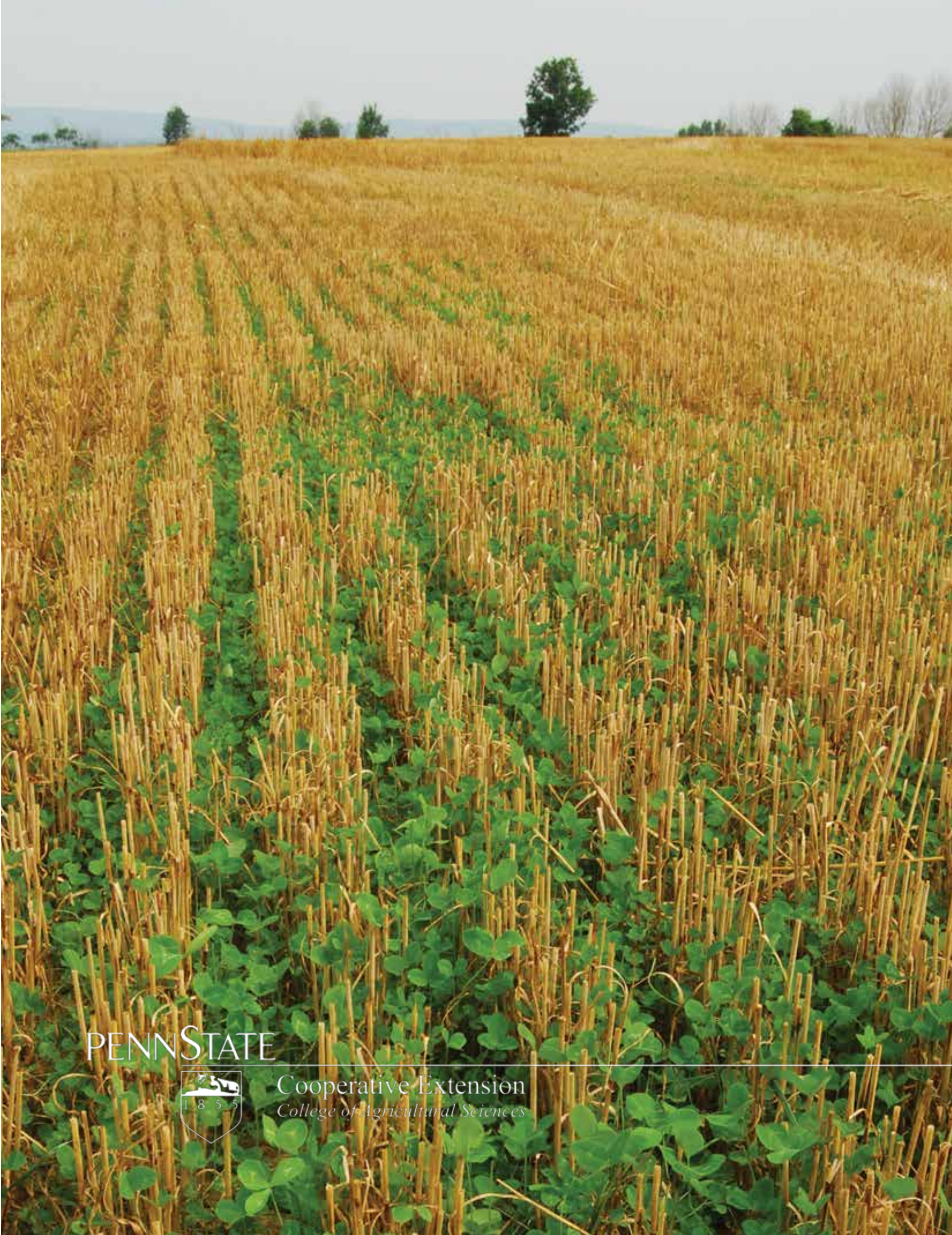
AGROECOLOGY IN PRACTICE

Penn State **Extension**

Managing Soil Health: Concepts and Practices



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INTRODUCTION

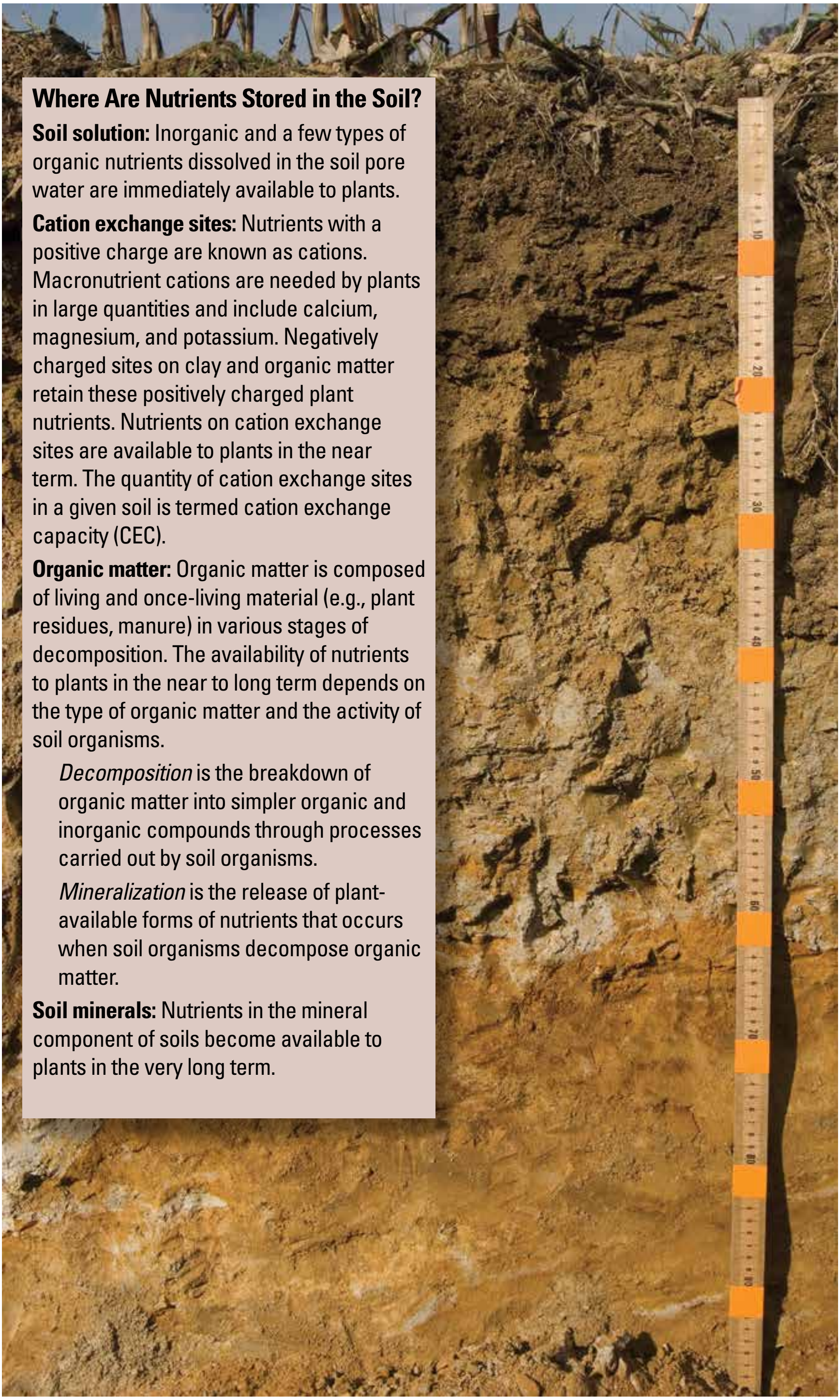
Healthy soil is the foundation for profitable, productive, and environmentally sound agricultural systems. By understanding how the soil processes that support plant growth and regulate environmental quality are affected by management practices, it is possible to design a crop and soil management system that improves and maintains soil health over time. This brochure is for farmers and gardeners who want to understand the physical, chemical, and biological components of healthy soil and how to manage them.

Soil is a critical resource—the way in which it is managed can improve or degrade the quality of that resource. Soil is a complex ecosystem where living microorganisms and plant roots bind mineral particles and organic matter together into a dynamic structure that regulates water, air, and nutrients. In an agricultural context, soil health most often refers to the ability of the soil to sustain agricultural productivity and protect environmental resources. A healthy soil provides many functions that support plant growth, including nutrient cycling, biological control of plant pests, and regulation of water and air supply. These functions are influenced by the interrelated physical, chemical, and biological properties of soil, many of which are sensitive to soil management practices.

NUTRIENT CYCLING

Nutrient cycling refers to the many pathways through which nutrients are added to, removed from, and changed within the soil. Nutrients are found in two basic forms in the soil: organic and inorganic (sometimes called "mineral"). Organic forms of nutrients contain carbon in the structure of the molecule, while inorganic forms do not. Nutrients are stored in several pools within the soil: as inorganic forms in soil particles, as organic forms in soil organic matter, as inorganic forms on cation exchange sites, and as organic and inorganic forms dissolved in the water surrounding soil particles, known as the soil solution (*see sidebar*). The management goal for a healthy agricultural soil is to supply the nutrients needed for optimal plant growth in the right quantity and at the right time while minimizing nutrient losses to the surrounding environment.

