

Managing Soil Health

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Introduction: Managing Soil Health

UNIT OVERVIEW

“Feed the soil to feed the plant” is a basic principle of organic farming and gardening. This unit introduces students to the ways that farmers and gardeners develop and maintain soil health and fertility in organic farming systems. Two lectures describe the objectives and components of soil health management and the various practices used to develop and maintain healthy, fertile soil. Supplements offer an overview of the soil ecosystem, and address the way that sustainable soil management practices can combat the environmental and social problems created by soil erosion. Note that this unit introduces and integrates a number of topics, including tillage and cultivation, composting, cover cropping, and irrigation, which are addressed in detail in subsequent units.

It should be emphasized throughout the lectures that the overall goal of a soil health management program is to balance nutrient inputs and outputs and ensure a good balance of nutrients for the crop. This balance requires a complex mix of soil management activities including proper tillage, irrigation, crop residue management, weed management, and crop rotation planning. Neglecting any of these components can compromise soil health and quality, affect crop performance, and create potential pollution problems due to erosion, nutrient runoff or leaching.

MODES OF INSTRUCTION

- > LECTURE (2 LECTURES, 3 HOURS TOTAL)
 - Lecture 1 presents the concepts, objectives, and components of sound soil health and fertility management programs for certified organic production systems.
 - Lecture 2 describes the sustainable agriculture practices (e.g., tillage, cover crops, composts, soil amendments) that go into organic soil health and fertility management.
- > ASSESSMENT QUESTIONS (0.5 HOUR)
 - Assessment questions reinforce key unit concepts and skills.

LEARNING OBJECTIVES

CONCEPTS

- Fundamentals of sustainable agriculture
- Soil fertility in organic and sustainable farming systems
- Soil quality
- The relationship amongst soil fertility, plant health, and the resistance and resilience of crop plants to pests and pathogens
- Goals of a sustainable fertility/soil management program
- Components of a soil fertility management program
- The role and impacts of tillage
- The role of cover crops in soil fertility management
- The use of composts, manures, and other organic amendments
- Nutrient budgets as a management tool
- Considerations in the design of crop rotations

Lecture 1: Managing Soil Health—Concepts, Goals, & Components

Pre-Assessment Questions

1. What is organic farming?
2. If you were to implement an organic and sustainable soil fertility management program for a farm or garden, what would be your overarching goals?
3. Then what would the main components of that fertility management program be?
4. How do you define soil quality?
5. How do you define soil fertility for an organic farming system?
6. How is soil quality related to pest management?
7. How is soil quality related to water management?

A. Sustainable and Organic Agriculture Defined

1. “Sustainable agriculture” defined

Sustainable agriculture can be defined as an approach to agriculture where the aim is to create environmentally sound, economically viable, and socially just food and agricultural systems. Emphasis is placed on renewable resources and the management of self-regulating ecological and biological processes and interactions in order to provide acceptable levels of crop, livestock, and human nutrition, protection from pests and diseases, and an appropriate return to the human and other resources employed. Reliance on external inputs, whether chemical or organic, is reduced as far as is practically possible. The objective of long-term sustainability lies at the heart of organic farming and is one of the major factors determining the acceptability of specific production practices. Note, however, that certified organic agriculture also has a specific legal definition (see below).

Sustainable agriculture is not just the conservation of non-renewable resources (soil, energy, and minerals) used to produce food and fiber. Sustainable agriculture also encompasses: The maintenance or restoration of surrounding ecological landscapes; the economic viability for all involved in agricultural production, processing and distribution; and more equitable distribution of agricultural products to assure that basic human needs are met (see Unit 3.4, Sustainable Agriculture and Sustainable Food Systems).

2. “Organic agriculture” defined

- a) Organic agriculture has both general and legal definitions. Generally, organic agriculture refers to farming systems that avoid use of synthetic pesticides and fertilizers. In the United States, organic farming is defined by rules established by the U.S. Department of Agriculture’s National Organic Standards Board (NOSB).

- i. “Certified Organic” agriculture as defined by The National Organic Program (NOP; www.ams.usda.gov/nop/)

Organic production: “A production system that is managed in accordance with the Act (The Organic Foods Production Act [OFPA] of 1990, as amended in the NOP) to respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity.”

Further, it is a system of agriculture that encourages healthy soil and crops through such practices as nutrient and organic matter recycling, crop rotations, proper tillage, and the strict avoidance of synthetic fertilizers and pesticides for at least three years prior to certification

- b) Requirements for organic certification under the National Organic Program
 - i. Organic System Plan: The NOP requires that all crop, wild crop, livestock, and handling operations requiring certification submit an organic system plan to their certifying agent and, where applicable, the State organic program (SOP). The organic system plan is a detailed description of how an operation will achieve, document, and sustain compliance with all applicable provisions in the OFPA/NOP. The certifying agent must concur that the proposed organic system plan fulfills the requirements. The organic system plan is the forum through which the producer or handler and certifying agent collaborate to define, on a site-specific basis, how to achieve and document compliance with the requirements of organic certification. See the USDA's National Organic Program (NOP) website, www.ams.usda.gov/nop/ for additional details of Organic System Plan requirements.

B. Soil Fertility and Soil Health in Sustainable Farming Systems

1. Soil health and fertility defined (see www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/, and soilhealth.cals.cornell.edu/)
 - a) "Soil health" and "soil quality" can be used interchangeably. They are: The capacity of a soil to function, within land use and ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health (Doran and Parkin 1994).
 - b) Soil fertility is a feature of soil health as applied to agroecosystems. It is the capacity of a soil to provide nutrients required by plants for growth.
 - c) Soil health is established through the interactions of soil's physical, chemical, and biological, properties (see more at Supplement 1, A Soil Primer with Sustainable Management Strategies, and Part 2, Applied Soil Science)
 - i. Physical properties include soil texture, a physical measurement of the percent of sand, silt, and clay; and soil structure, the arrangement of individual soil particles (sand, silt, clay) into aggregates or "clumps"
 - ii. Chemical properties of a soil measure its nutrient-carrying capacity and pH (acidity)
 - iii. Biological properties refer to the community of soil organisms (principally bacteria, fungi, and actinomycetes)
 - d) Soil health indicators (see soilhealth.cals.cornell.edu/)
 - i. Soil provides adequate levels of macro- and micronutrients to plants and soil microbes. This reflects the ability of the soil to mineralize nutrients and a moderate pH (~6.0–7.0) that allows the nutrients to be both held in the soil and available to plants as needed.
 - ii. Soil has good "tilth." This includes a good structure that resists degradation (e.g., erosion and compaction), provides adequate aeration and rapid water infiltration, and accepts, holds, and releases water to plants and groundwater.
 - iii. Soil promotes good root growth and maintains good biotic habitat that sustains high and diverse populations of beneficial organisms and low populations of pests and pathogens
 - iv. Soil has low salinity levels and low levels of potentially toxic elements (e.g., boron, manganese, and aluminum)
 - v. Soil has high resilience and is able to withstand deleterious events, such as drought and flooding
2. Soil fertility, plant health, and the resistance and resilience of crop plants to pest and pathogens
 - a) Soil fertility requires a balance of critical plant nutrients. Either a deficiency or an excess of nutrients can adversely affect plant growth, susceptibility to pests and pathogens, and post-harvest quality.

