Building Healthy Living Soils for Succesful Organic Farming in the SOUTHERN REGION

By Mark Schonbeck and Lauren Snyder

With contributions from John Bell, Bryan Hager, Krista Jacobsen, Emily Oakley, Danielle Treadwell, Steve Diver, and Elizabeth Little

ORGANIC FARMING RESEARCH FOUNDATION

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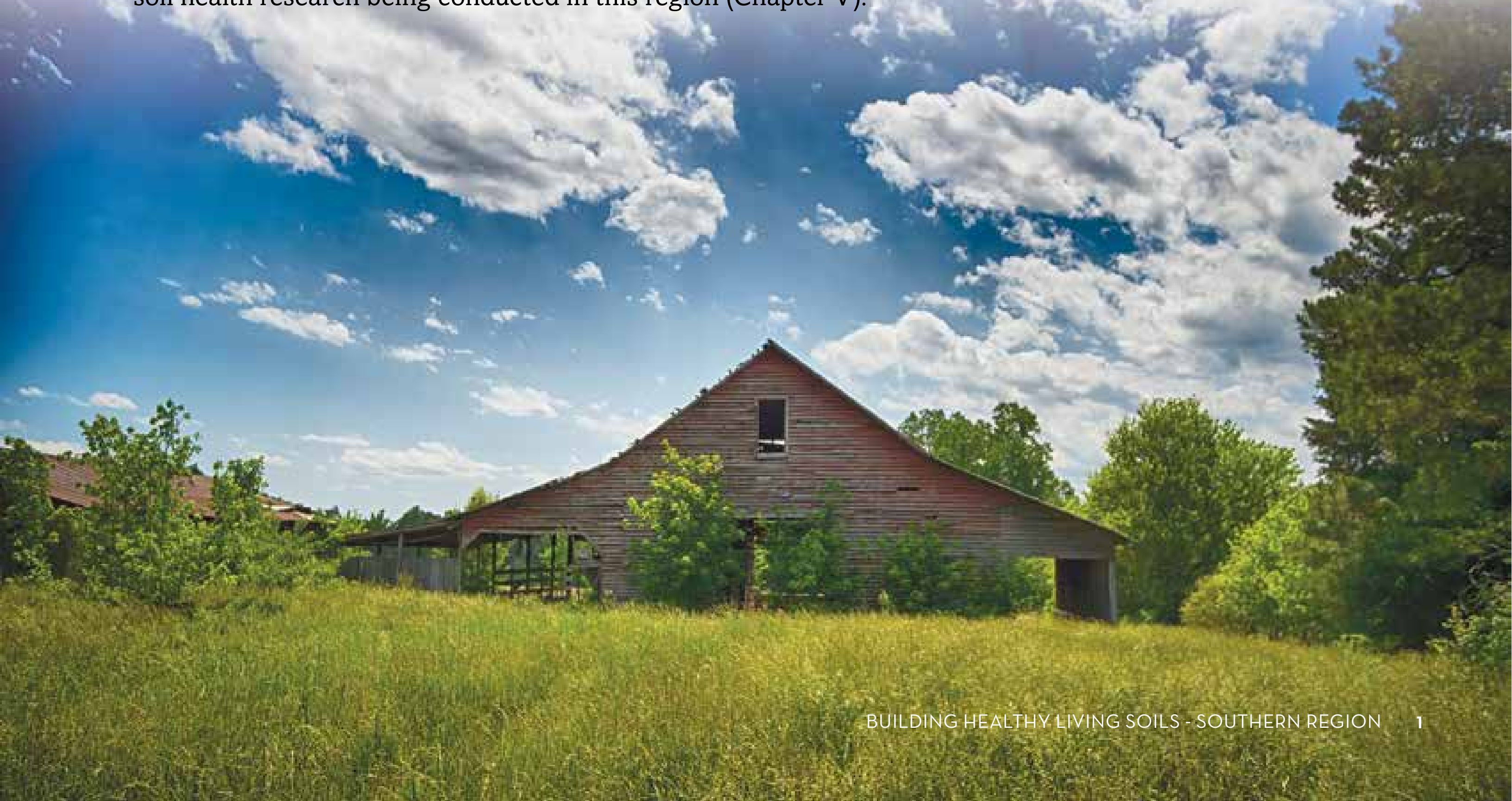
INTRODUCTION

Healthy, living soils provide the foundation for successful and profitable organic farming and ranching. Nowhere is soil health more vital than in the South, where organic producers face intense pressure from weeds, insect pests, parasitic nematodes, and plant-pathogens; extremes of summer heat, drought, and flood; and soil types with inherent fertility limitations. In addition, long growing seasons can make it harder to rebuild soil organic matter, especially during intensive crop production.

In a 2015 nationwide survey of organic producers, 79% of respondents from the South cited soil health as a high research priority, a little higher than the national average of 74% (Jerkins and Ory, 2016). Other priorities identified by farmers in the South included weed management (70%), fertility and nutrient management (67%), insect management (62%), disease management (62%), soil conservation (55%), cover crops (45%), and coping with climate change (42%). Many respondents understood the central role of healthy soil in dealing with pests and weather extremes and expressed a need for practical information on how to build soil health in hot climates that burn up soil organic matter (SOM) and promote aggressive weed growth.

These challenges have hindered the growth of organic agriculture in the Southern region, which accounted for less than 11% of USDA certified organic operations, and about 9% of U.S. organic sales in 2017 (USDA, 2019). The goal of this guidebook is to help the region's current and aspiring organic producers develop effective, site-specific soil health management strategies that support successful, resilient enterprises.

We begin this guidebook by reviewing the unique challenges and opportunities that organic producers face in building healthy soils in the Southern region (Chapter I). In Chapter II, we explore how to apply organic soil health principles to the region's soils through a series of practical steps and strategies, illustrated by innovative farmer stories and brief descriptions of underlying scientific concepts (Figure 1). The latter portions of the guidebook provide a list of resources for additional reading (Chapter III), a description of the inherent properties of soil types commonly found in the South (Chapter IV), and a summary of the latest soil health research being conducted in this region (Chapter V).



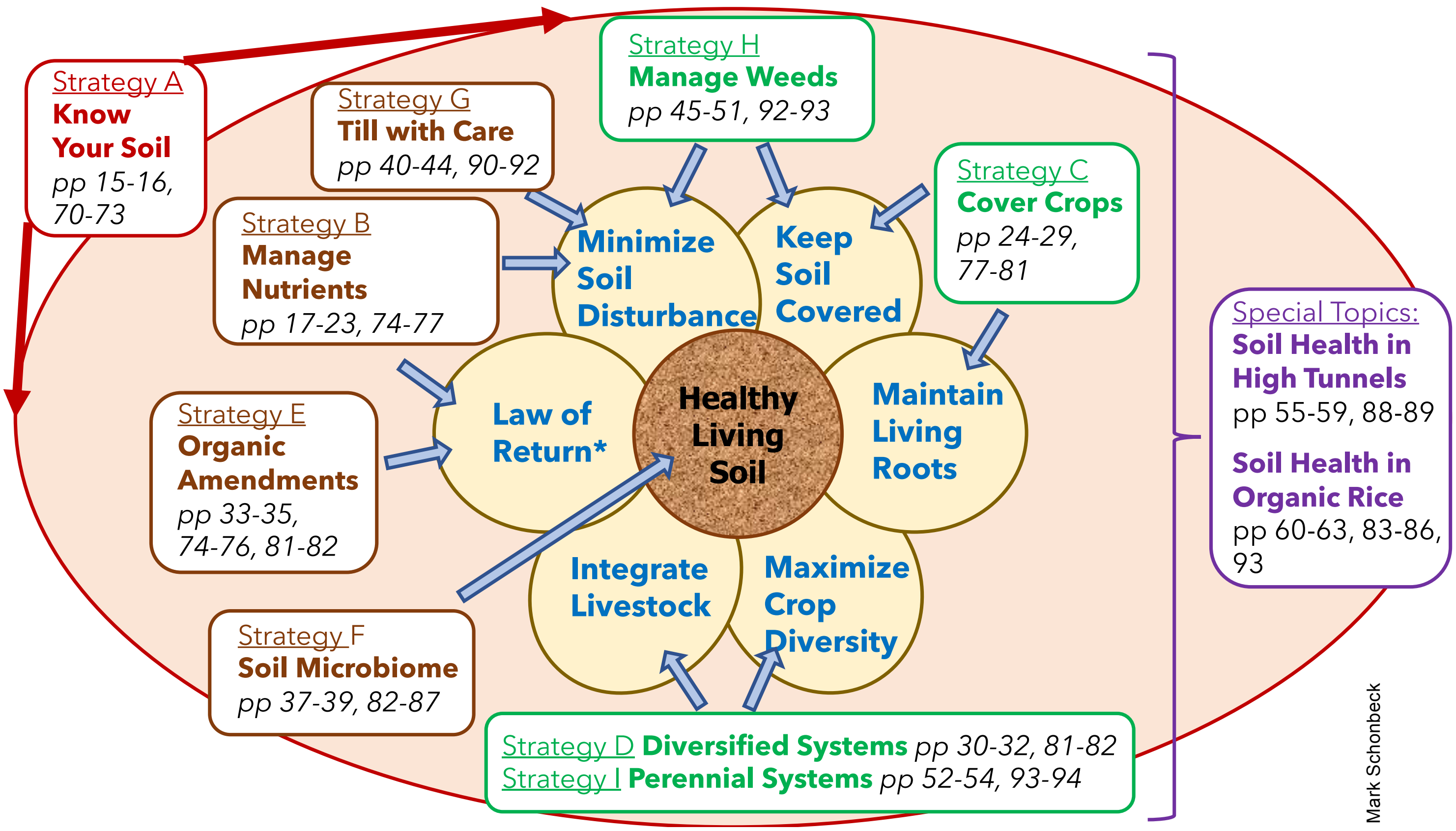


Figure 1. Relationship between six principles of soil health management (blue text) and the nine strategies and two special topics (purple) discussed in Chapter II of this Guidebook. Strategies include soil management (brown) and vegetative practices (green) informed by a knowledge of the site and soils (red). Page numbers (black) for each topic refer to the section of Chapter II that discuses that topic, and to summaries of related research in Chapter V.

** The Law of Return states that, in addition to replenishing soil nutrients as needed, the farmer needs to replenish soil organic matter consumed in the process of production (Howard, 1947).*

CHAPTER I
Soil Health Challenges and Opportunities in the Southern Region

Organic farmers restore and maintain healthy, fertile soils through practices that *build soil organic matter* (SOM) and *enhance soil biological activity and biodiversity* (Schonbeck et al., 2017, 2019). An optimum quantity and quality of organic matter maintains an open, well-aggregated soil structure that facilitates rain infiltration and retains ample plant-available moisture, drains well and allows sufficient oxygen to reach plant roots, resists the erosive effects of wind and rain, requires less tillage to prepare a seed bed, and allows deep and extensive root development. An active and diverse community of soil life partners with crops to enhance moisture and nutrient uptake, prevent or minimize disease, enhance overall vigor and resilience to drought and other stresses, and ideally improve the quality of the harvested product.

Organic farming publications present images of soft, crumbly, dark-brown soil teeming with earthworms and beneficial microbes as the goal and reward for best organic practices. This can leave southern farmers perplexed as their fields remain pale and sandy, or brick-red and clayey after years or decades of diligent organic management. What is happening here?

Soil microbial activity increases with temperature, doubling for every 18°F increase to reach a maximum at about 100°F (Weil and Brady, 2017, p 311). In warm, moist, well-aerated soil, soil organisms rapidly consume organic materials as they multiply, which releases plant nutrients and can provide other benefits, yet can also "burn up" SOM. In the South, long growing seasons, hot rainy summers, and mild winters keep the soil life active year-round. As a result, organic inputs like compost, manure, crop residues, or organic mulch may seem to disappear almost as soon as they are applied. In contrast, colder climates with long, hard winters put the soil life "on pause" for part of the year, allowing compost and organic residues to persist, giving organically managed soils a rich, dark-brown color, and a higher percent SOM on the soil test.

Climate also affects how soils develop over geological time, and thereby shapes inherent (given) soil properties. Most soils in the Southern region have developed though millennia of weathering and leaching under warm, rainy climates, resulting in soils with acidic pH and relatively low nutrient content and cation exchange capacity (CEC, the ability to hold positively charged nutrients). Some soil types have specific limitations, such as high susceptibility to erosion, compaction, or crusting, or a naturally occurring hardpan. Others have a subsoil clay called plinthite that hardens into ironstone if brought to the surface, or a "gumbo" clay topsoil that is especially difficult to work. In the western part of the region, soils developed in hot, dry climates pose different challenges such as alkaline pH, salinity, and extremely low SOM.

Tillage practices that benefit productivity on one soil type may fail or backfire on another. For example, in-row subsoiling fractures subsurface hardpan and allows deeper rooting and moisture access in sandy coastal plain soils but may simply create hard clods in clay soils of the Tennessee Valley, the Black Prairie region of Mississippi and Alabama, the Mississippi Delta, and parts of Oklahoma and Texas. Soil types can vary widely over short distances, so each farmer must get to know the soils on their farm and select tools and practices accordingly.

In addition, many of the region's soils have been depleted through decades of unsustainable farming. Physical disturbances such as tillage and cultivation act as a stimulant to the soil life, increasing its metabolic activity, which can release plant-available nutrients, but also consume organic matter. An exposed, tilled soil surface is especially vulnerable to erosion during heavy rain or high wind and SOM losses during hot weather. As a result, many agricultural soils in the Southern region have undergone severe degradation, as eloquently described by SARE grant recipient Carl Jordan at University of Georgia:

> *"Most agricultural soils in the Southeast are derived from highly weathered parent material of the ancient Appalachians or Coastal Plain sand. When early pioneers first arrived in the Southeast, they found soil relatively rich in organic matter. Clearing of the forests in the 1800s followed by over 100 years of intensive cropping exposed the once-fertile soils of the Tennessee Valley, Southern Piedmont and Inner Coastal Plain to leaching, erosion and loss of soil organic matter. For example, in the Piedmont region, continuous cultivation has destroyed the O and A horizons leaving only the subsoil, high in iron and aluminum, and low in organic matter, N, Ca and Mg, and in available P."* (C. Jordan, SARE project LS06-190).[a]

Despite these challenges, good organic management that maintains an active, diverse, and balanced soil biota can sustain crop production while building soil health for long-term benefits including fertility, water holding capacity, crop disease suppression, and resilience to climate change and other stresses (see **Concept 1**).

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[a] For project summaries and final reports on SARE projects, see link at **Resources 31,** page 69.

CONCEPT #1
Balancing Percent SOM and Microbial Activity in Warm Climates

Soil bacteria, fungi, and other micro-organisms feed on plant root exudates, plant litter, animal dung, and other organic residues; protozoa, nematodes, and micro-arthropods feed on the smaller microbes; and in turn these become food for larger organisms in a complex *soil food web*. The soil food web carries out two functions vital to soil fertility: *mineralization* and *stabilization*. In *mineralization*, organisms consume organic materials for energ y (respiration) converting organic nitrogen (N) and other nutrients into plant available forms. This process provides for plant nutrition in forests, prairies, and other natural ecosystems, and it plays a central role in crop nutrition on organic farms and ranches.

As soil organisms grow, reproduce, and die, they convert some of the root exudates and organic residues they consume into new biomass and ultimately into soil organic matter (SOM). Part of the SOM becomes *stabilized,* persisting for years, decades, or centuries, and contributing to good tilth, water-holding capacity, cation exchange capacity (CEC), carbon sequestration, and habitat for soil life. SOM becomes stabilized in several ways (Weil and Brady, 2017):

- Bits of plant and microbial residue become physically protected within soil aggregates.
- Soil bacteria secrete *polysaccharides* (complex carbohydrates) and mycorrhizal fungi form *glomalin* (sugar-protein) that serve as the “glue” to form soil aggregates.
- The soil life converts plant residues and root exudates into organic compounds that bind tightly to silt and clay particles (mineral-associated organic matter).
- Microbial remains can also become tightly adsorbed to soil minerals.
- Fire converts plant biomass into *char* (black carbon), which resists decay, and builds soil structure and microbial habitat (i.e., becomes “housing” rather than “food”).

The challenge is to balance mineralization and stabilization processes, and thereby optimize both soil health and crop nutrition. High temperatures and soil disturbances (tillage, excess soluble nutrients, etc.) accelerate microbial respiration and mineralization to a greater degree than SOM stabilization, and can degrade some of the existing SOM. As a result, soils of tropical, subtropical, and warm-temperate climates generally have lower total percent SOM and lighter colors than soils of cooler regions such as the Corn Belt or the Northern Great Plains.

Yet, mineralization and stabilization need not become a “zero sum” tradeoff. An active, well-fed, diverse soil microbiome that includes beneficial fungi enhances plant nutrition through robust mineralization, and at the same time converts a substantial fraction of the residues consumed into mineral-associated organic matter (Grandy & Kallenbach, 2015; Kallenbach et al., 2016; Weil and Brady, 2017). This microbial process may be virtually the sole source of stable SOM in well-drained soils in warm climates. Unlike aggregate-protected SOM that accumulates near the surface under continuous no-till, mineral-associated SOM is less readily degraded by high temperatures or tillage; can accrue throughout the soil profile; and helps maintain soil health and fertility in soils of warm regions even when a dark-brown “humus” color does not develop (Weil and Brady, 2017).

The good news for producers is that best soil health practices that maintain year-round living plant cover and utilize organic amendments such as compost generally enhance both mineralization and stabilization, thereby promoting overall soil health and fertility (Hooks et al., OREI project 2010-01954;[b] Hurisso et al., 2016; Lori et al, 2017; Osterholz et al., 2017).

[b] For project summaries and final reports for OREI projects, see link at **Resource 32**, page 69.

Although hot weather can accelerate soil degradation, the Southern region's warm climates and long growing seasons also expand opportunities to build soil health by growing plant biomass. Diversified crop rotations that include vigorous cover crops can be designed to keep the ground in vegetative cover year-round. Maintaining living plant roots throughout the soil profile replenishes SOM and sustains the soil life. Farmers can choose from a long list of cool-season cereal grain, legume, and crucifer (mustard-radish family) cover crops that will grow actively through mild Southern winters; and an equally long list of heat-loving grasses, legumes and forbs (herbaceous, broadleaf plants) for summer cover. Many producers from the Gulf Coast to South Carolina can harvest two cash crops and grow a high-biomass cover crop within one calendar year, and growers further north and inland are finding it easier to fit a production crop and a cover crop into one year as climate change lengthens the growing season.

The remainder of this section explores some specific soil health challenges related to Southern climates and management of weeds, tillage, pests, diseases, crop nutrients, and high tunnels in organic production. Chapter II covers practical strategies to address these challenges.

- **The living plant is the farmer's #1 tool for rebuilding soil.**
- **The longer the growing season, the more plant biomass you can grow.**

In the southeastern U.S. and the Gulf Coast, heavy downpours can lead to soil compaction and surface crusting, erosion from sloping fields, saturated and anaerobic (airless) conditions on level or slow-draining land, and nutrient losses through leaching, runoff, and denitrification. Since a slight slope can improve drainage yet increase erosion risks during intense rainfalls, this can pose a dilemma for new farmers when choosing land to buy or determining locations for new crop fields.

In the semiarid parts of Texas and Oklahoma, dry heat slows soil biological activity and, when combined with inherent soil properties such as salinity, alkalinity, or naturally occurring subsurface hardpans, can severely limit productivity. In addition, low soil moisture and limited vegetative cover during dry seasons leaves these soils especially prone to wind erosion. Climate change intensifies soil health challenges related to heat, drought, and deluge (See **Concept 2**).

CONCEPT # 2
How a Changing Climate Affects Soil Health in the South

Climate change has brought rising mean temperatures to the Southern region, especially summer nighttime temperatures; and more frequent intense rainfalls (over three inches in one day) that erode and compact soils (USCGRP, 2018). For example, Hurricanes Harvey (Texas, 2017) and Florence (North Carolina, 2018) dumped several feet of rain in their paths; and much of Virginia saw record annual rainfalls of 80 inches or more in 2018, leaving cropland soils compacted and waterlogged. Rainfall patterns have also become more erratic, with extreme drought and flooding occurring in successive years or even within the same year. For example, in 2019, parts of the Southeast experienced a "flash drought" and crop losses when several months of excessive rainfall that limited root growth were followed by two months of hot, rainless weather.

Farmers in the Piedmont region of Georgia report that winters have become shorter and warmer, spring comes earlier, and hot, dry fall weather followed by a sudden change to conditions too cold to support active plant growth hinders establishment of winter cover crops (Bryan Hager, 2020, pers. commun.). Producers across the South have also noted premature late-winter warming followed by unexpected late spring frosts, which can hurt cover crops and cause major losses in perennial fruit crops. In order to implement this essential soil health practice effectively, farmers must have access to cover crop varieties for both wet and dry conditions and temperature extremes, and must be prepared to make last minute planting decisions (Emily Oakley, 2020, pers. commun.)

High temperatures and long growing seasons stimulate weed growth and intensify weed competition against crops. Several of the region's most aggressive weeds (e.g., Palmer amaranth and purple nutsedge) reach their maximal growth rates at 95 – 100˚F, temperatures that stress warm-season crops such as cotton, soybean, and corn. Managing the intense weed pressure without synthetic herbicides necessitates more frequent tillage and cultivation, which burns up SOM, increases erosion, and harms beneficial fungi, earthworms, and other soil life. Thus, Southern organic producers commonly face a difficult tradeoff between protecting soil health and controlling weeds sufficiently to bring the current season's crop to harvest.

Organic producers in the South and across the U.S. have attempted to reduce tillage frequency and intensity to protect soil health and avoid stimulating weed seed germination. One strategy, sometimes known as rotational no-till, starts with a mature, high-biomass cover crop that is terminated by roller-crimper or flail mower, followed by no-till planting of the cash crop. After harvest, the field is tilled as needed to plant the next cover crop. While this system shows great promise for building SOM and soil health, it can be extremely challenging to manage, and yield reductions can occur. In the South, weeds pose the greatest barrier to organic no-till systems.

Rotating annual cropland into perennial sod for two or more years can reduce annual weed populations and rebuild soil health and fertility (Moncada & Sheaffer, 2010; Reberg-Horton 2012), and rotational grazing can further enhance the soil benefits. However, creeping perennial weeds such as nutsedge, Johnsongrass, and Bermuda grass can increase during the sod phase and become problematic in subsequent crop production (John Bell, 2020, pers. commun).

Populations of insect pests, parasitic nematodes, and microbial plant pathogens (fungi, water molds, bacteria, viruses) often "explode" in Southern climates and exert intense pressures on organic crops. Claims that organic soil management can largely prevent these problems are often overstated and must be kept in perspective. Best soil health management and non-use of synthetic agrochemicals can promote disease-suppressive microbes and crop disease resistance (Schonbeck et al., 2019), and some cover crops can suppress plant-parasitic nematodes. However, organic soil health practices alone often cannot protect a crop against a virulent foe and should be considered one component of an integrated pest and disease management strategy.

One challenge that all organic farmers face is how to translate conventional soil test recommendations into optimum rates for organic nutrient sources. Matching nitrogen (N) availability with crop needs can be especially tricky. Non-organic farmers who use soluble synthetic N fertilizers such as ammonium nitrate can "spoon feed" precise amounts of N by side-dressing crops at critical developmental phases. In contrast, organic N management depends on soil biological processes to convert organic N in SOM, crop residues, and organic amendments into plant-available form—processes that are not readily predicted by simple formulas. Depending on soil condition and recent management, N mineralization from SOM alone can vary from nil to more than the crop's entire N requirement.

If N is released too early or too late to match crop needs, yields are reduced, and unutilized N may be lost to leaching (adversely affecting groundwater) or denitrification into the powerful greenhouse gas nitrous oxide (N_2O). Cold, wet soil conditions can delay N mineralization and limit organic crop yields. Conversely, warm, moist soil conditions promote rapid N release, but untimely heavy rains may leach the N away before the crop can utilize it, especially when these conditions occur early in crop development.

Small-scale vegetable farmers and gardeners often try to compensate for SOM losses and uncertain N availability by heaping on compost, manure, or other organic amendments. However, this strategy can lead to accumulation of nutrient excesses, especially phosphorus (P), and sometimes calcium (Ca), magnesium (Mg), zinc (Zn), mineralizable nitrogen (N), and to increased soil salinity in lower-rainfall regions. For example, vegetable harvests typically remove only about 8 – 10 lb P (18 – 23 lb phosphate, P_2O_5) per acre, while an application of a one-quarter-inch depth of finished compost or solid manure (~30 cubic yards per acre) might add ten times this much P.

