming sections, we examine how we can farm differently to minimize the two soil robbers, water and wind.

> *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*

Wind

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 2025, we again have seen wildfires and dust storms claiming lives (traffic pileups) as strong winds blow over uncovered soils.

Figure 12.2.1.1: Sloan. 1936. Dust Bowl – Dallas, South Dakota. Retrieved from en.wikipedia.org/wiki/File:Dust_Bowl_-_Dallas,_South_Dako...

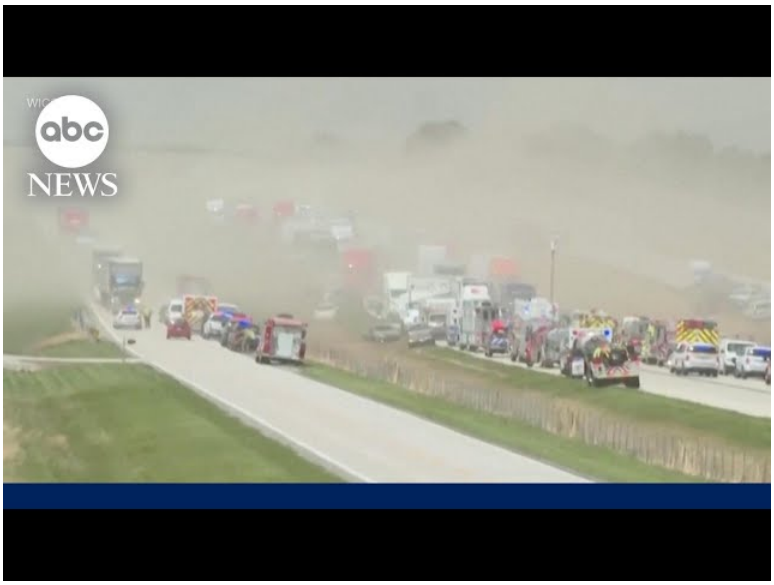

Figure 12.2.1.2: Modern day dust storm causes traffic accident in 2025

Water

The other major type of erosion is caused by rain storms and a lack of vegetation to cover and protect the soil. We've already discussed how managed grazing covers the soil with a protective blanket, but in some areas grazing and hay-making on pastured land have fallen by the wayside as farms concentrate their animals, truck hay into the farm, and focus machinery and management on growing annual grains like corn and soy to feed their concentrated livestock. In Northeast Wisconsin, for example, farmland in Brown County lost 70% of its hay/pasture land since 1990, having it converted to grains. This means land is tilled annually, and the result is that in springtime, erosion runs very high when this region receives rain on uncovered land before new crops grow and cover it. Up to 70% of the erosion occurs in just 17 springtime rain events. The soil washes into the bay of Green Bay, making it a new hypoxia hotspot.

The soil is gone from the landscape. Soil was formed in the Green Bay region just recently, after the last lobe of the glaciers retreated from the Midwest 10,000 years ago. The soil is young and fertile, but it is eroding more quickly than it can be built. In just the last 50 years, the region's farmers have reversed millennia of soil building. As they plow and plant they send soil into Lake Michigan.

In many other areas around the world, 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 12.2.1.2) after years of slash-and-burn agriculture. Much of the land has been turned into pasture or abandoned, and the area has become depopulated.

Figure 12.2.1.3: 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 water holding capacity in the soil.

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, the breaking up of soil aggregates with tillage lessens rainfall infiltration into the soil, which worsens runoff and erosion.

Climate and soil type are important factors affecting erosion. Intense or prolonged rainstorms are major 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. 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.

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12.2.2: Losing the Soil

Soil erosion is a geological process and a little bit of soil loss occurs naturally. In farming, it is possible to have no loss of soil, and in fact, to build soil. However, that's only possible when the plow is not used and perennial crops, such as well-managed pastures cover the fields. That is one reason to support 100% grass-fed cattle operations. Their soil loss is nil. Our goal should be to minimize erosion caused by farming operations while still feeding the world. There are ways to control the accelerated loss caused by the plow, tillage, and other cropping practices. Here we examine 'tolerable' soil loss.

Figure 12.2.2.1: A single raindrop impacts bare soil. Source: U.S. Dept. of Agriculture. Copyright info: Public Domain

The USDA Natural Resources Conservation Service (NRCS) is the federal agency charged with keeping soil on the land and out of the water. (It is the old soil conservation service). They do help farmers implement practices that help farmers do a better job of controlling erosion. The NRCS 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 NRCS-supported cost-share programs on farms. Practices used should bring estimated soil loss below the “tolerance” values estimated for the farm’s soils. For 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 takes many years to see a noticeable impact of soil loss. This is part of the concern: following these guidelines potentially diminishes long-term productivity.

Figure 12.2.2.2: A waterway scoured into a gully on a Midwestern cornfield after erosive spring rains. Photo by Andrew Phillips.

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 12.2.2.2). 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 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 the soil is lost, estimated at about 0.5 tons per acre (about 1 ton per hectare).

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.

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12.2.3: Off-Site Effects

The soil removed from fields 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 number one 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. Similarly, clay and silt particles suspended in the air can be transported long distances and can cause respiratory problems.

When soil washes (rain-caused) or blows (wind-caused) off a field it has downstream effects. In the humid Midwest, soil enters drain tiles, ditches, and streams and in short order enters the nearest river or lake. There are huge problems associated with soil becoming a pollutant in lakes. Not only do the lakes become cloudy and unpleasant for swimming, but the turbidity clouds the amount of light upon which many water plants depend. The plant ecology changes, which in turn changes which creatures can live in the water from crayfish to mollusks to small fry fish. Cloudy water also lowers the amount of dissolved oxygen in the water which affects which fish species can live there.

Sediment (silt) covers lake bottoms and grassy vegetation coating them and preventing ribbons of fish eggs from attaching and hatching. The formerly abundant perch population in Green Bay has crashed. Only one commercial fisherman now holds a license on the Bay. Of course, farming is not the only reason the fishery has collapsed, but it is a very big reason. Perhaps it does not make sense to have a million dairy cattle in the region, one of the largest concentrations in the world, in this close of proximity to a treasure like Green Bay and Lake Michigan.

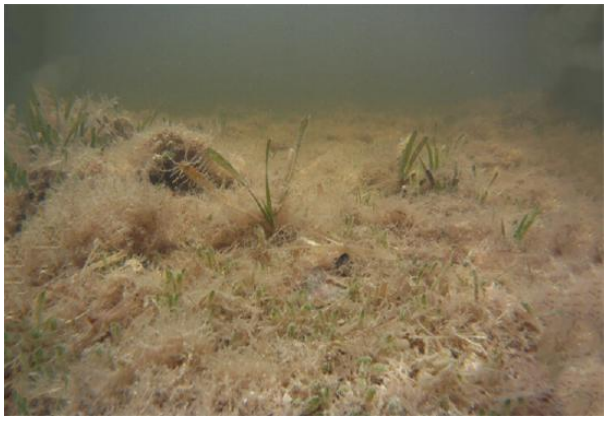

Figure 12.2.3.1: Sediment covering a sea grass bed. Source: FWC : Creative Commons

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. 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.

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12.2.4: Reducing 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 inches for the no-till planting system. Researchers in the state of Washington found that erosion on winter wheat 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 agronomic measures, and they also tend to be less effective.

Therefore, the use of soil-building conservation management practices is preferred for the 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 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 reduce runoff potential, but this effect is generally short-lived, as the soil settles. 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

Figure 12.2.4.1: No-till soybeans with corn residue.

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 12.2.4.1) is therefore the single most effective approach to reducing erosion. Incidentally, reduced tillage also generally provides better economic returns than 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 the 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. 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.

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 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% of soil cover reduces erosion by 70%.

As discussed, 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 the 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 12.2.4.2; 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.

Figure 12.2.4.2: Field and closeup views of soybeans grown in a black oat cover crop mulch in South America.*Photos by Rolf Derpsch.*

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.