C. Goals of a Sustainable Soil Fertility Management Program

1. To sustain high crop productivity and crop quality in food and fiber production (not maximum yields, which typically require excessive nutrient inputs to achieve)
 - a) Crop productivity, crop quality, and the economic viability of a given farming operation
2. To minimize environmental quality and human health risks associated with agricultural production
 - a) Important steps in minimizing human health risks and on- and off-farm impacts
 - i. Avoid the use of all synthetically compounded materials (e.g., fertilizers and pest control agents, etc.) known to have an associated environmental quality or human health risk
 - ii. Avoid creating non-point source (NPS) pollution through surface runoff and leaching. Excess nutrients (especially nitrogen and phosphorus) can degrade the quality of groundwater, surface freshwater (e.g., rivers, lakes and wetlands), and nearshore marine environments, causing eutrophication (low oxygen levels) and allowing weedy species to outcompete native species as well as polluting drinking water (see Supplement 5, Nitrate Contamination of Groundwater, in Unit 1.5, Irrigation—Principles and Practices) among other negative effects.
 - iii. Prevent soil erosion and sedimentation of waterways. Soil loss reduces production capacity and soil entering waterways may degrade aquatic habitat (see more at Supplement 2, The Global Socio-Environmental Effects of Soil Erosion).
 - iv. Close nutrient cycles as much as possible within the field and farm to reduce energy use and environmental impact of food and fiber production
 - v. Close nutrient cycles at multiple scales (e.g., watershed, regional, and national scales)
3. To assess and maintain soil health for long-term functioning of the above goals

D. Components of a Sustainable Soil Fertility Management Program: The Means to Achieving the Above Goals

1. Improving and maintaining physical, chemical, and biological properties of soil involves a suite of interrelated practices. Because these properties are so deeply and complexly interconnected, soil health management requires an overall approach focused on how the soil and plants are managed, rather than a product-based approach that focuses primarily on delivering chemical “solutions” to nutrient and pest “problems.”
 - a) Sustainable agricultural practices used to improve and sustain soil physical and biological properties
 - i. Maintain or increase soil organic matter (SOM) levels through inputs of compost and cover cropping (see Unit 1.6, Selecting and Using Cover Crops and Unit 1.7, Making and Using Compost). SOM has a high capacity to hold and release inorganic nitrogen and other essential nutrients to plants. Organic matter inputs enhance the stability of soil aggregates, increase the porosity and permeability to water and air, and improve the water-holding capacity of soils. The primary constituents of SOM are organic compounds rich in carbon. Building or maintaining the level of soil carbon provides the energy and nutrients necessary to stimulate the soil microorganisms responsible for decomposition and the formation of soil aggregates and more desirable soil structure. See also: www.nature.com/scitable/knowledge/library/soil-carbon-storage-84223790.
 - ii. Provide a balanced nutrient supply for the crop, also through compost and cover cropping. Use in-season supplemental fertilizers (when suggested as necessary by soil test results, plant growth observations, or plant tissue testing) to prevent or address plant nutrient deficiencies. See the Cornell Soil Health Assessment Training Manual for examples: soilhealth.cals.cornell.edu/.

- iii. Time tillage properly to stimulate the decomposition of SOM by breaking up compacted areas and large soil clods and thus increase aeration (O₂ supply to aerobic microbes) and expose a greater surface area for microbial breakdown. Appropriately timed tillage also increases water infiltration and good drainage (see Unit 1.2, Garden and Field Tillage and Cultivation).
 - iv. Manage irrigation carefully to avoid runoff, erosion, and leaching of soluble nutrients. For irrigation-dependent crops, manage soil moisture between 50% and 100% of field capacity through soil moisture monitoring and moisture retention techniques such as mulching (see Unit 1.5).
 - v. Manage crop rotations and crop sequences carefully to build SOM and to alternate rooting depths and nutrient demands of crops, where possible making use of different parts of the soil profile over time
2. Improve and maintain chemical properties of soil (see also Unit 2.2, Soil Chemistry and Fertility)
- a) Benchmarks of optimal soil chemistry
 - i. Balanced levels of available plant nutrients (see Unit 1.11, Reading and Interpreting Soil Test Reports, for more on this subject)
 - ii. Soil pH ~6.0–7.0: At this soil pH the greatest amount of soil nutrients are available to crops
 - iii. Low salinity levels: The accumulation of salts in the soil may result in plant water and salt stress
 - b) Sustainable agricultural practices used to develop and maintain optimal soil chemical properties
 - i. Provide a balanced nutrient supply for the crop. As plant growth is related to the availability of the most limiting nutrient, it is essential to consider the balance (ratios) of soil nutrients available. Yield and quality may be limited if levels of some nutrients are too high while others are too low.
 - ii. Conduct soil analysis with periodic monitoring. Soil analysis provides current quantitative information on the nutrient profile of a given soil. Soil analysis report data should be compared to established optimal benchmarks of soil fertility when developing soil amendment plans to assure adequate but not excessive nutrient applications. Comparing results from multiple years of sampling will show whether you are depleting or accumulating soil nutrients over time, and indicate whether changes in fertility management are needed.
 - iii. Conduct plant tissue testing. In-season plant tissue testing provides current quantitative data on the nutrient profile of growing plants. Such data may be compared with recommended nutrient levels and may be used to determine the need for mid-season supplemental fertilizing (see Resources section). However, be aware that most tissue testing information has been developed for systems using synthetic chemical fertilizers, and sufficiency levels may well differ for organic systems.
 - iv. Time seasonal nutrient release from organic amendments to correspond with crop requirements. Example: Along the Central Coast of California, crops are planted approximately 2–3 weeks after the incorporation of cover crops in late March–early April in order to synchronize the nitrogen demand of cash crops with the nitrogen liberated from cover crop decomposition. Important factors influencing the mineralization rate include:
 - The quality of the organic matter input: E.g., carbon:nitrogen ratio, lignins, tannins, polyphenols, etc.
 - Environmental factors such as soil temperature and moisture

- Note: When nitrogen from cover crops is mineralized in excess of crop demand, nitrate will be vulnerable to leaching
 - v. Generally keep fields covered with a crop, cover crop, or mulch. Avoid leaving fields bare to avoid wind and water erosion and nutrient leaching.
 - vi. Manage irrigation carefully to avoid runoff, erosion, and leaching of soluble nutrients
 - vii. Supply major nutrients primarily through organic matter and mineral soil amendments (e.g., cover crops, composts, limestone, rock phosphate, etc.)
 - viii. Allow sufficient time for fresh residue to break down before planting crops
 - ix. Use in-season supplemental fertilizers (when suggested as necessary by soil test results, plant growth observations, or plant tissue testing) to prevent or address plant nutrient deficiencies
3. Increasing soil health can also help minimize susceptibility to diseases and pests. Some practices in organic agroecosystem management are particularly helpful towards this end.
- a) Maintain soil nutrient levels and soil pH within optimal range to reduce plant nutrient deficiencies or excesses. Plant nutrient deficiencies or excesses often lead to increased susceptibility to pests and pathogens.
 - b) Build and maintain soil organic matter to promote desirable soil physical properties and supply essential plant nutrients. For example, adequate drainage discourages prolonged wet conditions that can lead to root rot, damping off, and other soil-borne diseases. Soil with high SOM can also provide habitat for beneficial soil microbes that may impart disease-suppressive qualities to agricultural soils.
 - c) Planting a high diversity of crops can increase the diversity of soil microbe populations by supplying the microbes with diverse food sources and other compounds, such as chemoattractants, from crop residue and root exudates. High microbial diversity can help suppress pests and diseases.
 - d) Design appropriate rotations to break pest cycles, and include disease-suppressive crops or cover crops. Changing the place in the garden or field where crops are grown interrupts the host/pest cycle and thereby reduces or limits the development of populations of pest and pathogens.
 - e) Maintain soil moisture within optimal ranges for plant growth and the avoidance of compaction and erosion
 - f) Use appropriate preventive (e.g., farmscaping) and active biocontrol practices to suppress the growth of pest populations (see Unit 1.8, Managing Arthropod Pests)
4. Summary

The sustainable farming practices described above, including crop rotations, soil amending and fertilizing, tillage, and irrigation techniques, should be used in concert to improve and maintain the quality and health of agricultural soils. Soil quality in turn affects crop performance (yield) and the resistance and resilience of crop plants to pests and pathogens.