Nutrients in the soil can change forms through many different nutrient cycling processes. A low spot in this field collected standing water during several weeks of rainy weather in early summer. While the soil was saturated, nitrogen was lost to the atmosphere through a process called denitrification, resulting in a patch of nitrogen-deficient, yellowish corn.



Where Are Nutrients Stored in the Soil?

Soil solution: Inorganic and a few types of organic nutrients dissolved in the soil pore water are immediately available to plants.

Cation exchange sites: Nutrients with a positive charge are known as cations. Macronutrient cations are needed by plants in large quantities and include calcium, magnesium, and potassium. Negatively charged sites on clay and organic matter retain these positively charged plant nutrients. Nutrients on cation exchange sites are available to plants in the near term. The quantity of cation exchange sites in a given soil is termed cation exchange capacity (CEC).

Organic matter: Organic matter is composed of living and once-living material (e.g., plant residues, manure) in various stages of decomposition. The availability of nutrients to plants in the near to long term depends on the type of organic matter and the activity of soil organisms.

> *Decomposition* is the breakdown of organic matter into simpler organic and inorganic compounds through processes carried out by soil organisms.
>
> *Mineralization* is the release of plant-available forms of nutrients that occurs when soil organisms decompose organic matter.

Soil minerals: Nutrients in the mineral component of soils become available to plants in the very long term.

Soil organic matter is a storehouse of several plant nutrients, including nitrogen, phosphorus, and sulfur. Every 1 percentage point of organic matter in the top 6 inches of soil contains about 1,000 pounds of nitrogen, 230 pounds of phosphorus, and 165 pounds of sulfur per acre. However, most nutrients in organic matter are not directly available to plants. To be used by plants, nutrients in organic matter must be converted to inorganic forms through decomposition and mineralization by soil organisms.

Particulate soil organic matter was extracted from five different soils with varying degrees of tillage history. Particulate organic matter such as this contains organic forms of nutrients that can be made available to plants through microbial decomposition processes. Vials to the left of center had increasing levels of tillage in the crop rotation, while vials to the right of center were from untilled soils under permanent grass sod and forest. The vial in the center is from a continuous no-till field with annual crop rotation.

Soil organisms form a food web (*see sidebar*) that decomposes organic matter and releases nutrients in the process. At the base of the food web are bacteria and fungi, which obtain energy by decomposing soil organic matter directly. Protozoa and some nematodes are organisms that graze on bacteria and fungi, releasing nitrogen that can then be utilized by plants.

Larger organisms—for example, small arthropods—some barely visible to the unaided eye, help mediate the decomposition of plant and other organic residues. Some common insects and related organisms that play an active role in decomposition in agricultural systems are millipedes, springtails, mites, fly larvae, and burying beetles. In addition to helping break down organic matter, decomposers are often eaten by other arthropods (e.g., spiders) and can contribute to supporting populations of beneficial predatory arthropods.

Nitrogen (N) is a nutrient that can undergo many transformations in the soil through microbial processes. The process of converting organic nitrogen to plant-available ammonium (NH_4^+) is called mineralization. A specific group of bacteria convert ammonium to nitrate (NO_3^-) in a process called nitrification. Nitrogen fixation is carried out by both free-living and root-symbiotic organisms. Nitrogen fixation is the conversion of atmospheric N_2 to ammonia (NH_3) and is one of the most important ways that nitrogen is added to the soil ecosystem. In symbiotic nitrogen fixation, nitrogen is fixed by bacteria within nodules of the roots of plants in the legume family and

The Soil Food Web

Soil is home to a complex assemblage of organisms that interact to significantly impact both aboveground and belowground processes (Hooper et al. 2000). The soil food web is the community of organisms living all or part of their lives in the soil. Soil-dwelling organisms play key roles in soil function, providing the foundation for such critical processes as soil structure development, decomposition and nutrient cycling, bioremediation, and promotion of plant health and diversity (Coleman et al. 2004). Soil organic matter is the base resource that supplies energy and nutrients used by plants and other organisms. Soil organic matter includes all the organic substances in or on the soil, including plant- and animal-derived material, in various stages of decay.