Figure 12.2.4.3: Corn and alfalfa grown in rotation through alternating strips. *Photo by Tim McCabe, USDA-NRCS*

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 12.2.4.3). 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

Figure 12.2.4.4: Equipment for manure injection with minimal soil disturbance.

Maintaining good soil organic matter levels helps keep topsoil in place. Soil with more organic matter usually has better soil aggregation and less surface sealing/crusting. These conditions ensure that more water is 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 the 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 12.2.4.4).

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12.2.5: 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 12.2.5.1). 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.

Figure 12.2.5.1: 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.

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 12.2.5.2). 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.

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 nutrients before runoff water enters ditches and streams (Figure 12.2.5.3). ***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. 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).

Figure 12.2.5.2: A grassed waterway in a Midwestern cornfield safely channels and filters runoff water.*Photo by Ann Staudt, Iowa Learning Farms.*

Figure 12.2.5.3: Edge-of-field filter strips control sediment losses to streams.*Photo courtesy of USDA-NRCS.*

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 the 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 dry winds. 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.

Figure 12.2.5.4: 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.

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 leaves enough sunlight for a pasture or crops, a form of silviculture. 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.

Figure 12.2.5.5: A field swale across a slope's contour holds water back enough to let it soak into this sandy soil so that it stays on the field longer. (photo credit: V. Dantoin)

Figure 12.2.5.6: An experiment with wide-spaced poplar trees planted in a New Zealand pasture to reduce landslide risk.

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SECTION OVERVIEW

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12.3.1: Introduction

> *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*

What is the single best thing you can do to help your soil rebuff the effects of gardening and farming? Yes, it is cover cropping. You were introduced to cover crops earlier in this chapter and here we go into more detail.

Cover crops have been used to improve and protect soil and the yield of subsequent crops since antiquity. A cover crop does just what its name implies. It covers the soil in a blanket of green. When it is not 'growing season' the mat of dead or dormant plant material on the surface is also very protective against wind and water that tries to sweep soil off the field. The best cover remains in place, a living blanket, and living, soil-holding roots all year around. That kind of blanket can be found on a managed grazing farm. But, most of our annual crops need some sort of entry point, a way to get seed in the ground and for that reason, cover crops are often turned under to allow for seedbed preparation. When a green, growing cover crop is plowed down into the soil it becomes 'green' manure.

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. Green manures add the plant material plowed down back into the soil adding nutrients and organic matter. However, at that point, the cover crop ceased being protective against erosion.

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 beyond protecting the soil with living vegetation during a time of the year when it would otherwise be bare. Cover crops' other benefits include:

- using the sun's energy and CO_2 from the atmosphere to sequester carbon
- increasing soil organic matter with their roots and surface residue
- protecting nitrates from leaching
- increasing the amount of soil nitrogen (especially using legumes)
- breaking up soil compaction
- providing habitat for beneficial organisms
- promote mycorrhizal fungi presence for the following crop.

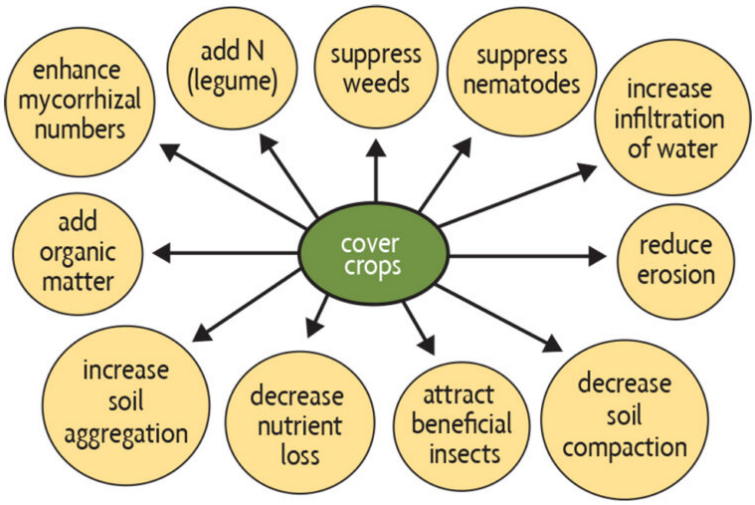

Figure 12.3.1.1: Cover crops enhance soil health in many ways.

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.

Cover crops are usually not perennial but they can be in a garden setting. Many commercial-scale gardens use white clover as a cover crop on pathways between beds and fields. White clover is low growing, needs mowing infrequently, keeps weeds from invading, and saves the gardener a lot of work trying to keep paths, alleys, and headlands free of weeds. It also attracts pollinators to the garden--a special benefit.

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12.3.2: Benefits of Cover Crops

In this section, we dig a little deeper into the multiple potential benefits of cover crops. As previously stated, they prevent erosion, improve soil physical and biological properties, supply nutrients to crops that follow them, 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 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. Here 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***.

Examples of Cover Crops with a Purpose

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 a 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, tillage radishes, hairy vetch, alfalfa). Especially useful to improve 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 the benefits into *canopy functions* (where benefits are primarily derived from the aboveground biomass) and *root functions* (where benefits are from the below-ground 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.

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 is also associated with almost all cover crops (except brassicas), which helps maintain or improve the inoculation of the next crop. (As discussed, 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. The use of cover crops in the Southeast has reduced the incidence of thrips, bollworms, budworms, aphids, fall armyworms, beet armyworms, 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.

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, 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 seeds 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)

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 water-holding 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.

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12.3.3: 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 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 winter annuals in the deep southern United States.

Figure 12.3.3.1: 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.

One of the main reasons for selecting legumes as cover crops is their ability to remove 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 of 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 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 12.3.3.1). 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 the 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 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 fertile soil for the 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.

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 fertile soil for the 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.

Figure 12.3.3.2: Velvet beans grown on hillsides in Central America, as growing vines (left) and mulched under a corn crop (right). Photos by Ray Bryant.

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 12.3.3.2). 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 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.

Figure 12.3.3.3: 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.

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.

Alfalfa is not used as a cover crop, but growing it for multiple years as part of a rotation provides some of the same benefits. It improves soil aggregation and water infiltration and breaks up compacted layers through its deep taproot (Figure 12.3.3.3). It also adds significant amounts of carbon and nitrogen to the soil. Following a three-year stand of alfalfa, there should be sufficient nitrogen for most crops for the next year, along with more N than might otherwise be present in the subsequent year or two. It is best grown on well-drained soils that are near neutral in pH and high in fertility. Alfalfa is commonly interseeded with small grains, such as oats, wheat and barley, and it grows after the grain is harvested.

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 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 12.3.3.4), 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.

Figure 12.3.3.4: 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.

A problem common to all 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 the germination of small broadleaf weed seeds. It grows quickly in the fall and also grows readily in the spring (Figure (\PageIndex{4}\)). 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.

Triticale, a cross between wheat and rye, is almost as winter-hardy as cereal rye. It is also easy to establish and has a good production of spring vegetation and roots (Figure 12.3.3.3), 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).

Annual ryegrass (not related to cereal rye) grows well in the fall if established early enough. It develops an extensive root system (Figure 12.3.3.3) 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 12.3.3.3). 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 different regions of the world. The two most commonly used 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 12.3.3.4, 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 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.

> *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)*

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, allowing deeper rooting by the next crop. 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.

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.

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12.3.4: 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.

Figure 12.3.4.1: Brassica cover crop roots. Growing oilseed (forage) radishes (left) and the soil hole built by a forage radish root (right). Photos by Ray Weil.

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 grass and legume, such as cereal rye and hairy vetch, oats and red clover, or field peas and 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.

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 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. However, 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 occur, 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 12.3.4.1and Table 12.3.4.1for 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 12.3.4.1.

Table 12.3.4.1: Estimated Available N from Previous Cover Crop[1]

Cover crop total N	**Estimated avail…**	Estimated available N (pounds N per acre)
% N in dry matter	**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).

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 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 overwintering 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 Cover Crops

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 12.3.4.2), 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. In this case, as with the system shown in Figure 12.3.4.2, 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 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.