Lecture 2: Soil Fertility Management—Sustainable Agriculture Practices

A. Main Goals of Managing for Soil Health

1. One of the key concepts of Lecture 1 was that soil fertility is a feature of soil health as applied to agroecosystems. It is the capacity of a soil to provide nutrients that plants require for growth.
2. Key indicators of soil health include
 - a) The ability of the soil ecosystem to mineralize nutrients and make them available to plants
 - b) A moderate pH, which promotes nutrient retention and makes nutrients available to plants
 - c) Good structure, or tilth, that resists degradation and provides adequate air and water to roots
 - d) Good biotic habitat, particularly for beneficial organisms
3. One of the main ways to support these goals is by increasing the carbon content of the soil in the form of soil organic matter (SOM)
 - a) SOM has three main constituents. As summarized by Cornell University Cooperative Extension, these are:
 - i. Plant debris and living microbial biomass
 - ii. Detritus (active soil organic matter, made of partially decomposed plant, animal, and microbial tissues)
 - iii. Humus (stable soil organic matter)
 - b) The microbes help decompose the plant debris and the detritus, while humus (a black, sticky substance) is the final product of decomposition
 - c) SOM has many benefits for the soil, supporting the key indicators of soil health listed above. Some of these functions include those below (and see the Cornell University Cooperative Extension Fact Sheet 41 [franklin.cce.cornell.edu/resources/soil-organic-matter-fact-sheet] for more functions and details):
 - i. It provides the source of substances for mineralization
 - ii. SOM, especially the humus fraction, helps maintain soil pH biochemically
 - iii. It helps soils resist crusting and decreases erosiveness
 - iv. Plant debris and detritus fractions of SOM provide food for the microbial biomass
4. All these benefits of SOM make it “money in the bank” for the agroecosystem. Maintaining and increasing SOM are the basis of the soil health practices described in this lecture.

B. Soil Cultivation in Sustainable Agriculture (see also Unit 1.2, Garden and Field Tillage and Cultivation)

1. Cultivation is physically working the soil for seedbed preparation or weed control, using hand tools or mechanical implements. It is synonymous with tillage.
2. Services provided by tillage
 - a) Prepares soil for seeds or transplants by improving soil aeration and breaking up soil clods
 - b) Incorporates crop or cover crop residue, helping make carbon and macronutrients, especially nitrogen, available to soil microbes

- c) Enables the incorporation of amendments such as compost and lime
 - d) Allows soil to dry more rapidly
 - e) Allows soil to warm up more rapidly
 - f) Increases microbial activity and mineralization rates in the short-term
 - g) Deep tillage can break through compacted layers that are a barrier to root growth and water movement
 - h) Controls weeds by burial or exposure of seeds or seedlings (see Unit 1.10, Managing Weeds)
 - i) Controls overwintering insects by exposure to the surface
3. Disadvantages of tillage
- a) May accelerate the rate and extent of long-term declines in soil organic matter
 - b) May increase sub-soil compaction problems and impede drainage and root growth
 - c) Has high energy and labor costs
 - d) Loss of soil organic matter (SOM) from excessive tillage can lead to crusting of bare soils, impeding seedling emergence and water infiltration
4. Advantages of conservation tillage systems
- a) Residue cover on the soil surface protects the soil from wind and water erosion
 - b) Increases moisture retention
 - c) Increases SOM over time (years), reaching a higher “steady state” than tilled systems in the same environment
5. Limitations of conservation tillage systems
- a) Residue cover lowers soil temperature, which delays seed germination and slows seedling growth and may place grower at an economic disadvantage
 - b) Weed control is very difficult without use of herbicides
 - c) Conservation tillage requires specialized equipment such as no-till drills for seeding
 - d) Increased leaching of nutrients and herbicides into the groundwater has been shown in some systems after years of reduced or no-till agriculture
6. Conservation tillage practices can also be employed on a small scale
- a) For example, laying down a base of cardboard followed by a layer of wood chips can be effective at reducing weed pressure while increasing SOM with relatively little work (see Unit 1.10)

C. Cover Crops in Sustainable Agriculture (see also Unit 1.6, Selecting and Using Cover Crops)

1. Services provided by cover crops
- a) Cover crops increase nutrient availability
 - i. Rhizobium bacteria, in association with legume cover crops, are able to convert freely available atmospheric nitrogen (N_2) to a plant usable form (NH_3). The legumes absorb the NH_3 and use it for growth and reproduction.
 - ii. Grass/cereal cover crops, when used alone or with N-fixing legume cover crops, may reduce nutrient losses by capturing mobile nutrients (e.g., NO_3^-) that would otherwise be vulnerable to leaching or to loss through soil erosion
 - iii. After cover crops are mown and incorporated at the end of the season, the residues from both the N-fixing and N-capturing plants are broken down by soil organisms, releasing the cover crop nutrients into the soil solution for plant use

- iv. As a source of labile carbon, cover crops can stimulate microbial activity and increase the breakdown of existing SOM. Cover crops are a source of labile carbon (C) in the soil ecosystem, and as such have a range of potential effects. Plant-derived labile C can affect mineralization of SOM (called a “priming effect”), which can release atmospheric CO₂ from the SOM and allow mineralization of N from the SOM, making stored nutrients available to plants. However, how much this happens depends on the specific soil and other interacting factors.
 - v. Deep-rooted cover crops are able to recycle nutrients acquired from deeper in the soil profile (e.g., phosphorus), acting essentially as nutrient “pumps”
- b) Cover crops improve soil physical properties: Carbon and nutrient cycling through the use of cover crops result in short-term improvements to soil physical properties
2. Influences on nutrient release from cover crops
- a) Decomposition of cover crops in the soil begins with primary consumers that consume the cover crop residue. These include large invertebrates such as earthworms, millipedes, sowbugs, and slugs. As the large organisms consume the plant materials, they shred it, creating greater surface area for microscopic invertebrates, such as nematodes, and microbes such as bacteria and fungi to continue the decomposition process.
 - b) Temperature and moisture conditions affect the level of microbial activity (lower bioactivity at cooler temperatures, and under dry or waterlogged conditions)
 - c) Location of the residue: Residue may be left on the soil surface (as in conservation tillage) or incorporated into the soil
 - i. Incorporation into the top 6–8 inches of the soil: With adequate moisture, will decompose most rapidly due to high oxygen levels and large populations of decomposing organisms
 - ii. Leaving cover crop residue on soil surface: Will decompose more slowly due to drying. However, in some systems and under certain conditions (especially warm temperatures and adequate moisture), soil organisms may move surface residue below ground, facilitating decomposition.
 - iii. Below 6–8 inches: May decompose more slowly due to lower oxygen levels and fewer decomposing organisms
 - d) Composition of the cover crop residue
 - i. The carbon to nitrogen (C:N) ratio of the cover crop residue has a close link with N mineralization. Higher cereal biomass produces higher C:N, while more legume-heavy biomass produces lower C:N. Microbes need both C and N, the C in carbohydrates to combust for energy and the N for building amino acids necessary for maintenance and reproduction. The relative amount of C and N available for microbes determines how large the pool of mineralized nitrate in the soil will be.
 - C:N ratios of 22:1 or less result in net mineralization of N. Nitrate is liberated into soil solution and is thus available for plant uptake or leaching.
 - C:N ratios above 22:1 result in net immobilization of N. Nitrogen is bound in organic forms and is unavailable for plant uptake. Nutrient deficiencies may result if this state is prolonged.
 - Because the C:N ratio of cover crops increases as they age, it is generally recommended that cover crops be harvested or incorporated into the soil when close to full bloom (but prior to seed set) to assure a C:N ratio of 22:1 or less so that net mineralization occurs
 - ii. The presence of lignins and tannins in cover crop residue slows the rate of decomposition. Lignins and tannins are organic compounds that are produced by plants and have high C:N.