Nematodes and mites are visible in a soil pore. Reductions in soil disturbance help maintain soil as a habitat for beneficial soil organisms by conserving existing pores and channels where these microscopic organisms live.

ammonia is then taken up by the plant to be turned into an organic form of nitrogen. The rhizobium/legume symbiosis is the most well known of the nitrogen-fixing associations. Legume cover crops will fix more N when grown in a soil with low NH_4^+ and NO_3^-.

In addition to serving as a source of stored nutrients, soil organic matter provides a significant portion of the cation exchange capacity (CEC) in soil. Cation exchange helps to hold positively charged nutrients in the soil, protecting them against loss through leaching. Increasing the organic matter content of soil is one of the few ways to increase soil CEC.

Soil pH, a measurement of the activity of hydrogen ions (H^+) in soil solution, is a variable that drives many aspects of nutrient cycling and soil biology. A pH of 7 is considered neutral, below 7 is acidic, and above 7 is alkaline. Most crops do best in the soil pH range of 6–7, though there are some exceptions. As soil pH drops below 6, aluminum in the soil changes form and becomes toxic to plant roots. Manganese can also increase to toxic levels at a low soil pH. Humid regions of the world have soils that will naturally tend toward the acidic, so liming agents that neutralize acidity must be applied to keep soil at an optimum pH.

Soil pH regulates the availability of several micronutrients, with iron, manganese, and zinc becoming more available as pH becomes more acidic. Molybdenum availability increases as pH becomes more alkaline. Crops that prefer a pH outside the general range of 6–7 often do so because of specific micronutrient needs. Legumes, which require molybdenum for the nitrogen-fixing enzyme, favor a soil pH near 7. Blueberries, which have a high iron requirement, favor a pH from 4.5 to 5.

Soil organisms are affected by soil pH as well. Earthworms and bacteria prefer a near-neutral soil pH. Fungi do well at most soil pH levels, so in acidic soils, fungi tend to dominate the soil microbial community. Soil pH also influences the cation exchange capacity supplied by organic matter. As soil pH increases, the cation exchange sites on soil organic matter will also increase.

BIOLOGICAL CONTROL OF PEST ORGANISMS

One ecosystem service provided by soil organisms that is of particular interest in agricultural systems is biological control of arthropod pests. Biological control is the term for reduction of pest organisms by natural enemies, which include predators, parasites, and pathogens (disease-causing organisms). Healthy agricultural soil communities typically include a wide range of predators, parasites, and pathogens that contribute to the suppression of agricultural pests. Spiders, harvestmen, and ground (carabid) beetles are important ground-dwelling natural enemies of insect pests. Ground beetles play a major role in agroecosystems by contributing to the mortality of insects, weed seeds, and slugs.

Arbuscular Mycorrhizal Fungi

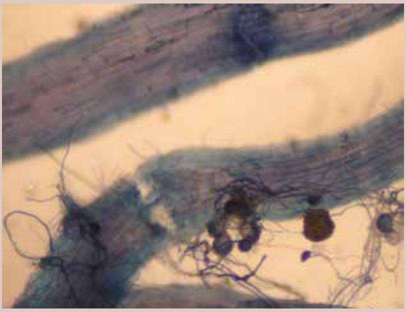
Arbuscular mycorrhizal fungi are beneficial soil organisms that contribute to many aspects of soil health. Mycorrhizal fungi form a symbiotic association with plant roots. Symbiosis is a close association between different species. This association provides the fungus with relatively constant and direct access to sugars supplied by the plant. In return, the plant benefits from the ability of the fungus to grow out into the soil, creating a threadlike network of fungal biomass known as hyphae or mycelium, thus effectively increasing root volume. Mycorrhizal fungi are dependent on the host plant for an energy source and cannot survive for long periods of time without a plant host. Approximately 80 percent of land plants form the symbiotic relationship with mycorrhizal fungi. A few notable crops and weeds that are nonmycorrhizal include brassicas (broccoli, cabbage, radish, canola, etc.) and chenopods (spinach, chard, lambsquarters, etc.).

Mycorrhizal fungi are especially effective in helping plants acquire phosphorus, a nutrient that is highly immobile in the soil. Because of the low mobility, when plant roots extract phosphorus from the soil, a phosphorus depletion zone develops around the root. Mycorrhizal fungi act as an extension of the plant root system, acquiring phosphorus from nondepleted zones and transporting it to the root.

The external hyphae of mycorrhizal fungi also improve soil aggregation by exuding a gluelike compound called glomalin. Glomalin helps soil particles stick together in aggregates that resist erosion and maintain soil porosity.

Mycorrhizal symbioses increase a plant's stress tolerance. The network of fungal hyphae around the roots can block infection of the plant roots by plant pathogens. Mycorrhizal fungi can also suppress plant pathogens by enhancing plant nutrition, increasing root toughness, changing the chemical composition of the plant tissues, alleviating abiotic stress, and changing the microbial community on roots.