As soil test P rises above optimum, plants invest less and less of their photosynthetic product to support mycorrhizal fungi, and as a result these highly beneficial root-symbiotic fungi go dormant and no longer colonize plant roots (Douds, 2009; Hu et al., ORG project 2012-02978).[c] Most vegetable and field crops, host arbuscular mycorrhizal fungi (AMF) that grow within root tissues and out into the soil, effectively expanding the root system several-fold. AMF perform multiple vital functions, including crop resilience to drought and other stresses, disease suppression, SOM stabilization, and enhanced N fixation in legumes, as well as assisting nutrient uptake (Hamel, 2004; Rillig 2004; Weil and Brady, 2017). In soils of tropical and warm-temperate regions, AMF associations commonly play a critical role in crop vigor and yield (Soti and Racelis, 2017). While crops growing in soil with elevated P levels might not need microbial assistance to obtain P, other key mycorrhizal functions are diminished or lost. High levels of soluble N, whether from synthetic fertilizer or organic sources, can also suppress AMF and other beneficial soil organisms. Thus, too much compost or manure can compromise soil health.

Organic farmers with limited financial resources face the opposite problem: because of the high cost of organic fertilizers, they cannot afford to apply sufficient nutrients and organic matter to sustain fertility. Innovative farmers and rural communities have met this challenge by utilizing locally generated organic “wastes” such as cotton gin trash, rice hulls, litter from poultry houses, food waste, municipal leaves, and chipped brush (see **Resources 10e** and **10f**, page 67).

The high tunnel production system, widely used by organic producers in the South, can further accentuate soil health challenges by maintaining warmer conditions year-round, which allows intensive vegetable production (two to four crops per year) but also accelerates SOM losses. Exclusion of natural rainfall can result in an accumulation of excess salts in the topsoil. Efforts to replenish SOM and meet crop N needs through heavy applications of compost commonly accrue large P excesses in the soil and may aggravate salinity problems. Cover crops can play a crucial role in high tunnel soil health by replenishing SOM and N without adding P or salts. However, many growers hesitate to use cover crops in high tunnels due to logistical challenges and foregone income.

[c] For project summaries and final reports for ORG projects, see link at **Resource 32**, page 69.

CHAPTER II
Organic Soil Health Management Strategies for the Southern Region

During the early 2010s, the USDA Natural Resources Conservation Service (NRCS) established four science-based principles of soil health management (USDA NRCS, undated), to which livestock producers using rotational grazing have added a fifth (Brown, 2018). In addition, founders of the organic agriculture movement emphasized that, in order to keep the land healthy and productive, farmers must replenish the soil with compost and other organic amendments that rebuild SOM and replace nutrients removed in harvest (Howard, 1947). Together, these six principles provide a road map for building healthy soils in the South.

Keep the soil covered year-round with desired vegetation or residues. *This protects the soil surface from the direct impact of heavy rains, high winds, and hot sun, and thus prevents compaction, crusting, and erosion; and protects soil life from weather extremes.*

- **Maintain living roots** throughout the soil profile to feed the soil life. *Many soil organisms depend on root exudates and fine root sloughing for their "daily bread" especially in soils where other organic residues decompose and disappear rapidly. Living roots take up nutrients so they do not leach into groundwater. In the South, long growing seasons and mild winters make it easier to maintain living roots year-round.*
- **Maximize crop diversity** to build soil functional biodiversity. *Crop diversity enhances SOM stabilization and other key biological functions. Growing crops with different root depth and architecture enhances soil structure and water and nutrient use efficiency.*
- **Minimize soil disturbance**, including physical (tillage, traffic), chemical (concentrated fertilizers, pesticides), and biological (overgrazing, invasive exotic species) disturbances. *Hot weather in combination with tillage destroys SOM. Organic systems protect soil life from chemical disturbance, and organic reduced-till systems help stabilize SOM.*
- **Integrate crops and livestock with Advanced Grazing Management (AGM)**. *These practices enhance nutrient cycling and minimize the need to import nutrients in the form of fertilizer or livestock feed. Advanced rotational grazing systems have greatly enhanced SOM and soil health in Georgia and Texas as well as in cooler climates* (Machmuller et al., 2015; Teague, 2016; Wang et al., 2015). *Grazing a cover or sod crop can also reduce or eliminate the need for tillage prior to planting the next production crop.*
- **The Law of Return** states that when harvests remove biomass from the land, organic matter as well as nutrients must be replenished. *In hot climates that "burn up" SOM, the challenge is to replenish organic matter without overloading P or other nutrients. Using cover crops and on-farm generated organic residues can minimize nutrient excesses.*

No single management practice addresses all six of these principles; rather, a multi-component strategy is needed to restore and maintain soil health. Yet, it is often most practical to add new practices one at a time, fine-tuning each to integrate with your existing system before moving on to the next step. Adopting a whole suite of new practices at once can be overwhelming and economically unsustainable. Instead, start with the "low hanging fruit," such as a fallow period that can easily accommodate a cover crop, weeds that might be mowed or flamed in lieu of cultivation, an inexpensive tillage implement with lower impact on soil structure, or a new market opportunity for a crop that would diversify your rotation. Keep what works, modify or drop what does not, and build your system gradually over time.

There is no formula for building healthy soils organically in the South or anywhere else. Experienced organic farmers take a site-specific approach to these six principles, combining ingenuity with years of observation and trial-and-error to develop unique soil health strategies for their operations. See **Farm Story 1** for an example of a crop-livestock integrated system that has evolved an effective strategy.

This season, take ONE SIMPLE STEP:

- **Add a cover crop**
- **Add a cash crop**
- **Omit one tillage pass**
- **Test your soil and adjust inputs as needed**

FARM STORY 1
Applying the Six Principles of Soil Health Management

Windy Acres Farm, Orlinda, TN

Windy Acres Farm, the first certified organic grain farm in Tennessee, has provided customers with organic grains and grass-fed beef since 2010. The farmers apply all six soil health principles to their 422-acre crop-livestock integrated operation. The current managers, Sam and Lyle Harvey, continue to refine the system to enhance biodiversity, minimize soil disturbance, and optimize year-round plant biomass, soil biology, and grazing management.

In 2018, the two couples who had managed Windy Acres for many years, Holden and Rebekah Thompson and Alfred and Carney Farris, transferred the farm's acreage to the Agrarian Trust (https://agrariantrust.org/), a non-profit organization committed to sustainable farming and ensuring land access for the next generation of farmers. Sam and Lyle, who had been raising pastured livestock on Sam's parents' land in Tennessee since 2011, moved their operation to Windy Acres in 2018. When Holden and Rebekah left the farm in 2019 and Alfred passed away early in 2020, Sam and Lyle took over management of the farm, building on the previous farmers' decades of excellent land stewardship, while continuing to serve customers with organic grains and beef, and adding pastured broilers, eggs, and pork.

The farm is divided into 20 fields that cover all phases of a six-year rotation:

- **Year 1:** A winter cover crop of hairy vetch with a little rye or wheat is terminated with a roller-crimper for no-till corn planting. The vetch residue provides N for the corn and suppresses weeds until the corn is tall enough to shade them out. After corn harvest, the field is disked and promptly sown to a cereal grain–vetch–winter pea cover crop mix.
- **Year 2:** The winter cover crop is roller-crimped and soybean is planted no-till. Soybeans are cultivated for weed control. Immediately after soybean harvest, a winter cereal (usually wheat or barley) is planted for grain production.
- **Year 3**: After grain harvest, the field is rotated into a fescue-orchardgrass-clover pasture with small amounts of radish, alfalfa, and chicory for additional diversity and deep root penetration. Sometimes, an annual forage of sorghum-sudangrass or corn is planted after the grain harvest and grazed prior to fall planting of perennial pasture.
- **Years 4 and 5**: Pasture is rotationally grazed by beef cattle. Poultry are rotated through one or two fields to enhance fertility.
- **Year 6**: Grazing continues until fall, when the sod is broken by disking three to four inches deep, and the vetch cover crop is sown to precede the next corn grain crop.

This system **keeps the soil covered** and **maintains living roots** continuously for the three grazing years, and for most of the other three years through tight planting schedules, including grain double cropped after soy. Combined with buffer plantings of redbud and false indigo, this rotation maintains high **plant diversity**. Sam and Lyle have further enhanced biodiversity by adding pastured poultry and pigs to the system, and eliminating certain crops (wheat, white clover) from the pasture mix that tend to outcompete and suppress other desired plant species.

The farmers **minimize soil disturbance** by excluding synthetic chemical inputs, disking in lieu of turn plowing (deep inversion), and terminating annual cover crops with a roller-crimper. They plant Purple Bounty hairy vetch and Abruzzi rye because, unlike many other strains of vetch and rye, they mature (flower) early enough for timely cash crop planting and are easily and reliably killed by roller-crimping. Sam and Lyle are exploring ways to further reduce disturbance, including a no-till drill to establish cover crop after corn, and cereal grain after soy. Understanding that tillage breaks up the mycorrhizal network in the soil, they are exploring rotation strategies that can eliminate disking altogether.

Crop-livestock integration has always been a central feature of Windy Acres Farm. Rotating fields into a botanically diverse pasture for three years builds a robust microbial community, and manure deposition during grazing further enhances soil health and fertility. Sam and Lyle have upgraded **grazing management** by moving cattle to new paddocks more often than in the past and ensuring that pasture has recovered sufficiently (dense enough to be hard to walk through) before grazing again. Livestock are moved every day or two, a frequency that balances forage health and pasture weed control with practical considerations.

Pastured poultry are used to build the fertility of a selected pasture each year, with mobile pens moved daily for broilers and every four days for layers. Pigs currently forage in wooded areas and are moved every four to six weeks, but the farmers are exploring ways to integrate them into the pasture. In addition, Sam noted the cattle need shade, which the low-growing shrub buffers do not offer. In the short term, he will use tobacco wagons with tarp covers to provide mobile shade and improve manure distribution. The long-term solution is to plant oaks and other tall trees strategically located to provide shade (silvopasture).

Windy Acres Farm observes the **Law of Return** primarily by using living plants (especially cover crops and pasture) and livestock to replenish soil organic matter (carbon) and nitrogen, and to cycle potassium and other nutrients within the farm. All feed grains and hay needed by livestock are produced and utilized on farm. They also conduct a complete soil nutrient analysis periodically and apply boron, sulfur, rock phosphate, and/or micronutrients as needed to maintain optimum and balanced levels of nutrients in the soil. This strategy has maintained ample soil potassium (K) without the need for K fertilizers and has avoided the buildup of excess phosphorus (P) or other nutrients that can occur on organic farms that rely heavily on livestock feed or soil amendments imported from off-farm sources.

When unexpected problems arise, Sam and Lyle use innovative remedies that take soil health as well as immediate production needs into consideration. For example, when a lot of volunteer annual ryegrass emerged with the cover crop ahead of corn and regrew after roller-crimping, they had their cattle graze the field once to reduce the competition. As summer heat arrived, the ryegrass went dormant, leaving a weed-suppressive mat while the corn recovered sufficiently to give a satisfactory yield. Because soybeans are planted later than corn, the farmers are now looking into using ryegrass as the cover crop ahead of soybean to enhance weed control.

This story is based on a presentation by former co-manager Holden Thompson at the 2017 Southern Sustainable Agriculture Working Group Conference, and a 2020 phone conversation with current manager Sam Harvey.

Improving soil health can also make crop and livestock production more resilient to increasingly erratic and extreme weather related to climate change. For example, soil building practices that improve soil structure (aggregation) enhance the soil's capacity to absorb heavy rainfall and store it for future crop uptake. Cover crops that penetrate subsurface hardpan allow the following crops to root deeper and access subsoil moisture reserves during dry spells. Biologically active and biodiverse soils increase crop tolerance to pathogens and abiotic stresses. In addition, healthy soils help mitigate climate change by converting atmospheric carbon dioxide into stable soil organic matter through plant photosynthesis and soil microbial activity.

> The **Resources** listed in Chapter III on pages 64-69 provide additional information that can help you design and implement an organic soil health management system for your farm.
>
> **Resources 4, 5, 6, 7, 8, 9, 11**, and **17** provide an overview of science-based practical guidance on best organic practices to build healthy, resilient, and productive soils.
>
> For additional farmer stories illustrating successful, site-specific approaches to soil health, see **Resources 6c, 7b, 10a-c, 16, 18, 19, 23**, and **27**.
>
> For soil enhancement through improved pasture and grazing management, see **Resources 8c, 9i**, **9j** and **11.**
>
> For more on building resilience to climate change and reducing greenhouse gas emissions through best soil health practices, see **Resources 4g, 4i, 4j, 4k,** and **6L**.
>
> For an update on soil health systems research in the South, see pages 74-94.

STRATEGY A
Get to Know your Soil

The six soil health principles outlined at the beginning of Chapter II apply to all soils, climates and farming systems, yet practices must be adapted to your climate and to the specific capabilities and limitations of the soil type(s) on your farm. Thus, a vital step toward effective soil management is to get to know your soil.

Each soil has both *inherent* (given) properties such as texture, mineralogy, and the horizons (layers) that have developed over millennia of soil formation; and *dynamic* properties such as structure (tilth or aggregation), pH (acidity/alkalinity), plant-available nutrients levels, SOM, and microbial activity. These dynamic soil properties are affected by farming practices and land use history, and thus can be readily ameliorated through soil health practices.

Direct observation can tell you something about your soil's texture and other inherent properties, as well as its current state of health. Thoroughly moisten a golf ball sized mass of topsoil and squeeze it between your fingers. Does it feel gritty and simply fall apart in your hand (sand), or barely hold together in a ball (loamy sand), or feel gritty yet stick together enough to form a short ribbon (up to one inch) before breaking off (sandy loam) or a longer ribbon (sandy clay loam)? If it does not feel gritty, does it form a short ribbon (loam), a slightly longer ribbon (clay loam), or a strong, shiny ribbon longer than two inches (clay)? Does the moist soil feel silky and smooth (silt loam, silty clay loam, or silty clay depending on length of ribbon)?

Is the topsoil a dark rich brown (usually indicating sufficient SOM), or a lighter reddish, yellow, or gray color (mineral colors, low SOM)? Is it well aggregated into crumbs 0.1 to 0.5 inches in diameter (good structure and drainage, maintained by active soil life), or loose and powdery, crusted at the surface, or hardened into larger lumps or masses (poor structure, prone to compaction and erosion)? When you drop some topsoil into a glass of water, does it hold together in stable aggregates, or disperse to give you a glass of muddy water (unstable)? Does a heavy rain shower soak right in (good infiltration and water holding capacity), pond at the surface (poor drainage), or run off (poor infiltration, less water stored for crops)? During a dry spell, pour a gallon of water onto the soil surface to see how far it spreads before soaking in.

Do you often see earthworms, fungal mycelia (network of whitish filaments), ground beetles, and other organisms as you work the topsoil (high biological activity)? Do crops, weeds, and native vegetation look healthy and stand up well through a dry spell (healthy soil), or do crops look stunted, yellowish or otherwise unhealthy while certain weeds seem to gain the upper hand (depleted or unbalanced nutrients, moisture, or soil life to which the weeds are adapted)?

When soil conditions are moist but not saturated, dig a hole 18 to 24 inches deep. How far down can you dig easily? At what depth do you see a change in the soil's color or texture? Do you encounter a hardened layer that is more difficult to dig through? Does it get softer again as you go deeper? Does the subsoil have a higher clay content (longer ribbon in the above test)? In Coastal Plain and Piedmont soils, it is normal to encounter "red clay" at a depth of six to 18 inches; red clay at or near the surface indicates a history of severe erosion.

You can learn more about your soil through the NRCS Web Soil Survey (**Resource 1**). This is an excellent online tool that can help you identify the map units on your farm. For each map unit, the survey identifies the soil series and provides in-depth information on both inherent and dynamic properties including:

- Soil depth, drainage, and permeability.
- Topography, slope, and any history of erosion.
- Whether the native (unamended) soil tends to be acidic, neutral, or alkaline.
- Description of soil profile including any root-restrictive layers.
- Farmland classification and crop productivity index.
- Land use capability and limitations such as erodibility or wetness.
- Soil health, including vulnerability to SOM depletion, crusting, compaction, etc.

This information can help you understand your soil type(s) and identify the best uses and management strategies for each field or landscape feature on your farm. Some of these properties may apply broadly to the majority of soil types in your region. Others may be more specific to your site. Direct observation, combined with soil survey information, will enable you to:

- Understand your soil's inherent properties, constraints, strengths, and vulnerabilities.
- Identify management-related soil health problems that can be addressed through improved practices.
- Identify crops, cultivars, production systems, and tools best suited to your soil.
- Set realistic goals for SOM and other soil health properties. Note that a total SOM of 2% may indicate excellent soil health on a sandy coastal plain soil, while a heavier (loamy or clayey) soil in a cooler upland climate can reach 4-5% under good management.

> For more information on getting to know the inherent properties of your soil, see **Resources 1, 2,** and **3**, and Chapter IV, A Deeper Dive into Soil Types beginning on page 70.

STRATEGY B
Manage Nutrients for Soil Health, Crop Production, and Net Returns

One critical question arises at the beginning of each growing season: *how much nitrogen, phosphorus, potassium, lime, and other nutrients do I need to apply to sustain satisfactory and profitable yields?* Soil tests offered through Extension or private soil testing labs purport to answer this question, based on measurements of the soil's pH and amounts of P, K, Ca, Mg, and other nutrients found in a standard laboratory extraction procedure. However, recommendations are designed for conventionally fertilized soils and overlook the capacity of a healthy soil microbiome to provide crop nutrients. As a result, fertilizer recommendations commonly exceed actual crop needs and may not give you the best guidance for organic production. For example, since organic and natural mineral nutrient sources generally cost more per pound of NPK than synthetic fertilizers, using more than needed can significantly cut into your profits.

The standard soil test report does not include N unless a special test for nitrate-N is requested. Nitrogen recommendations are usually based on the total expected N utilization by the crop grown, rather than soil type or soil test results. Some soil testing services estimate N release from SOM at 20 lb/ac for each 1% SOM or use other formulas, but actual N mineralization varies widely with quality of SOM and soil biology. Others credit "available" N from organic N sources at 50% of total N content for animal manure or legume residues, and 10-25% for compost. Using enough manure or compost to provide the recommended amount of "available N" adds to input costs and can overload the soil with P and other nutrients. However, a vigorous legume cover crop can provide 40 -100 lb N per acre to the following crop and contributes an additional 40-100 lb to N reserves in SOM without adding P. Cover crops are discussed in greater depth in Strategy C on pages 24-29.

To provide N without adding excess P:
Grow legume cover crops, alone or with grasses or crucifers.
Inoculate legume seed with the right rhizobium strain.

Despite its limitations, the standard soil test can help you identify fertility constraints and nutrient imbalances. For example, while N, P, and K are considered the major essential nutrients, crops can also suffer from a micronutrient deficiency. Boron (B) is often scarce in soils of the Southern region, and deficiencies in zinc (Zn), copper (Cu), or manganese (Mn) occasionally occur. All are easily remedied with small amounts of micronutrient mineral amendments allowed by the USDA National Organic Program (NOP) Standards. Often, adjusting soil pH and building SOM and soil biology can remedy micronutrient deficiencies without using a mineral amendment.

Test your soil every year or two at the same time of year to monitor trends in soil nutrient levels, pH, and SOM over time. When soil pH moves outside the optimum range (6.0 – 7.5 for most crops; ~5.0 for acid-loving crops like blueberry), applications of lime (to raise pH) or elemental sulfur (to lower pH) are warranted. To minimize shocks to soil life, use these amendments in moderate annual increments (0.5 – 1.5

tons/ac limestone or 200 – 300 lb/ac sulfur) until the desired pH is achieved. In the Southern region, lime acidic soils to pH 6.0 – 6.5 (not higher) to avoid tying up micronutrients.

A downward trend in SOM or shifts in soil test nutrient levels toward low, very high, or excessive ranges in the soil test report can signal a need to adjust input rates and management practices. Once soil test nutrient levels reach optimum or high ranges, budget nutrient inputs to replenish nutrients removed in harvest, but not more (see **Concept 3**). A medium nutrient level on the soil test is considered a little below optimum and may or may not be yield-limiting.

CONCEPT #3
Nutrient Budgeting in Organic Systems

How much N, P, K, and other nutrients should an organic fertility system add? The Law of Return suggests that nutrients harvested off the field, plus organic matter consumed through crop production, must be replenished regularly (Howard, 1947). Although vegetable crops are considered heavy feeders, the amounts actually removed in harvest are relatively low, especially for P (Table 1). Thus, using compost or poultry litter fertilizers as the primary source of organic matter, N, and K will eventually overload the soil with P. Once soil test P is optimum or high, you can switch from poultry litter to a blended organic fertilizer that better matches expected crop removals. If you are using compost, reduce rates to match P removal and use legume cover crops to provide additional N. For soils with excess P, provide N via legumes, draw down P levels through harvests, and use potassium sulfate to supplement K and feather meal or blood meal to supplement N if needed.

Table 1. What do crop harvests remove and what do organic soil amendments give back?

	Nutrients removed, lb/ac		
Crop type and yields	N	P	K
Vegetables, average yields	35 – 70	6 – 12	40 – 90
Grains, average yields	120 – 150	20 – 30	30 – 35
Grass hay, 5 tons/ac	185	25	195
Corn silage, 5 tons dry/ac	170	30	185
Organic amendment	Nutrients delivered, lb/ac		
Compost (typical analysis ~ 1-1-1*), 5 tons/ac	100	44	83
Pelleted poultry litter (5-4-3), 1 ton/ac	100	35	50
NOP allowed blend (10-2-8), 1,000 lb//ac	100	9	66
Feather meal (13-0-0), 500 lb/ac	65	0	0
Potassium sulfate, (0-0-51), 150 lb/ac**	0	0	63

* Amendment analyses are given as lb N, P_2O_5, and K_2O per acre. 1 lb P_2O_5 = 0.44 lb P; 1 lb K_2O = 0.83 lb K.

** Caution: rates higher than this can stress soil life.

Sources for table: Dunne, 1990; Virginia Tech Extension; Virginia Tech, 2018; Wander, 2015

Often, soil K reserves can help meet crop needs. However, the high K rates recommended by soil test labs are usually unnecessary, can hurt soil health (K fertilizers, including NOP-allowed potassium sulfate, are salty), and cut into a farm's net profit (Khan et al., 2013). In the South, many soils with clay-enriched subsoils hold effective K reserves, provided that crop root access to the subsoil is not hindered by acidity or a hardpan. Cereal grain and other grass cover crops enhance K cycling, and hardpan can be relieved by tillage radish, sorghum-sudangrass, pearl millet, or subsoiling followed by deep-rooted crops. See Strategy C on pages 24-29 for more on cover crops.

Agronomic crop harvests remove more N and P than most vegetables. Hay and silage crops remove large amounts of K, while grain harvest takes relatively little K, as most of this nutrient is returned to the soil in aboveground crop residues. Soils with a long history of hay harvests without nutrient amendments often show good SOM levels but very low soil test P and K, which can be replenished with manure, poultry litter, compost, or other sources to restore productivity. Crop-livestock integrated farming systems in which manure is returned to the fields greatly reduce the need for nutrient inputs from off-farm sources.

Be sure to consider other nutrients in addition to N, P, and K. Organic amendments can contribute significant amounts of calcium (Ca), magnesium (Mg), or micronutrients. For example, compost based on hardwood leaves (leaf mold), bark, or chipped brush is rich in Ca, zinc (Zn), and some other micronutrients, and can raise soil pH. Test compost and amendments from different sources to identify the one(s) that best match your soil's nutrient needs.

When the soil test recommends X lb of a certain nutrient, consider whether you really need this input or if a lesser amount would suffice. Two simple tools can help answer this question: a side-by-side *field trial* and *crop foliar analysis*. To do a field trial, find a relatively uniform part of your field and plant the same variety of a test crop in three or more adjacent beds. Apply different rates of the recommended nutrient or fertilizer to different beds, including a zero rate, the recommended rate, and one or more intermediate rates. Record and compare crop vigor, yields, and quality through the season.

Is the soil test right? Ask the plant!

- **Do a simple field trial on a recommended input:**
  Compare 0%, 50%, and 100% recommended rate.
  Did the crop respond?
- **Evaluate the condition of your crops Do they seem healthy or hungry?**
  Check yield trends over several seasons.
  Do a foliar nutrient analysis.