3. The timing of nutrient release, crop demand, and the fate of essential plant nutrients
 - a) Growers generally should try to manage the timing of nutrient release from cover crops to coincide with crop demand (see D. 2. in Lecture 1)
 - b) Nutrients (particularly N in the form of nitrate) can become vulnerable to loss if timing is mismatched
 - c) If timing is mismatched, nutrient deficiencies (especially N) may result during key stages in the growth cycle, leading to reduced yields. This is especially true with longer-season crops, e.g., peppers and tomatoes.

D. Composts and Animal Manures in Sustainable Agriculture Fertility (see also Supplement 1, A Soil Primer with Sustainable Management Strategies and Unit 1.7, Making and Using Compost)

1. Both compost and animal manure are sources of organic matter for the soil ecosystem and provide benefits for soil, including:
 - a) Nutrients for crops
 - b) Increased soil organic matter content
 - c) Increased soil cation exchange capacity (CEC)
 - d) Habitat and food for beneficial soil microbes
 - e) Increased soil aggregates
2. Compost application
 - a) Common annual application rates: ~4–5 tons/acre/year on field scale; 10–12 tons/acre/year on garden scale (cropping dependent)
 - b) The nutrient contribution (N:P:K) of compost varies greatly, depending on the raw materials of the compost, and how long and under what conditions it matured. Check with the supplier or have a compost nutrient assessment done to determine nutrient levels and proportions.
 - c) Compost C:N: Compost with C:N of less than 20:1 can provide N to the following crop, but compost with C:N greater than 20:1 can immobilize the N, making it less available to the crop. This depends greatly on the raw materials, as well as the compost's maturity. Here, too, check with the supplier or have a compost nutrient assessment done.
 - d) Application timing: Ideally, nutrient release should coincide with crop demand. However, this is difficult to control in organic systems because it is a biologically-driven process, dependent on microbes breaking down the organic matter.
 - i. Compost is generally applied at the start of the season or when planting new crops during the growing season
 - ii. Compost may be applied midseason as a sidedress (applied adjacent to or between rows of growing crops), although it needs to be incorporated into the soil surface
 - iii. Depending on the quality of the compost, particularly the C:N, it may be an inefficient source of N in the short term
 - iv. Release of N may last 6 weeks to several months following incorporation, depending on the C:N, soil characteristics, and environmental conditions (e.g., weather). Up to 10–15% of the compost N is released the first year.
3. Other considerations of compost use
 - a) Requirements for on-farm compost production (see Supplement 2, Field-Scale Compost Production: A Case Study in Unit 1.7). The feasibility of making compost on the farm (versus “buying in” compost from a commercial source) depends on the farm or garden scale and the overall labor and economics of the operation.
 - i. Labor and knowledge: On-farm compost production requires labor inputs and knowledge of compost production techniques to both build and monitor compost piles

- ii. Equipment and water: On-farm compost production requires proper equipment for pile building and turning, and a water source
 - iii. National Organic Program (NOP) standards for on-farm compost production: The NOP has strict standards for compost production and use, e.g., the number of days the compost is maintained at a particular temperature during the initial composting process. Consult with your certification agency or see the NOP website.
- b) Requirements for off-farm compost purchasing
- i. Local/regional availability
 - ii. Variability in quality
 - iii. Price
 - iv. Shipping or delivery costs
 - v. Storage, if purchased in large quantities
4. Manure application
- a) Composted vs. uncomposted manure: While composted manure provides the benefits of compost as described above, fresh or uncomposted manure may present several problems:
- i. High ammonium levels may result in nitrogen “burns” on plants
 - ii. High ammonium and/or nitrate levels may cause rapid population growth of soil microbes and the subsequent immobilization of N
 - iii. Undigested seeds from the animals’ feed (e.g., hay) or pasture may introduce weeds
 - iv. N is easily leached if stored manure is exposed to rain or if manure is incorporated into the soil shortly before significant precipitation (enough to move the available nitrate and ammonium below the root zone). This contributes to water pollution as well as reduces the amount of N that would be available to plants later.
 - v. Pathogens such as *E. coli* and other disease-causing organisms may be present in fresh manure. The National Organic Program includes guidelines on fresh manure use to prevent contamination of food.
 - vi. Composting the manure also helps address these problems
- b) Restrictions on the use of manure are included in the National Organic Standards of 2002 (see Resources reference on National Organic Program)
- c) The nutrient contribution (N:P:K) of fresh manures varies. See the *Rodale Book of Composting* in the Resources section for more information.

E. Soil Amendments and Supplemental Fertilizers in Sustainable Agriculture

1. Soil fertility management and nutrient budgets: In sustainable agriculture systems, the goal often is to balance nutrient inputs with nutrient outputs each year. A nutrient budget takes into account nutrient inputs, including those from compost and cover crops, and those nutrients lost to crop production and other activities.
- a) Goal: Balance inputs and outputs once you have achieved desired/optimal nutrient levels and ratios
- b) Inputs > outputs = accumulation. Potential risk of excess nutrients leading to non-point source pollution through leaching and runoff (see Supplement 5, Nitrate Contamination of Groundwater, in Unit 1.5, Irrigation—Principles and Practices). As described earlier, it also can increase disease and pest problems.
- c) Inputs < outputs = soil depletion. Potential risk of plant nutrient deficiencies and stress, reduced yield, and increased susceptibility to pests and pathogens.
- d) Example of inputs factored into budget for nitrogen
- i. Inputs = N imported in fertilizers and amendments (including compost and manure) + N fixation through cover crops

- ii. Outputs = N exported in crop harvest + N lost through leaching, erosion, and denitrification
 - iii. Calculating N budgets: See Demonstration 2, Nitrogen Budgeting in Unit 1.11, Reading and Interpreting Soil Test Reports
2. Organic amendments
 - a) OMRI/NOP-certified materials in certified organic farming systems (see the Organic Materials Review Institute website, www.omri.org)
 3. Supplemental fertilizers
 - a) Supplemental fertilizers are used to prevent or remedy acute soil or plant nutrient deficiencies identified through soil analysis reports, plant tissue testing, and/or plant growth observations
 4. Application of nutrient budgets in assessing the health of larger-scale units, such as watersheds and regions
 - a) Example of accumulation and depletion: Confinement animal production facilities import nutrients as feed from large areas, and concentrate waste disposal in small areas

F. Crop Rotation and Crop Sequencing in Sustainable Agriculture (see also *Crop Rotations on Organic Farms: A Planning Manual*, by Charles L. Mohler and Sue Ellen Johnson in Resources)