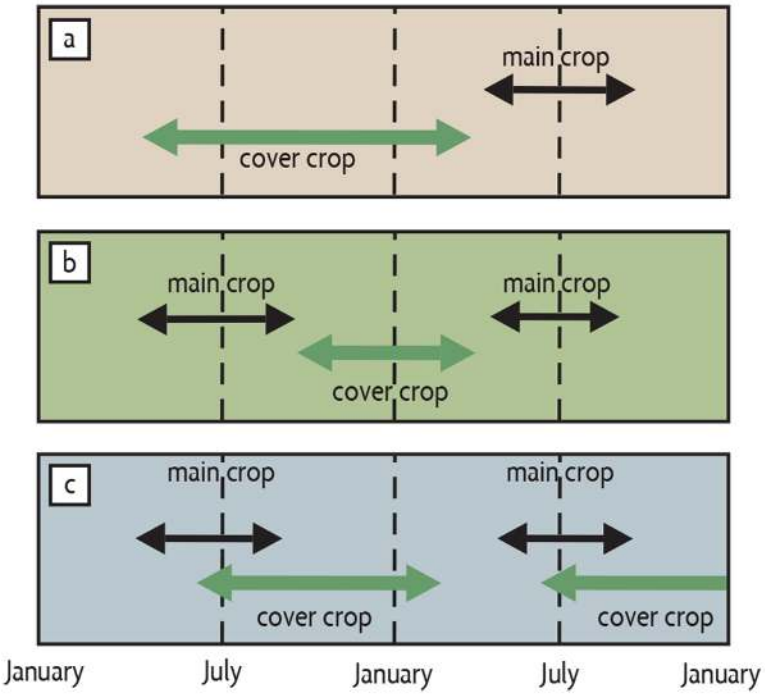

Figure 12.3.4.2: Three ways to time cover crop growth for use with a summer crop.

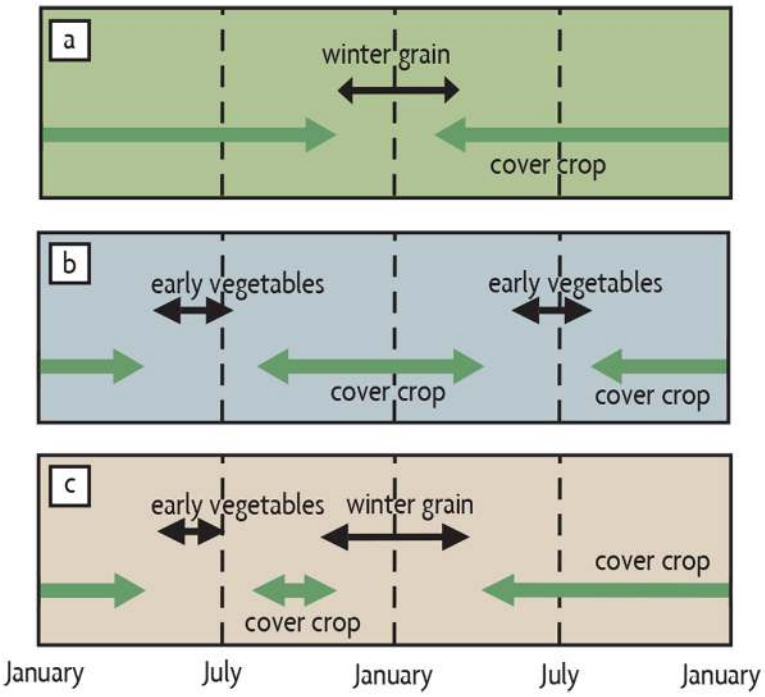

Figure 12.3.4.3: Timing cover crop growth for the winter grain, early vegetable and vegetable-grain systems.

Cover crops are also established following grain harvest in late spring (Figure 12.3.4.3a). With some early maturing vegetable crops, especially in warmer regions, it is also possible to establish cover crops in early summer (Figure 12.3.4.3b). Cover crops

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also fit into an early vegetable-winter grain rotation sequence (Figure 12.3.4.3).

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.

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 seeds 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 corn. When growing is on a smaller scale, the 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.

Figure 12.3.4.4: 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).

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 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.

"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.

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 the use of herbicides), or mowing, rolling and crimping and no-till planting in the same operation, or naturally by winter injury. In 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 cutworms and wireworms. 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.

Figure 12.3.4.5: A wide cover-free strip and living mulch, which is also used for traffic.

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. 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, the late killing of a winter cover crop may result in moisture deficiency for the main summer crop. In that situation, 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 water holding 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 a good habitat for soil organisms and also for some undesirable species. Animals like rats, mice and snakes (in warm climates) 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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12.3.5: A Case Study, Gabe Brown

Changing Farming Practices in Bismarck, North Dakota

It is 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 the 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 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 the 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 the 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 tour,s 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.

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SECTION OVERVIEW

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12.4.1: Introduction

> *A lasting injury is done by ploughing land too wet.*
>
> *—S.L. Dana, 1842*

We've already discussed the benefits of cover crops 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 previously, and in this section, we discuss strategies to prevent and lessen soil compaction. If measures to loosen 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.

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12.4.2: 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 12.4.2.1.

Table 12.4.2.1: 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 the 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

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. This type of compaction is often a problem for vegetable farmers or gardeners who till their beds, expecting to plant and have good germination, but then it rains and they have to till again before planting. This results in soil that has a tendency to crust. Therefore, be sure you have a clear planting window in the day or two after the final tillage or pre-planting cultivation passes. If crusting does occur, a quick pass of a scuffle hoe over a crusted bed allows seedlings to poke through.

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 12.4.2.1). Certain soil types, such as sandy loams and silt loams, are particularly susceptible. Their aggregates 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.

Figure 12.4.2.1: 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.

Surface Layer Compaction

Figure 12.4.2.2: Large soil clods after tillage are indicative of compaction and poor aggregation.

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 12.4.2.2). A field penetrometer 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 roots, 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 12.4.2.3). 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 structures and contain large pores from worm activity.

Figure 12.4.2.3: Corn roots from a compacted surface layer are thick, show crooked growth patterns, and lack fine laterals and root hairs.

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.

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 a 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 layer—typically down 6–8 inches—even if it has not actually been tilled for a while. 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. 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 the loss of 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.

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. Countermeasures 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 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.

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12.4.3: 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. 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 the compaction of the plow layer. But this puts them in a downward cycle and it should be avoided.

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 as remedies for all forms of compaction. The ways in which organic matter helps:

- 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 the 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. The extensive root systems of perennial forage crops in a rotation, undisturbed by tillage, work to improve soil structure.

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 12.4.3.1) 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 12.4.3.1). It is 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.

Figure 12.4.3.1: Tools that provide compaction relief with minimal soil disturbance: aerator (left) and strip tiller (middle and right). Right photo by Georgi Mitev.

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 a 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 12.4.3.2) 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 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 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. 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 to 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.

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 the use of organic matter amendments.

Figure 12.4.3.2: Top: Subsoiler shank provides deep compaction relief (wings at the tip provide lateral shattering). Bottom: Zone building provides compaction relief and better rooting with minimal surface disturbance.*Right photo by George Abawi.*

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. 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 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.

Figure 12.4.3.3: Compaction and smearing from wet (plastic) soil conditions: wheel traffic (left), plowing (middle) and zone building leaving an open and smeared slot (right).

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, 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.

Figure 12.4.3.4: 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

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. The 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 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 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 the 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.