Several factors affect the populations of mycorrhizal fungi in the soil. Tillage disrupts the network of delicate fungal strands, reducing populations. High levels of phosphorus in the soil also suppress mycorrhizal populations because plants are less likely to support the symbiosis. Finally, because mycorrhizal fungi are dependent on a host plant for an energy source, long periods without a host, such as occurs in bare fallow fields or when a nonhost crop is grown in the rotation, will cause populations to decline over time. Most native soils have ample populations of living mycorrhizal fungi or dormant spores that will awaken when a host crop is grown. Inoculation of field soil with mycorrhizal fungi is therefore usually unnecessary.



The hyphae of mycorrhizal fungi are seen as dark blue, threadlike structures in the photo above. In the background is a corn root colonized by mycorrhizal fungi.

REGULATION OF AIR AND WATER IN SOIL

Plants require both oxygen and water in the root zone for optimum growth. In soil, water and air are held in the pore space between soil particles and soil aggregates (*see sidebar*). The sizes of the pores that occur between and within soil aggregates determine how water and gases move in and are held by the soil. Larger pores, known as macropores, are important to promote good aeration and rapid infiltration of rainfall. Smaller pores, known as micropores, are important for absorbing and holding water. Macropores are often visible to the naked eye, while micropores between and within microaggregates are not. To maintain both adequate aeration and water supply for optimum plant growth, it is necessary to have both macro- and micropores in the soil.

Pores in the soil are formed when soil particles clump together into a hierarchy of aggregates (*see sidebar*). Soil organisms play an important role in developing soil aggregates and improving aggregate stability. Clay, organic matter,

Properties of Different-sized Soil Aggregates and Pores

Macroaggregates (>0.25 mm in size)

- The largest aggregate size; can be observed when a soil crumbles upon handling or sieving
- Formed from an assemblage of smaller aggregates
- Created and held together by plant roots and fungal hyphae

Microaggregates (0.002–0.25 mm in size)

- The smaller aggregates that assemble to form macroaggregates
- Created and held together by root hairs, fungal hyphae, and polysaccharides

Macropores (>0.075 mm in diameter)

- The large pores found between macroaggregates
- Allow water to quickly infiltrate the soil, reducing runoff
- Gravity drains water from the macropores, promoting aeration

Micropores (<0.075 mm in diameter)

- Small pores found between and within the microaggregates
- Absorb water like a sponge, holding it for plant use

Soil on the left easily crumbles upon handling, revealing well-formed macroaggregates and the macropores between the aggregates. Soil on the right is cloddy, with only a few macropores where the soil has been ruptured. Soil on the right is from an intensively tilled field, whereas soil on the left is from the grass sod adjacent to the same field.

root hairs, organic compounds from bacteria and fungi, and fungal hyphae help "glue" soil aggregates together. Aggregate stability refers to the ability of soil aggregates to hold together against the erosive forces of water. Good aggregate stability will help maintain macropores in the soil, reduce surface crusting, promote aeration and reduce rainfall runoff, and reduce soil erosion. Aggregates also help conserve soil organic matter, as particles of organic matter that reside within aggregates are physically protected against microbial consumption.

Many large soil organisms are capable of moving soil and creating macropores in the soil. These include such organisms as ants, dung beetles, and earthworms. Earthworms are probably the best-known soil organism that contributes to the development and maintenance of soil structure. The burrowing activity of earthworms benefits soil health through increased nutrient availability, better drainage, and a more stable soil structure.

Earthworm burrows seen from the soil surface (left) and in the subsoil (right). Burrows create macropores at the soil surface and in the subsoil, enhancing water infiltration, drainage, and root growth into the subsoil. Earthworm casts, as seen at the surface surrounding the burrow on the left and filling an abandoned burrow on the right, are nutrient rich and glue soil into water-stable aggregates. Note the roots growing in the abandoned burrow in the photo on the right.

SOIL ORGANIC MATTER

Soil organic matter plays an important role in integrating many aspects of soil health. Soil organic matter can be divided into labile and stable pools, each of which has different characteristics and functions in the soil. In agricultural soils, organic matter can range from 1 to 8 percent depending on climate, soil type, and soil management practices.