1. Crop rotations
 - a) Crop rotation defined: The movement of crops from site to site on the farm in a planned sequence
 - b) Rationale behind crop rotation: It interrupts pest-host cycles and prevents the buildup of pests, weeds, and pathogens. Rotation also allows crops to access nutrients from different soil depths, based on their rooting characteristics. Integrating cover crops and fallow periods into rotations helps build soil organic matter and improve aggregation.
2. Rotation and sequencing considerations
 - a) Try to avoid repeated planting of crop species that are subject to similar pests, diseases, and weed pressures in the same beds. Rotate with different crops to remove hosts and break pest cycles.
 - i. Example: Solanaceae rotation. It is common practice to change the location of Solanaceae family crops each year. Because these crops (tomatoes, eggplants, peppers, potatoes, etc.) share common pests and pathogens, repeated cropping in the same location can lead to the buildup of pest populations.
 - b) Rotate crops to maximize use of nutrient inputs and distribute nutrient demand placed on the soil
 - i. Examples of multi-year crop rotations (see Mohler and Johnson 2009 and Coleman 1995 in Resources)
 - c) Rotate crops with various types of root systems to improve soil health and structure. E.g., tap-rooted crops promote water infiltration; fibrous-rooted crops help maintain soil organic matter levels.
 - d) Incorporate fallow periods and perennial cover crop rotations. Fallow periods—areas intentionally left uncultivated and planted to perennial cover crops—allow the soil to remain undisturbed and the aggregation processes to proceed uninterrupted. This can help restore the desired physical components of soil health. See more at Supplement 1, Strategies for Improved Weed Management on Small-Scale, Diverse Farms in Unit 1.10.
3. Crop rotations and within-season sequences are farm specific and will depend on the diversity of crops being grown, as well as factors such as farm location, soil types, climate, and economic factors. See examples at Mohler and Johnson 2009 in Resources.

Assessment Questions

- 1) What is certified organic agriculture?
- 2) Describe the goals of a sustainable soil health management program.
- 3) Define soil fertility/health.
- 4) Describe the relationship amongst soil fertility, plant health, and the resistance and resilience of crop plants to pest and pathogens.
- 5) What are the major components of a sound soil health management program? How does each component function to maintain soil fertility and quality?

Assessment Questions Key

1) What is certified organic agriculture?

- *A certified organic production system is a farming system managed in accordance with The Organic Foods Production Act and the National Organic Standards of 2002. The production system is to be designed and managed to respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity. Further, it is a system of agriculture that encourages healthy soil and crops through such practices as nutrient and organic matter recycling, crop rotations, proper tillage, and the strict avoidance of synthetic fertilizers and pesticides for at least three years prior to certification. Certified organic farming operations are required to develop and submit an “organic system plan” to their certifying agency detailing how an operation will achieve, document, and sustain compliance with all applicable provisions in the OFPA/NOP. The certifying agent must concur that the organic system plan and ongoing management practices fulfill the NOP requirements.*

2) Describe the goals of a sustainable soil health management program.

- *To sustain high crop productivity and crop quality in food and fiber production*
- *To minimize environmental quality and human health risks associated with agricultural production*

3) Define soil fertility/health.

- *The capacity of a soil to provide nutrients required by plants for growth. This capacity to provide nutrients to crop plants is in part influenced by the physical properties of soils and is one component of soil fertility. Desirable soil physical properties and the capacity of the soil to provide nutrients for growing crops are both soil quality indicators.*

4) Describe the relationship amongst soil fertility, plant health, and the resistance and resilience of crop plants to pest and pathogens.

- *Crops grown in fertile soils are higher quality, better yielding, and are more resistant and resilient to pests and pathogens*

5) What are the major components of a sound soil health management program? How does each component function to maintain soil fertility and quality?

1. *Improve and maintain physical and biological properties of soil*
 - *Organic matter inputs: Compost and cover crops*
 - *Fallow periods*
 - *Properly timed irrigation and tillage*
 - *Soil testing and proper soil amending*
2. *Improve and maintain chemical properties of soil*
 - *Organic matter inputs: Compost and cover crops*
 - *Soil testing and proper soil amending*
 - *Supplemental fertilizing when necessary*
 - *Avoid leaving soils exposed*
 - *Proper irrigation to avoid leaching of nutrients*
3. *Minimize disease/pest susceptibility*
 - *Design appropriate crop rotations and fallow periods*
 - *Polycultures/non-monoculture production*
 - *Use appropriate preventive and active biocontrol practices*
 - *Provide optimal level and balance of nutrients for good plant healths*

Resources

Note: Additional resources related to soil health management are listed in Units 1.2, Garden and Field Tillage and Cultivation; 1.6, Selecting and Using Cover Crops; 1.7, Making and Using Compost; and 1.11, Reading and Interpreting Soil Test Reports

PRINT RESOURCES

Brady, Nyle C., and Ray R. Weil. 2008. *The Nature and Properties of Soil, 14th Edition*. Upper Saddle River, NJ: Prentice Hall.

Comprehensive (965 pages) textbook on soils—great for those who want to “go deeper” into the origins, classifications, and workings of soil.

Chaney, David E, Lori E. Drinkwater, and Stuart Pettygrove. 1992. *Organic Soil Amendments and Fertilizers*. Publication 21505, UC Sustainable Agriculture Research and Education Program. Oakland, CA: University of California Division of Agriculture and Natural Resources.

A concise overview of the materials commonly used in certified organic farming systems to improve and maintain soil fertility. Addresses the role of soil organic matter in farming systems and how to evaluate organic materials for on-farm use. Briefly profiles each of the types of organic amendments and fertilizers commonly available.

Clark, Andy (ed.). 2007. *Managing Cover Crops Profitably, 3rd edition*. Sustainable Agriculture Research and Education (SARE) program, Handbook Series Book 9.

Explores how and why cover crops work, and provides all the information needed to build cover crops into any farming operation. Includes information on the characteristics, costs, seeding rates, and management of different cover crop species. Available from www.sare.org as hard copy and free download.

Colemann, Eliot. 1995. *The New Organic Grower: A Master's Manual of Tools and Techniques for the Home and Market Gardener, 2nd edition*. White River Junction, VT: Chelsea Green Publishing Co.

An overview of intensive organic production methods on a small scale. Good section on crop rotation planning.

Fortier, Jean-Martin. 2014. *The Market Gardener: A Successful Grower's Handbook for Small-Scale Organic Farming*. Gabriola Island, BC: New Society Publishers.

Includes a section on organic soil fertility management, with a focus on small-scale, diverse systems. Discusses soil tests, crop requirements, and the use of compost, cover crops, and crop rotations in organic vegetable production to maintain and improve soil health.

Gaskell, Mark, Jeff Mitchell, Richard Smith, Steven Koike, and Calvin Fouche. 2000. *Soil Fertility Management for Organic Crops*. Publication 7249. Oakland, CA: University of California, Division of Agriculture and Natural Resources. anrcatalog.ucdavis.edu/pdf/7249.pdf

A five-page overview of soil fertility for organic production systems

Gugino, Beth K., Omolulu J. Idowu, Robert R. Schindelbeck et al. 2009. *Cornell Soil Health Assessment Training Manual, Edition 2.0*. Geneva, NY: Cornell University, College of Agriculture and Life Sciences. soilhealth.cals.cornell.edu/extension/manual/manual.pdf

Well-written and easy to understand manual addresses soil health, in-field assessment, soil testing, soil health indicators, and sustainable management strategies to maintain and improve soil health.

Hinman, Tammy, Andy Pressman, and Hannah Sharp. 2012. *Resource Guide to Organic and Sustainable Vegetable Production*. ATTRA, National Center for Appropriate Technology (NCAT), IP188.

Includes an extensive listing of publications and websites related to organic and sustainable vegetable production. Available at www.attra.ncat.org

Magdoff, Fred, and Harold Van Es. 2009. *Building Soils for Better Crops, 3rd Edition*. Handbook Series Book 10, Sustainable Agriculture Research and Education (SARE) Program.