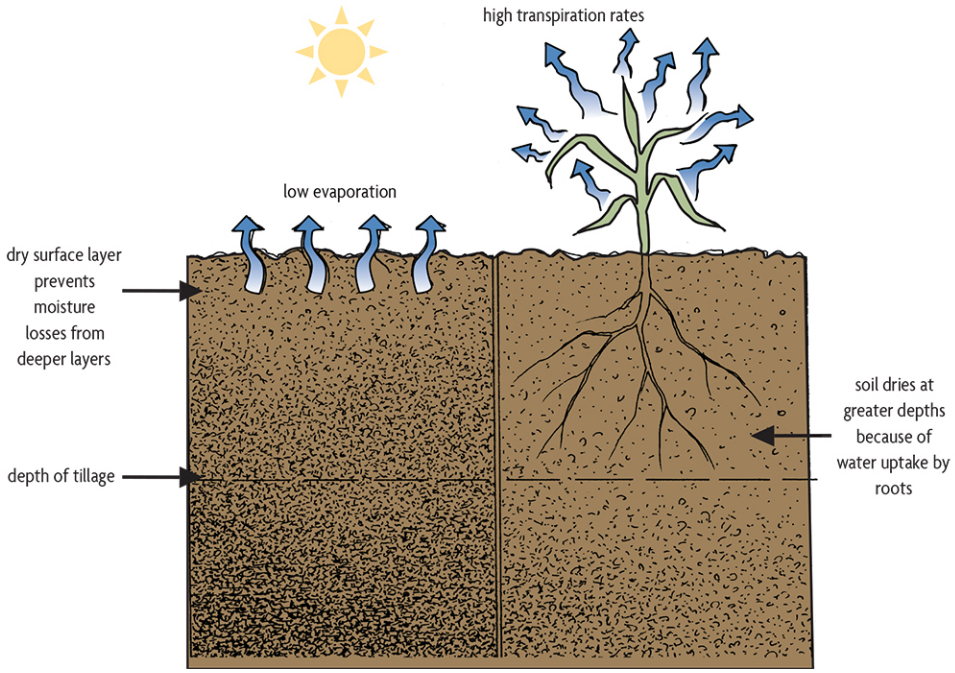

Figure 12.4.3.5: Cover crops enhance the drying of a clay soil. Without cover crops (top), evaporation losses are low after the surface dries. With cover crops (bottom), water is removed from deeper in the soil because of root uptake and transpiration from plant leaves, resulting in better tillage and traffic conditions.

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 a plastic to a friable state. Because these soils have high moisture-holding capacity, there is normally little concern about cover crops depleting water for the following crop.

Figure 12.4.3.6: A combination of deep alfalfa roots and shallow, dense grassroots helps address compaction at different depths.

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. In many cases, a combination of cover crops with shallow and deep rooting systems is preferred. Ideally, such crops are part of the rotational cropping system, as is typically used on ruminant livestock farms.

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 glue 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 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.

Figure 12.4.3.7: A tractor with wide wheel spacing to fit a controlled traffic system.

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 combined widths need to be compatible (although not necessarily the same), and wheel spacing may need to be expanded. A controlled traffic system is most easily adopted with row crops in zone, strip or no-till systems (not requiring full-field tillage) because crop rows and traffic lanes remain recognizable year after year.

The 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 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.

Ridge tillage dictates controlled traffic, as wheels 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. 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.

Figure 12.4.3.8: Controlled traffic farming with precision satellite navigation. Top: 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). Bottom: zucchini on mulched raised beds (Queensland, Australia).

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12.4.4: 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 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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SECTION OVERVIEW

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12.5.1: Introduction

> *... 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. However, 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 the 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 the 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.

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 the 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.

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 American farmers did not use full-field tillage for crop production. They instead used mostly direct seeding with planting sticks (Figure 12.5.1.1), 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 12.5.1.1: 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.

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 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—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.

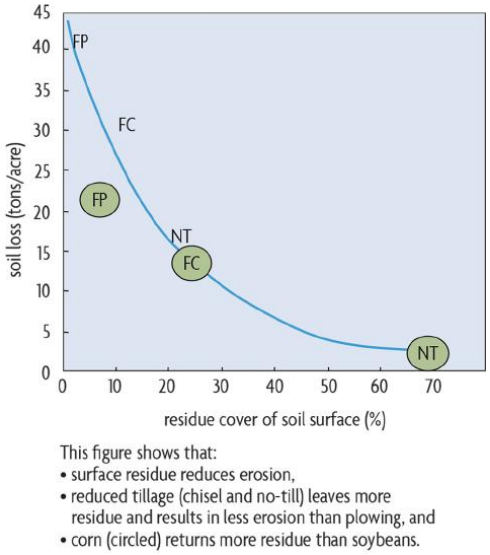

Figure 12.5.1.2: Soil erosion dramatically decreases with increasing surface cover. Note: FP = fall plow, FC = fall chisel, NT = no-till; circles = corn, no circles = soybeans. Modified from Manuring (1979).

Full-field tillage systems became more widespread because they were 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, and 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 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.

Table 12.5.1.1: 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

Tillage system	Agronomic benefits	Agronomic limitations	Economics and environment
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

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12.5.2: Tillage Systems

Tillage systems can be classified by the amount of surface residue left on the soil surface. Here we consider three types of tillage systems, 1) conservation tillage, 2) conventional tillage, and 3) restricted tillage.

Conservation tillage

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. 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 methods (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 thereby reducing the amount of residue on the surface helps reduce runoff and erosion. Table 12.5.2.1shows 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%.

Table 12.5.2.1: Estimated Crop Residue Levels Remaining After Field Operations

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%

Note: Speed, depth and soil moisture can affect the amounts. *Source*: USDA-NRCS

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 limitations of various tillage systems are compared in Table 12.5.2.1.

Figure 12.5.2.1: Conservation tillage system (full width) that leaves at least 30 percent or more residue on the surface. Residue adequately controls erosion by both wind and water on this soil type. Photo courtesy of USDA-NRCS.

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 12.5.2.2 top), chisels (Figure 12.5.2.2 bottom) and heavy disks (Figure 12.5.2.3 top), while secondary tillage is accomplished with finishing disks (Figure 12.5.2.3 bottom), 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.

Figure 12.5.2.2: Top: Moldboard plowing inverts the soil and leaves no surface protection. Bottom: Chisel plow shanks loosen soil and leave some residue cover.

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 12.5.2.1). 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. 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. 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 causes a lot of soil disturbance.

Figure 12.5.2.3: Top: A heavy disk (disk plow) can be used for primary and secondary tillage.Photo by Mark Brooks. Bottom: A finishing disk.

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 the 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 the 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 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

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.

Figure 12.5.2.4: Powered tillage tools used with horticultural crops: Top: rotary tiller; Bottom: spader.

In more intensive horticultural systems, powered tillage tools are often used, which are actively rotated by the tractor power takeoff system. 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. However, it is quite damaging to the 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.

Figure 12.5.2.5: 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; the seed is delivered by vacuum; and seed placement is digitally monitored. Photo by Larissa Smith.

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) or seed drill (for crops seeded in narrow rows). 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.

No-till systems have been used successfully on many soils in different climates. The surface residue protects against water and wind erosion 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.

Figure 12.5.2.6: Top: A no-till seed drill requires no-till or seedbed preparation for narrow-seeded crops or cover crops. Bottom: 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.

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.

Table 12.5.2.2: 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		
Phosphorus (lbs/ac)	13	20
Potassium (lbs/ac)	20	21
Magnesium (lbs/ac)	88	95
Early season nitrate-N (lbs/ac)	310	414
Calcium (lbs/ac)	7,172	7,152
*pH	8	7.8
Biological		

Note: Higher values indicate better health, except for those listed with an asterisk, for which lower values are better. *Source*: Moebius et al. (2008)

	Plow	No-Till
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)

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 is 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 are advanced pieces of engineering that need to be adaptable to different soil conditions yet also be able to place a seed precisely at a specified depth. This technology has come a long way since Jethro Tull's early seeders.

Figure 12.5.2.7: Top: A strip-till tool with hilling disks and rolling basket to create a zone of loosened soil.Photo by Robert Schindelbeck. Bottom: Strip-till after corn harvest results in a narrow tilled zone that leaves much of the soil surface undisturbed.Photo by Georgi Mitev.

The quality of no-tilled soil improves over time, which compares physical, chemical, and biological soil health indicators after 32 years of plowing 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 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. Strip-till provides soil quality 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 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 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 or to 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.