Crop foliar nutrient analysis reflects the crop's nutritional status. Results of foliar nutrient tests may not match the soil test, especially if soil-root microbiomes in healthy soils allow crops to access nutrients that the soil test cannot see or, conversely, if biologically depleted or compacted soil conditions interfere with crop nutrient uptake. Test both healthy and hungry crops to identify what the latter are lacking. Also watch for unusually high levels of one or more nutrients, which can indicate imbalances that compromise crop health.

Good organic soil management can greatly reduce fertilizer needs even on soils thought to have low inherent fertility. For example, in an organic corn-soy-wheat rotation with winter cover crops grown in Orangeburg loamy sand in the coastal plain of South Carolina, the grains maintained full yields with half the recommended N and *no* P or K (Kloot, 2017, 2018). The high-biomass legume + grass cover crops fixed N and retrieved K from the subsoil. Over a five-year period, this organic rotation boosted SOM from 1.2% to 1.7% (an excellent result for this soil type) and did not draw down soil test P or K, even when these nutrients were not applied. Similarly, in Clemson, South Carolina (Piedmont), SOM mineralization and a clover-rye cover crop fully met the N requirements of tomatoes and squash in a sandy loam under long term organic management (D. Robb, SARE GS13-126).

Soil test recommendations and organic farming: "Living soil changes everything." (Kloot, 2017)

Healthy soils may need much less fertilizer.
Depleted or newly organic fields may need more.

In a California study, fields under long-term organic management with finished compost, cover crops, and sparing use of concentrated N sources gave high tomato yields while maintaining soil nitrate-N levels near 5 ppm, a level normally associated with crop N deficiency (Bowles et al., 2015). These soils demonstrated "tightly coupled nitrogen cycling," in which the soil microbial community released sufficient N to crop roots without flooding the bulk soil with soluble N. In other organic fields, liberal use of concentrated N sources such as poultry litter or bat guano sustained high yields but compromised N use efficiency and sometimes reduced SOM and microbial activity as well (Bhowmik et al, 2017; Bowles et al., 2015).

Organic crops can suffer N deficiency when:

- The field is in the early years of transition from conventional practices.
- The soil is depleted, with low SOM, microbial activity, and biodiversity.
- Soil compaction restricts root growth.
- The soil is clayey, slow-draining, or poorly aerated.
- The crop rotation lacks N-fixing legumes.
- Straw or other organic materials with a high ratio of carbon to nitrogen (C:N ratio) have recently been tilled in (these materials do not tie up N when used as surface mulch).
- A heavy N feeder is planted after a cereal grain or other grass cover crop.
- A cool-season heavy feeder like spinach or head brassicas is planted in early spring when lower soil temperatures delay N mineralization.

In these situations, higher applications of organic N fertilizers (up to the N amount recommended in the soil test) may be warranted. However, using high rates of organic fertilizers such as poultry litter year after year as insurance against nutrient deficiency can make the soil life lazy and less efficient in nutrient cycling. This can perpetuate your dependence on costly organic fertilizers to sustain yields.

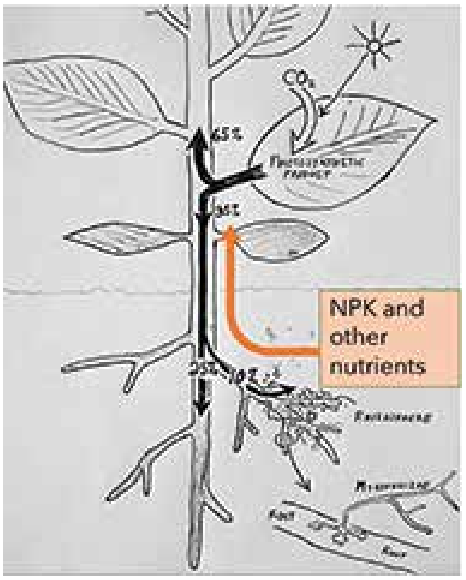
You may need only 20-30 lb/ac starter N, and possibly none at all if:

- The soil is in optimum health through years of sound organic management, with sufficient SOM, excellent structure, drainage, and porosity, and a deep, open profile.
- Compost and other organic amendment applications have developed high SOM and optimum or very high nutrient levels.
- The rotation includes a balance of heavy feeders, light feeders, and legumes.
- The cash crop follows a cover crop that is about 50% legume or more.
- The cash crop is planted in warm, moist, biologically active soil. Warm season crops and fall vegetables often need little N when grown in healthy soil.

Relying mainly on poultry litter for fertility and SOM can hurt soil health.

- 500 lb/ac poultry fertilizer (5-4-3) replaces P in vegetable harvest.
- Higher rates overload soil P and inhibit mycorrhizal fungi.
- Poultry litter alone burns up SOM and reduces nutrient efficiency.
- Poultry litter + carbon (straw, wood chips, etc.) can build SOM.

Ultimately, soil fertility does not come from a bag labeled NOP approved; it develops through a mutual exchange between plants and microbes, a partnership that dates back to the Earth's earliest land plants, some 450 million years ago (Figure 2). Yet, compost and other organic amendments do more for your farm than simply adding nutrients. They work with a living plant cover to build healthy soil, as discussed in Strategy E on pages 33-36.



Mark Schonbeck

Figure 2. True soil fertility arises from a partnership between plants and soil life. Plants contribute 10 – 30% of their photosynthetic product to the soil microbiome. In return, beneficial soil microbes help plants obtain nutrients and moisture, protect plant roots against pathogens, build stable SOM, and improve soil conditions for plant growth.

In summary:

- Use crop rotation and cover crops as your primary means to "grow" SOM and soil life.
- Get a complete nutrient analysis on compost, manure, and other organic amendments to facilitate nutrient budgeting.
- Use crop N requirement on the soil test as a guideline but remember that you don't need to provide *all* that N via fertilizer or manure.
- Use legumes to meet approximately half of total N need for the crop rotation.
- To supplement N, deliver small doses of concentrated organic N near the crop row.
- Amend soil to attain but not exceed optimal P levels.
- Grow deep-rooted cover crops to break hardpan and access subsoil nutrient reserves.
- Maximize within-farm nutrient cycling through crop-livestock integration.
- Use soil tests and foliar analyses to track trends and adjust inputs.
- Use pH adjustment materials (lime, sulfur) and salty mineral fertilizers (potassium sulfate, sul-po-mag) in moderate increments to avoid stressing soil life.
- When nutrients reach optimum levels, budget inputs to balance outputs in harvest.

> For more on organic nutrient management and soil health, see **Resources 4c, 4h, 4i, 5b, 6a, 9e, 11,** and **12.** Recent research developments in organic nutrient management are discussed on pages 74-77.

STRATEGY C
Build Soil Health with Cover Crops

Cover crops play a central role in cropland soil health and fertility, especially in warm climates where the soil life remains active year-round. During unplanted fallow periods, soil microbes and their larger predators quickly "go hungry" in the absence of living roots and root exudates, and organisms near an unprotected soil surface may die off from excessive heating or drying. When this happens, their vital functions of maintaining soil structure, cycling nutrients, and protecting and supporting the next crop are curtailed. Bare soil also invites weeds and risks erosion in every downpour or windstorm.

Planting a cover crop promptly after harvest feeds the soil life and provides a "green bridge" to sustain arbuscular mycorrhizal fungi (AMF) and other root-symbiotic microbes from one production crop to the next. You can provide even greater continuity by interplanting covers into a cash crop at mid-growth, or by overseeding the cover before harvest to maintain continuous living roots. Adding cover crops to your crop rotation builds biodiversity in the soil as well as above ground and strengthens nutrient cycling and other soil functions. A vigorous cover crop with full canopy closure and a robust root system will also:

- Prevent erosion (See Figure 3).
- Build and maintain SOM and soil structure.
- Fix nitrogen for subsequent crops (legumes).
- Keep the soil surface cooler and protect soil life from heat and drying.
- Improve soil porosity, rain infiltration, and plant-available water holding capacity.
- Retrieve subsoil nutrients, break through hardpan, and open the soil profile for subsequent crops (deep rooted species).
- Release organic acids that bind excess aluminum (Al), manganese (Mn) and iron (Fe), reducing the toxicity of these elements in acidic subsoils (acid-tolerant species).

Figure 3. In Floyd, VA, timely planting of a late summer cover crop of sorghum-sudangrass (left) after a July potato harvest prevented catastrophic soil loss when a freak rainstorm on September 29, 2015 sent three feet of flood waters into the field (center). The raging river toppled the fence and flattened the cover crop but took no soil at all (right).

FILL IN THE GAPS

Summer fallow:
sorghum-sudangrass, millets, southern pea, sunflower

Short gap (4 – 6 weeks, frost-free):
buckwheat, Japanese millet, foxtail millet, southern pea

Fall (winterkill ~ 15°F):
oats, spring barley, radish, mustard, bell bean

Winter fallow:
cereal grains, vetches, clovers, winter peas, canola

Orchard floor, alleys in vineyard or berries:
perennial grass-legume mix or succession of annuals

Cover crops help farmers meet the challenge of the Law of Return by growing organic carbon (C) and nitrogen (N) in place and retrieving potassium (K) and micronutrients from the subsoil, without adding excess phosphorus (P) from off-farm sources. In addition, cover crops can do double duty as a forage crop in livestock-crop integrated systems and manure deposits may enhance soil biodiversity. Cover crops also play a vital role in soil health in perennial horticultural crops. Keeping an orchard floor and vineyard alley in cover crops or perennial sod can double SOM compared to clean cultivation (Lorenz and Lal, 2016).

Build cropland soil health by filling gaps in your crop rotation with cover crops whenever practical. Start simply by planting rye or crimson clover in winter, buckwheat or forage soybean during the frost-free season, millet or southern pea (i.e., cowpea) in summer, or oats in fall.

While the region's long, warm growing seasons intensify the need for cover cropping, they also expand and diversify cover cropping opportunities. In much of the South, winters are mild enough to sustain active growth and high biomass in cereal grains and frost-hardy annual legumes. In the Gulf Coast region and the Caribbean, long, hot summers support high biomass production and N fixation in southern pea, sunn hemp, forage soybean, and several tropical legumes (See **Concept 4**).

CONCEPT #4
Cover Crops for Tropical and Sub-tropical Regions

Cool season cover crops such as cereal grains, vetch, winter pea, and crimson clover may not perform well in the hottest parts of the Southern region, from the Rio Grande Valley of southern Texas across the Gulf Coast region to Florida, Puerto Rico, and the Virgin Islands. However, the following tropical legumes can make especially effective cover crops for this region.

Southern pea (*Vigna unguiculata*) and **mung bean** (*V. radiata*) are heat- and drought-tolerant summer annual legumes whose seeds are widely available. Cultivars vary from short and upright to vining; the latter give the best weed suppression and ground cover.

Sunn hemp (*Crotolaria juncea*) is a tall, vigorous, deep-rooted, high-biomass (to five tons/ac), strong N fixer that thrives in heat and tolerates both humidity and drought as well as acidic, low-fertility soils. In south Texas, it has enhanced availability of P and micronutrients as well as AMF populations to a greater degree than other summer cover crops. Sunn hemp has shown superior biomass, drought and heat tolerance, N fixation, and other benefits in multiple studies.

Pigeon pea (*Cajanus cajan*) is a short-lived (two to five year) perennial whose deep, massive taproots access subsoil water and nutrients. It is extremely drought and heat tolerant, remains green through the south Texas summer, fixes up to 250 lb N per acre, "unlocks" insoluble mineral P, and improves subsequent corn yields. Pigeon pea provides bee forage, edible beans, cattle forage, and a windbreak for other crops. Pigeon pea starts slowly and requires cultivation or a low-growing companion crop to suppress weeds during establishment. As a tropical perennial, it dies in freezing weather, but requires tillage for termination in frost-free regions.

Partridge pea (*Chamaecrista fasciculata = Cassia fasciculata*) native to much of the eastern U.S., and **roundleaf cassia** *(C. rotundifolia)* native to Texas and Mexico, thrive in well-drained sandy soils where moisture is adequate. They are so tolerant to low fertility and excess soluble aluminum (Al) that they can be used to reclaim surface-mined areas and other severely degraded soils. Low growing, they combine well with taller species like pigeon pea or sunn hemp. Cassia spp. become toxic as they mature and should not be grazed after flowering.

Lablab or **hyacinth bean** (*Lablab purpurens*) is a strong nitrogen fixer that thrives in acidic to neutral soil (pH 4.5 – 7) and its root system is especially effective in relieving compaction, improving soil porosity, and reducing runoff. A slow starter, it needs adequate moisture and weed control early in the season, but later becomes drought-tolerant and forms a dense, weed-smothering canopy. Lablab needs a long, warm growing season yet may die back in the hottest part of a Rio Grande Valley summer, and has not done well as far north as North Carolina.

Perennial peanut (*Arachis glabrata*) is a low-growing rhizomatous legume that is normally propagated by rhizomes or plugs. It is well suited as an orchard floor cover where rainfall is sufficient (>30 inches per year), fixes up to 150 lb N/ac, and provides nutritious livestock forage. It has a wide soil pH tolerance range (4.5 – 8.0) but does not tolerate waterlogged soil.

*This Concept is based on a presentation at the 2020 Southern SAWG conference and an ATTRA bulletin by Justin Duncan, Sustainable Agriculture Specialist, National Center for Appropriate Technology (**Resource 14a**).*

As you develop your cover cropping practice, build diversity into your rotation with cereal grains and other grasses, legumes, and members of other plant families such as radish, canola, buckwheat, sunflower, sesame, and phacelia. Multispecies cover crop mixtures ("cocktails") support a diverse soil food web, but can present logistical challenges in planting and termination. Start with one- or two-species cover crops (grass + legume combinations work especially well) and build diversity by using different cover crops at different phases of the rotation. Include deep- and shallow-rooted crops with both fibrous and taproot architectures to relieve compaction, build organic matter, and support soil life throughout the soil profile. Examples include buckwheat (shallow, fibrous), cereal grains (moderately deep, fibrous), pearl millet and sorghum-sudangrass (deep, fibrous), clovers, vetches, and peas (shallow to moderately deep taproot), and radish, sunflower, sunn hemp, pigeon pea, and sweetclover (deep taproot).

Some additional tips for effective cover cropping include:

- Use local information resources, including other organic and conservation-minded farmers, to identify the best cover crop species and cultivars for your site and soil type.
- Select cover crop species for the season and the length of the cover crop growing period.
- Base your cover crop selection on your priority goals to:
  - Build SOM and feed soil life, plant crops that grow vigorously in your locale. Mix a cereal grain or other grass with a legume for best results.
  - Stop erosion or fight weeds, plant crops that rapidly cover the ground.
  - Fix N, plant legumes. Mix with grass or crucifer to stimulate N fixation.
  - Sustain mycorrhizal fungi, plant legumes, cereal grains, millets, sorghum-sudangrass, or cereal grains.
  - Scavenge surplus N, plant sorghum-sudangrass, pearl millet, radish, or rye.
  - Break hardpan, open soil profile, or retrieve subsoil nutrients, plant deep-rooted crops.
  - Attract natural enemies of crop pests with buckwheat, phacelia, sunflower, sunn hemp, and clovers grown through their flowering period.

- Consider cultivar or strain as well as species when selecting cover crops (see **Concept 5**).
- Prepare for unpredictable weather extremes by purchasing seeds that tolerate heat and drought (e.g., pearl millet, sunn hemp) and wet conditions (e.g., Japanese millet).
- If rainfall at time of cover crop planting is highly variable year to year, plant wet- and dry-tolerant species together. This can facilitate successful cover cropping in late summer or fall when the rain is often unreliable.
- Mow spring and summer cover crops at the first signs of flowering and tillering to obtain an additional flush of vegetative growth and root development. This allows you to get more return on seed and planting costs.
- If intense heat, pests, and rampant weeds complicate midsummer production, rotate fields to aggressive, heat-loving cover crops to smother weeds, protect and build soil, and give you a break from working in the heat.
  - To facilitate field preparation for early spring production crops, plant a late summer or fall cover crop that will develop a lot of biomass, then reliably winterkill in the coldest part of your winter. The cover will protect your soils in the winter and will be easy to incorporate or clear from seed rows at planting time.

- When the timing is compatible with cash crops, allowing cover crops to self-seed can plant the next cover without tillage or seed costs.
  - Example: self-seeded crimson clover emerging in a transplanted fall brassica.
  - Example: buckwheat alone or with longer-lived summer cover crops can self-seed for a second generation.
  - Caution: never let vetches or Japanese millet self-seed – they become weeds!

- Be sure to use the correct strain of rhizobium inoculant for the legume you are planting. A poorly matched inoculant fixes little N and may become mildly parasitic on the crop.
- When rotating a crop field into perennial sod for soil restoration, grazing, or weed management, sow oats or other annuals with perennial grasses, clovers, and forbs to hold the soil and reduce weeds while the slower-starting perennials get established. Sow the annual "nurse crop" at a reduced seeding rate that will not choke-out the perennials.
- When planting annual or perennial covers for orchard, vineyard, blueberry, and other perennial cash crops, select and manage cover crops so they:
  - Will not compete with young fruit crops for the first few years after planting.
  - Form sod that protects and builds soil and is easily managed by mowing.
  - Provide some competition to limit excessive vine growth in established vineyard (see **Resource 9h**).
  - Attract beneficial insects, do not host pests, and will not flower at times when they might divert pollinators from the cash crop.

CONCEPT #5
Cover Crop Genetics: Cultivar can Make a Difference

While cover crop seeds are often sold as "variety not stated" (VNS), different strains of a given cover crop species can vary considerably in their adaptation to your locale, including heat and cold tolerance, maturity (flowering) date, N fixing capacity (legumes), disease resistance, tendency to self-seed, and ease of termination, as well as overall vigor, biomass, and weed competitiveness. Therefore, it can pay to seek out a particular cover crop cultivar, obtain cover crop seeds from local or regional sources, or conduct an on-farm trial of different sources of a cover crop. The Southern Cover Crop Council website (**Resource 13**) provides cover crop cultivars recommendations for different regions and cropping systems.

Some examples of cover crop cultivar variations include:

- Many strains of hairy vetch mature late in spring and are difficult to kill without tillage. The Purple Bounty cultivar matures earlier and is easier to terminate by roller-crimper.
- Winter rye VNS often matures too late for timely roller-crimping ahead of corn and soybean. Aroostook rye matures a few weeks earlier but may be less weed-competitive. Wren's Abruzzi also matures early. Although it is less cold hardy (~ 0°F versus -40°F for Aroostook and most VNS), and its active winter growth improves erosion control and weed suppression in warmer climates.
- Southern pea (*Vigna unguiculata*) cultivars range from culinary types (blackeye pea, crowder pea, etc.) to aggressive, long-vine strains that can be difficult to manage. The Iron-Clay cultivar mix is often preferred for cover cropping, as it combines substantial biomass, N fixation, and weed suppression with easy manageability. A culinary cultivar like Purple Hull Crowder can do double duty as food and cover crop when pods missed in harvest are allowed to self-seed.
- Most bell beans (*Vicia faba*) winterkill at about 20°F but a few newer cultivars can survive 0°F or colder (Landry et al., 2018).
- Some cover crops, especially winter annual legumes, are subject to certain plant diseases, yet show considerable varietal differences in disease resistance.

Scientists at USDA Agriculture Research Service (ARS) in Beltsville, Maryland are coordinating a nationwide, farmer-participatory plant breeding program to develop regionally adapted strains of hairy vetch, Austrian winter pea, and crimson clover for organic producers (S. Mirsky, OREI project 2018-02820). Trial sites in Georgia, North Carolina, Texas, and Oklahoma are developing cultivars that meet the needs of southern region growers, including early- and late-flowering crimson clover lines with either high or low self-seeding capacity, for use in a diversity of crop rotation niches and management systems. Other breeding goals include overall vigor, N fixation, disease resistance, winter survival, and ease of roller-crimper termination. The project has made significant progress on white mold resistant winter pea and crimson clover for different niches. The ARS lab in Tifton, Georgia is also doing plant breeding and cultivar evaluation on winter rye and lupin cover crops

> For more information on cover crop see **Resources 4b, 5c, 6b-h, 6j, 7c, 7d, 8a, 9a-i, 12-19, 25, 26, and 30c.** For recent research on cover crops in the Southern region, see pages 77-81, 93-94.

STRATEGY D
Build Soil Health with Crop Diversity and Crop-livestock Integration

Selecting and using cover crops is one part of the larger task of designing a farm ecosystem that meets your production and marketing goals while building a healthy living soil. Diversifying cash crops and integrating livestock into the system can further enhance soil biodiversity, SOM quality and quantity, nutrient cycling, and climate resilience. For example, adding a specialty grain to a vegetable rotation can improve soil through fibrous roots and abundant residues, while a corn-soy-wheat rotation might benefit from increased soil functional biodiversity by adding one or more crops in other plant families.

Adding a perennial sod phase to the rotation is an especially effective way to restore SOM, structure, and fertility, reduce annual weed pressure, and interrupt pest and pathogen life cycles. While the sod phase may entail foregone income on a crops-only farm, it provides valuable grazing or forage harvests for a crop-livestock integrated system.

Management intensive rotational grazing is especially effective in building soil health. Brief, intense grazing followed by sufficient recovery periods results in repeated cycles of root sloughing (response to grazing shock) and deep, vigorous root growth (during recovery) that keeps soil life fed and builds a ton or more of stable SOM per acre per year. At Elmwood Stock Farm, a rotation of three years annual crops with tillage and five years pasture maintains SOM, biological activity, and fertility (see **Farm Story 2**).

FARM STORY 2
Diversified Crop Rotation with Livestock-crop Integration

Elmwood Stock Farm, Georgetown, KY

Elmwood Stock Farm, managed by John Bell, Ann Bell, and Mac Stone produces organic beef, pork, lamb, chicken, turkey, eggs, and a wide range of vegetables for an 800-family CSA and other markets. Of their 550 acres, they grow crops on about 200 acres of the most level land and keep the rest in permanent pasture and woodland. Their highly integrated crop-livestock system maximizes within-farm nutrient cycling and maintains soil health through an eight-year crop and pasture rotation. For vegetable production the rotation is:

- Year 1: Plow sod and plant long-season heavy feeders like tomato, potato, other Solanaceae, and cucurbits, followed by a fall cover crop.
- Year 2: Disk cover crop when it is six to eight inches tall, plant cool season greens and root crops, double crop or fall cover crop.
- Year 3: Light feeders including peas, beans, and sweet potatoes. In fall, sow alfalfa with festulolium (a fescue-ryegrass hybrid) and a little fescue, orchardgrass, bluegrass, and/or plantain, with a nurse crop of rye or wheat. If fall conditions are unfavorable for alfalfa, the farmers frost-seed red and white clovers in late winter, or plant oats, alfalfa, and grasses together in April. Cereal grains are harvested for hay, mulch, or grain in Year 4.
- Years 4 – 8: Pasture with mob grazing. Pasture is grazed intensively for one to four days three to five times a year. Forage is grazed at different stages: knee-high for best livestock nutrition, or at maturity to build the soil and feed the biology. While hay is cut from all over the farm, it is fed only on the 200 acres of cropland.

Scientists at the University of Kentucky have conducted studies on this rotation and found that plowing in Year 1 causes a rapid burst of SOM mineralization, releasing both plant-available N and CO_2 (Shrestha et al., 2019). However, the sod phase maintains a deep, perennial living root biomass, and within five years, it restores total and active SOM, soil organic N, and microbial community structure to levels similar to permanent pasture (Lin et al., 2020).

Elmwood Stock Farm also produces essentially all feed grain needed for hogs, poultry, and turkeys, using the following rotation:

- Year 1: Plow sod and plant field corn, followed by a winter cover crop.
- Year 2: Soybean followed by winter wheat or barley.
- Year 3: Harvest cereal grain and plant perennial grass-legume mix.
- Years 4 – 8: Pasture with mob grazing.

The farm relies on the nutrient cycling provided by multispecies livestock grazing and utilizes minimal off-farm inputs. In a typical year, they use only about two tons each sulfate of potash and high calcium limestone for their entire 200 acres of crop fields, and about two tons each Redmond salt and a mineral/oyster shell/fish meal supplement that they mix in with farm-grown soybean and corn for their poultry and hogs.

Organic fertilizers are limited to 300-400 lb of solid 10-2-8 or 5-6-6 and 10 gallons of liquid 3-1-1 for growing vegetable starts and high tunnel crops.