An overview of the ecological management of soil fertility covering the basics of soil organic matter, physical, and chemical properties of soil, ecological soil and crop management. Provides

step-by-step information on soil-improving practices as well as in-depth background—from what soil is to the importance of organic matter. Includes case studies of farmers from across the U.S. Practical and accessible information. Available from www.sare.org as hard copy or free download.

Magdoff, Fred, and Ray R. Weil. 2004. *Soil Organic Matter in Sustainable Agriculture*. Boca Raton, FL: CRC Press, Taylor and Francis Group.

This textbook contains evaluations of the types of organic soil constituents—organisms, fresh residues, and well-decomposed substances. It explores the beneficial effects of organic matter on soil and the various practices that enhance soil organic matter (SOM). Examines the impacts of crop management practices on soil organisms, organic matter gains and losses, the significance of various SOM fractions, and the contributions of fungi and earthworms to soil quality and crop growth.

Martin, Orin. 2007. *Soil Cultivation: Fundamental Concepts and Goals*. For the Gardener series. UC Santa Cruz: Center for Agroecology & Sustainable Food Systems. casfs.ucsf.edu/documents/for-the-gardener/soil_cultivation.pdf

Describes the basic concepts associated with soil cultivation and garden bed preparation, including organic matter incorporation, nutrient release, and promoting good tilth and structure.

Michigan State University Extension. 1998. *Michigan Field Crop Ecology*. Extension Bulletin E-2646.

A well-illustrated 85-page publication covering the soil ecosystem processes managed in agricultural systems (e.g., major nutrient cycles, soil biology, pest and disease management). Available from bookstore.msue.msu.edu/.

Mohler, Charles L., and Sue Ellen Johnson (eds.). 2009. *Crop Rotations on Organic Farms: A Planning Manual*. Ithaca, NY: NRAES-177.

Offers an in-depth review of crop rotation and its many applications, such as improving soil quality and health, and managing pests, diseases, and weeds. The authors consulted with expert organic farmers to develop crop rotation and crop sequencing guidelines and

strategies that can be applied under various field conditions and with a wide range of crops. Includes instructions for making crop rotation planning maps using Microsoft Excel and discusses intercropping and crop rotation during the transition to organic farming. Note: Single download and printing for personal use permitted.

Smillie, Joe, and Grace Gershuny. 1999. *The Soul of Soil: A Soil-Building Guide for Master Gardeners and Farmers, 4th Edition*. White River Junction, VT: Chelsea Green Publishing.

Provides essential information on soil ecosystem management for organic growers. Topics include organic matter management, building and maintaining humus, on-site composting, green manures and crop rotations, cultivation and weed control, nutrient balances and soil testing, and using mineral fertilizers.

Tugel, Arlene J., Ann M. Lewandowski, and Deb Happe-vonArb, (eds). 2000. *Soil Biology Primer*. Ankeny, IA: Soil and Water Conservation Society.

An introduction to the living component of soil and how that component contributes to agricultural productivity and to air and water quality. The Primer includes information describing the soil food web and how the food web relates to soil health.

Van Horn, Mark. 1995. *Compost Production and Utilization: A Growers Guide*. Publication 21514. Oakland, CA: University of California Division of Agriculture and Natural Resources.

A short publication focusing exclusively on on-farm composting for growers. Includes sample calculations for achieving optimal C:N ratios, suggestions on compost management, nutrient profiles, and nutrient release patterns of composts.

WEB-BASED RESOURCES

Alternative Farming Systems Information Center, USDA

www.nal.usda.gov/afsic/

Technical information on organic farming, sustainable agriculture, community supported agriculture. Access to National Agricultural Library to research journal article abstracts and order articles.

Appropriate Technology Transfer for Rural Areas (ATTRA)

www.attra.org

A national sustainable farming information center. Information on sustainable farming production practices, alternative crop and livestock enterprises, innovative marketing.

Organic Farming Compliance Handbook: A Resource Guide for Western Regional Agricultural Professionals

www.sarep.ucdavis.edu/sfr/organic/ofch

Developed to help agricultural professionals in the Western U.S. understand effective practices, materials, and processes that comply with organic standards; access expertise and informational resources on organic farming, and answer questions from their clientele regarding effective practices that meet organic standards. Includes information on organic systems plans, principles of organic production, and organic marketing and economics.

Organic Materials Review Institute (OMRI)

www.omri.org

List of materials compatible in organic farming, brand name review, technical information.

UC Sustainable Agriculture Research and Education Program (SAREP)

www.sarep.ucdavis.edu/

Sustainable agriculture news, technical information, grant programs, Biologically Integrated Farming Systems program.

USDA National Organic Program

www.ams.usda.gov/nop/

Regulations on certification, materials, and labeling for organic producers and processors.

USDA Natural Resources Conservation Service: Soils

www.nrcs.usda.gov/wps/portal/nrcs/site/soils/home/

Includes information on soil taxonomy and soil classification resources, soil surveys, as well as a guide on how to receive soil conservation assistance.

USDA Natural Resources Conservation Service: Soil Health

www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/

A comprehensive portal to information on soil health, including soil biology, health assessment, health management, and extensive lists of resources and publications.

VIDEO RESOURCES

Symphony of the Soil. 2012. Directed by Deborah Koons Garcia (103 minutes).

www.symphonyofthesoil.com

An artistic and scientific exploration of soil, examining its complex dynamics as well as the human relationship with soil, the use and misuse of soil in agriculture, deforestation and development, and the latest scientific research on soil's key role in ameliorating the most challenging environmental issues of our time. Filmed on four continents, featuring esteemed scientists and working farmers and ranchers.

SUPPLEMENT 1

A Soil Primer with Sustainable Management Strategies

Soil is often thought of as an inert substrate, useful in propping up plants and a mere vehicle for applied fertilizer and water. It is, in reality, a distinct ecosystem, defined as a system formed by the interactions of a community of organisms with their physical environment.

Although we tend to take it for granted, human society is principally possible only because the earth's crust is "dusted" with a thin and often fragile layer of life-supporting material on which we can grow food: the soil.

Two distinct parts of the soil—the biotic and abiotic components—function together to form a stable system. The biotic, or living (or that which was once alive) component is comprised largely of living plants, living organisms (macro and micro), and organic matter (plant and animal residues), which can be fresh, partially decomposed, or fully stabilized (humus). Soil's abiotic component is made up of minerals, air, and water.

By understanding the soil's ecosystem, growers can harness and promote the biotic components with judicious additions of compost and "green manures" (cover crops worked into the soil) to create a healthy environment for plant growth, and thus virtually eliminate the need to apply purchased fertilizer. This can lower costs—both out of pocket and environmental.

This supplement introduces the soil's four basic components and three major properties, discusses how these interact, and describes ways that gardeners and farmers can improve their soils by learning how to become "biological growers."

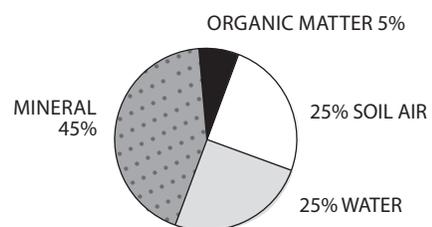
Soil's Four Components

When you pick up a handful of soil, only half of that volume is solid material (minerals and organic matter). The other half should be pore space occupied by air (25%) and water (25%). Thus soil consists of four basic components:

1. Mineral (45%, + or -, by volume): The mineral component of soil consists of rocks ground down over geologic time as a result of physical, chemical and biological actions. Think of it as rock or stone "flour."