Figure 12.5.2.8: Planting green with a roller-crimper creates a weed-suppressing cover-crop mat through which it is possible to plant seeds or transplants. 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.

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12.5.3: 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 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.

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 the 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.

Farmers need to be aware of potential soil compaction problems with reduced tillage. If a strict no-till system is adopted on compacted soil, especially on medium- or fine-textured soils, yield reductions may occur in the first years. 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 the 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.

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 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 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. 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” 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 slow 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.

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.

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12.5.4: 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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12.5.5: A Case Study, Steve Groff

No-Till Farming in 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.

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.

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SECTION OVERVIEW

12.6: Putting It All Together

12.6.1: Introduction

12.6.2: General Approaches

12.6.3: Practices to Help Remedy Specific Constraints

12.6.4: Some Final Thoughts

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12.6.1: Introduction

> *… 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. 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 12.6.1.1. 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.

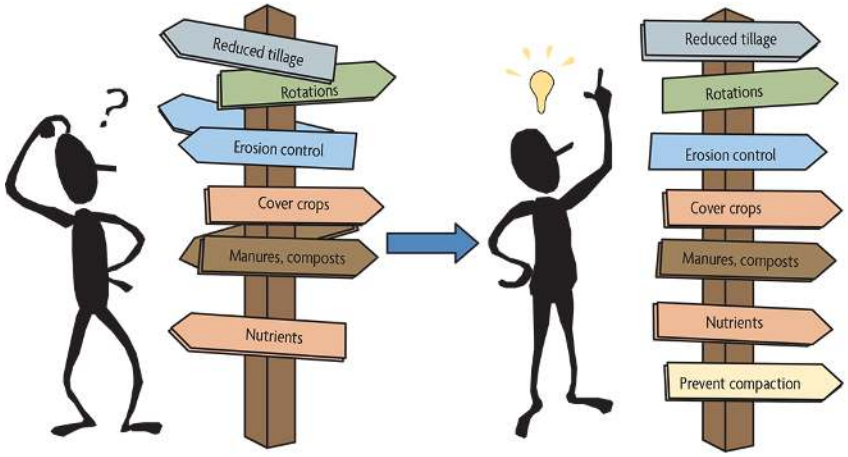

Figure 12.6.1.1: Are all the practices discussed in this book just confusing? Solutions can be found by matching them with the needs and opportunities of your farm.

The bottom financial line therefore may not improve immediately. Changing management practices may involve an 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 times you have extra cash flow—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.

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12.6.2: General Approaches

The ultimate purpose of ecological soil management is to create a healthy habitat below ground, with good soil structure, thriving and diverse soil organisms, and nutrients in sufficient (not excessive) supply for high crop yields without causing off-site pollution. When this is combined with a 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 sections 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 12.6.2.1). 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 main economic output. However, growing crops with high quantities of residues, plus frequent use of green manures and composts, help 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.

Table 12.6.2.1: Balance Sheet for Soil Health Management*

Practice or condition	Improves soil health	Reduces soil health
Tillage moldboard plowing chisel plowing disking harrowing conservation tillage	X	XX X X X
Compaction light severe		X XX
Organic matter additions bedded manure liquid manure compost mulch	XX X XX XX	
Cover crops winter grain winter legume summer grain summer legume	XX X XX XX	
Rotation crops 3-year sod 1-year sod	XX X	

*X = a moderate effect; XX = a greater effect.

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12.6.3: 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 practice or combination of practices depends largely on specific soil health problems and possible constraints imposed by the farming system. We discussed how traditional (chemical) soil tests are used to provide quantitative nutrient and lime recommendations. Newly 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 12.6.3.1 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 the 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.

Table 12.6.3.1: 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

Suggested management practices		
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

Note that many of the management solutions listed in Table 12.6.3.1involve 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. 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. 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.

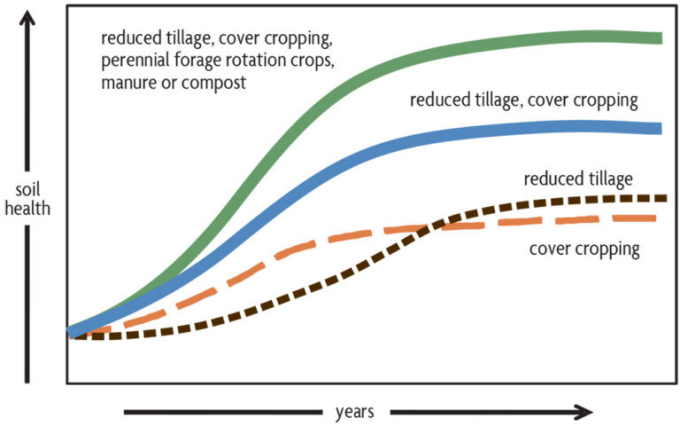

Figure 12.6.3.1: Combining practices that promote soil health has an additive effect.

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. However, 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, travels 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 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 in 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 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 reduce pest problems, and they import manure or compost to maintain fertility.

Finding Creative Solutions

Dairy farmers in Vermont were concerned about soil health in 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 shorter-season corn varieties that both 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.

More Is Not Always Better With Grapevines

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 sets 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 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*.

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 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.

However, many vegetable crops are highly susceptible to diseases, and the 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.

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12.6.4: 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 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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CHAPTER OVERVIEW

13: The Long View - Conventional, Sustainable, Organic

13.1: Two Paths, One Sustainable Road

13.2: An Ethical Predicament

13.3: Soil Comes Full Circle

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13.1: Two Paths, One Sustainable Road

In this book we have tried to inform you about the science of soil, what it is made of, and how it works. We have covered how to test soil for nutrients, how those nutrients behave in the soil, how they cycle, and how they are taken up and used by the plant. We have explored extensively how nutrients and carbon flow around the world based on our current farming system and its need for mineral fertilizers. We saw how nitrogen and phosphorus enter the biological realm and how they leak out as pollutants. We also added information that many other soils books do not include like a strong emphasis on organic matter and soil biology. We explored composting as well as green manures, cover crops, and low-impact tillage methods. In other words, we have let you know how different farming methods impact soil health. That is the bottom line of this book. Modern agriculture has profound impacts on soil. And change is needed from our current trajectory or our soils and fertilizers will be gone in a few hundred years at most.

Our current farming system as practiced in the U.S. by most conventional farmers has been a system that evolved. We went from planting sticks and broadcasting seeds to plowing and making seedbeds for row crops. We replaced the horse and single bottom plow with 400 horsepower tractors that can pull a 24-bottom plow and seed 48 rows at a time. We reduced the number of people working in agriculture and increased machine power. Now, according to the American Farm Bureau Federation, less than 2% of the population is on a farm and each farmer feeds about 170 people. Farming just wandered to the place it is now without a clear understanding that there are ways to still feed people without compromising the soil and the environment.

Farm Bureau's facts continue to sound the well-worn alarm that "the global population is expected to increase by 1.8 billion by 2050, which means the world's farmers will have to increase total annual grain production by almost 1 billion tons and total meat production by more than 200 million tons." We are already living in a world with 8 billion people. We currently DO have enough food to feed everyone especially since "Americans throw away **about 25%** of the food they purchase for at-home consumption" and "A whopping **40%** of all food grown and produced in the U.S. is never eaten." The tragedy in this is we lose soil while throwing away the food it grows. We fail to recycle the precious phosphorus we import to grow the crops which we then end up discarding in landfills. We don't return our own human selves, or our bodily 'wastes' back into the nutrient agriculture stream. We export about 20% of the crops we do grow and when we do that we unintentionally disrupt the ability of local farmers to profitably feed their own people. And people living in poverty still can't access food even if it is in a market right across the street whether that is in Columbus, Ohio or in Addis Ababa, Ethiopia. Even Iowa, one of the states with the deepest, richest soil anywhere, is a net importer of food because it exports the wealth of its soil as commodity corn and soy. Iowa farmers grow ingredients, not food. Economics, energy, and food policy are all part of a food system that previously has not valued soil health and that will need to change.