The labile pool of organic matter, which accounts for 5–20 percent of the total pool of soil organic matter, includes the living biomass of soil organisms and plant roots, fine particles of organic detritus, and relatively simple organic compounds such as polysaccharides, organic acids, and other compounds that are synthesized by microbial activity or are by-products of decomposition processes. Labile organic matter is readily decomposed by microbes and is the principal energy source that fuels the soil food web. It is the principal reservoir of organic nitrogen that can be readily mineralized and made available for plant use. Polysaccharides in labile organic matter also enhance aggregate stability. When microbial consumption of labile organic matter is greater than the input of fresh organic matter into the soil, labile organic matter levels will decline. Excessive tillage of the soil can speed the decline of labile organic matter by oxygenating the soil, which increases microbial activity, and by exposing organic matter that had been protected within soil aggregates.

The stable pool of organic matter, which accounts for 60–95 percent of the total pool of soil organic matter, consists of organic compounds that are relatively resistant to decomposition because of either their chemical structure, their adsorption to clay particles, or their protection within microaggregates. Stable organic matter contributes cation exchange capacity and water-holding capacity to soil. The pool of stable organic matter is increased or depleted slowly as only a small portion of the labile organic matter that cycles through the food web is stabilized into forms that are resistant to decomposition.

The quantity of organic matter in a given soil is the result of a balance between organic matter inputs, such as crop residues, manure, and compost, and the rate of organic matter decomposition. Organic matter inputs can be influenced by crop management, such as the use of cover crops, crop rotations, and residue management, as well as soil management, such as using organic forms of nutrients like compost and manure. The quantity of labile organic matter generally responds to changes in management practices more quickly than the quantity of stable soil organic matter, so changes in labile organic matter levels can serve as a leading indicator of long-term trends in total organic matter levels.

MANAGEMENT PRACTICES TO IMPROVE SOIL HEALTH

1. Reduce Inversion Tillage and Soil Traffic

Excessive tillage is harmful to soil health in a number of ways. Tillage increases oxygen in the soil, stimulating microbial activity, and results in the decomposition of organic matter. Tillage also disrupts soil aggregates, exposing particles of organic matter that had been physically protected within aggregates to microbial consumption. If additions of organic matter are not sufficient to counteract the losses from decomposition, organic matter levels will decline over time, reducing soil health. Inversion tillage also reduces the soil coverage provided by crop residues, leaving soil more exposed to erosion (*see tillage sidebar*). Tillage can also disrupt the hyphal network of mycorrhizal fungi, which can lead to their decline over time. When not managed carefully, most inversion and noninversion tillage methods compact the subsoil, creating a plow pan, which restricts root growth and access to water and nutrients in the subsoil. Excessive wheel and foot traffic can compact the surface soil, reducing macroporosity and impeding root growth (*see compaction sidebar*).

Physical disturbances such as inversion tillage can also have profound effects on the biological properties of soil. Compaction and removal of surface residue may contribute to reduction in soil moisture and living space for soil-dwelling organisms. Diversity and abundance of arthropod predators associated with the soil surface can be greater under con-

Common Primary Tillage Implements

Moldboard Plow

- Inverts the soil to bury residues, terminate cover crops and perennial sod, and kill weeds

Disk Plow

- Concave disks mounted in a gang cut residue and invert soil laterally, loosening soil and mixing residue into the soil
- Soil disturbance and residue incorporation depends on the size, shape, and tilt angle of the disks

Chisel Plow

- Curved shanks with chisel points are dragged through the soil without inversion
- Loosens surface soil, mixes some residue into the soil
- Soil disturbance and residue incorporation depends on the width and twist of chisel points

Tillage with a moldboard plow (left side of the photo) inverts the soil, burying weeds, sod, and surface residue. Chisel plowing (right side of the photo) loosens the soil without inversion, retaining residue on the soil surface.
]

Soil Compaction

Soil compaction occurs when soil is exposed to excessive foot and equipment traffic while the soil is wet and plastic. This traffic compresses the soil, reducing pore space and increasing bulk density. Macropores are compressed more so than micropores, leading to poor water infiltration and drainage and increased runoff. Soil compaction increases soil hardness, making it more difficult for plant roots to grow through the soil. The reduction in pore space also affects habitat for many soil organisms that are very small, cannot move soil particles, and are restricted to existing pore space and channels in the soil.

servation tillage management in comparison to conventional inversion tillage, and natural control of pest insects in soil may be enhanced in conservation tillage systems. Beneficial insects associated with the soil are more likely to survive in fields where noninversion (e.g., chisel plowed) tillage is used. In comparison with inversion tillage practices (e.g., moldboard plow), noninversion tillage causes less soil disturbance and thus less direct mortality of beneficial soil organisms.