- 2. Organic matter (5%, + or -):** Organic matter is made up of a wide range of organic (carbon-containing) substances, including living organisms, plant biomass, and the carbonaceous remains of organisms and plants. Some soil microorganisms break down the remains of plants, animals, and other microorganisms; others synthesize new substances.
- 3. Soil air (25%):** Soil air occupies the interstitial spaces between soil particles. Its primary role is to provide oxygen to fuel the aerobic (oxygen-requiring) activities of microorganisms and plant roots. Soil bacteria that associate with roots of legumes such as beans and peas use the nitrogen component of soil air to "fix" nitrogen in a form that plant roots can assimilate.
- 4. Water (25%):** Soil water or the soil solution carries dissolved nutrients that flow to and are actively intercepted by plant roots. Thus the soil solution is the vehicle for nutrients to "flow" into plants and, along with the products of photosynthesis, "grow" the plant. The soil solution also gives plants their turgor and rigidity.

◀ **FIGURE 1.1** | SOIL COMPOSITION:
AN IDEALIZED SOIL



Soil's Three Distinct Properties: Physical, Chemical, and Biological

Physical properties of soil are divided into texture and structure.

Soil texture is a physical measurement of the percentage of sand, silt, and clay particles in a soil (as determined by grain size, with sandy soils being the largest and clay the smallest). It is a given, and cannot be altered (see more in Unit 2.1, Soil Physical Properties).

Sandy soils usually feature low nutrient- and water-holding capacity and an associated lower organic matter content. On the plus side, sandy soils drain well, warm quickly, and allow early cultivation and planting in the spring. Clay soils are the opposite: they carry high levels of nutrients and water, but are often difficult to work. You can determine soil texture by a simple field “feel” test called ribboning, or have it measured with a lab soil test.

Soil structure refers to the arrangement of individual soil particles (sand, silt, clay) into aggregates or “clumps”; ideally, it takes the form of a granular or crumb structure, much like the cross section of a loaf of good whole grain bread. Such a structure features an amalgamation of small, intermediate, and large, stable aggregates. Some major contributors to stable aggregates and good soil structure are:

- The addition of organic matter—fresh, as green manures, and stabilized, as finished compost. Organic matter is a feedstock for soil microorganisms that break down the organic materials and in the process exude mucilaginous glues and slimes that help bind soil particles into stable aggregates. Plant roots, both living and decomposed, also contribute “binding” substances to the system.

- Timely and skilled cultivation techniques—rough plowing or digging physically forces soil particle contacts, beginning the process of aggregation. Organic matter contributes to stabilizing the aggregates that form. Note: Too much cultivation (especially secondary cultivation, or pulverizing) damages soil structure, as does working a soil when it's too wet. See details about cultivation in Unit 1.2, Garden and Field Tillage and Cultivation.

Chemical properties of a soil measure its nutrient-carrying capacity and pH (acidity; see Unit 2.2, Chemical Properties of Soil). These are best determined by a soil test.

Biological properties of the soil refer to the “community of creatures” that live in and form the soil,

principally bacteria, fungi, and actinomycetes (microorganisms that are especially effective in breaking down hard-to-decompose compounds, such as chitin; see Unit 2.3, Soil Biology and Ecology).

While the three properties of soil are discreet, they are also synergistically interactive—think in terms of a Venn diagram.

Some examples:

- By providing a “feedstock” for soil's biological components with compost, green manures, and fertilizers, you stimulate microbial populations. These microbes break down organic matter so that it can be dissolved in soil water and taken up by plants for growth. The microbes, in turn, die and contribute their own organic materials to the organic matter content of the soil. Thus by “working smart instead of hard,” as Buckminster Fuller once said, you improve the chemical property of your soil by promoting the biological properties.
- Similarly, by adding organic matter at least once a year, and using timely, skilled cultivation techniques, you create good soil aggregation and improve soil structure (a physical property). This creates large, continuous “pore spaces” in the soil; with their balance of air and water, these pore spaces create a favorable habitat for the microbes and plant roots that live and grow there. Thus you harness the physical properties of a soil to create and maintain hospitable conditions for soil organisms and plants (the biological properties).

A Biological Approach to Managing Soils

In Europe they refer to organic growers as biological growers, which is probably a more appropriate and descriptive term. While all aspects of soil analysis and management are critical, the twin engines of soil biology and organic matter inputs coupled with the appropriate style and frequency of cultivation drive the system of a biological-ecological approach to soil management.

Although it makes up only 3–5% of the soil, organic matter has a pronounced influence on all soil properties. When added to the soil, it yields:

- A sufficient nutrient supply
- An open, permeable soil surface that allows air/gas exchange to replenish the soil's oxygen content, and makes it easy for water to enter, percolate through, and drain out of the root zone

- A “feedstock” to nourish microbes
- A low population of soil-borne plant diseases and pathogens
- A high population of beneficial soil microorganisms
- Good soil consistency, that is, the ability to resist degradation (compaction, erosion, etc.)
- Good tilth, which refers to the “workability” of a soil

Short of calling it a panacea, whatever the problem with soils, the answer is almost always to add organic matter in the form of compost and/or green manures from cover crops:

- On a mono-grained, structureless sandy soil it creates aggregation and aids with moisture and nutrient retention, building the “body” of a soil.
- On a sticky clay it adds more continuous macropores from the surface to the subsoil. This type of pore system reduces puddling, crusting, and erosion of surface soils and allows easy root growth.
- It also increases the aerobic (oxygen) content of clay soils, thus facilitating better root growth and a flourishing biological community.

One of organic matter’s key properties is that it provides nutrients both for immediate use by microbes and plant roots, and also holds and releases nutrients over time. This is especially true of nitrogen, the most volatile and motile (moveable) of all nutrients, and the one needed by plants in the largest quantity.

On a soil test, the estimated nitrogen release (ENR) is a reflection of the amount of organic matter in a soil (3–5% organic matter is considered good for California soils), as well as the organic matter’s ability to release nitrogen each growing season. ENR is expressed in pounds/acre, where >80–100 pounds is considered good. Along with a nitrate nitrogen reading (20–40 parts/million is adequate), knowing the percent of organic matter in your soil helps to determine whether you need to add nitrogen as a fertilizer.

Assessing and Amending Your Soil

One good way to assess the overall chemical properties (including nutrient content) of a soil is to get a professional lab soil test. For example, A&L Western Agricultural Labs in Modesto, California (www.al-labs-west.com) is an excellent lab with good customer service, and their test results will give you an

accurate baseline as per the macro and micronutrients plus the pH of your soil. Peaceful Valley Farm Supply (www.groworganic.com) sells an easy-to-use booklet, *Understanding Your Soil Analysis Report*, that will help you interpret the results and makes recommendations for addressing deficiencies.

With soil science there is no alchemy, which is to say, if a nutrient is deficient you have to add it. Once added, it can be managed for both availability and retention. For instance, phosphorus facilitates early root growth, flowering, fruiting, sugar development, and energy transfer within plants. Organic sources include bone meal, oyster shell flour rock, and colloidal rock phosphate.

Once added to the soil, phosphorus is relatively immobile—that is, it doesn’t readily leach downward as does nitrogen. But it is quickly “locked up” by both aluminum and calcium in the soil, and thus unavailable for plant growth. As a biological soil manager you can grow phosphorus-concentrating crops such as brassicas, legumes, and cucurbits, then use them for compost or as green manure to work the phosphorus in their plant parts into the organic fraction of the soil, where it will be available to crops.