Nutrient exports are limited to ready-to-prepare food that goes to their CSA customers and other markets. They sell meat, not whole animals, and they sell cleaned vegetables, returning all residues and trimmings to the land. Grain crops are grown primarily to feed the farm's livestock, who then recycle about 80% of the plant nutrients in their feed and forage to the land via manure deposited in pastures (See Resource **14b**). Occasionally, the farmers sell surplus grain or buy organic grain when drought lowers yields and leaves the farm short of feed.

These strategies enable Elmwood Stock Farm to avoid the nutrient excesses or depletion that can occur when intensive crop and livestock production are separated from one another, or when organic cropping operations rely on manure and compost from off farm sources to maintain SOM and meet crop N needs.

The farmers sometimes use brief intensive grazing of dense, mature forages to capture the benefits of converting the biomass into green manure (cover crop tilled in) without the drawbacks of tillage. John describes this practice as "a great soil builder."

The farmers have several concerns with their system:

- Turn-plowing to break sod undoes some of the soil health benefits of five years' pasture and mob grazing.
- While permitting forages to mature before mob grazing optimizes soil benefits, it allows perennials like Johnsongrass to set seed and become problem weeds in subsequent crops.
- Producing vegetable or grains only three years out of eight decreases revenue compared to a tighter rotation and entails putting more acres into a rotation that includes tillage.

The farm is experimenting with several strategies to address these challenges:

- Terminating the sod phase by grazing it hard in late fall and tilling shallowly (rototill two to three inches) in spring rather than turn-plowing.
- Roll-crimping cover crops in lieu of disking. Corn is planted no-till after a winter cover crop mix of annual legumes and a little cereal rye. Soybean is planted no-till after rye.
- Growing annual forages in lieu of perennials, producing two vegetable or feed grain harvests from a four-year rotation. They are saving money by using some of their feed corn and soybean to grow annual forage that is grazed when three to five feet tall.
- While the annual rotation reduces tillage and maintains high biomass production, it does forego the five years' continuous living root and may not build as much SOM (D. Butler, SARE OS11-057). The farmers would like to see additional on farm research to compare the soil health outcomes of the different approaches with which they have been experimenting.

> For more on crop diversification, see **Resources 4h, 4j, 6k, 6L, 7c, 8b, 16** and **28.** For more on grazing and livestock management for soil health, see **Resources 4h, 6L, 7a, 8c, 9i, 9j**, and **11**. For recent research on diversified systems, see pages 81-82 and 93-94.

STRATEGY E
Use Compost, Manure, and Organic Amendments as Supplements

Compost and other organic amendments play an important complementary role, working synergistically with living plants to build active and stable SOM, and support microbial activity, nutrient cycling, and other key functions of a healthy soil. Multiple studies have shown that compost in combination with cover crops confer greater soil health benefits than either practice alone (Brennan & Acosta-Martinez, 2017; Delate et al., ORG project 2010-03956; Hurisso et al., 2016). While plant root exudates and fresh organic residues provide food for existing soil life, a good quality finished compost can introduce new beneficial soil organisms, suppress plant diseases, and help build stable SOM. These benefits can often be realized at low compost use rates that do not build P excesses and can persist for multiple years after a single heavier application (Cavigelli et al., 2013; Reeve and Creech, 2015).

For best soil building results with compost:

- Use compost in conjunction with high biomass cover crops and diverse rotations.
- Use compost made from a diversity of materials to enhance soil biodiversity.
- Test your soil and compost to aid in nutrient budgeting (see Strategy B, pages 17-23).
- Test different composts and choose the one that best matches your soil nutrient needs.
- If soil tests are low in P and other nutrients provided by the compost, you can use the compost at rates of five to 20 tons per acre annually to build SOM and fertility.
- When soil test P reaches "high" or "optimum," cut back accordingly, or use plant-based compost which is lower in P than manure compost
- Check compost maturity and quality—it can vary widely. See **Concept 6**.
- When compost use is limited by nutrient, economic, or logistical considerations, get the most out of a small amount of high-quality compost by:
  - Placing compost in transplant holes or seed furrows.
  - Using compost in potting mix to grow starts.
  - Making compost tea.

CONCEPT #6
A Simple Test for Compost Maturity and Quality

Compost quality varies widely, and immature, poor quality, or contaminated compost can harm crops. Here is a simple way to test compost quality. Mix one-part compost with three parts of your regular organic potting mix, fill a small pot with the mix, and sow some lettuce, radish, or tomato seeds in it. Sow a control pot with an unamended mix.

- If compost-grown seedlings grow faster or look healthier than controls, the compost is of *high quality*.
- If compost-grown seedlings look similar to controls, the compost is *safe for crops*.
- If compost-grown seedlings emerge and grow more slowly, or look less healthy (e.g., pale or yellow), the compost:
  - Is *immature* and still undergoing active microbial decomposition, which can tie up nutrients or produce plant growth-inhibiting substances; or
  - Has a high level of *soluble salts,* (common in nutrient-rich manure compost).
- If seedlings fail to emerge, become stunted and twisted, or sicken and die after emergence while control seedlings grow normally, the compost is likely *contaminated with persistent herbicides, other toxic pollutants,* or *active plant pathogens*.

Immature compost can be kept in a pile or windrow to mature for a few months, after which adverse effects generally subside. Immature or high-nutrient compost can benefit soil health if field-applied at low rates to an established cover or forage crop (much less sensitive than your test seedlings) or incorporated with crop residues. Re-composting at 131°F or hotter can destroy pathogens and improve quality. *Never* use compost that shows signs of herbicide damage or other serious contamination, as this could jeopardize your organic certification as well as crop production. Report the problem to the compost provider and find another source.

Other organic amendments can also benefit soil health. Plant-residue mulches such as straw, hay, autumn leaves, or chipped brush protect the soil surface, retain moisture, then feed the soil life and release plant nutrients as they break down. Uncomposted animal manure can provide a nutrient-rich complement to high-carbon inputs such as straw or a mature cover crop. Adding manure and carbon together builds SOM and microbial activity more effectively than either one alone (Grandy & Kallenbach, 2015).

Tips for safe and effective use of manure include the following.

- Check your sources: ensure that manure, compost, or mulch hay from off-farm sources are free of weed seeds and residues of herbicides and other NOP-prohibited substances.
- Apply uncomposted manure no less than 120 days prior to your next food crop harvest to protect food safety and comply with NOP Standards.
- Obtain a manure nutrient analysis and adjust use rates according to a soil test.
- Spread manure on a nutrient-demanding cover crop such as sorghum-sudangrass or rye.
- Incorporate manure into the soil immediately after application to an exposed soil surface.
- Spread manure just before incorporating crop residues or organic mulch after harvest.
- Never spread manure on frozen, snow-covered, or saturated ground—these conditions promote runoff of nutrients and pathogens to nearby streams.

Maintaining a moderate C:N ratio in the totality of organic inputs enhances microbiome functions; whereas, relying too heavily on concentrated organic N sources like poultry litter amendments or bat guano may diminish SOM, reduce microbial activity, compromise nutrient cycling efficiency, and increase nutrient pollution of ground and surface water (Bhowmik et al., 2017; Bowles et al., 2015; D. L. Osmond et al., ORG Project 2009-05488). An initial large input of compost or manure in combination with high biomass cover crops can help jump-start a depleted soil. However, continuing the high inputs year after year may not be necessary or cost-effective, and can compromise soil health in the long run. Off-farm inputs such as fish fertilizer, bat guano, and Chilean nitrate also impose environmental costs at their points of origin.

Biochar is another potentially valuable tool for improving the health and fertility of Southern region soils. Biochar amendments can help stabilize or "anchor" SOM, expand habitat for mycorrhizal fungi and other beneficial soil life, and improve nutrient cycling (see **Concept 7**).

CONCEPT #7
Biochar

Biochar is a product of pyrolysis, a process in which organic residues are heated in an oxygen-limited environment, to create "black carbon" similar to that left in grassland soils by periodic, low-intensity prairie fires. While research has given variable results, application rates of about ten tons per acre have shown significant soil health benefits, especially when biochar is aged for several years to enhance its cation exchange capacity and ability to bind to soil clays, and it is used in combination with compost (Mia et al., 2017; Wilson, 2014).

The biochar concept is based on the anomalously fertile "terra preta" soils that indigenous communities in the Amazon Basin developed over centuries by amending soils with cooking fire charcoal and organic residues. Unlike the region's fragile, infertile native soils, terra preta soil productivity remains stable under cultivation, which suggests that biochar may be a valuable tool for stabilizing SOM and soil health in the Southern region of the U.S. (Wilson, 2014).

In recent years, vendors of organic amendments have begun to offer biochar products, though their cost and high use rates make them most practical for small scale applications such as high tunnels, market gardens, or urban farms. Exploitive use of native plant biomass such as forests to make commercial biochar products has raised serious environmental and social concerns, yet pyrolyzing accumulations of manure and other organic "wastes" to make this soil amendment converts a waste disposal problem into a valuable resource and can contribute to net agricultural carbon sequestration (Lal et al., 2018; North, 2015).

> For more on compost and organic amendments, see **Resources 3, 4a, 4c, 5b, 6a, 8a, 10e**, and **10f**. For recent research on organic amendments, nutrients, and soil health, see pages 74-77.

STRATEGY F
Enhance the Soil Microbiome

The community of soil life underpins every vital function of healthy soil. As research continues to reveal the fascinating world of soil life and its central role in soil fertility, crop and livestock production, and agricultural resilience, organic producers seek new, practical tools and strategies to optimize soil microbiomes on their farms. Living plants, their residues, and animal manures feed the soil life; well-made finished compost can introduce new beneficial organisms to complement the existing food web; and all practices that improve soil structure build new "housing" for the soil life. However, effects of a given practice or suite of practices on soil biological functions, crop health, and yield remain variable and hard to predict, so farmers naturally seek more precise tools for assessing and enhancing soil life.

"If you build it, they will come."
(Gabe Brown, 2018, p 25)

- Enhance soil health and your soil microbiome will respond.
- Look close to home for microbial supplements.
- Buy inoculants for your crops, not for your soil.

Vendors of organic amendments offer an ever-expanding plethora of microbial inoculants and biostimulants claiming to build soil health, improve crop yield and quality, and suppress diseases, pests, and weeds. While many of these organisms have been shown through research trials to combat specific pathogens, improve nutrient cycling, stabilize SOM, or enhance crop vigor and resilience, commercial products often have little impact in practice (Kleinhenz, 2018). Typically, the indigenous soil microbiome overwhelms the "newcomer" so that it dies out, especially in biologically active soils under long-term organic management.

The primary risk in using commercial inoculant products is the cost. In addition, there is some risk that a particularly vigorous organism derived from a soil ecosystem far from the farm's locale could become invasive, disrupt the farm's existing soil microbiome, or even threaten nearby native plant communities. Locally Effective Microorganisms (LEM), derived on-farm from a field with healthy soil or from nearby forest or other natural area, are safer and more effective than exotic microbial products.

On the other hand, inoculants applied *directly to plant roots or seeds* can improve crop production. Inoculating legume seeds with an appropriate strain of *Rhizobium* or *Bradyrhizobium* to ensure effective N-fixation is the most well-researched and time-honored example. Inoculating seeds or transplants with appropriate strains of arbuscular mycorrhizal fungi (AMF) for most crops, or ectomycorrhizal fungi for orchard crops can substantially improve crop establishment and early growth, especially in low-fertility soils. A review of over 100 studies worldwide found that crops receiving seed or root treatments with the right mycorrhizal strain prior to planting respond dramatically (average 50% increase in growth), except in soils with surplus P or soluble N (Hoeksema et al., 2010). Several microbial products have also shown promise for suppressing specific plant pathogens or inducing systemic disease resistance (Schonbeck et al., 2019).

Providing food and protecting habitat for indigenous soil life can often restore soil biology without applying inoculants. A review of 54 studies found that either reducing tillage intensity or planting a cover crop can enhance AMF colonization of subsequent cash crops by about 30%, with greater benefits from implementing both practices (Bowles et al., 2017).

Some tips for enhancing soil biology for soil health and crop production include the following.

- Keep the indigenous microbiome well fed through the living roots of a diversity of crops.
- Use compost and other amendments to stabilize SOM and soil structure (i.e., microbial habitat) and enhance soil microbial diversity (see Strategy E, pages 33-36).
- Keep the soil surface covered with living plants or residues to protect soil life from weather extremes.
- Reduce tillage when practical (see Strategy G, pages 40-44).
- Avoid nutrient excesses, especially NPK (see Strategy B, pages 17-23).
- Inoculate seeds, starts, and planting stock with appropriate rhizobia (legumes), mycorrhizal fungi, or other organisms known to benefit the specific crop(s) grown.
- Use Locally Effective Microorganisms (LEM) or compost tea from on-farm or locally made compost to restore a depleted soil microbiome.

Beneficial soil organisms help prevent crop diseases by improving soil structure, drainage, and aeration, thereby enhancing root health and deterring pathogens that thrive in wet, airless soil conditions. In addition, plant-symbiotic microbes including AMF can protect their hosts by outcompeting, preying on or parasitizing pathogens, releasing antibiotic substances, or inducing systemic resistance (ISR) throughout the plant against both soil-borne and foliar pathogens.

Farmers and researchers have developed several organic alternatives to conventional soil fumigation. These include tilling a crucifer green manure or mustard seed meal into the soil to release antimicrobial isothiocyanate compounds ("biofumigation") sometimes with clear plastic mulch to heat the soil ("biosolarization"). Anaerobic Soil Disinfestation (ASD) is another method, first developed in Europe and Asia for greenhouse production and more recently implemented successfully in the U.S. to prevent disease in field grown organic strawberries (see **Resource 5g**). In ASD treatment, a decomposable organic material such as rice hulls is tilled in, the soil is watered to saturation, and plastic tarp is laid for several weeks to induce a burst of anaerobic activity that kills pathogens. Recent research indicates that ASD and "biofumigation" work primarily by stimulating the growth of microbial natural enemies of plant pathogens, which can provide protection for one or more years.

Organic disease management strategies include the following.

- Rotate crops to disrupt pathogen life cycles.
- Plant crop cultivars with horizontal (multi-gene) disease resistance.
- Build soil health, especially microbial activity, porosity, drainage, and aeration.
- Use ASD, crucifer green manure, or mustard seed meal to promote a disease-suppressive soil microbiome.
- Modify the soil environment to deter target pathogens (e.g., acid pH against potato scab, and neutral pH against clubroot of crucifer crops).
- Use NOP-allowed biological disease controls in conjunction with the above practices.

For more information on optimizing the community of soil life and suppressing plant diseases, see **Resources 4i, 5d, 5f, 5g, 9f, 10d, 12,** and **29**. Recent soil biology research is discussed on pages 82-89.

STRATEGY G
Till With Care

Reducing tillage when practical can be especially important for conserving SOM and soil health in the Southern region. While continuous no-till is generally impractical in organic production of annual crops, various tools and techniques are available for organic producers to reduce the frequency and intensity of tillage, thereby saving SOM, soil structure, and soil life. Diversified organic crop rotations with cover crops, organic amendments, and careful routine tillage can build more active and total SOM and attain higher levels of functional soil health than continuous no-till rotations with conventional inputs (Cavigelli et al, 2013; Delate et al., 2015; Delate et al., ORG project 2010-03956).

Experienced farmers have developed their own approaches to ease the impacts of steel on soil, including measures as simple as slowing rotary tiller speeds to prepare a seedbed without pulverizing soil aggregates (See **Farm Story 3**). Others choose newer implements that get the job done with less disruption to soil structure and soil life than traditional implements. These include:

- Rotary or power harrow for shallow, gentle tillage to prepare a seedbed and incorporate amendments and light residues (shallow, powered tillage can replace the moldboard plow in tilled cropping systems).
- Cultivation tools that work only an inch deep to take out small weeds.
- Rotary or reciprocating spaders for deep, non-inversion tillage (the spader avoids plowpan and can incorporate a heavy cover crop and make a seedbed in one pass).
- Chisel plow to break sod and fracture sub-surface hardpan.
- Cover crops with deep taproots or robust fibrous root systems to "biotill" the soil.
- Strip tiller or zone tiller to prepare wide-spaced crop rows for planting, leaving 70-90% of the surface undisturbed and covered by residue or living mulch.
- Blade plow or undercutter to sever cover crops and weeds just below the surface, leaving residue in place and most of the soil profile undisturbed. Undercutting terminates most cover crops (see **Resource 17b**) and works best in fairly dry soils.

FARM STORY 3
Gearing-down the Tiller to Improve Sandy Soils

Mattawoman Creek Farm, Eastville, Virginia

Rick and Janice Felker of Mattawoman Creek Farm in Cape Charles, Virginia (Eastern shore) produce a wide range of vegetables for their four-season Community Supported Agriculture (CSA) on 11 of the farm's 30 acres. Their sandy Bojac soils have relatively little clay on which to build and hold organic matter. Outdoor crops are grown in rotation with a winter rye + hairy vetch cover crop, which is mowed, tilled shallowly, allowed to decompose for a few weeks, and then worked in three to four inches deep to prepare the seedbed. Tillage is done with a tractor-drawn rototiller with the PTO on a low gear and a forward speed of about 2.5 mph to get the job done with less damage to soil structure. Just before the second pass, they apply poultry litter fertilizer (5-4-3) or spent mushroom soil at rates based on crop needs.

For transplanted crops, they use a disk bedder after the first tillage pass, laying drip tape as the bed is formed. Finding that this operation leaves an uneven surface that can interfere with seed germination, they now omit the bedder for direct-seeded crops.

Despite routine tillage, soil health and fertility have improved steadily over the farm's 20+ years of operation. The sandy topsoil has developed visible crumb structure, SOM has climbed to 2.0-2.2% (excellent for this soil), phosphorus has not built up to excessive levels, and nitrogen availability has improved so that fertigation with fish-seaweed fertilizer is no longer needed. In Rick's words, "the soil gets better every year, and we have excellent growth."

Several practices account for their success.

- Tractor and tiller speeds are adjusted to avoid pulverizing soil aggregates. (Many producers rototill with the PTO on high gear with a forward speed of about 1.0 mph, which leaves a fine, fluffy seedbed that readily crusts over, erodes, and loses SOM).
- Fields are planted in a year-round succession of vegetables and winter cover crops, and buckwheat is planted to fill summertime gaps in the rotation. This keeps the soil covered by a diversity of plant families and maintains living roots much of the year.
- Drip tape is laid under crop rows, three to four inches below the surface. Subsurface irrigation encourages deeper root development, which enhances heat and drought resilience in vegetable crops, and feeds beneficial microbes deeper in the soil profile.
- Cover crops provide the primary source of organic carbon and nitrogen, and applied nutrient sources are used in moderation.
- All residues are returned to the soil. Heavy residues such as tomato are flail-mowed before shallow tillage and prompt cover crop planting.
- Installing deer fence around 22 acres greatly improved yields, so that they double-crop only infrequently, and can rest some beds each year under season-long cover crops.

In addition to field crops, Rick and Janice grow cool-season vegetables in nine high tunnels of varying sizes (15,180 sq ft or 0.35 ac total enclosed area) to supply their winter season CSA. In the fall, beds are planted densely in leafy greens or root crops (rows one foot apart), sometimes with a second planting in late winter. During the summer, high tunnels are rotated to cherry tomato, pepper, cucumber, or buckwheat cover. Here too, soil quality and yields "get better year to year" with no salt buildup, even in their first high tunnel that has been in continuous production since 2010. Contributing factors to high tunnel soil health include:

- Continuous cropping and residue return. At the end of each harvest, residues are mowed, tilled shallowly, and replanted to the next crop, often all on the same day.
- Good water management. "We water thoroughly, and then not again for a while, up to two weeks in winter." This strategy limits salt accumulation in the topsoil.
- Organic nutrient inputs are used at moderate rates, slightly higher than in the field to support intensive cropping, but not so high as to build up excesses.

This story is based on a presentation entitled Growing Healthy Greens, given by Rick Felker (https://www.mattawomancreekfarms.com) at the Virginia Biological Farming Conference on January 30, 2016, and a phone interview with Rick on September 27, 2020.

More and more organic farmers seek to take conservation tillage further by terminating a mature cover crop and planting the next cash crop without tillage. Most cereal grains, annual legumes, and some other cover crops can be terminated with a roller-crimper, flail mower, or mob grazing after the crop has flowered, shed pollen, or begun to form immature seeds. Provided that the cover crop has developed sufficient aboveground biomass (three to five tons per acre), the mulch left by roll-crimping delays weed emergence and growth for four to eight weeks while the cash crop becomes established. It also conserves soil moisture, protects soil life and developing roots from excessive heat, and slowly releases nutrients. Cover crop roots improve soil structure and drainage as they decompose in an undisturbed soil profile.

Once cash crop harvest is finished, the field is tilled just enough to establish the next crop. If weed pressure is light, one shallow pass with a rotary harrow or disk will do the job, and in some cases a second no-till planting is feasible. Elmwood Stock Farm has maintained no-till for 22 months, starting with a September planting of rye, peas, and vetch in tilled soil, roll-crimped in late spring for corn or soybean. After harvest, a winter cereal grain is no-till drilled, and the next tillage takes place after the cereal is combined the following July (John Bell, pers. commun.)

This system, called *rotational no-till* or *organic no-till* generally enhances SOM, biological activity, and soil health more than either organic with full tillage or conventional no-till, but it can be challenging to manage. Organic no-till vegetable yields have varied from satisfactory (similar to full-till organic yields) to poor (Delate et al., ORG project 2010-03956; Morse et al., ORG project 2003-04625; Osmond et al., ORG project 2009-05488). Causes of yield loss include wet soil conditions or late cover crop maturity that delays cash crop planting, difficulties planting through the residue, delayed soil warming and N mineralization, and insufficient residue to suppress weeds yet too much residue to cultivate with standard implements. Cover crop mixtures can yield greater biomass, weed suppression, and soil health benefits than single species, but careful variety selection is needed to ensure that all components of the mix mature (flower) at the same time to allow no-till termination.

TO TILL OR NOT TO TILL?

No-till planting into roll-crimped cover works best when:

- Cover crops are robust (at least three feet tall, cannot see the ground) and weed-free.
- Weed pressure is light with few or no perennial weeds.
- The soil is healthy and biologically active.
- You have the experience and equipment for no-till, or time and resources to acquire them.

Don't try no-till if:

- The cover crop is thin, uneven, weedy, or lodged (fallen over).
- You are terminating perennial sod for crop production.
- Perennial weeds such as nutsedge or Bermudagrass are present.

Try it out on a small area at first and adapt the method to your farm.

In the Southern region, long, warm growing seasons enhance cover crop biomass and facilitate scheduling but intensify weed pressure. Farmers use various tactics to deal with weeds that come up through the cover crop residue, including manual pulling or cutting, high-residue cultivators that undercut weeds without burying or dragging residue, laying additional organic mulch over the residue, or occultation (opaque plastic mulch or weed mat over the mowed or rolled cover). In some trials, legumes such as soybean have thrived in roll-crimped rye, which slows weed growth by tying up soil N while the legumes fix their own N. However, organic farmers in Kentucky have observed greater success with no-till corn after winter annual legumes, which provide N to the corn (John Bell, pers. commun.).

No-till planting into rolled cover crops requires special equipment and works best for transplanted vegetable starts or larger-seeded direct-sown crops such as corn, beans, or squash. One option is to use a strip tiller, which parts the residue and prepares a narrow (~6 inch) swath of tilled soil into which crops can be seede d or transplanted with standard equipment. Strip tillage can facilitate soil warming, N mineralization, and weed control in crop rows while leaving most of the field undisturbed under cover crop residue.

> For more on organic conservation tillage, see **Resources 4e, 6e, 7c, 9b, 9d, 10a, 10b, 13, 17c, 19** and **23.** See pages 90-92 for recent and ongoing research developments in organic no-till.

STRATEGY H
Use Soil-saving Weed Management Strategies

Weeds pose the greatest barrier to building healthy soils in organic cropping systems in the Southern region. The secret is to replace synthetic herbicides, not with cultivation alone, but with an integrated management strategy based on an ecological understanding of weeds.

The soil's "bank" of weed seeds, tubers, rhizomes, and viable root fragments will exploit every square inch of bare soil to emerge and grow. Keep the ground well covered by crops and residues so that fewer weeds gain a foothold. Plant cover crops promptly after harvest, using fast-growing species that will cover the ground before weeds get a foothold.