Some tillage is still a necessary practice in certain production systems, especially organic systems that do not use herbicides for weed control. When tillage is used, it is important to offset the increased rate of organic matter decomposition with increased inputs of organic matter through crop residues, manure, and compost. Integrating several years of a perennial forage crop into a rotation with annual crops that require tillage is one way to reduce tillage intensity over time.

2. Increase Organic Matter Inputs

To maintain or increase soil organic matter levels, inputs of organic matter must meet or exceed the losses of organic matter due to decomposition. Healthy crops can be a valuable source of organic matter, and crop residues should be returned to the soil to the extent possible. Incorporation of cover crops or perennial crops and judicious additions of animal and green manure and compost can also be used to increase or maintain soil organic matter.

Soil organic matter content can be monitored over time if you request an organic matter analysis when submitting soil fertility samples to your soil testing laboratory. Be sure that your organic matter comparisons over time are based on data from the same lab or from labs that use the same procedure for organic matter analysis, as results can differ significantly between analysis methods.

3. Use Cover Crops

Cover crops contribute numerous benefits to soil health. They keep the soil covered during the winter and other periods of time when crops are not growing, reducing the risk of erosion. The biomass produced by cover crops is usually returned to the soil, enhancing organic matter levels. Cover crops with taproots can create macropores and alleviate compaction. Fibrous-rooted cover crops can promote aggregation and stabilize the soil. Species of cover crops that host mycorrhizal fungi can sustain and increase the population of these beneficial fungi. Legume cover crops can add nitrogen to the soil through nitrogen fixation. Cover crops

Forage radish, a taprooted cover crop (left), and cereal rye, a fibrous-rooted cover crop (right).

can retain nitrate and other nutrients that are susceptible to leaching losses.

4. Reduce Pesticide Use and Provide Habitat for Beneficial Organisms

Beneficial insects that contribute to biological control or pest organisms can be harmed by the application of broad-spectrum insecticides. Farmscaping is a whole-farm, ecological approach to increase and manage biodiversity with the goal of increasing the presence of beneficial organisms. Farmscaping methods include the use of insectary plants, hedgerows, cover crops, and water reservoirs to attract and support populations of beneficial organisms such as insects, spiders, amphibians, reptiles, bats, and birds that parasitize or prey on insect pests. Farmscapes placed in contours between fields, steep ditches, or places that are easily eroded give stability to the soil. Farmscaping can also be used as a filter strip to prevent water runoff and soil erosion. Plants used in farmscapes contribute to healthy soil by adding organic matter, the base of the soil food web.

5. Rotate Crops

Diverse crop rotations will help break up soilborne pest and disease life cycles, improving crop health. Rotations can also assist in managing weeds. By growing diverse crops in time and space, pests that thrive within a certain crop are not given a chance to build their populations over time. Rotating crops can also help reduce nutrient excesses.

6. Manage Nutrients

Carefully planning the timing, application method, and quantity of manure, compost, and other fertilizers will allow you to meet crop nutrient demands and minimize nutrient excesses. Healthy, vigorous plants that grow quickly are better able to withstand pest damage.
However, overfertilizing crops can increase pest problems. Increasing soluble nitrogen levels in plants can decrease their resistance to pests, resulting in higher pest density and crop damage.

Maintaining a soil pH appropriate for the crop to be grown will improve nutrient availability and reduce toxicity. Maintaining adequate calcium levels will help earthworms thrive and improve soil aggregation.

Using diverse nutrient sources can help maintain soil health. Manure and compost add organic matter as well as an array of nutrients, but using just compost or manure to meet the nitrogen needs of the crop every year can result in excessive phosphorus levels in the soil. Combining modest manure or compost additions to meet phosphorus needs with additional nitrogen inputs from legume cover or forage crops in a crop rotation can help balance both nitrogen and phosphorus inputs.

Maintaining residue on the soil surface helps to suppress weeds, conserve moisture, and provide habitat for insect predators.

Managing Nutrients in Soil

Nitrogen (N) Management

- Nitrate nitrogen is susceptible to leaching losses because the negative charge of the molecule is not held by cation exchange sites of soil particles. Leaching occurs mainly in the fall, winter, and early spring.
- Nitrogen in urea-containing fertilizers and manure is susceptible to volatilization losses as ammonia gas when not incorporated into the soil.
- Nitrate nitrogen can be lost to the atmosphere through conversion into nitrous oxide and nitric oxide gases by microorganisms in warm, poorly aerated soil.
- Nitrogen losses can be minimized with appropriate timing and application of fertilizers and manures and by using cover crops to limit leaching losses in the winter.