Another strategy is to add a dusting of colloidal rock phosphate powder to manure layers in a compost pile. Nitrifying bacteria proliferate in manure and they also consume and immobilize the phosphorus, then “give it up” as they die and decompose. Again, it becomes available in the organic matter fraction of the soil when the finished compost is applied.

Closing tips:

- Cultivate judiciously and skillfully (see *Soil Cultivation: Fundamental Concepts and Goals* in Resources)
- Add organic matter at least once a year as compost or green manures from cover crops
- Don’t water excessively, as water leaches nutrients and when applied heavily via overhead or furrow irrigation can damage soil structure and reduce the aerobic (air-holding) capacity of a soil
- Protect the soil surface, either with a living mulch (cover crops), or straw, chips, etc.
- Minimize soil compaction
- Get a lab soil test done and use the results to develop a fertility management plan. Then monitor the soil via periodic tests every 1–3 years to see if your plan is working.

SUPPLEMENT 2

The Global Socio-Environmental Effects of Soil Erosion

Soil erosion is the natural process of detachment and movement of surface soil by water or wind, and has occurred simultaneously with soil formation on the Earth for millennia. In natural ecosystems the formation of soil from decomposing plant and animal matter occurs in balance with the rate of erosion, maintaining overall soil health and fertility and preventing a net loss of topsoil. In the last several centuries, however, human activities have increased the rate of soil erosion, currently outpacing soil formation by 10 times in the U.S. and 40 times in China and India.

In the last 40 years, 30 percent of the world's arable land has become unproductive and 10 million hectares (about 25 million acres) are lost each year due to erosion.¹ Additionally, accelerated erosion diminishes soil quality, thereby reducing the productivity of natural, agricultural and forest ecosystems. Given that it takes about 500 years to form an inch of topsoil, this alarming rate of erosion in modern times is cause for concern for the future of agriculture. This supplement explores the major causes of soil erosion and the social impacts it has on communities, underscoring the importance of agricultural practices that prevent or minimize erosion.

Anthropogenic causes of accelerated soil erosion are numerous and vary globally. Industrial agriculture, along with overgrazing, has been the most significant contributor, with deforestation and urban development not far behind.^{2, 3, 4} Heavy tillage, fallow rotations, monocultures, and marginal-land production are all hallmarks of conventional agriculture as it is variably practiced around the world and significantly encourage accelerated soil erosion. Repeated tillage with heavy machinery destroys soil structure, pulverizing soil particles into dust that is

easily swept up by wind or water runoff. Fallow rotations, common with cash crops around the world and subsidized in bio-fuel production in the U.S., leave land vulnerable to the full force of wind gusts and raindrops. Monocultures tend to be planted in rows, exposing the soil between to erosion, and are commonly associated with fallow rotations. More and more marginal land, land that is steep and particularly susceptible to water erosion, is being planted by farmers either attracted by higher crop prices or forced by loss of productivity on flatter, but already eroded lands. In an increasingly complex global food web, seemingly separate causes of erosion begin to influence each other, magnifying their effects. For example, deforestation of tropical forests in Brazil clears the way for industrial soybean production and animal grazing to feed sprawling urban populations in the U.S. All the while, fertile topsoil is carried away by wind and water at alarming rates.

Environmental harms resulting from accelerated erosion are well documented. Decreased soil fertility and quality, chemical-laden runoff and groundwater pollution, and increased flooding are just a few of these detrimental effects. There are, in addition, disproportionate social harms resulting from high rates of erosion that are less obvious, but no less directly linked. Hunger, debt, and disease are serious problems in mostly poor, rural communities around the world that are exacerbated by accelerated erosion.

As global agricultural development and trade have accelerated in the last half-century, mainly via the “green revolution” and the formation of the World Trade Organization (WTO), increasing trade

1, 2 Pimentel, David. 2006. Soil erosion: a food and environmental threat. *Environment, Development and Sustainability*, 8: 119–137.

3 Montanarella, Luca. Soil at the interface of agriculture and environment. Agriculture and Environment, the European Commission. ec.europa.eu/agriculture/envir/report/en/inter_en/report.htm

4 Mmbaga, John. 2013. How human activity affects soil erosion. *Sciences 360: Ecology and Environment*. www.sciences360.com/index.php/how-human-activity-affects-soil-erosion-849/

pressures have raised export crop production in less developed countries. As a result, farmers mainly in Asia, Latin America, and sub-Saharan Africa are increasingly abandoning traditional farming techniques and locally significant crops in favor of adopting the industrial practices mentioned above that lead to high rates of erosion.⁵ While development institutions and governments proclaim concerns for the rural environment, agricultural policy supporting high commodity prices and limited credit access continually pushes farmers to intensify land use. Coupled with the fact that the total area of arable land in cultivation in these parts of the world is already very high (e.g., 80% in South Asia), land degradation by soil erosion threatens food security by removing from cultivation land sorely needed for domestic food production. The majority of the world's 868 million undernourished people live in Eastern and Southern Asia and sub-Saharan Africa.

One of the international responses to soil degradation in the developing world has been to promote soil conserving tillage practices known as minimum- or no-till agriculture. No-till agriculture protects soil by leaving crop residue on the field to decompose instead of plowing it into the ground before planting the next crop. Weed management is addressed with heavy herbicide use to make up for the loss of weed control from tillage. The practice, extensively adopted in the U.S., has been popular in Brazil and Argentina, and much effort is being expended to expand no-till to Asia and Africa.

There are, however, costs associated with no-till agriculture, both economic and social. First, no-till agriculture is expensive to adopt. Herbicides, seed drills, fertilizers, and other equipment require a high initial investment not possible for poor farmers without incurring significant debt. Second, heavier herbicide use increases human exposure to chemicals and contributes to water and air pollution. Third, weed pressures can change in unexpected ways as reliance on a handful of herbicides breeds resistance. Weed resistance to the popular herbicide, glyphosate, is an increasing concern in conventional agriculture and is leading to development of more harmful herbicides to compensate for glyphosate's reduced effectiveness. Lastly, no-till agriculture also

promotes monoculture cropping systems that, as described above, have a deleterious effect on soil quality.

The techniques illustrated in this manual emphasize long-term soil stewardship using an integrated approach to soil health and management. For example, cover crops hold soil aggregates together in the wet season, protecting soil from the erosive effects of rain. Properly timed tillage limits its destructive effects on soil particles and soil structure. Compost promotes a healthy soil ecosystem, improving soil's structure and its ability to more successfully withstand wind and water erosion.

In addition to environmental benefits, agroecological systems^{6,7} are often based on traditional farming practices that promote soil-conserving techniques and varietal choices adapted to the particular region, stemming the tide of land consolidation and commodity crop production. Food security is enhanced and debt risk reduced by way of diverse cropping systems and labor-intensive, rather than input-intensive, production methods. And there are public health benefits from eliminating exposure to harmful pesticides and herbicides. In sum, the serious challenge presented by accelerated soil erosion coupled with the uncertainty about whether no-till agriculture's benefits outweigh its harms underscores the importance of employing an agroecological approach to farming that prevents soil erosion on farms.

5 Kwa, Aileen. Agriculture in developing countries: which way forward? Occasional Papers 4. Trade-Related Agenda, Development and Equity (T.R.A.D.E.). focusweb.org/publications/2001/agriculture_which_way_forward.html

6 Silici, Laura. 2014. Agroecology: What it is and what it has to offer. IIED Issue Paper. International Institute for Environment and Development, London. Available online at: pubs.iied.org/pdfs/14629IIED.pdf?

7 Gliessman, Stephen R. 2014. *Agroecology: the Ecology of Sustainable Food Systems 3rd Edition*. Boca Raton, FL: CRC Press, Taylor Francis Group.