Most agricultural weeds thrive on predictable seasonal patterns, including tillage, planting, and harvest dates, as well as the crops grown. A diversified farming system that integrates crops with different growth habits and competitive traits, varied tillage and planting methods, and shifting schedules of field operations subjects the weed flora to an unpredictable set of stresses that can disrupt weed life cycles and reduce weed pressure.

Good nutrient management (Strategy B, pages 17-23) favors crops over weeds. Many agricultural weeds thrive on abundant soluble nutrients and respond to broadcast applications of poultry litter or other concentrated nutrient sources by outgrowing crops. Slower-release nutrient sources and in-row placement can give the crop an advantage over the weeds. Avoiding P excesses encourages AMF and gives their crop hosts an advantage over non-mycorrhizal weeds such as pigweeds, horseweed (i.e., mare's tail), and nutsedges (Kloot, 2017).

OUTSMART THE WEEDS

Exclude weeds

- Avoid weedy manure and mulch hay.
- Plant cover crop on harvest day or sooner.

Confuse weeds

- Vary crops, tillage, and timing.

Starve weeds

- Feed crops in row.
- Avoid surplus plant-available N and P.
- Mop up leftover nutrients with cover crops.

Different production systems develop different weed floras. Weeds that emerge in annual crops with routine tillage differ from those that invade minimum-till systems, perennial crops, or pasture. During the sod phase of a crop rotation, annual weeds that respond to tillage fail to reproduce, while ground beetles and other weed seed consumers reduce the existing seed bank. However, other weeds adapted to no-till conditions with periodic mowing or grazing may increase. Thus, rotating a given field through different farming systems (e.g., annual crops and pasture – see **Farm Stories 1** and **2** above) may reduce weed problems.

Timely cultivation can knock out emerging weeds and give the crop a head start, but each cultivation stimulates the next flush of weed germination. Repeated cultivation can pulverize near-surface soil aggregates and burn off SOM, leading to surface sealing, reduced rain infiltration, poor soil aeration, and increased runoff and erosion. If cultivation is needed, use the best tool for the job. Examples include a tine weeder, finger weeder, or rotary harrow for small weeds (these tools are easier on soil aggregates than a rototiller) and undercutting tools such as sweeps to sever larger weeds just below the root crown. Consider alternatives to cultivation such as mowing, flame weeding, manual pulling or cutting, solarization, or tarping.

Some tips for effective and soil-friendly weed management include the following.

- Maintain a tight crop rotation. Plant the next cover or production crop as soon as the current harvest is finished—or do it sooner by interplanting or overseeding.
- Alternate cool- and warm-season crops, and short- and long-season crops.
- Vary crop architecture and cultural practices. For example, follow wide-row crops like tomato or head brassicas with a cereal grain cover or cash crop that forms a solid canopy.
- Plant cover crop mixes that include grass and broadleaf species—these often provide better weed suppression than single-species covers.
- Plant aggressive cover crops when expected weed pressure is greatest.
- Manage nutrients and moisture to feed and water the crop and not the weeds.
  - Maintain sufficient but not surplus NPK. Weeds thrive on surplus nutrients!
  - Band concentrated fertilizers like feather meal within and near crop rows.
  - Use within-row drip irrigation and fertigation. Subsurface irrigation waters the crop while leaving near-surface in-row weed seeds unwatered.
  - Plant nutrient-rich legume or crucifer cover crops within future crop rows, and N-immobilizing cereal grain between rows.
  - Precede soybean or other legume cash crop with a cereal grain cover to retard N-responding weeds without hindering the N-fixing legume.
- Vary method, depth, and timing of tillage and cultivation.
- Terminate a cover crop without tillage if practical (see pages 43-44).
- Cultivate shallowly for small weeds to minimize soil disturbance. Large-seeded crops can take a "blind" cultivation with rotary harrow or tine weeder just before crop emergence.
- Reduce or eliminate cultivations by using alternative methods such as:
  - Plastic film mulch or landscape fabric – *stops most weeds except nutsedges but does not feed soil and may stress near-surface microbiome. Sow soil-building covers in alleys between plastic mulched beds and mow periodically.*
  - Straw or other organic mulch after first cultivation – *feeds soil life but is less effective on grass and perennial weeds; may be impractical at larger scale.*
  - Use flame-weeding for stale seedbed or between rows with shields to protect the crop. *Flame works best on small (up to one inch) broadleaf weeds. To avoid fire danger, never flame mulched fields!*
  - Flame direct-seeded crops just before emergence. *Mix in a few faster-emerging seeds (e.g., beet with carrot, or radish with beet) to pinpoint flame timing.*
  - In established crops, mowing between-row weeds may be sufficient.
  - If practical, manually cut or pull large weeds before they set seed or hurt yield. *Cutting avoids disturbing soil and crop roots, though some weeds will regrow.*

- Use tarping or occultation with landscape fabric or old silage tarp to provide a weed-free no-till seedbed (See **Farm Story 4**).
- Solarize a cover crop or weeds after mowing or roller-crimping to complete termination and provide a weed-free no-till seedbed (See **Farm Story 5**).
- NOP-approved herbicides can limit weed growth but may not be cost effective. Vinegar-based herbicides can reduce AMF activity (Atthowe, 2010).

- Integrate crops with livestock to manage both cropland and pasture weeds.
  - Rotate fields out of annual crops into sod for two or more years. Do this after several years cropping or when weeds become difficult to manage.
  - Utilize management-intensive rotational grazing or mob grazing to minimize selective grazing and proliferation of less-preferred species as pasture weeds. *Continuous grazing promotes development of pasture weeds.*
  - Graze different livestock species together or in succession. *Sheep, goats, or poultry may eat "pasture weeds" that cattle refuse.*
  - While most cropland weeds subside during the sod phase of a rotation, other weeds may increase; when this happens, rotate back to crops.

FARM STORY 4
Landscape Fabric for Weed Control and Cover Crop Termination

Crager Hager Farm, Bremen, Georgia

Farmer Bryan Hager has developed a no-till system utilizing landscape fabric to manage weeds and cover crops for organic vegetable production in the Piedmont region of Georgia. He uses 3.0 oz (weight per square yard) or heavier black fabric with UV block to terminate cover crops and block weeds during production of above-ground (leaf, head, or fruit) vegetable crops. This material allows moisture and air to reach the soil, effectively kills cover crops, and controls most weeds except for nutsedge and Bermuda grass.

Bryan uses a plywood jig, a metal can with top and bottom removed, and a small propane torch to burn neat circular holes in the fabric at precise intervals appropriate to the crop (single row three feet apart for tomatoes and two feet apart for squash and okra, double staggered row two feet apart for head brassicas, and triple row nine inches apart for lettuce and other leafy greens). Double-row arrangements are also used for strawberries and high-tunnel tomatoes (Figure 4). Bryan uses a simple labor-saving reel system to lay fabric (Figure 5).

A typical schedule for field operations is as follows.

- At the end of vegetable harvest, apply lime and manure as indicated by soil test, broadcast winter cover crop seed, and pack with tractor-drawn rototiller with PTO off.
- If cover crop planting is delayed, cover beds with blank fabric (no holes) to suppress weeds until the cover crop can be sown.
- One month before vegetable planting, mow the cover crop (two passes, the second one close to ground), then cover with blank fabric.
- One day before planting, remove fabric, apply any fertilizers needed, work in shallowly.
- Lay drip tape and fabric with hole spacing appropriate to the crop, then plant.
- One month after planting, remove any weeds emerging through holes.

Bryan Hager (2)

Figure 4. Landscape fabric for strawberries (left) and high tunnel tomatoes (right).

Bryan Hager (2)

Figure 5. For labor-efficient laying and pickup of the landscape fabric, Bryan uses a landscape fabric reel consisting of a 1.3 inch diameter metal tube with a wooden handle, supported on two sawhorses. The six-foot wide landscape fabric is laid on raised beds spaced five feet center to center, overlapping in alleys and anchored with eight-inch metal staples. This method makes landscape fabric practical for his three-acre mixed vegetable operation.

The black fabric can lead to intense heating at and near the soil surface during summer. This helps kill emerging weeds but can hurt crops during early establishment. Bryan found that sprinkling hay mulch around newly transplanted or emerging crops can prevent heat damage. He also noted that worms “love it under the fabric” but so do mice and fire ants. Excess rain can puddle on the fabric, and the raised bed system minimizes this problem. Fabric may need to be weighted down with rocks or metal pipe to keep it from flapping while the plants are small.

Bryan notes that reduced weeding labor repays the cost of the fabric within one or two years. His oldest fabric is five years old and holding up well.

This story is based on an e-mail conversation with Bryan Hager in September 2020, and a PowerPoint presentation on this method that he shared with the author.

FARM STORY 5
Repurposing Old High Tunnel Plastic for Soil Solarization, Weed Control, and Cover Crop Termination

Abingdon Organics, Abingdon, Virginia

Anthony Flaccavento, an organic vegetable grower and sustainable development consultant in Abingdon, VA, has participated in several on-farm research trials, including cover crop based organic reduced-tillage systems and strategies to manage the invasive exotic Brown Marmorated Stink Bug. After growing a summer cover of pearl millet and southern pea as a trap crop for the pest, he mowed the mature cover crop with a bush hog and covered it with old high-tunnel plastic (removed after five years' continuous use) for a few days to enhance cover crop termination by solarization. In addition to controlling weeds and cover crop regrowth, the solarization enhanced N mineralization so that fall broccoli and cauliflower produced excellent yields and quality without adding fertilizer.

Anthony also had success with peppers transplanted after an overwinter cover crop of cereal rye and crimson clover was mowed and solarized. However, without no-till equipment, he found transplanting vegetables into heavy cover crop stubble difficult, labor-intensive, and impractical for market-scale production. He still uses old high tunnel plastic for weed control and finds that it builds sufficient heat to kill weeds and can be used at least twice in this way before it begins to fall apart. During sunny, warm (≥75°F) weather, two days' solarization results in 100% weed kill; in cooler or cloudy weather, the plastic must be left in place for a week or longer. Anthony has used this method to clean up weedy beds ahead of spring brassica plantings, and to reduce weed pressure in asparagus (bush-hogged and solarized in late summer for a few weeks).

One weed that cannot be controlled in this way is Canada thistle, which propagates through a robust network of horizontal rhizomes about eight inches below the surface. Anthony cleaned up a severely infested field through repeated shallow tillage or hoeing to remove top growth through the growing season, followed by a winter cover crop, then a millet-pea cover crop the next summer. This exhausted the rhizomes and made the field suitable for vegetable production.

In order to make solarization for cover crop termination more practical, Anthony noted several equipment needs, including:

- A flail mower or roller crimper for better distribution of cover crop residues.
- A mechanized system for laying and then removing the clear plastic.
- A no-till transplanter or a strip tiller to facilitate transplanting through residues.

This farm story is based on telephone conversations with Anthony Flaccavento in 2016 and in September 2020.

Creeping perennial weeds like Bermuda grass, Johnsongrass, nutsedges, and Canada thistle can become so aggressive that nothing other than rigorous tillage can manage the problem. These weeds propagate vegetatively by underground rhizomes, tubers, bulbs, or extensive root systems, and/or near-surface stolons, through which a single plant can generate dozens or hundreds of new "daughter plants" during a single growing season. One pass with a heavy disk or a rototiller will chop these weeds into millions of viable fragments per acre. However, repeated tillage passes done when the fragments have expended reserves to regenerate new shoots can eventually bring the infestation under control. Most perennial weeds reach their "low point" when new shoots have three or four leaves. Tilling again at that time will set them back, while waiting longer will allow the weeds to rebuild reserves and proliferate further.

Occasionally, heavy weed seed set can build near-surface weed seed populations so high that no amount of cultivation, mulching, flame, or cover cropping can keep up. When this happens with small-seeded weeds like pigweeds, galinsoga, or foxtails, inversion tillage to bury the seeds at least four inches deep can prevent their emergence and facilitate crop production.

When weeds require rigorous tillage, maximize efficacy and take steps to restore soil health after the disturbance. Some tips include the following.

- For creeping perennials, repeat tillage when regrowth has three to four leaves per shoot.
  - Till just deep enough to sever or undercut the new growth.
  - When this process has weakened the perennial weeds, plant an aggressive cover crop to suppress regrowth and begin rebuilding soil structure and fertility.
- Canada thistle can be set back by close mowing after considerable top growth has taken place. Plant sorghum-sudangrass or alfalfa in the thistle infested field, and mow just before thistle flowers. This weakens the thistle while the crop regrows vigorously, so that the field may be suitable for cash crops the following year.
- If a heavy weed seed set occurs, use a moldboard plow to fully invert the soil. Set the plow to work about six inches deep to bury seeds without bringing subsoil to the surface.
  - After turning weed seeds under, avoid deep tillage for several years to let most of the weed seeds decay. Use shallow, non-inversion tillage only.
- After intensive tillage for weed control, restore soil health with high-biomass cover crops, reduced tillage, and organic amendments, or sow pasture for rotational grazing.

> For more on soil-friendly organic weed management, see **Resources 4d, 5e, 9c, 10a-c, 17a,** and **17c.** Recent research into organic weed management is discussed on pages 92-93.

STRATEGY I
Make the Crops Fit the Land: Perennial Plantings for Soil Health

Not all land is suitable for annual crop production—including some that is currently under cultivation. Steeply sloping fields and highly erodible soils will inevitably undergo erosion losses in an annual cropping system, even under the best organic management. Naturally wet or poorly drained soils and shallow, stony soils will not support viable yields of most crops without artificial drainage or heavy inputs that entail considerable direct and environmental costs. Extremely sandy or clayey soils can also prove unsuitable for annual crops.

If part of your farm falls under one of these categories, the area can still play an important role in your production system in any of several ways:

- Pasture or silvopasture under soil-enhancing rotational grazing management.
- Habitat for beneficial insects and wildlife.
- Woodlot managed by sustainable harvest of timber or non-timber forest products such as ginseng, goldenseal, other medicinal herbs, shiitake, and other edible mushrooms.
- Orchard, vineyard, blueberry, bramble, and other perennial horticultural crops, with perennial sod cover for alleys and orchard floor.
- Native fruit crops such as pawpaw, muscadine grape, and American persimmon.
- Perennial vegetables adapted to soils too wet, dry, shallow, or infertile for annual crops.
- Less-known perennial crops for which new or emerging markets might exist, such as goji berry or yaupon holly.

Use the NRCS Web soil Survey to check the *land capability class* and *subclass* for each soil map unit on your farm. Suitability for annual crop production declines from class 1 (best) through class 8 (not suitable for any agricultural activity). Class 3 indicates significant constraints that require diligent conservation measures to protect the soil resource; class 4 is only marginally suited for annual crops and is best kept in pasture or other permanent vegetative cover; and class 5 and above should never be tilled. Subclass "e" indicates that constraints relate to risks of erosion, "w" indicates wet or poorly drained conditions, and "s" indicates a shallow or stony soil. The land capability classification can guide you toward best use and management for different parts of your farm landscape.

You can grow annual crops on moderately sloping land and prevent erosion by alternating strips of annual crops with either *contour buffer strips* or *berm-and-swale terraces,* which can be maintained in perennial sod or a diverse perennial plant community that can provide marketable products, beneficial habitat, and other ecosystem services (see **Farm Story 6**).

Permaculture and agroforestry are two approaches to land management and food production that take a whole-landscape approach to integrating perennial plants into the farm ecosystem. Many perennial crops can become profitable enterprises while protecting and restoring the soil. Permaculture consultants or NRCS field staff can help you design perennial-based systems that integrate your steep or otherwise non-arable land into your production system.

FARM STORY 6
Berm and Swale Terraces with Multifunctional Perennial Plantings

Radical Roots Farm, Keezletown, Virginia

Lee and David O'Neill established Radical Roots Farm in the year 2000, producing five acres of mixed vegetables on a south-facing hillside in central Virginia. Some of their fields are moderately sloping (5 – 10%) with a land capability class of 3e, indicating a need for robust conservation measures to prevent erosion. In 2005, they applied their permaculture training to plan and install a series of berm-and-swale terraces on contour, designed to retain and conserve moisture and nutrients during heavy rains, provide level areas for growing annual crops, and minimize the possibility of erosion. Berms are planted with diverse herbaceous and woody perennial plants, and swales are maintained in sod and provide access to the growing area, consisting of a series of eight to ten raised beds within each terrace. The farmers also installed a small irrigation pond below one of the berms, supplied by roofwater catchment and occasional runoff from swales during heavy rains (Figure 6).

The berm plantings include coniferous trees as windbreaks and buffers along farm boundaries; apple, Asian pear, and other tree fruit; native berries including elderberry, serviceberry, and chokeberry (*Aronia*); and herbaceous perennials including medicinal herbs and habitat for natural enemies of crop pests. Alders are coppiced periodically to provide wood chips to mulch fruit trees (which enhances beneficial fungi that help these crops thrive). In addition to planted species, black locust has come up volunteer, some of which they plan to remove to reduce shading and competition against other desired species.

The terrace system keeps the soil in place while cover crops, diverse rotation, organic amendments, and reduced tillage build SOM and biological activity in the vegetable beds.

Lee O'Neill

Figure 6. Farm employees and CSA sharers pick crops from level, fertile growing beds in 2019, with apple trees, native berries, and comfrey on the terrace berm in the background (left). Irrigation pond at time of installation of the perennial planting (right, inset) and about six years later (right). The perennial plant community supports a diversity of wildlife and keeps the pond free from excess sediment and nutrients.

While the fruit trees and berries have produced well in some years, the farmers consider biodiversity—above ground and below ground – as their primary benefit from the perennial planting. “We used to see maybe 20 species of birds; now we see hundreds of species,” Lee observed. “The pond has amazing biodiversity, with herons, snapping turtle, and bald eagle.”

This farm story is based on a farm tour in 2011 and a follow-up telephone conversation in September 2020.

> For more information on perennial agricultural production systems, see **Resources 20 – 24.** Recent research on perennial-annual integrated systems is summarized on pages 93-94.

Managing Soil Health in the High Tunnel

The high tunnel extends the growing season, allows more precise control of soil moisture and foliage wetness, and minimizes problems with certain pests and diseases. Organic growers commonly use high tunnels to grow high-value, disease prone crops such as tomato or cucumber, realizing much greater net returns than an equivalent area of field production. High tunnels facilitate access to lucrative early and late season markets, though in parts of the South they can become too hot for midsummer production. The high tunnel allows organic production of heirloom tomato cultivars that draw robust market demand and high prices, but can succumb to diseases when grown outdoors. Growers often follow high tunnel tomatoes with greens and other cool-season vegetables for winter and early spring production.

The high tunnel environment poses a unique set of soil health challenges. Excluding natural rainfall can lead to an accumulation of salts in the topsoil, sometimes visible as a whitish deposit on the surface. Salt concentrations can reach levels that compromise soil biological function, inhibit crop growth, and hurt yield. Alkaline soil pH and high levels of sodium (Na), calcium (Ca), magnesium (Mg), or sulfate-sulfur (S) can also develop.

In addition, the lengthened growing season and higher temperatures in the high tunnel accelerate the decomposition of soil organic matter. Producers often use compost liberally to replenish SOM to sustain intensive, year-round production. This can aggravate salinity problems and build up excesses of P and nitrate-nitrogen (N). For example, Pennsylvania State Extension found that a one-inch depth of compost added 585 lb P/ac (13 times the recommended rate), and annual applications at this rate caused soil salinity to increase five-fold in two years, reaching the threshold for crop damage (Sanchez, 2017).

Conversely, potassium (K) is often drawn down to very low levels in high tunnel soils, especially when tomato vines and other crop residues are removed from the tunnel at the end of the season for disease control (Krista Jacobsen, University of Kentucky, 2020, pers. commun.). Low K combined with high Mg can lead to ripening disorders in tomato and other fruiting vegetables.

As the farm's most "high value real estate," the high tunnel is often cropped intensively year-round without cover crops. Planting high tunnel space to a cover crop often entails income foregone, although heat-tolerant cover crops such as pearl millet, sorghum-sudangrass, sunn hemp, and southern pea can be grown during summer when the high tunnel becomes too hot for production. Moisture limitations can interfere with stand establishment and hinder decomposition of cover crop residues. Overhead sprinkler irrigation or removing the plastic cover to admit natural rainfall facilitates cover cropping and leaches out salts but can add to labor costs. Finally, managing bulky cover crops within an enclosed space requires different equipment and strategies than cover crops in the field. These logistical challenges constrain the use of cover crops, making it that much harder to keep high tunnel soils healthy.

Organic high tunnel growers in the South report another serious problem: root knot nematode (RKN), which attacks roots of tomato, carrot, and other vegetable crops, forming visible swellings or galls, sapping crop vigor, and reducing yield. Higher temperatures and intensive rotations dominated by susceptible crops, and heavy use of organic amendments that maintain a loose soil structure promote very high populations of RKN in high tunnel soils (Elizabeth Little, plant pathologist at University of Georgia, pers. commun., 2020). A long season crop like tomato allows RKN to multiply through several generations, intensifying RKN injury to following susceptible crops and rendering root crops such as beet or carrot unmarketable. Researchers are continuing to explore cropping sequences that reduce RKN populations by including non-host crops while maintaining satisfactory income from the high tunnel system.

Some tips for meeting the soil health challenge in high tunnels include the following.

- Conduct annual soil tests to monitor trends in pH, SOM, salinity, nutrients, and plant-parasitic nematodes.
- Conduct foliar analysis of high tunnel crops to identify any crop nutritional imbalances.
- If soil salinity approaches undesirable levels:
  - Allow natural rainfall to reach the soil (e.g., leave the tunnel area uncovered for several months after removing old plastic before installing new cover), *or*
  - Do a heavy (six-inch) overhead irrigation after harvest and before planting the next crop.
- Limit the use of compost, poultry litter, and other P sources to prevent or remedy excess soil P.
- Provide supplemental K if needed with clean hay or straw mulch (1-2% K) or potassium sulfate (caution: salty).
- Add cover crops to the rotation whenever practical
  - Include legumes for N, grasses for SOM.
  - In rotations without cruciferous vegetables, include a radish, mustard, or other crucifer cover crop to help reduce plant pathogens.
  - Choose cover crops known to suppress RKN and other plant-parasitic nematodes.
  - Choose cover crops that are easily managed in the high tunnel, such as buckwheat, mustard, oats, and crimson clover, *or*
  - Periodically cut taller cover crops such as pearl millet or sorghum-sudangrass with a weed whacker or flail mower on a walk-behind tractor.
  - Provide overhead irrigation right after sowing the cover crop to ensure rapid emergence and uniform stand establishment, *or* plant the cover crop when the roof has been removed to admit natural rainfall.
  - Use occultation (black tarp or landscape fabric) after mowing for effective and labor-efficient no-till cover crop termination.
- Lengthen and diversify the crop rotation to limit buildup of RKN and plant pathogens.
- After harvest, return residues of healthy crops to the soil to recycle K. Remove diseased residues from the high tunnel; uproot and remove crops with visible RKN galls.

Organic management strategies against RKN and other pest nematodes include the following.

- Test your soil to identify nematodes. While RKN is the most common nematode pest, other species may be present that require different crop rotation strategies.
- Rotate the high tunnel to a non-host crop or cover crop for at least four months each year. For RKN, these include sorghum-sudangrass, sunn hemp, some cultivars of southern pea including Iron-Clay, velvetbean, French marigold, white lupin, oats, rye, and wheat.
- Solarize infested soil under clear plastic for at least four to six weeks during summer. Solarization or biosolarization (tilling in mustard or other green manure just before laying clear plastic) after a non-host cover crop can be as effective as chemical fumigation.

- NOP-allowed biological nematicides based on the parasitic fungus *Paecilomyces lilacinus,* used in conjunction with the above measures, can further reduce pest nematode populations. These products cannot by themselves control RKN.
- Good soil health practices, including crop diversity, cover crops, and sound nutrient management can promote a microbiome that enhances crop vigor and may include natural enemies of pest nematodes.

As with field soil management, development of a soil health program for high tunnel production requires a site- and operation-specific approach. See **Farm Story 7** (below) and **Farm Story 3** on page 41 for examples of successful soil health strategies in high tunnels.

FARM STORY 7
Haygrove High Tunnel Rotation

Elmwood Stock Farm, Georgetown, Kentucky

For protected crop production, Elmwood Stock Farm uses a Haygrove high tunnel system, which covers a wider area of field under a series of three hoop structures joined together along what would be the sidewalls of a single hoophouse (Figure 7). Each unit is 270 ft long and 26 ft wide (total width 78 ft, area covered 21.060 sq ft or 0.48 ac). Because this system is not designed to bear snow loads, which can be substantial in Kentucky, the farmers remove the plastic roof in the fall and replace it in March. While this entails additional labor, it allows winter precipitation to reach the Haygrove production area and leach out salts.