In the breadbasket in the U.S. Midwest, there is a responsibility to feed the hungry and we must be smarter about how we do that. We must be smarter so that we preserve the soil for future generations and can continue to feed people well into the future. Future farmers will need to repair the damage we are currently doing as we flex our mechanical and technological muscles at the expense of soil biology, structure, and health. There is hope, we do know what to do to save our soil. We still have time.

Contrasts

In this section, we see the contrast between conventional, modern U.S. agriculture and the sustainable approaches that will have to be taken as we shift directions to conserve soil.

Conventional approaches

Conventional farming from the 1970s until the early 2000s treated soil like dirt, as just a place to stick a seed and nothing more. The tractor and plow ignored the structure (grapes) of the soil. As we have seen, plowing ruins pore spaces, burns up organic matter, and reduces water-holding capacity. Conventional agriculture adds chemical nutrients as salt-based fertilizer rather than relying on the natural capacity of healthy soil biology to provide nutrients. The crop plants became 'lazy' because they do not have to reach out, in collaboration with their natural, beneficial fungal partner, to obtain their own nutrients. Conventional plants are totally dependent on the farmer's spoon-fed nutrients as well as herbicides which burn down weeds and much of the soil microbiology as well.

Figure 13.1.1: Conventional farming may kill the soil. It feeds the plant “junk food”.

The dominant cultural view in agriculture is that soil is just a media that holds plants in place and synthetic nutrients must be applied or synthetic helpers like herbicides and pesticides must be administered to plants that have been genetically modified (GM) to withstand them. This, however, is not sustainable, especially since Corporations own GM seeds and the farmer must continuously buy seed rather than save and re-use their own seed. As this book explained, synthetic nitrogen leaches or volatilizes and leaves the system; that is unavoidable as farms try to maximize nitrogen fertilizers for the highest yield. Remember, it is estimated that less than 50% of applied nitrogen is actually taken up by the plant. Conversely, sac-body bacteria & gummy-worm nitrogen does not leach. It is slow release; available just when the plant needs it. Salty, synthetic fertilizers make a hostile habitat for soil livestock. If we could see sick soil life, like we can see a sick person, we would be aghast at the devastation we have caused in the soil.

In modern agriculture, soil is viewed as a disposal area on which to spread liquid manure. Both manure and soil are problems that farmers try to keep on fields and out of water. Soil is viewed as continually and unavoidably being degraded. Soil itself is a commodity that modern agriculture will eventually, regrettably, use up. Annual tillage oxidizes soil carbon and good spongy organic matter. Agriculture undoubtedly contributes to climate change, flash flooding, and water pollution. Heavy equipment crushes the fragile, wonderful, “grapes” of soil aggregates and degrades soil. Continuous corn and soybeans, and continuous plowing, year after year, with soil grapes all gone, lead to cement feet result.

Figure 13.1.6: Manure tankers ready to spread, crush the soil structure.

> *“Pardon me oh thou bleeding piece of earth that I am meek and gentle with these thy butchers”*
>
> *- Shakespeare*

Sustainable/Organic - A New Path

Sustainable/organic farmers understand that soil is alive--a biological system. They purposefully foster the soil livestock; that complex web of soil life that we have only just begun to explore. These farmers foster soil that is fecund with microbes. Organic farmers bank wealth in the soil for their children’s children. They respect all life, even a bacterium. They cheer on soil life and its magic of resurrection.

Figure 13.1.7: Organic farmers feed the soil; let the soil feed the plant. Photo credit: C.J. Jansen, Northeast Wisconsin Technical College.

Organic farmers are sustainable farmers. Both 'strains' of farmers use science and biological principles to return organic matter to the soil, recycle nutrients, and add biological nitrogen. These farmers do not use herbicides pesticides or synthetic fertilizers. And because they don't, the soil is healthier. It is a myth that yields from sustainable/organic (S/O) farms are always lower than conventional farms. On the contrary, during seasons of high rainfall or drought, the organic matter in these soils acts like a sponge either soaking up excess water during a flood or holding more moisture in the soil during a drought. Resiliency is the hallmark of S/O farms. Self-reliance is another. On Full Circle Organic Farm, for example, when fertilizer or fuel prices skyrocket the farm does not need to increase prices for its 100% grass-fed beef because the grass continues to grow, the sun still shines, and the rain still falls regardless of those external costs for inputs the farm does not use.

The good news is that conventional farmers now see what S/O farmers saw a while ago--that soil health is important and needs to be protected. Tillage and cultivation are used by many sustainable and organic farmers, but they along with conventional farmers, are trying out new methods of planting and weeding that are less disruptive to soil. We are finding many more tools in the toolbox that we didn't know we needed and had not looked for previously, because the land was very forgiving. But with our ever-larger machinery and ever-increasing farm size and concentration of livestock, we do need new solutions to problems. Sustainable and organic farmers tend to look for biological solutions while conventional farmers tend to look for technological fixes. Ideally, the S/O farms will lend age-old solutions to the toolbox, a re-discovery of things that work to preserve soil health. Conventional farming lends its brightness and ingenuity to creating tools that work for all farmers, not just the very largest operations. An example of new tools is an effort by the Greenfire conservation group to pay farmers for measuring and keeping phosphorus on their land. It is all hands on deck as we attempt to move all of modern agriculture from an 'endless buffalo' mindset to the realization that not only do we have to conserve our soil, but we may also have to start regenerating it.

This then is the new undiscovered country, how to farm and feed the world without destroying it.

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13.2: An Ethical Predicament

Can Non-Farming Landlords and Tenant Farmers Who Have a Less Long-Term Stake in Farmland's Health Fulfill the Obligations of a Land Ethic?

The essay below is reprinted with permission from Stanley A. Temple, Beers-Bascom Professor Emeritus in Conservation, University of Wisconsin-Madison, and Senior Fellow, Aldo Leopold Foundation. 2015. It speaks to a new threat to soil health--land ownership by absentee investors.

When renowned American conservationist Aldo Leopold (1887-1948) was confronting the problem of land abuse in the American heartland 85 years ago, most farmland was in private ownership. The individual owners, therefore, had to play a central role in sustaining local and regional land health. Back then, the owners of America's farmland were mostly family farmers, "owner-operators" who had lived on the land and worked it, often for several generations. They had close ties to their land and usually hoped to pass it on to the next generation. Leopold reasoned they should have had compelling reasons to take care of their property, and many did just that. However, too many abused their land, leading to the soil and water erosion and loss of biodiversity that characterized the 1920s and 30s.

Leopold recognized that it would be challenging to rely on government regulations and incentives to coerce irresponsible owners into taking care of the soil, water, native plants, and wildlife on their farms. Owners resented regulations and only complied with subsidized practices as long as there weren't more lucrative uses for the land. Leopold instead conceived of what he called a "land ethic" as a promising approach. In his influential 1949 book, *A Sand County Almanac*, Leopold made several key observations about a land ethic:

> *"We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect."*
>
> *"All ethics so far evolved rest upon a single premise: that the individual is a member of a community of interdependent parts… The land ethic simply enlarges the boundaries of the community to include soils, waters, plants, and animals, or collectively: the land… In short, a land ethic changes the role of Homo sapiens from conqueror of the land-community to plain member and citizen of it. It implies respect for his fellow-members, and also respect for the community as such."*

Aldo Leopold's land ethic invoked the individual owners' personal sense of right and wrong to guide their land management practices. Because family farmers were so close to their land, Leopold thought these owner-operators should feel a moral responsibility to avoid abuses, such as soil erosion, that rendered their property less productive for current and future generations, as well as abuses that damaged community resources such as water and wildlife. His ethical approach is still an important component of most public and private land conservation strategies today.