Phosphorus (P) Management

- Phosphorus is tightly bound to soil particles and does not easily diffuse through the soil.
- Mycorrhizal fungi can assist plant roots in P acquisition in low-P soils.
- Adding organic matter can mask the P binding sites on soil particles, increasing P availability.
- Phosphorus can accumulate to excessively high levels when P inputs in manure and fertilizer exceed P removal by crops; this can occur in soil that receives annual manure applications at rates to supply crop nitrogen needs.
- Erosion can transport soil particles with high levels of P into waterways where P can become a pollutant.
- Environmental P pollution can be limited by reducing erosion and maintaining soil P levels in the optimum range of 30–50 ppm Mehlich 3 P.

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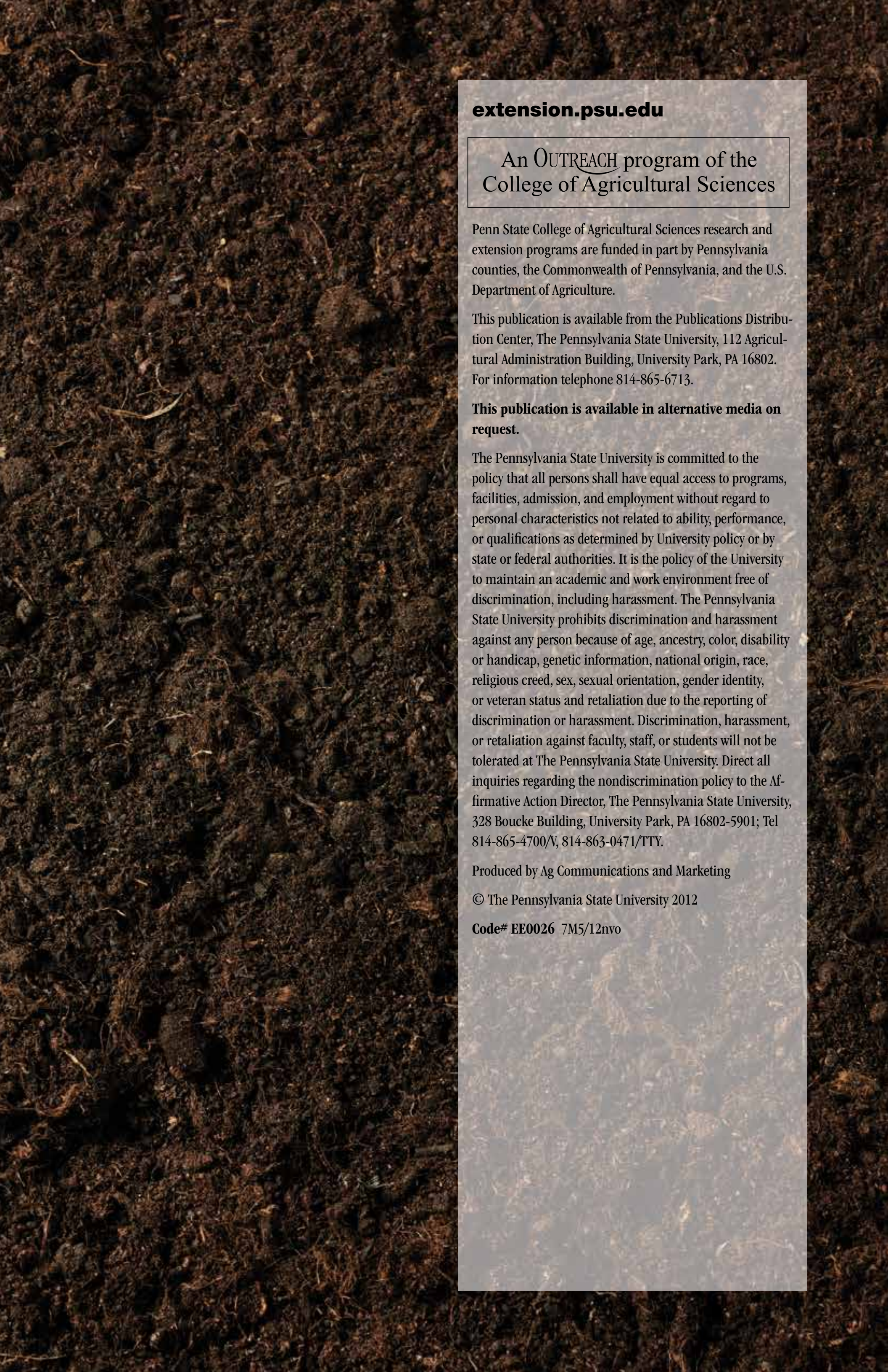

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