Figure 7. Leafy greens nearing harvest and tomatoes in vegetative growth (left), and strawberries on landscape fabric (right) in the Haygrove high tunnel system at Elmwood Stock Farm.

For many years, the farmers implemented a three-year rotation with one bay for each phase of the rotation:

- Year 1, March: Rototill winter cover crop (cereal grain, vetch, pea), install plastic roof on the tunnel, apply 100 lb organic fertilizer (10-2-8 ~ 60 lb N, 12 lb P_2O_5, and 48 lb K_2O per acre), and transplant tomatoes. Mulch with hay grown on the farm.
- Year 1, September: Finish tomato harvest, remove stakes and string. Spread 100 lb 10-2-8 and till fertilizer + tomato residues into soil. Lay landscape fabric with planting holes and transplant strawberry starts. Remove plastic roof later in fall.
- Year 2: Replace roof in March, pick strawberries in May-June, Thin strawberry vines and crowns in July (thinnings sometimes used to start new plugs), remove roof in fall.
- Year 3 spring: Replace roof in March, pick strawberries in May-June.
- Year 3, end of June: Remove strawberry plants, landscape fabric, and tunnel roof, and plant a summer annual grass + legume cover crop. In some years, one to one and a half tons of on-farm compost is applied (six to nine tons per acre) just before cover crop planting.
- Year 3 fall: Till in summer cover and plant winter cover of rye or wheat with hairy vetch and winter pea.

Based on successes with winter greens after ginger in another single-bay high tunnel at Elmwood Stock Farm, the farmers modified the Haygrove rotation. Instead of removing the plastic roof after the second strawberry year, they reinforced the bows with props and followed the summer cover crop with a succession of kale, arugula, mizuna, baby greens, turnips, radishes, lettuce, and spinach through winter, until tomato planting time. Because this rotation leaves insufficient time for soil restoration (and strawberries have entailed a lot of labor for little profit) they will remove strawberries from the rotation, grow greens each winter, and alternate summers between tomato production and soil-building cover crops with the cover off.

Several features of this rotation address key soil health challenges in high tunnel production:

- A fairly diverse rotation with tomatoes once every two or three years reduces disease and pest risks and allows residues to be tilled in to recycle K and organic matter.
- Grass-legume cover crops restore SOM, soil organic N, and soil life.
- Hay mulch on tomatoes replenishes K.
- Use of compost and a balanced organic fertilizer (10-2-8 approximates the ratio in which harvests remove N, P, and K) at moderate rates minimizes buildup of P and salts.
- Regular removal of the plastic roof allows natural precipitation to leach out salts.

Over the years, the soil has remained healthy and friable, sustained crop growth and yields, and maintained sufficient biological activity to decompose residues well. A soil test five years ago when the Haygrove tunnels were under the original rotation, showed 4.1% SOM, optimum K levels in good balance with other nutrients, and mildly elevated P (126 ppm, optimum range 50 -100). Since the farm's soil type is naturally high in P, this soil test result reflects sound nutrient budgeting and management.

> For more information on soil health in organic high tunnels, see **Resources 25 – 30.** Recent research on RKN management in high tunnels is discussed on pages 88-89.

Managing Soil Health in Organic Rice Production

Rice is normally grown in flooded fields or paddies, which create a very different soil environment and microbiome from other agricultural soils. Under saturated soil conditions, anaerobic decomposition of organic residues forms soluble organic compounds, and N mineralization yields ammonium (NH_4^+) rather than nitrate (NO_3^-). Living roots of rice and other flood-tolerant plants bring sufficient oxygen into the rhizosphere (root zone) to convert some NH_4^+ to NO_3^- and facilitate plant uptake of both forms of soluble N. Although leaching ammonia volatilization and denitrification tend to reduce N use efficiency in rice fields, good organic management with cover crops, organic amendments, and microbial inoculants can improve N cycling and sustain yields (Velarca, 2016). However, microbial processes in saturated soil convert some organic carbon and soluble N into methane (CH_4) and nitrous oxide (N_2O) respectively, two powerful greenhouse gases (GHG) that add to the climate impacts of rice production.

Although rice prefers moist yet aerated soil conditions, it is more flood-tolerant than most weeds. Thus, flooding is used in lieu of cultivation or herbicides as the primary weed control tactic in most U.S. rice production. Some weeds, notably barnyard grass, remain problematic in rice and can be difficult to manage without herbicides.

Rice fields are normally drained after grain harvest, providing an opportunity to restore soil aeration and soil life, grow winter cover crops, or rotate into other cash crops or pasture. 'Durana' white clover prior to a rice crop fixes substantial amounts of N, builds organic matter, and has become a leading cover crop in organic rice production in southeast Texas (Steve Diver, University of Kentucky, 2021, personal communication). However, growing a cover crop before rice can complicate field preparation for rice planting and increase CH_4 emissions during flooding (Dou et al., ORG project 2012-02983).

Organic farmers can take either of two approaches to the soil health challenges of rice production: grow the crop in naturally wet soils or grow it with no or minimal soil flooding.

Many soils in the Mississippi Delta region and southeast Texas drain slowly and are naturally subject to periods of saturated or flooded conditions for part of the year. In such soils, good soil health might include the capacity to support a diversity of aerobic and anaerobic organisms that maintain fertility and efficient nutrient cycling through both wet and drier periods. Naturally wet soils with level topography are especially suited to rice production, since they will hold water better during the flooded phases of the rice crop cycle and may support a microbiome that facilitates nutrient cycling in wet conditions. In addition; prior to cultivation, these areas provided vital habitat for migratory water birds and other wetland wildlife, which a crop rotation that includes rice production helps maintain.

Microbial inoculants, used in combination with cover crops and compost, can enhance organic rice yields. Historically, nitrogen-fixing cyanobacteria (blue-green algae) living symbiotically with the aquatic plant azolla (duckweed fern) have played a key role in rice crop production worldwide; however, azolla can become invasive and its use in the U.S. is limited. Clay formulations of viable dormant cyanobacteria, and multispecies microbial inoculants have improved organic rice yields and reduced fertilizer needs in field trials (Steve Diver, 2021, personal communication).

SPECIAL TOPIC

The strategy of growing rice without flooding is based on observations that rice roots remain healthier and utilize nutrients more efficiently in non-flooded, aerobic soil conditions (Thakur et al., 2016). An alternate wetting and drying (AWD) strategy, in which rice fields are periodically drained for parts of the crop life cycle, then re-flooded, can reduce water usage and GHG emissions while sustaining rice yields (Oo et al., 2018; Tariq et al., 2017). Small-scale organic rice farmers in Africa, India, and south Asia have taken this a step further in a labor-intensive method called the System of Rice Intensification or SRI (Uphoff, 2013-14) that eliminates flooding, manages weeds by cultivation, utilizes organic methods including compost for nutrients, and can greatly increase yields over traditional paddy rice production by improving plant and soil health (see **Concept 8**).

The AWD method is more practical than SRI for larger scale mechanized rice production. In addition, wildlife conservationists have raised concerns that not flooding rice fields in the lower Mississippi Valley would eliminate vital habitat for migrating sandhill cranes and other water birds since most of the region's native wetlands have been lost (Sesser et al., 2016). NRCS conservation programs offer cost-share for extending field flooding beyond rice harvest to enhance water bird habitat.

CONCEPT #8
System of Rice Intensification

In traditional, small-scale, labor-intensive paddy rice production, seedlings are grown in outdoor nurseries for up to 60 days and are set out in clumps of three to five seedlings in high density plantings to compensate for the stress of flooding. Because continuous flooding can damage up to 75% of the root system by the time of rice harvest, yields are low, which contributes to food insecurity in developing countries that depend on rice as a dietary staple. As part of his efforts to relieve poverty and hunger in the late 20th Century, Jesuit priest Henri de Laulanié worked with traditional farmers in Madagascar to develop the System of Rice Intensification (SRI) (Uphoff, 2013-14). This organic rice production system has several key components:

- Young (15 day) rice seedlings are set out singly on 10- or 12-inch centers.
- Compost is applied for fertility.
- Soil is kept moist but not flooded.
- Weeds are hoed as needed (facilitated by wide, even plant spacing).

Farmers who adopted this approach reported that yields doubled or even quadrupled over the flooded system. Further research by Dr. Norman Uphoff of Cornell University and others showed that SRI greatly improves soil health and allows the crop to grow much larger, deeper root systems to partner with mycorrhizal fungi and other beneficial soil microbes, utilize N and other nutrients more efficiently, and sustain higher yields. Moist but non-flooded soil conditions sharply reduce CH_4 emissions while somewhat increasing N_2O emissions. Enhanced root function and nutrient efficiency allow farmers to reduce N fertilizer rates, input costs, and N_2O emissions.

Tips for maintaining soil health and good yields while limiting GHG emissions and other environmental impacts during rice production include the following.

- Utilize slow draining or naturally wet soils in level bottomland for flooded rice production.
- Utilize N-fixing cyanobacteria to provide N during flooded rice production.
- Rotate rice with other crops that do not entail flooding the soil.
- Plant rice cultivars with enhanced competitiveness toward weeds.
- Utilize cover crops and organic amendments to build SOM and soil health. Schedule their use so the field is not flooded when large amounts of fresh or decomposing organic residues are present.
- If your rice fields were originally upland or well-drained bottomland, and are not important water bird habitat, consider AWD methods, or SRI for small-scale production.
- If your rice production area was originally wetland and/or is currently providing vital habitat for water birds or other wildlife, use standard flooded field methods or an AWD schedule compatible with maintaining water bird habitat (Sesser et al., 2016).

Recent research on organic rice production is summarized on pages 83-86.

CHAPTER III: RESOURCES

Knowing your Soil

1. **NRCS Web Soil Survey** https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm Use this tool to identify your soil types and their inherent capabilities and limitations.

2. **Conservation Tillage Systems in the Southeast: Production, Profitability, and Stewardship**. SARE Handbook 15. Jason Bergtold and Marty Sailus, editors, 2020. https://www.sare.org/resources/conservation-tillage-systems-in-the-southeast/
   Chapters 17 – 20 (pp 243 – 298) discuss inherent soil properties and best conservation tillage strategies for Coastal Plain, Piedmont, Blackland Prairie, and Tennessee Valley regions.

3. **The Nature and Properties of Soils,** 15th ed., by Ray R. Weil and Nyle C. Brady, 2017. Pearson publishers, 1086 pp.
   In-depth descriptions of soil types, inherent and dynamic (management-influenced) properties in accessible language.

General Resources on Soil Health Management and Cover Crops

4. **Organic Farming Research Foundation** (OFRF) offers practical guidebooks on soil health and organic farming, https://ofrf.org/research/reports/.
   Based on a review of 15 years of USDA-funded organic research and farmer experience, the guidebooks include:

   a. *Building Organic Matter for Healthy Soils: An Overview*
   b. *Cover Crops: Selection and Management*
   c. *Nutrient Management for Crops, Soil and the Environment*
   d. *Weed Management: An Ecological Approach*
   e. *Practical Conservation Tillage*
   f. *Plant Genetics: Plant Breeding and Variety Selection*
   g. *Water Management and Water Quality*
   h. *Organic Practices for Climate Mitigation, Adaptation, and Carbon Sequestration*
   i. *Understanding and Optimizing the Community of Soil Life*
   j. *Reducing Risk through Best Soil Health Management Practices in Organic Crop Production*
   k. *An Organic Approach to Increasing Resilience*

5. **eOrganic** provides on-line articles, videos, archived webinars, and other information resources for organic producers at https://eorganic.info/, including:

   a. Webinars based on OFRF soil health guidebooks https://eorganic.org/node/25148.
   b. Soil and Fertility Management https://eorganic.org/menu/867.
   c. Cover cropping https://eorganic.org/menu/872.
   d. Plant Disease Management https://eorganic.org/menu/876.

e. Weed Management https://eorganic.org/node/2551.
f. *On-farm Production and Utilization of AM Fungus Inoculum*. David Douds, 2015. Practical instructions for propagating indigenous AMF inocula on bahiagrass in grow bags. https://eorganic.org/node/3130.
g. Anaerobic Soil Disinfestation (ASD) for Soilborne Disease Management. Webinars https://eorganic.org/node/5831 and https://eorganic.org/node/10408.

6. **USDA Sustainable Agriculture Research and Education (SARE)** offers books, bulletins, and other information resources, https://www.sare.org/resources/. Titles include:

    a. *Building Soils for Better Crops*, by Fred Magdoff and Harold Van Es, 3rd ed. (SARE Handbook 10)
    b. *Managing Cover Crops Profitably*, by Andy Clark,. 3rd ed. (SARE Handbook 9)
    c. *National Cover Crop Surveys* offer farmers' viewpoints on cover crop benefits. https://www.sare.org/publications/cover-crops/national-cover-crop-surveys/.
    d. *Cover Crop Economics: Opportunities to Improve your Bottom Line in Row Crops*. 2019 bulletin, 24 pp. Based on Cover Crop Surveys in 2012-2017.
    e. *Conservation Tillage Systems in the Southeast* (SARE Handbook 15, see above).
    f. *Special Topics with Cover Crops and Soil Health*: 2017 National Conference sessions on organic and specialty crops, and grazing cover crops.
    g. *Cover Crop Innovators Video Series,* interactive map of video stories, 2016.
    h. *Cover Crops for Sustainable Systems*, Andy Clark, 2015.
    i. *Transitioning to Organic Production*, 2003 bulletin.
    j. *Cover Crops for Sustainable Crop Rotations*, 2015 bulletin.
    k. *Diversifying Cropping Systems*, 2004 bulletin.
    l. *Cultivating climate resilience on farms and ranches*. Laura Lengnick, 2018.

7. **USDA Natural Resources Conservation Service (NRCS)** offers conservation technical and financial assistance with a strong emphasis on soil health. Visit NRCS home page https://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home/, scroll down and click on "Visit NRCS State Websites" to learn more about NRCS programs in your state.

    a. **Environmental Quality Incentives Program** (EQIP) and **Conservation Stewardship Program** (CSP, offer payments for cover cropping, rotational grazing, and other soil health practices, with separate funding pools for organic producers. Find out more by clicking "financial assistance" on home page.
    b. **Soil Health** web page, with links to farm stories and information on management practices https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/.
    c. **Conservation for Organic Farmers** including crop rotations, cover crops, reducing tillage, organic weed management, and a link to upcoming and archived webinars https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/organic/.
    d. **PLANTS Database** provides information on plants of the US including cover crops. Go to https://plants.sc.egov.usda.gov/java/, enter the cover crop in "name search" and download the Plant Guide (pdf or doc) under General Information.

8. **Appropriate Technology Transfer for Rural Areas** (ATTRA, https://attra.ncat.org/) offers individual consulting (1-800-346-9140 or askanag@ncat.org) and information bulletins, webinars, and podcasts on a wide range of topics including:

    a. Soil health (https://attra.ncat.org/topics/soils-compost/)
    b. Organic production (https://attra.ncat.org/topics/organic-farming/).
    c. Pasture, rangeland, and grazing management (https://attra.ncat.org/topics/pasture-rangeland-and-grazing-management/)

Cover Crops and Other Soil Health Practices for the Southern Region

9. **Southern SARE Resources** https://southern.sare.org/resources/. Searchable database of SARE books, bulletins, videos, and other resources. Relevant titles includ e:

    a. *Annual Cover Crops in Florida Vegetable Systems* (three U. Florida info sheets).
    b. *Organic Grain Production Video Series*, including organic no-till soybean.
    c. *Cover Crops for Weed Management in Row Crops*, by Rachel Atwell, Chris Reberg-Horton, and Andrew Price, 2016. Conventional and organic systems.
    d. *Reduced Tillage and Cover Cropping Systems for Organic Vegetable Production*, Mark Schonbeck and Ron Morse, 2007. Based on research in VA and GA.
    e. *Nitrogen Release from Cover Crops*, by Steven Mirsky, Victoria Ackroyd, Julia Gaskin, Russell Hendrick, 2016.
    f. *Soil Biology: Cover Crops and Disease Suppression*, by Kathryne Everts, 2016.
    g. *Economics of Cover Crops I (agronomic crops, NRCS cost share) and II (vegetable crops)* based on research in Alabama and Georgia.
    h. *Perennial Grass Cover Crops Can Optimize Wine Grape Growth*, by Gill Giese, 2016. Sod saves soil and limits excessive vine growth in vineyards.
    i. *Grazing Cover Crops in Cropland*, by Jose Dubeux, Jason Warren, and Alan Franzluebbers, 2016. Cover crops to provide grazing while building soil health.
    j. *Introducing Annuals in Grazed Pastures*, by Bisoondat Macoon, J.B. Daniel, Johnny Rogers, and Alan Franzluebbers. 2016. Enhance soil health and extend grazing season in the southern High Plains.

10. **Southern SARE Project Reports**. The following provide practical information from on-farm trials:

    a. *Modified method for roller-crimper no till system in the Southeast Coastal Plain*. Mary Connor, Three Sisters Farm in SC. Occultation (silage tarp) to enhance weed and cover crop control. https://projects.sare.org/project-reports/fs16-288/
    b. *Financial analysis of growing no till organic field corn and wheat using cover crops for weed suppression*. Virginia farmer Joel Thomas Yowell shares successes and lessons learned. https://projects.sare.org/project-reports/fs08-231/
    c. *Mechanical* [intensive tillage] *and biological* [cover crops, less tillage] *strategies to remove invasive Bermuda grass in organic vegetables*. Jennifer Taylor, Lola's Organic Farm, Glenwood, GA. https://projects.sare.org/project-reports/fs13-267/

d. *Using mycorrhizal fungi to improve soil health and increase yields in organic vegetable farms*. Drs. Alexis Raceils and Pushpa Soti, U. Texas Rio Grande Valley. https://projects.sare.org/project-reports/os17-108/
e. *Improving tropical soils by utilizing organic wastes*. Farmers solve soil infertility and water pollution by composting locally generated wastes to use on fruit crops. Andre Sanfiorenzo, Puerto Rico. https://projects.sare.org/sare_project/fs95-028/?ar=1995
f. Organic soil amendments of agricultural by-products for vegetable production systems in the Mississippi Delta region. Tina Gray Teague, Arkansas State U. https://projects.sare.org/project-reports/ls92-049/

11. **Carolina Organic Commodities and Livestock Conference 2012: Selected Live Broadcasts**, including several on soil health and fertility. https://eorganic.org/node/7469

12. **Assessing Nitrogen Contribution and Rhizobia Diversity Associated with Winter Legume Cover Crops in Organic Systems Webinar**, by Julie Grossman, NC State U, 2010. Practical tips for on-farm assessment and evaluation of winter legume cover crop cultivars. https://eorganic.org/node/5668

13. **Southern Cover Crop Council**, recommended cover crop species and cultivars, planting, management, and termination for Coastal Plain, Piedmont and Appalachian, and Blackland Prairie regions. Articles also cover tools and techniques for no-till and minimum-till cash crop planting into cover crop residues. https://southerncovercrops.org/

14. ATTRA Cover Crop information for the Southern region:

    a. **Cover Crop Options for Hot and Humid Areas**. J. Duncan, 2017. Info sheet https://attra.ncat.org/product/cover-crop-options-for-hot-and-humid-areas/. Podcastat https://attra.ncat.org/cover-crop-options-for-hot-and-humid-areas-part-3-suggested-cover-crops/
    b. **Putting your Garden to Rest**, by Nina Prater and Luke Freeman, Sept 23, 2020. https://attra.ncat.org/putting-your-garden-to-rest-workshop/

15. **USDA Plant Hardiness Zone Map**, updated in 2012, can help you select the best cool-season cover crops for your region. https://planthardiness.ars.usda.gov/PHZMWeb/.

16. **Growing Small Farms Cover Crop Portal**, North Carolina State University. https://growingsmallfarms.ces.ncsu.edu/growingsmallfarms-covcropindex/. Includes three grower profiles on cover cropping strategies and rotations in North Carolina.

17. **Center for Environmental Farming Systems, NCSU.** https://cefs.ncsu.edu/. Organic research unit offers science-based bulletins on soil health topics including:

    a. *Weed Management on Organic Farms*, by Denise Finney and Nancy Creamer, 2008, 34 pp. https://content.ces.ncsu.edu/weed-management-on-organic-farms
    b. *Summer Cover Crops*, by Nancy Creamer and Keith Baldwin, 2019. https://content.ces.ncsu.edu/summer-cover-crops
    c. *Conservation Tillage on Organic Farms,* by Keith Baldwin, 2006. https://content.ces.ncsu.edu/conservation-tillage-on-organic-farms

18. **Cover Crops for Vegetable Growers**, 2016, by farmer and author Pam Dawling, of Louisa, VA. Detailed guidance on cover crop selection and scheduling for complex diversified vegetable operations in the central Virginia Piedmont. https://www.slideshare.net/SustainableMarketFarming/cover-crops-for-vegetable-growers-66632291. More on cover crops, soil health, and vegetable production at author's website, https://www.sustainablemarketfarming.com/.

19. **No-till Cover Crops**, 2019 video by Shawn Jadrnicek at Wild Hope Farm. Tractor scale, 12 acres in organic vegetables. https://www.youtube.com/watch?v=3HSeEpYwP44.

Perennial Cropping Systems, Permaculture, and Agroforestry

20. **USDA National Agroforestry Center** provides excellent information on alley cropping, silvopasture, windbreaks, and other production systems that utilize trees for production, soil conservation, and soil health. Resources include information sheets and other publications, videos, webinars, research reports, and more. https://www.fs.usda.gov/nac/

21. **Perennial Vegetables**, by Eric Toensmeier, 2007, 224 pp. How to grow over 100 perennial food-producing plants including species adapted to wet, dry, infertile, or otherwise challenging soils in temperate, subtropical, or tropical climates. Order at https://www.chelseagreen.com/product/perennial-vegetables/.

22. **Edible Forest Gardens**, by David Jacke and Eric Toensmeier, 2005, two-volume manual on how to build a diverse, integrated, forest-garden ecosystem that provides food, fiber, fuel, forage, medicinal products, and biomass to restore and sustain soil fertility. https://www.chelseagreen.com/product/edible-forest-gardens-2-volume-set/.

23. **The Bio-Integrated Farm: A Revolutionary Permaculture-Based System Using Greenhouses, Ponds, Compost Piles, Aquaponics, Chickens, and More**, by Shawn Jadrnicek and Stephanie Jadrnicek, 2016. Chelsea Green Publishing, 384 pp. https://www.chelseagreen.com/product/the-bio-integrated-farm/. Additional information at https://www.wildhopefarm.com/. Excellent video, No-till Cover Crops (2019) at https://www.youtube.com/watch?v=3HSeEpYwP44.

24. **ATTRA bulletins on Agroforestry**, https://attra.ncat.org/topics/agroforestry/.
    a. Agroforestry, an Overview, Alice Beetz, 2011.
    b. Fruit Trees, Bushes, and Vines for Natural Growing in the Ozarks, Guy Ames, 2016.
    c. Sustainable Pecan Production, Steve Diver and Guy Ames, 2000.

Soil Health in the High Tunnel

25. **Covers Under Cover: Managing Cover Crops in High Tunnels**. Tim Coolong, Julia Gaskin, Erin Haramoto, Krista Jacobsen, Jenny Moore, Tim Phillips, Rachel Rudolph, and Annette Wszelaki. U. Kentucky Extension, 2020, 4 pp. Available at: http://www.uky.edu/ccd/sites/www.uky.edu.ccd/files/CoversUnderCover1.pdf.

26. **Soil Management Using Cover Crops in Organically Managed High Tunnels**, by John Beck, Sanjun Gu, Melissa Bell, 2016, 2pp https://southern.sare.org/resources/soil-management-using-cover-crops-in-organically-managed-high-tunnels/?tid=1.

27. **Year Round Hoophouse Vegetables**, by Pam Dawling, 2019, powerpoint slide presentation includes tips on managing salinity and RKN in high tunnels (slides 158-168). https://www.slideshare.net/SustainableMarketFarming/year-round-hoophouse-vegetables-pam-dawling.

28. **Breaking Bad Habits: Integrating Crop Diversity into High Tunnel Production Systems**. Webinar by Cary Rivard, Kansas State U. Includes tips on developing a profitable, diverse rotation for high tunnel production. https://eorganic.org/node/29206.