But, there are changes on America's farmland that may require the land ethic to evolve to deal with situations Leopold never anticipated. Some 400 million acres (nearly half of US farmland) are predicted to change hands in the next 20 years. In the process traditional family farms are being gradually purchased by a new class of non-farming owners who no longer live and work on the land and have little personal connection to it; many may never even set foot on their land. More than ever, the new owners—often large corporations, LLCs, and investment companies--really do regard farmland as a commodity. Land management decisions are left to hired farm managers who rent the land to tenant farmers who do the actual work. Today, 39 % of American farmland is rented and worked by tenant farmers, and non-farming landlords own 80 percent of all rented farmland. Although they have access to sophisticated management tools that help increase yields and conserve soil and water, absentee owners, hired managers, and renters are less easily influenced by a land ethic than owner-operators with more personal investment in the land's health. Can these new non-farming landlords and tenant farmers who have a less long-term stake in farmland's health fulfill the obligations of a land ethic?

It is a very big issue. Of the 1.9 billion acres of land in the 48 contiguous states, 914 million acres (nearly half) are in agricultural use; most of the precipitation that falls in the US falls on (and runs off) that land with consequences for water quality; and about 40% of US threatened and endangered species are found there. In spite of its importance, there are many indications that land health is not being sustained on American farmland. Run-off from farmland and resulting downstream problems are major

concerns. The expanding dead zone in the Gulf of Mexico attests to the enormous scale of the problem. Wildlife species that depend on farmland for habitat are struggling. Meadowlarks and other grassland birds that were once common on farms are in severe decline as more land is farmed intensively. Even the ever-popular monarch butterfly that once flourished on farmland has declined to the point at which it is being considered for listing as a threatened species, in part a victim of changes in farmland management that have decimated the milkweeds and nectar-producing wildflowers on which the butterflies depend.

Is the answer more government regulations of modern farming and more public subsidies for farmland owners who do sustain land health? Although necessary parts of the equation, those weren't the keys in Leopold's day, and they probably aren't today. As Leopold observed long ago, "We seem ultimately always thrown back on individual ethics as the basis of land conservation. It is hard to make a man, by pressure of law or money, do a thing which does not spring naturally from his own personal sense of right and wrong."

The challenge is how to make a land ethic relevant to the new farmland owners and their operators and how they care for their land. With farmland increasingly regarded as a commodity, the challenge is to find the balance between profit-maximizing behavior and non-economic concerns. Many corporations have adopted ethical guidelines for the way they do business, and responsibility for the environment is typically prominent. However, the new class of farmland owners has not yet conspicuously embraced the concept of a Leopoldian land ethic, and too few have clearly acknowledged and fulfilled their ethical responsibilities for land health. One problem may be that the products of America's farmland are not often closely associated with either the owners or the health of the land that produced them. Although there is growing consumer demand for transparency about where and how food is produced, exactly what that will mean in the broader context of land health remains somewhat unclear.

The conservation-minded community at large needs to engage new owners, managers, and renters of farmland and help them understand and adopt a land ethic, perhaps by rewarding them for their efforts. It's a task even more challenging than it was in the bygone era when Leopold's land ethic was conceived and will require new levels of engagement with these new owners and their significant stakeholders. Who and what are important to the modern, non-farming landowners? Is it just shareholders and profits, or is it also the larger community and an ethical responsibility for land health?

In the end, Aldo Leopold realized that it would take time for his concept of a land ethic to lead to land health on America's farmland. "We shall never achieve harmony with the land, any more than we shall achieve justice or liberty for people. In these higher aspirations, the important thing is not to achieve, but to strive…" And he provided a sort of golden rule to guide those strivings. "Quit thinking about decent land use as solely an economic problem. Examine each question in terms of what is ethically and esthetically right, as well as what is economically expedient. A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it does otherwise."

Stanley A. Temple, Beers-Bascom Professor Emeritus in Conservation, University of Wisconsin-Madison and Senior Fellow, Aldo Leopold Foundation

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13.3: Soil Comes Full Circle

An editorial essay by 2024 Leopold Conservation Award winner Valerie Dantoin, Full Circle Farm.

As you know, the soil is the place where plants grow and therefore where our food grows. Sometimes the average person forgets that food comes from land, especially if they aren't closely connected with soil and farming or growing food. A family farm invests in its soil because it cannot simply pick up and move production operations to a new factory in another state. It has to take care of the soil it is stuck with. The farmer has to move the soil, full circle forward, from perhaps mistreatment in the 1970s through the early 2000s to a better way of management, now that we know better. This full circle includes picking up the best ideas of the past--crop rotations, fallowing, perennial crops, composts, and manures--and then rolling them forward into a new way of farming.

For the last 50 years, farmers have sometimes lost sight of the fact that they are actually growing food that people will eat and that they are stewards of this precious resource. We have purchased bigger, more muscular machines, and we have more bills to pay. Sometimes farmers just go about their everyday business of plowing and putting seed in the ground, spraying down the weeds, and harvesting all from an enclosed tractor with computer-guided GPS points to tell them where to add a little more fertilizer or to record the harvest as it flows in off the acreage. They forget to get out of the tractor seat and walk the land. Farmers forget that the land remains, even after they are done with it.

Farmers have been asked to produce food--and a lot of it--in great quantity, to feed the world by maximizing bushels per acre. Farmers in America's Midwest today are great at growing corn and soybeans. But both of these are ***ingredients*** and not in themselves food we can eat. Most farmers would starve if they lived off the crops of their land. In fact, the state of Iowa is a net importer of food. Think about it, they export mountains of corn, soy, pork, and beef, but they must import the actual food on the grocery store shelves. Some of the most fertile farmland on the planet, and it is not feeding its own people.

What farmers are really growing are commodities and not true, edible food. A commodity describes mass-produced items that are identical, indistinguishable, and undifferentiated from each other. Yellow dent #2 corn from one farm is exactly like that from the farm down the road. Food, on the other hand, is that delicious, delectable bite that needs no processing or fancy recipes to fill our eyes, our plates, our stomachs, and our souls.

Indeed, the Midwest farmer's job is to "feed the world" (since we sit on top of a bread basket) so we currently aim for quantity over quality. But we are following a sadly well-worn path other civilizations have trod as they feed the population today but lose the capacity to feed the people of tomorrow because the soil becomes a commodity and is compromised or lost from the land. Our society is losing the nutritional value of its food while at the same time losing its soil resources and future productivity. The same thing has been repeated by civilizations for the last 7,000 years. Maybe this time it can be different since we are a global society and have everything to lose, not just one culture. Let's not give in to the fear of having to feed more than 8 billion human mouths and just go pedal to the metal across our fields.

The very definition of sustainability is "*the ability to meet the needs of the current generation without compromising the needs of future generations*". We are not doing that since we are losing topsoil that grows our food at rates faster than it can form. Also, we are growing commodities that have much lower nutritional values than foods grown on richly mineralized soils from half a century ago. It is like we are trying to sustain ourselves on very flavorful cardboard 'food' devoid of true nutrients. This results in people who eat and eat and eat empty calories but who are never filled. We grow fat, not healthy. There is something almost biblical in that. It is almost like a curse when a society is not thankful for food, wastes much of it, over-processes it, overeats it, and then looks away as soil washes down the rivers and into wetlands and lakes. Wildlife habitat was destroyed as farmers ripped out fence rows and followed a 1970s edict from USDA Agriculture Secretary Earl Butz to get bigger or get out. Are the results of empty food and mistreatment of the land--obesity, diabetes, cancer, high blood pressure, drought, flood--modern-day plagues? Do we want to live in a dirty, muddy world with invasive species, confined animals, and people in ill health?

Here are a couple of quotes from Wisconsin's leader in modern conservation, Professor Aldo Leopold:

> *"There are two spiritual dangers in not owning a farm. One is the danger of supposing that breakfast comes from the grocery, and the other that heat comes from the furnace."*
>
> *"We abuse land because we see it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect."*

Change is afoot, however, as people are reconnecting the dots between their health, the food they eat, and the environment in which we all live. The sustainable, local, organic (SLO) food movement is gaining traction as evidenced by the sustained double-digit increases in sales of organic foods each year as well as the growth of farmers markets and farm-to-school movements. The next big change is that the healthcare system may get involved and purchase fresh vegetables from local farmers as a method of treating illness. (*Let thy food be thy medicine.*) Also, more people, including many of you who are reading this essay, are trying to get back on the land and help make a change for the better in food and farming. Good farmers, as land stewards, are being treated with respect and paid justly for good food.