29. **Rotations and Management Strategies in the Organic High Tunnel**. NRCS webinar by Krista Jacobsen, U Kentucky; Julie Grossman, U Minnesota; and Cary Rivard, Kansas State U, Dec. 16, 2020. Excellent information on crop rotations and cover crops for high tunnels. http://conservationwebinars.net/webinars/rotations-and-management-strategies-in-organic-high-tunnels/?sr=wp~ondemand.

30. **University of Florida information sheets** on pest nematode management, including:
    a. *Nematode Management in Organic Agriculture*, by Romy Krueger and Robert McSorley, 2017. https://edis.ifas.ufl.edu/pdffiles/NG/NG04700.pdf .
    b. *Nematode Management in the Vegetable Garden,* by William Crow, 2017. https://edis.ifas.ufl.edu/ng005.
    c. *Cover Crops for Managing Root Knot Nematodes,* by Harsimran K. Gill and Robert McSorley, 2017. https://edis.ifas.ufl.edu/pdffiles/IN/IN89200.pdf.

Keeping Up with Soil Health Research Developments: Searchable Databases

31. **Sustainable Agriculture Research and Education** (SARE) grants database at https://projects.sare.org/search-projects/. Select region or state, and topic of interest from the menu under the Practices field. Or enter the Project Number for a specific project.

32. **USDA Current Research Information System** (CRIS) https://cris.nifa.usda.gov/cgi-bin/starfinder/0?path=crisassist.txt&id=anon&pass=&OK=OK. To learn more about OREI and ORG projects referenced in this Guide, enter the award number (e.g., 2020-12345) in the "Grant No." field.

33. **Organic Farming Research Foundation** (OFRF) funded projects including progress and final reports at https://ofrf.org/research/research-grant-database/. Search on surname of principal investigator.

34. **The Organic Center** provides updates on breaking research at https://www.organic-center.org/research, including new findings in soil health practices and outcomes.

35. **Organic Seed Alliance** (OSA) https://seedalliance.org/ supports the development of organic crop seed and cultivars for organic production, with a priority on engaging farmers as equal partners in plant breeding and seed production endeavors.

CHAPTER IV
A Deeper Dive into Soil Types and Inherent Soil Properties in the South

The Southern region's dominant soil order, Ultisols, consist of old, highly weathered soils that developed under forest cover in warm, rainy climates (Weil and Brady, 2017). Millennia of weathering has leached much of the clay out of the topsoil (A horizon or plow depth) and deposited it further down the profile to form a clay-enriched subsoil (B horizon) which might be several feet thick and is often brick red, orange, or yellow in color due to the presence of iron oxide clays. In some Ultisols, a leached-out, light colored E horizon, low in both clay and organic matter, occurs below the A and above the B. Thus, the soil's most concentrated biological activity and highest organic matter (A horizon) is physically separated from the region of highest clay content (B horizon). Ultisols tend to be acidic and relatively low in nutrients; however, appropriate liming and good soil health management can greatly enhance their productivity. Since the B horizon can hold significant reserves of plant-available potassium (K), sulfur (S), nitrogen (N), and other nutrients, as well as moisture, it is especially important to ensure that crop roots can penetrate deep enough to access these resources.

The Ultisol soils of the Southern Coastal Plain, stretching from eastern Virginia to much of Mississippi, typically have sandy topsoils with low SOM and low moisture holding capacity (about one inch in the top foot) and a sandy E horizon that is prone to compaction by machinery or heavy rainfall (Bergtold & Sailus, 2020). The underlying B horizon has more clay and higher moisture holding capacity. When autumn rains moisten the soil profile, winter cover crops like rye can penetrate the E horizon and allow subsequent cash crops to access B horizon moisture and nutrients, resulting in higher yields (Marshall et al., 2016). Another challenge with many coastal plain soils is that the B horizon is highly acidic and extremely low in organic matter, resulting in toxic levels of plant-available aluminum (Al), iron (Fe), and/or manganese (Mn) that can stop root growth even in the absence of a compacted layer. Liming, followed by subsoiling to work some of the lime into the acidic B horizon, can address this problem.

Despite these inherent challenges, good crop rotation and organic management of sandy, coastal plain soils can build SOM and sustain high yields with minimal nutrient inputs (Kloot, 2018). In addition, level to minimally sloping topography reduces risk of water erosion in the coastal plain, and many of these soils are considered prime farmland.

Just inland from the coastal plain, the Southern Piedmont stretches from central Virginia through North Carolina, northwest South Carolina, and across north Georgia into Alabama. Most of the soils here are also highly weathered Ultisols, deep and well drained but with fairly low CEC and inherent fertility. They have loam or sandy loam A horizons and red-clay B horizons whose "blocky" structure allows deep root penetration when moisture is adequate. However, the rolling topography increases risks of erosion by intense rainfalls, and many Southern Piedmont soils have a history of severe erosion with five to ten inches lost since the year 1700 (Bergtold & Sailus, 2020). If you see red clay at the *surface* of your field, erosion has removed much of the A horizon, leaving a clayey surface that is more prone to crusting, runoff, and additional erosion when exposed. Such fields may need diligent work to rebuild SOM and structure, yet several years of repair with deep-rooted cover or sod crops, organic amendments, and careful tillage can restore biological activity, tilth, moisture infiltration, and fertility.

Some soils in cooler parts of the South are Alfisols, whose formation process is similar to Ultisols but with less intense weathering and leaching and higher inherent fertility. In addition, some soils throughout the region are geologically younger without distinct horizons (Entisols) or with slight horizon development (Inceptisols) and may not have clay-enriched B horizons. For example, river bottom soils periodically receive sediment from flooding, which temporarily disrupts vegetation and soil biology but can also replenish mineral nutrients. Bottomland soils can be highly productive (except in a flood year) and less prone to drought than upland soils, though some are too poorly drained to farm, or too susceptible to erosion from flooding.

In the “ridge and valley” region of the Southern Appalachians from southwest Virginia and east Tennessee into northwest Georgia and northern Alabama, the ridges have sandy, acidic, somewhat shallow soils, while the valleys have limestone soils with high clay and silt content. Both have suffered severe erosion when tilled for crop production, and the valley soils are prone to topsoil compaction, forming hard clods when deep tillage brings clay to the surface. Yet, these soils respond well to cereal grain cover crops, whose fibrous roots relieve compaction and enhance tilth, water storage, and earthworm populations. (Bergtold & Sailus, 2020).

The Blacklands Prairie region, covering about 6,300 square miles in central Alabama and northeast Mississippi, contrasts with the surrounding Southern Coastal Plain, in that these soils are in the order Vertisols, which are inherently fertile but slow draining and difficult to manage (Bergtold & Sailus, 2020). Vertisols also occur in the Mississippi Delta region and the prairie regions of east-central Texas and southernmost Oklahoma. Rich in a type of clay that swells and shrinks dramatically with wetting and drying, these soils become very sticky and impossible to till when wet, forming deep, wide cracks as they dry. This shrink-swell action minimizes subsurface compaction and promotes deep infiltration of rainfall but necessitates precise timing and methods of tillage for successful production (Weil and Brady, 2017). Frequent tillage to combat cloddiness and facilitate planting can cause extreme erosion losses from sloping land (12 – 25 tons per acre annually), but strict no-till reduces yields and may not optimize soil health. Cover crops improve SOM and tilth, although some farmers report that winter cover crops can keep the soil too wet for timely cash crop planting (Bergtold & Sailus, 2020).

The lower Mississippi Delta includes flood plains and terraces along the Mississippi, Arkansas, and Red Rivers, whose fertile soils and smooth topography favor agriculture, with over half of the land area currently in crops. Soil types include clayey Vertisols and Alfisols, as well as Entisols and Inceptisols, tend to be wet, and often require artificial drainage and levees to protect fields from flooding.

The Ozark Plateau region of eastern Oklahoma and western Arkansas includes a diverse mosaic of soil types, most of which are more suitable for grazing, agroforestry, or native vegetation than for annual crops. The best farmland is located near rivers and streams, on “secondary banks” that are less subject to flooding than bottomland immediately adjacent to the watercourse. These soils present challenges similar to other Southern region soils, including erodibility, low SOM and fertility, and extra care required to avoid bringing clay clods to the surface during tillage.

Much of central and western Texas and Oklahoma have prairie soils of the Mollisol order. These soils are quite fertile, maintain higher SOM levels than most Southern soils, and remain soft and easy to work even when dry. Challenges include moisture limitation and vulnerability to wind and water erosion. Cover crops benefit soil health but must be selected and managed to avoid consuming too much moisture and thereby reducing the yield of the following crop. Irrigated systems that rely on groundwater must be managed to prevent accumulation of sodium, soluble salts, and/or alkalinity in the topsoil, and avoid unsustainable drawdown of the aquifer.

Most of the Florida peninsula has very different soils from the rest of the Southern Coastal Plain. Based on marine deposits, many of these soils have a sandy texture throughout the soil profile, and often a high water table. Dominant types include the acidic “flatwoods soils” formed under longleaf and slash pine forest, in which organic matter has leached out of the A and E horizons and accumulated in the B (Spodosols); geologically young soils without distinct horizons (Entisols); and alkaline, calcareous (marl) soils. Peat soils with very high SOM (Histosols) in the Everglades outflow regions of southern Florida are fertile but difficult to farm sustainably, as the organic matter oxidizes rapidly upon drainage and tillage for crop production, often causing the soil surface to subside by an inch or more per year (Weil and Brady, 2017). All of these soils are productive but nutrient losses through leaching can be costly to farmers and to water quality, and maintaining adequate SOM without building up surplus P can be challenging (see **Researcher Perspective 1**). In addition, the combination of semi-tropical climate and sandy soil exacerbates root knot nematode (RKN) problems.

Each of the soil types discussed in this chapter present both challenges and opportunities for organic production. Good soil restoration and conservation practices tailored to a site’s particular soil and climate can overcome serious challenges and render an initially difficult soil productive, whether the problems stem from its texture or other given traits, past unsustainable management, or both. Knowing your soil type, its inherent properties, and its current condition based on management history, will help you fine tune your land use strategies and soil health practices for successful outcomes.

RESEARCHER PERSPECTIVE 1.
Farming Florida Soils Sustainably

Dr. Danielle Treadwell, University of Florida

Florida soils are productive, evidenced by the value and volume of crop and livestock commodities produced annually. For years, many assumed that our sandy soils function mainly as a physical substrate for crop production, but that is changing, as more and more farmers understand that soil biology is essential to soil health, and soil health is vital to crop health. Many growers have adopted practices to improve soil quality, including reduced tillage, compost applications, and cover cropping. In north-central Florida, there is growing interest in integrated crop-livestock systems. Against all odds, farmers are reporting gains in soil organic matter and are improving their soil health assessment scores over time.

The majority of vegetable farmers plant cover crops annually in the summer (south of I-4) or the winter (Gainesville and north). Farmers growing high-value crops often succession-plant two to four cash crops followed by a cover crop.

Tillage is challenging to minimize in vegetable systems. Plasticulture and drip irrigation manage water and nutrients effectively and efficiently. In these systems, crop residue must not interfere with bed shaping and plastic mulch installation, and is therefore incorporated into the soil. Row middles are sprayed or cultivated, which entails additional tractor passes. Tillage is less intensive in annual row crop systems. Nonetheless, tillage probably poses the greatest hurdle to achieving soil health goals in Florida, particularly for organic producers who rely on cultivation to manage weeds.

While many crops are produced on sandy Entisols (citrus, vegetables), the muck soils near Lake Okeechobee and Zellwood, the sandy clay loam and loamy sands of the panhandle and even the marl soils of Homestead support profitable farms. Water management is key. Because the nitrogen and potassium flow with water, farmers use technology and hard work to retain or drain water from production areas. In poorly drained soils, soils with high water tables, and soils located in areas with heavy precipitation, farmers use drainage tiles, raised beds, or canal systems with ebb and flow networks to drain water. Irrigation scheduling is supported by soil moisture meters to manage irrigation precisely, following University of Florida guidelines at https://edis.ifas.ufl.edu/hs172. The challenge is to keep the nutrients in the root zone, which can be hard to do with the region's intense rainfalls and hurricanes.

Some soils are naturally high in P; in fact, P is mined throughout the state, particularly around the Tampa area. Poultry litter is the primary source of animal waste used in compost. It is available and affordable, and often processed and sold as a dehydrated and pelletized fertilizer 3-2-3 ($300/ton delivered). In some counties in southwest Florida, P application is prohibited during months of heavy rainfall. Low P inputs available to farmers include compost made locally from citrus meal, municipal waste, and other organic raw materials, and spent mushroom compost that Florida's mushroom industry sells in bulk to farmers. Small-scale farmers rely on locally produced compost.

This story was provided by Dr. Danielle Treadwell, Associate Professor and Extension Specialist in Organic and Sustainable Vegetable Production at University of Florida.

CHAPTER V
Soil Health and Organic Farming in the South: A Summary of Recent and Ongoing Research

Farmers, ranchers, and researchers have grappled for decades with the challenges of how to build healthy, fertile soils while maintaining crop yields. Because the efficacy of a particular practice or experimental treatment can vary with soil, climate, and farming system, results from a single site can be misleading. Our goal in developing this guidebook is to draw on the experience of multiple farmers and scientists in the southern region to identify robust trends that can point to practical applications. The following sections delve a bit deeper into recent and ongoing soil health research in the region.

Three USDA programs have effectively engaged producers and scientists in collaborative endeavors: Sustainable Agriculture Research and Education (SARE), Organic Research and Extension Initiative (OREI), and Organic Transitions Program (ORG) (**Resources 31** and **32** listed in Chapter III, page 69). Non-governmental non-profit organizations that support organic research include the Organic Farming Research Foundation (OFRF), Organic Center, and Organic Seed Alliance (**Resources 33 – 35**).

SARE has funded more than 170 projects on organic systems in the Southern Region, of which at least 75 addressed one or more aspects of soil management. OREI and ORG have funded 31 soil-related projects that included study sites in one or more southern states, and OFRF has funded six farmer-centered projects on aspects of soil management in the south.

Project reports referenced in the following discussion can be found at the following websites:

- SARE: https://projects.sare.org/search-projects/.
- OREI and ORG: https://cris.nifa.usda.gov/cgi-bin/starfinder/0?path=crisassist.txt&id=anon&pass=&OK=OK.
- OFRF: https://ofrf.org/research/research-grant-database/.

Nutrient Management and Organic Amendments

Organic farmers face a serious challenge: how to apply the "4 R's" of nutrient management, consisting of right form, amount, placement, and timing for organic nutrient sources. Too little N hurts yields; too much hurts soil health and water quality and increases GHG emissions; and even the right amount of N from poultry litter can overload P, inhibit AMF activity, and pollute surface waters with P in runoff (Hu et al., ORG 2012-02978; Osmond et al., ORG 2009-05488). While the negative impacts of conventional NPK fertilizers on SOM and biological nutrient cycling have been well documented (Khan et al., 2007; Khan et al., 2013; Mulvaney et al., 2009), relying on concentrated organic fertilizers can also weaken crop-soil-microbiome

- **Organic crops in healthy soils may need less NPK than recommended.**
- **Overapplying organic fertilizer can undermine soil health.**
- **Balancing carbon and nitrogen is critical.**

partnerships and perpetuate the need for costly nutrient inputs. Fortunately, research has begun to unlock the "black box" of nutrient dynamics in organic systems, and to provide guidance on best use of organic fertilizers.

The balance between carbon and nitrogen in the totality of organic inputs (amendments and cover crops) appears critical to soil health. Researchers in Washington compared soil health indicators after 11 years in organic vegetable rotations fertilized with compost (C:N ~20) or poultry litter (C:N ~7) at equivalent rates of total N. Compared to poultry litter, the compost-amended soil had 43% higher total SOM, 60% higher active SOM, and 35% higher microbial activity. Compost significantly increased the soil's potential to mineralize N, *and* to immobilize excess soluble N and thereby reduce N leaching and N_2O emissions (Bhowmik et al., 2016, 2017). Several studies in the Southern region have given similar results:

- In Virginia, yard waste compost built more SOM than either poultry litter or conventional fertilizer, while corn and soybean yielded equally well in all treatments (Bowden, SARE GS04-031).
- In an Arkansas apple orchard soil mulched with "municipal green compost" (C:N low enough to release N), fertilizing with poultry litter reduced SOM and microbial biomass. However, poultry litter improved SOM and microbial biomass in soil mulched with wood chips (high C:N) (Ford, SARE GS13-123).
- Field trials in Maryland showed greater soil health benefits from a grass + legume cover crop (balanced C:N) than either grass or legume alone, (Hooks et al., OREI 2010-01954).

Researchers estimated N mineralization from organic sources in four different soils in Georgia. Feather, blood, and fish meals released up to 80% of their N during the season of application, while alfalfa and other plant meals and poultry litter products mineralized N more slowly (10 – 50%) and finished compost released little N. Results were similar across soil types. However, N mineralization *from SOM* varied dramatically with soil texture and percent SOM, ranging from 9 mg/kg soil (~18 lb/ac) in a very sandy soil with ~1% SOM to 30 – 75 mg/kg (60 – 150 lb/ac) in sandy loams with ~3% SOM. In one field with a history of high N inputs from legumes and feather meal, SOM released more than 200 lb N within 12 weeks, a rate that would oversupply crops with N and result in nitrate leaching or denitrification. When a sudangrass cover crop was grown and removed to reduce excess N, annual N mineralization diminished to 60 – 100 lb/ac (Caberra, SARE LS16-269).

Standard soil test recommendations are based on a soil sample that goes only six inches deep, ignores soil life and N mineralization from SOM, assumes that the soil will "leak" nutrients, and overlooks the capacity of deep-rooted crops to recover subsoil nutrients. (Kloot, 2017). As a result, recommendations can far exceed the needs of crops in healthy, living soils. In a five-year University of South Carolina trial on Orangeburg loamy sand, organic corn, soybean, and wheat sustained high yields with half the recommended N and no supplemental P or K, while topsoil SOM increased from 1.2% to 1.7% and soil test P and K levels remained stable and sufficient. Winter grass-legume cover crops in the rotation attained high biomass (9,000 lb/ac) and provided ~ 110 lb N (legume fixation), 27 lb P, and over 200 lb K (from subsoil reserves) to following crops. Trials on 13 different soil types gave similar results and farmers in North Carolina, Ohio, Illinois, and North Dakota have greatly reduced NPK inputs on healthy soils without affecting yields (Kloot, 2017, 2018).

In organic field trials near Clemson, South Carolina, tomato and squash planted with or without tillage after rye + crimson clover showed no yield response to 50 or 100 lb N/ac. The cover crop contained about 130 lb/ac total N. In addition, years of organic management with diversified crop rotations and high biomass cover crops had boosted SOM to 4.6%, an unusually high level for the sandy loam at this site. Mineralization from SOM and cover crop apparently met crop N needs (Robb, SARE GS13-126).

Winter annual legumes provide a vital food source for the soil microbiome and support C and N cycling. The fine roots of crimson clover, hairy vetch, and Austrian winter pea were found to comprise 70% of total root biomass, and rapidly released plant-available N as they decomposed. Flail-mowed cover crops supported greater microbial biomass and released more N than the same covers terminated by disking or herbicide (S. Hu et al., ORG2010-04008).

A study of 13 organic tomato fields in California identified four with "tightly coupled nitrogen cycling," in which bulk soil nitrate-N remained low (~5 ppm, a level that protects water quality, minimizes N_2Oemissions, but normally causes crop N deficiency), yet the tomato crop sustained high yields and good quality. Seven fields were "N-saturated" with similarly high yields and higher soil nitrate-N, and two fields were N-limited, with low microbial activity, slow N mineralization, and lower tomato yields.

Tightly coupled fields had the highest levels of active and total SOM and a microbial community that interacted with plant root enzymes to promote efficient N release and uptake in the root zone. While crops received a little soluble N as fish emulsion or Chilean nitrate in crop rows, the bulk soil was amended with a yard waste compost with a moderate C:N ratio (15-18:1). N saturated fields received more N, mostly from lower C:N sources such as guano, poultry litter, and all-legume green manures. Total microbial activity was similar to the tightly coupled fields, but the microbial community showed less capacity to release N or build SOM. The authors believe that tightly coupled N cycling can be achieved in other crops and other regions through improved plant-soil-microbiome interactions (Bowles et al., 2015; Jackson and Bowles, 2013).

In the long-term trials at CEFS, organic rotations accrued more soil organic N than the conventional system and showed enhanced potential N mineralization yet *less* N leaching. This suggests that these rotations promoted more efficient N cycling, possibly through mechanisms similar to the California study (Mueller, SARE LS08-210).

On super-sandy soils, "spoon feed" water and N to crops.

Nutrient management can be especially tricky in soils that are very sandy throughout the profile, in which N mineralized before or after peak crop demand is rapidly lost to leaching. On-farm demos utilized soluble dyes to illustrate the movement of irrigation water through Florida's sandy soils, showing how easily these soils can be overwatered when crops are young and not consuming much moisture. When the water front moves below the reach of crop roots, soluble N is lost. Project participants minimized N losses by adding organic amendments in crop grow zones to improve water holding capacity, using larger starts for transplanting, applying short and frequent irrigations early in crop development, and reducing pre-plant fertilizer rates followed by side-dressing established crops (Simone, SARE OS05-026).

Current research in organic nutrient management includes:

- Farmer-participatory research to develop nutrient and water management strategies to optimize nutrient cycling, soil health, crop production, and weed and RKN management in Florida's sandy soils (Maltais-Landry, SARE LS 20-334).
- Cropping strategies to build SOM and soil health, avoid manure-related N-P imbalance, and maintain economic viability during the three-year organic transition (Weil, ORG 2019-03517; Woodley, ORG 2020-02277).
- Effects of N-P balance on weeds, insects, and soil microbiome, and optimizing N-P balance and crop yield with cover crops, low-P compost, and reduced poultry litter rates (Snyder, ORG 2019-03516).
- N cycling efficiency in organic and conventional crop rotations; optimizing N dynamics for production, water quality, and GHG mitigation (Hu, ORG 2018-03531).
- Investigation of N cycling benefits of cover crops (sunn hemp alone or with grasses) and reduced poultry litter rates in organic vegetables (Landry et al., OREI 2020-02119).

Amending soil with locally generated organic byproducts saves money and reduces "waste" problems.

The high cost of organic fertilizers can present significant barriers to organic transition for some growers. Researchers at Arkansas State University worked with limited-resource African American farmers to utilize locally available organic byproducts including cotton gin trash, rice hulls, and raw poultry litter. Farmers saved money and improved yields by composting these materials on farm for use on their crops (Teague, SARE LS92-049).

A group of farmers near Lake Carite in Puerto Rico have implemented the Law of Return to address two severe problems: extremely depleted and eroded soils that cannot grow healthy crops, and lake pollution from agricultural runoff and organic waste from nearby fruit processing plants and a poultry farm. By composting the waste for use on their citrus, coffee, banana, and annual crops, they have reduced the need for fertilizer, improved crop health, and protected the lake (Sanfiorenzo, SARE FS95-028).

Cover Crops for the Southern Region

Cover cropping entails initial expenditures for seeds, planting, and termination, but the investment pays off. Respondents in the nationwide SARE farmer surveys on cover cropping (**Resources 6c** and **6d**) reported that cover crops improve soil health, reduce input costs, help with weed control, and stabilize crop yields. Cover cropping improves farmers' bottom lines especially when:

- The cover crop is one component of an integrated soil health system.
- Cover crops are used annually for several years or longer.
- Cover crops are selected for specific goals (fix N, build SOM, control weeds, etc.).
- Cover crops are rotationally grazed in a crop-livestock integrated system.

Farmers often hesitate to plant cover crops because they fear that, like weeds, the cover crop will consume precious moisture and nutrients without providing a marketable product. It is true that a cover crop can leave the next crop short of moisture in a dry climate or a drought year, and that a high C:N crop like millet or rye can temporarily tie up N. However, cover crops can also:

- "Mop up" excess soluble N and slow-release it to following crops, thereby reducing fertilizer costs and protecting water quality.
- Recover subsoil nutrients and return them to the topsoil.
- Improve soil structure, aeration, and moisture holding capacity.
- Break through hardpan and give the following crop access to subsoil moisture and nutrient reserves.
- Sustain the soil microbiome between successive cash crops.

Cover crops:

- Utilize moisture and nutrients.
- Improve soil moisture holding capacity and nutrient cycling.

RESEARCH NEED:
Practical soil health strategies for semiarid regions.