There are those who understand that soil is a limited natural resource. Unlimited growth in the economy is not truly possible because of the physical and biological limits of soil. Oh, we can add synthetic fertilizers and optimize their application with computer aids. We can genetically engineer crop plants to withstand herbicides and pesticides. We can concentrate cows to the tune of a thousand per acre, store their poop in a pit and pump it into the land twice a year. But if we do not keep soil on the land, in a well-aggregated, physically sound form, then nature will catch up with us and make us pay.

When we cleared the virgin forests in the 1870s in the Midwest and plowed with horse-drawn implements in the early 1900s we changed the landscape almost irrevocably. We paused when the Dust Bowl days blew in the 1930s and when World Wars diverted steel and engines to other uses. But now, after just 75 years of fossil fuel-powered plowing and cultivation, we have degraded the soils of the American Midwest and washed them into the Bay of Green Bay and the southern gulf resulting in sedimentation of wetlands and hypoxia in productive fisheries close to the point of collapse. We have an “acceptable” erosion rate of 5 tons of soil per acre per year. We drive truly monstrous-sized tractors to pull gigantic implements on consolidated fields from which fence lines have been cleared, sub-soil water has been drained away, and liquid manure has been knifed into the ground to grow annual crops year after year--but this is not sustainable.

The soil literally cannot hold up under the increasingly heavy load of bigger and bigger machinery. The fragile nature of soil aggregation is squashed. The soil cannot hold up under the expectation of higher and higher yields. This is especially true as farmers try desperately to spread costs over more and more acres; so the farmer starts tilling and planting too soon in the spring, ends too late in the fall, and drives too often on cold, soggy soil. The good biology and microscopic life in the soil are blasted by both compaction and a kind of holocaust of salt-based fertilizers and liquid manures and loss of pore space. Soil collapses. It literally puddles up and dies. But that’s OK, right? Surely we can always add more synthetics, and genetically engineered band-aids or power bigger tractors to fix it. No, sorry folks, technology will not save us from our folly. The soil cannot be cornered or trapped in a technology box, it must breathe and be treated as a living organism with an ecosystem we still do not fully understand.

Our society is losing the nutritional value of its food while at the same time losing its soil resources and future productivity. Well, the same thing has been repeated by civilizations for the last 7,000 years. Maybe this time it can be different since we are a global society and have everything to lose, not just one culture.

For the last 30 or so years, the price of land has always gone up. Many farmers bank on that as their retirement nest egg. If they bought land at $1,000 per acre in 1990 it is now worth $10,000 per acre. Our 260-acre grass-covered farm is now worth $2.6 million dollars. But what will become of this oasis of green, with soils built up to be sustained for at least another generation if not another 100 years since our family first took title to this acreage, if we sell? Should we sell it to a corn and soy cash crop farmer and watch the soil, organic matter, and nutrients drain from the land as if someone pulled a plug? Do we watch the Bay and local waters become so covered in sediment and algae that our grandchildren cannot fish or swim there? We are searching for a way to pass this land on to the next farmers who will care for the land the same way we have, or even better.

> *“Ethical behavior is doing the right thing when no one else is watching- even when doing the wrong thing is legal.”*
>
> *– Aldo Leopold*

The ethical thing to do is to care for the land and the soil. To care for it as if your children’s children are the ones who will farm it after you are gone. It’s ethical to bank wealth in the soil as you add stable, organic matter through grazing, green manures, and cover crops. It is ethical to include hay in between annual crop rotations to build soil. It is ethical to graze cattle carefully so that their feet touch the earth and the sun is on their backs. It is ethical to treat people right by growing nutrient-dense food for them. It is ethical to leave a corner of the farm as a wetland for frogs and migrating waterfowl. It is ethical to enjoy the sunset and see the fruits of your labor in the earth--to marvel at the magic of the land around you without eyes set only on what it’s worth. It is ethical to appreciate all that the land will gift you and then to deliver that gift, whole and healthy, into the future.

Figure 13.3.1: A sustainable farm at sunset. Photo by: Valerie Dantoin 2022. Full Circle Farm

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CHAPTER OVERVIEW

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14.1: Introduction

> *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 the 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 well-being.

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 aspiring urban farmers or gardeners. 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 for human health. Also, we will discuss challenges with establishing and maintaining urban green infrastructure like parks, street trees, and ornamental gardens.

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14.2: 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 earlier, 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 14.2.1). All of this results in disturbed, compacted soils low in organic matter and biological activity (Figure 14.2.2) 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 14.2.1: 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 14.2.3). 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.

Figure 14.2.2: Construction activities cause bare compacted soil with potential for water and wind erosion, and challenges with revegetation.

Figure 14.2.3: This former storage site in Portland, OR, was contaminated with volatile organic compounds. Photo courtesy of the U.S. Environmental Protection Agency.

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). However, there is a wide range of 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 14.2.1).

Cases that are of special concern 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 the 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 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 14.2.2). 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 into 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.

Table 14.2.1: 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

*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)

Land Use	Common Contaminants
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)

Table 14.2.2: 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. Affects 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. Affects the central nervous system and mental capacity.
Petroleum products	Benzene, toluene, ethylbenzene, xylene, kerosene, gasoline, diesel	The risk from drinking water and inhalation from volatilized products. Irritation; affects the central nervous system and mental capacity.
Salts	Sodium chloride	Cause sodic soil conditions, aggregate breakdown, and compaction.
Agricultural inputs	Nitrates, pesticides/herbicides	Impaired water quality. Irritation; affects the central nervous system and is 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.

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14.3: 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 will have fewer problems than one with a commercial or industrial past.

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, micronutrient,s and metals, including lead.

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.)

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)

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14.4: 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 14.4.1). 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.

Table 14.4.1: 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.			

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 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.

Figure 14.4.1: 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.*

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 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 free of contaminants and weeds. Local restaurants, cafes, arborists, and municipal compost piles are common sources (Figure 14.4.1.

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.

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
- Crop rotation
- Composting

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 time with the buried soil deeper in the ground through biological activity.

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14.5: Urban Green Infrastructure

We have discussed concerns related to urban soils in the context of crops and food production. 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 upfront. Generally, you want the soil to support attractive vegetation at a low maintenance cost. This requires good drainage, high water holding 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 topsoil. 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 the 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 14.5.1). 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.

Figure 14.5.1: Top: scoop-and-dump method for de-compaction of soil and mixing in compost. Bottom: Ameliorated soil with plantings and mulch. Photos by Cornell University, Urban Horticulture Institute.

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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-gradedsoils* that can meet both objectives (Figure 14.5.2). 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 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.

Figure 14.5.2: Top: 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. Bottom: Healthy street trees on a sidewalk with gap-graded soil. Photos by Cornell University, Urban Horticulture Institute.

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14.6: 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 is revegetated or used again for crop production or green infrastructure.

It's important to understand and 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, 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 14.6.1).

Figure 14.6.1: Proper pipeline construction: Top: fertile topsoil is first removed and separately stockpiled from the subsoil. Bottom: after installation, the topsoil is restored over subsoil.*Photos by Bob Schindelbeck.*

Generally, urban areas experience increased runoff as a result of sealed surfaces. Roofs, streets, parking lots, and other types of development have a 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 14.6.2). Stormwater mitigation practices are generally required by state law for large site developments, and design manuals are available to help developers comply.

Figure 14.6.2: Retention of urban stormwater. Top: a swale that contains runoff from a parking lot in the distance. Bottom: Gravel-based swale with subsurface drains (under gravel) that captures roof runoff from a regional airport terminal.

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14.7: 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 is 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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14.8: A Case Study, City Slicker Farms

Urban Farming in 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 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 bio-intensive 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 space 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 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 residues, 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 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 is 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.

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