In two coastal plain soils in South Carolina (Faceville sandy loam and Fuquay loamy sand), roots of a moderate biomass winter rye cover crop (2,200 – 5,000 lb/ac) penetrated the compacted E horizon, allowing the following cotton crop to access moisture and nutrients in the underlying clay-enriched B horizon. Within two years, rye increased topsoil SOM to 1.4% (vs. 0.9% for no cover), enhanced the soil's water holding capacity by 1.1 to 1.5 inches, and boosted cotton yields by 20 – 50% by improving access to moisture (Marshall et al., 2016).

In trials at CEFS, southern pea (C:N 15), sorghum-sudangrass (C:N 57), foxtail millet, and a millet-southern pea mix reduced soil soluble N levels (compared to fallow) while they were growing and for a few weeks after they were tilled in. Yet, soils from all cover crop treatments showed net N mineralization during a four-week incubation, with the greatest amount from the legume. Thus, the cover crops absorbed excess soluble N, then gradually released N after termination (O'Connell, SARE GS10-088).

Researchers at Clemson University evaluated water consumption by winter rye, crimson clover, and mixtures of winter cereals, legumes, and crucifers. Compared to either weedy or weed-free fallow, none of the covers depleted soil moisture while growing, or after termination. A five-way mix of rye, oats, crimson clover, hairy vetch, and Austrian winter pea developed the most biomass with the highest water use efficiency. The authors noted that these trials were conducted during two years with above average rainfall and should be run again in drier years (St. Aime et al., 2020; Narayanan, SARE project OS16-096).

In drier regions, short-term water use by cover crops can become a bigger worry. For example, alfalfa can deplete soil moisture and severely hurt subsequent dryland grain yields (Menalled et al., 2012). On the other hand, cover crops improved soil porosity and cut irrigation needs by 57% on a potato farm in Colorado (Krebs, 2019). Researchers at Texas A&M are conducting innovative studies with organic farmers in the Texas High Plains to optimize cover cropping practices for low-rainfall regions. Projects include:

- Diversified crop rotations of cotton with other production and cover crops, and subsurface compost application to improve soil moisture, microbial activity, nutrient cycling, and net economic returns (DeLaune, ORG 2020-02286).

- Documenting the effects of rye, vetch, radish, and mixtures on soil moisture levels from surface to 60 inches, active and total SOM, and microbial and enzyme activities (Lewis, SARE LS19-313).
- Transition from irrigated crops to low-irrigation and dryland production systems. Project will measure effects of crop rotations including moisture-efficient forages on soil health and water holding capacity (West, SARE LS20-341).

Cover crops for the Coastal Plain and Piedmont:

- Late-planted winter covers can generate high biomass.
- Best summer covers include sorghum-sudangrass, pearl millet, and sunn hemp.

Adverse weather delayed establishment of two winter cover crop trials near Clemson, South Carolina (upper Piedmont). A November 8, 2016 planting was followed by drought; severe freezes early the next winter delayed planting to January 26, 2018. Yet, cereal grains attained substantial biomass (two tons per acre) by late April or early May. While crimson clover, radish, and turnip only reached about one ton per acre, a five-way mix of rye, oats, hairy vetch, crimson clover, and Austrian winter pea developed the highest biomass, about three tons per acre. Additional on-farm research is documenting benefits of these cover crops for SOM, compaction, N mineralization, and crop yields (St. Aime et al., 2020; Narayanan, SARE OS16-096S and OS18-118).

Researchers at Auburn University in Alabama noted that winter rye yielded weed-suppressive mulch that persisted for "much of the growing season" while sunn hemp was the best summer cover crop, combining high biomass, weed suppression, drought tolerance, and non-palatability to deer (Kloepper et al., OREI 2005-04494).

In the coastal plain of North Carolina, sorghum-sudangrass, pearl, Japanese, and foxtail millets, southern pea, sesame, and buckwheat suppressed weed biomass 85 – 97% compared to weedy fallow. Pearl millet and sorghum-sudangrass gave the most biomass and weed control, while southern pea suppressed weeds much better than a similar biomass of soybean (Creamer, 1998). Others have reported much higher biomass for sorghum-sudangrass and pearl millet than southern pea, soybean, or buckwheat (Shroeder-Morino, SARE LS07-200).

Sunn hemp, sorghum-sudangrass, and sesame performed well as summer cover crops in Louisiana, Mississippi, and Alabama. However, sorghum-sudangrass exerted allelopathic activity against fall lettuce and reduced nutrient availability to fall broccoli and cabbage, requiring higher poultry litter rates to maintain yield. Japanese millet outperformed buckwheat as a short season cover crop in the heat of summer. (Motsenbacher, SARE LS10-230).

Ongoing cover crop research includes:

- Interseeding white clover, buckwheat, or radish into corn to suppress weeds, relieve compaction, and mobilize P. Trial in Clemson, SC (Narayanan, SARE LS20-133).

- Role of cover crops in mitigating the impacts of climate change and hotter temperatures on the soil microbiome, soil health, and crop yield. Study sites include Alabama, Tennessee, and Kentucky (Haruna, SARE LS20-335).
- Development of crimson clover, winter pea, and hairy vetch cultivars adapted to the South as well as other regions (Mirsky et al., OREI 2015-07406 and 2018-02820).

Cover crops for tropical and semi-tropical regions:

- Sunn hemp has outperformed other tropical legumes in several trials.

Sunn hemp, sorghum-sudangrass, pearl millet, and lablab bean were evaluated in Harlingen, TX (lower Rio Grande Valley). Cover crops were planted in July in a silty clay loam with poor drainage, alkaline pH (8.0), high calcium (Ca) and very low SOM, grown for eight weeks, and tilled in. Pearl millet failed to establish and appeared unsuitable for summer planting at this site. Four weeks after incorporation, the other three cover crops enhanced SOM, soil test P and K, and mycorrhizal fungal spore counts, while SOM decreased in the no-cover control. The difficult soil conditions and low rainfall limited cover crop biomass, which ranged from 2500 lb/ac for sorghum-sudangrass, to 850lb/ac for lablab. Sunn hemp prefers well drained soil with a pH of 5.0 -7.5, and its growth was likely limited in this soil, yet it enhanced SOM, plant available N, and AMF spore count more than the other crops. In nearby Edinburg, Texas, sunn hemp developed twice the biomass and height attained by southern pea, hosted a greater diversity of insects, yet suffered much less insect damage (Rugg, SARE GS15-148; Soti, SARE OS18-121).

In Gainesville, Florida and St. Croix, Virgin Islands, sorghum-sudangrass and pearl millet supported predators and parasitoids of insect pests, but increased root knot nematode (RKN) populations, while sunn hemp suppressed RKN. With conventional tillage after each crop, SOM declined during two years of a three crop per year (two vegetable, one cover) rotation in St. Croix. In Florida, sunn hemp provided greater net economic benefits (N, weed control) to a following squash crop than velvetbean, southern pea, sorghum-sudangrass or tilled fallow. Sunn hemp also accumulated K and served as an effective catch crop for this nutrient (Chase, ORG 2007-03671 and SARE LS08-205).

In another trial in Gainesville, Florida, two or more years in bahiagrass sod enhanced SOM and water holding capacity, reduced RKN populations, and reduced fertilizer and irrigation costs while sustaining good organic vegetable yields in a subsequent year-round rotation of winter rye + oats cover, spring snap bean, soybean (cover), and fall broccoli. Strip tillage in rolled cover crops further enhanced soil health benefits (Anderson et al., ORG 2010-03958).

In the Virgin Islands, a spring-summer cover crop of sunn hemp or sorghum-sudangrass suppressed weeds, while southern pea and lablab did not. When cover crops were planted in August (beginning of the "heavy rainy season") and terminated at full bloom 70 days later, sunn hemp developed the highest biomass (7,000 lb/ac), accrued 200 lb N, 100 lb K, and 12 lb P per acre, and limited weed growth to 400 lb/ac. Sesame yielded only about 3800 lb/ac cover crop biomass but suppressed weeds almost completely, while velvetbean (4,000 lb/ac cover crop) allowed 1,200 lb/acre of weed growth. Sunflower had more weeds than cover crop (total biomass 4,000 lb.ac), and the perennial pigeon pea got off to a slower start and did not flower until 120 days after planting. Sunn hemp also performed well when sown in April and grown through the June-July dry season (Weiss, SARE OS11-062, and LS12-252).

Evaluation of 16 accessions of sunn hemp in Griffin, Georgia, Gainesville, Florida, and Lajas, Puerto Rico revealed substantial genetic variation and potential to select regionally adapted strains (Chase, SARE LS08-205).

Integrated Soil Health Strategies and Crop Diversity

- **Soils require living plant cover to stay healthy.**
- **Compost and manure can enhance cover crop benefits.**
- **Crop diversification builds SOM and soil biodiversity.**

Research at University of Kentucky suggests that cover crops may restore soil health more actively than finished compost. Samples of three different agricultural soils (sandy loam, silt loam, and silty clay loam), were pulverized to destroy aggregates, moistened, and incubated with different amendments. Hairy vetch residue stimulated fungal growth, which re-aggregated 45 – 65% of the soil volume within 12 days. Manure did so to a lesser degree, while soil amended with compost showed little change in microbiome and did not regain structure. In another study, one organic farm that relied on cover crops and did not use compost showed cropland soil structure, biological activity, and SOM approaching that of nearby undisturbed soil under natural vegetation. Two other organic farms, which relied on compost and used cover crops sporadically, showed lower cropland soil structure, SOM, and biological activity than adjacent undisturbed land (Lucas, SARE GS08-065; Bhavsar, SARE GS00-003).

In long-term trials, organic cropping systems that utilize both cover crops and manure boosted SOM, microbial activity, and other soil health indicators more than either cover crops or manure alone (Delate, ORG 2010-03956; Hooks, OREI 2010-01954). Compost and cover crops have distinct and complementary effects on the soil ecosystem: cover crops promote microbial activity while compost builds stable SOM (Brennan & Acosta-Martinez, 2017).

Researchers at Clemson University are evaluating the effects of all combinations of winter cover crop or no cover, manure or no manure, and conventional or strip till on soil biology, soil health, and organic vegetable yields in coastal plain sandy soils (Ye, ORG 2020-02281).

Crop diversification can improve SOM and biological activity, even when total plant biomass is not increased (King and Hofmockel, 2017; Tiemann et al., 2015; Wander et al., 1994). An organic farmer in central Mississippi enhanced SOM in a silt loam under a diverse four-year rotation with cover crops and poultry litter for nutrients. The rotation consisted of (1) rye + vetch → vegetables, (2) wheat → melon, (3) rye → crowder pea, (4) onions, garlic, greens → buckwheat (Gramelspacher, SARE FS01-134).

In the Georgia Piedmont, tight, diverse vegetable rotations with summer and winter cover crops increased active SOM within three years, while total SOM, which responds more slowly, remained unchanged. RKN populations increased but remained tolerable. Sunn hemp supplied ~90 lb N/ac to a following onion crop and appeared to reduce RKN (Boyhan, SARE LS10-225).

In long term trials at North Carolina State University's Center for Environmental Farming Systems (CEFS) in Goldsboro, diversified organic systems have accrued 10 - 20% more SOM and soil organic N than a conventional system. The organic rotations maximized year-round cover and living root, and eliminated one tillage by overseeding a winter cover crop into soybean before harvest. The six year organic rotation began with three years in fescue, orchardgrass, and red clover hay, followed by winter wheat. Soybean was planted after wheat harvest in year four and was overseeded with crimson clover, hairy vetch, and rye. In year five, the winter cover was terminated and followed by sunflower, then clover and vetch, which were disked in spring for corn in year six (Mueller, SARE LS08-210).

Soil Microbiome, Inoculants, and Organic Disease Management

In organically managed soils in the Carolinas, native rhizobia outcompeted applied inoculants in hairy vetch, crimson clover, and Austrian winter pea. Legume residues released plant-available N more slowly after mowing or roll-crimping than after disking, but enhanced AMF colonization in a following corn crop the most after no-till termination (Grossman, SARE LS10-227).

Indigenous AMF outperform purchased inoculants.

RESEARCH NEED:
Translate soil biology research into practical applications.

In the organic farming systems trials at CEFS in Goldsboro, organic strawberry yields were not enhanced by arbuscular mycorrhizal fungi (AMF) inoculants or by preceding summer cover crops. While a diverse (>15 spp) indigenous AMF community was documented, very high soil test P levels (>300 ppm) likely kept AMF dormant (Shroeder-Moreno, SARE LS07-200).

In the Lower Rio Grande Valley of Texas, efforts to enhance soil fertility with a commercial AMF inoculant failed to improve soil or crop health. Indigenous AMF inocula grown on sorghum-sudangrass in pots showed some promise, but simply growing AMF host cover crops (sunn hemp, southern pea, sorghum-sudangrass) for eight weeks was most effective. These cover crops and solanaceous vegetables (also strong AMF hosts), enhanced AMF spore counts three or four-fold over non-host crops (crucifers) or weeds (pigweed), and growing AMF host cover crops after kale (non-host) restored AMF levels (Soti et al., 2016; Racelis, SARE OS17-108).

Using compost to meet crop nutrient needs on three Virginia fields with a history of conventional management enhanced SOM, soil structure, and soil microbial activity. While compost did not increase yield compared to soluble fertilizer, it boosted populations of disease-suppressive *Gliocladium* and *Trichoderma* and other beneficial microbes. Compost-amended soils in North Carolina showed increased suppressiveness toward the southern stem blight pathogen

- **Compost can suppress disease if it is of good quality.**
- **Anaerobic Soil Disinfestation (ASD) combats strawberry pathogens.**
- **ASD and "biofumigation" build a disease-suppressive soil microbiome.**

Sclerotium rolfsii (Evanylo, SARE LS95-070; Ristano, SARE LS01-128).

Compost quality is critical. When compost tea failed to reduce southern stem blight in snap bean in on-farm trials, microbial analysis of the compost used to make the tea showed few fungi and many ciliate protozoa, indicating a low-quality product (Reynolds, SARE FS17-303).

Incorporation of a turnip green manure or mustard seed meal into the soil, solarization, and cover crop plus solarization were evaluated as disease controls in organic strawberries. While the treatments did not reduce pathogen populations, the green manure and seed meal treatments boosted numbers and biodiversity of soil bacteria, actinobacteria, and fungi, which could make the soil more suppressive to pathogens in future seasons (Cox, SARE GS09-084).

Based on excellent results with Anaerobic Soil Disinfestation (ASD) against the virulent strawberry pathogen *Verticillium dahliae* in California (see **Resource 5g**, page 65), researchers in North Carolina conducted an ASD field trial using dried molasses at 5,000 lb/ac as the carbon source to protect organic strawberry from the black root rot disease complex. ASD greatly reduced disease and maintained crop vigor similar to conventional fumigation, but gave lower fruit yields possibly because the molasses tied up N. The untreated crop succumbed to disease and failed. Conventional fumigation depressed microbial activity and slightly reduced AMF colonization in the strawberry crop six months after treatment, while ASD did not (Louws, SARE OS09-050).

ASD and mustard seed meals work primarily by inducing a shift in the soil microbiome toward beneficial, disease-suppressive microbes. The initial pathogen kill effect lasts only a few days, but the modified microbiome can suppress pathogens for two or three years. Conventional fumigants protect crops only for a single season because they kill off all microbes, leaving a biological vacuum that pathogens soon re-enter (Mazzola, 2017; Mazzola et al., 2015).

Mustard cover crops did not reduce numbers of sclerotia (resting structures) of the white mold pathogen *Sclerotinia sclerotiorum* in high tunnel soils in Kentucky. However, solarization killed sclerotia to a depth of six inches during a hot summer, and two inches during a cool summer (Bromford, SARE LS06-185).

Researchers at University of Florida are evaluating the effects of a summer cover crop (southern pea), different composts and organic fertilizers, and grafting (tomato) on soil quality and vegetable production in a pac choi-spinach-tomato triple crop in an organic high tunnel (Zhao et al., OREI 2017-02475).

Paddy rice production presents unique soil health challenges, as flooding disrupts the activity of aerobic organisms, alters carbon and nitrogen cycles, and promotes anaerobes including some root pathogens (Thakur et al., 2016). Studies at the USDA station in Beaumont, Texas indicated that a combination of cover crops, organic N fertilizer, and microbial inoculants can sustain grain yields and soil health in organic rice (see **Researcher Perspective 2**). However, in other trials, winter cover crops of ryegrass (Durana) white clover incorporated before flooded rice production increased GHG emissions without improving rice yield (Dou et al., ORG 2012-02983).

Results of laboratory and greenhouse trials suggested that applications of feather meal to provide 180 lb N/ac in conjunction with soil incorporation of clover cover crop residues at 5,400 lb/ac would result in the highest organic rice yields and nitrogen use efficiency (Velarca, 2016). However, in field trials, organic

N fertilizers at 135 or 185 lb N/ac increased yield by only 11% and significantly boosted GHG emissions. In other organic rice trials in Texas, Arkansas, and South Carolina, microbial seed treatments with commercial formulations of *Bacillus subtilis*, *B. pumilus*, and fungal endophytes reduced seedling diseases and improved crop stands by up to 25%. 'Caliente 199' mustard seed meal at 1,500 or 3,000 lb/ac also reduced seedling diseases (Dou et al., ORG 2012-02983 and SARE LS12-249ll Zhou, OREI 2015-07384).

RESEARCHER PERSPECTIVE 2. Organic Rice Research in Southeast Texas

Steve Diver, University of Kentucky

In developing this guidebook, we reached out to Steve Diver to learn more about soil health and fertility in organic rice fields. Steve has extensive experience in soil biology and fertility. In 2007-2010, through his work with biological amendments and soils consultancy in Texas, Steve explained this "led to on the ground collaborations with Jodie Cammack, the Farm Superintendent who managed organic rice production trials at the USDA Rice Research Station near Beaumont, TX, in concert with their research leader Dr. Anna McClung." Some outcomes from this program are summarized on pages 11-12 and 23 - 24 of the station's 2013 Rice Research Summary at https://beaumont.tamu.edu/eLibrary/Newsletter/2013_Highlights_in_Research.pdf. Unfortunately, the Beaumont Organic Rice program was closed in 2011 because of budget cuts.

"Southeast Texas is a leader in organic rice production, along with Lundberg in California," Steve noted. Based on consulting work with the Harris County Flood Control District, which included sampling soils from current and former agricultural fields and prairie lands in the Houston area, Steve observed that "the geology, flat lying topography, and soils of the Gulf Coastal Plain are uniquely suited to rice production. These soils have a relatively impervious clayey subsoil which results in standing water under seasonal conditions," and thereby facilitates the practice of flooding rice fields after crop emergence. As a result, this is one of the largest and most productive regions for U.S. rice production.

Steve stated that "it is not too difficult to grow organic rice. It involves crop rotations with an emphasis on soil-building biomass crops during summer green fallow and a legume-based cover crop preceding rice, plus organic fertilizers. Nitrogen is a driver. The standard application rate is 175 lbs N/acre, pre-plant incorporated. Jodie ran a huge field trial in 2010 that included a number of organic fertilizers combined with selected microbial inoculants (Figure 8). He concluded that a good organic rice production system would include a legume cover crop, a bulk organic fertilizer to provide supplemental N, and a biofertilizer or microbial spray."

Steve Diver (2)

Figure 8. Extensive organic rice field trials at the USDA Rice Research Station in Beaumont, Texas (left) showed best results with legume cover, organic fertilizer, and microbial inoculants used together. Durana white clover (right) has become a leading cover crop in organic rice rotations, preferred for its perennial nature and substantial N contributions.

Steve's work with Jodie Cammack "clearly highlighted Durana white clover as a major innovation, superseding most other cover crops including hairy vetch and crimson clover. In summer green fallow, they raised lots of biomass producers like sorghum-sudan and the like. Nowadays there are many multi-species mixes in use."

When we raised a concern that purchased soil inoculants often do not enhance yields or pay for themselves when applied to healthy, organically managed soils (Kleinhenz, 2018), Steve shared evidence that, in organic rice, inoculants can work effectively with cover crops and other soil health practices to enhance rice yields and reduce fertilizer needs. "Worldwide there is a huge amount of literature on organic rice production using biofertilizers, inoculants, and amendments," Steve noted, adding that nitrogen fixation by *Azospirillum, Azotobacter*, and the symbiosis between *Azolla* fern and the cyanobacterium *Anabaena azollae* play a key role in successful low-input rice production.

However, in the southeastern U.S., Azolla is considered an invasive wetland species in several states. Steve said an alternative approach is to use an inoculant formulation of dormant cyanobacteria in a kaolin clay base. When this material is applied to rice paddy soil, the cyanobacteria become activated, fix N, and improve soil tilth through rapid production of polysaccharides, which increase soil aggregation. Researchers and farmers in Texas and Romania have also had success with a multispecies microbial inoculant, which significantly increased organic rice yields while reducing fertilizer needs 20–30% in the Beaumont trials. For more information, contact Steve at steve.diver@uky.edu.

This story is based on an e-mail conversation in January, 2021 with Dr. Steve Diver, Farm Superintendent at the University of Kentucky's Horticulture Research Farm.

Crop genetics can affect the crop's capacity to host disease-suppressive microbes. The Tomato Organic Management and Improvement (TOMI) project works with farmers in North Carolina and several northern states to develop new multi-disease-resistant tomato cultivars. Target traits include enhanced association with microbes that suppress soilborne pathogens and induce systemic resistance (ISR) against foliar diseases such as late blight and gray mold (Hoagland, OREI 2014-05405 and 2019-03080).

Ongoing research into biological control of pathogens and pest nematodes includes the following.

- Evaluation of ASD for disease control in organic carrots and greens in northern Florida (Vincent, SARE GS20-221; Zhao, SARE OS20-135).
- IPM for nematodes in organic vegetables using cover crops (sunn hemp, sesame, marigold, radish, rye), NOP allowed controls, and Bt strains and entomopathogenic nematodes that show activity against RKN (Hajihassani, ORG 2020-02288).

Organic strategies against root-knot nematode (RKN):

- **Graft tomato onto RKN-resistant rootstocks.**
- **Rotate to non-host crops for four months per year.**

RESEARCH NEED:
Practical strategies to manage RKN and soil health in organic high tunnels

Three cherry tomato cultivars and 'Green Zebra' specialty tomato showed greatly enhanced crop vigor and 50 - 330% higher yield in organic high tunnels when grafted onto Multifort and Estamino rootstocks with resistance to *Fusarium, Verticillium*, and RKN. Grafting reduced *Fusarium* by 21 - 71% in susceptible Black Cherry and Green Zebra. Leaf mold (*Passalora fulva*) seriously affected Sun Gold and Supersweet 100, and grafting reduced damage by 25 -31%. RKN galling levels were similar in the two grafted rootstocks, while the nongrafted tomatoes could not be evaluated because roots had decayed by end of harvest. In field trials, grafting Brandywine (large red) and Flamme (small orange) onto Multifort or Survivor rootstocks reduced RKN galling by 57 - 97%. Multifort shows tolerance to RKN but it allows the pest to reproduce in its roots. In contrast, Survivor is a non-host and thus helps to reduce soil RKN populations. Grafting rootstocks also have more robust root systems that enhance nutrient and moisture uptake and resilience to drought and other abiotic stresses. In some cases, these traits can lead to excessive vegetative growth or somewhat reduced fruit quality (Zhao, SARE OS13-083). See **Researcher Perspective 3** for more on RKN management in organic field and high tunnel production.

RESEARCHER PERSPECTIVE 3. Grappling with Root Knot Nematode

Elizabeth Little, University of Georgia

When the authors of this guidebook contacted Dr. Elizabeth Little to learn more about plant-parasitic nematodes problems in high tunnels, she confirmed that “root knot nematode (RKN) is a major problem in Georgia for crop production of all sorts. Other plant pathogenic nematodes may be there, but in organic vegetable production the main concern is RKN. Here in the Piedmont, appropriate management can be achieved in organic fields if recommendations for soil quality, cover cropping, and rotation are observed.” Crop rotations that include at least four to five months per calendar year in a crop that does not host RKN can keep nematode populations down and limit damage to the susceptible crops in the rotation. However, this can be challenging since most vegetable and some row crops are susceptible to RKN. The best option is to include a RKN resistant cover crop of at least four months duration within each year of the rotation. Examples include winter cereals after tomato, or a summer cover of sunn hemp and sorghum-sudangrass after cool-season vegetables.

RKN thrives in warm climates with long growing seasons and sandy soils with plenty of macropore space that facilitates the worms’ migration from host to host. “In the Piedmont where we are, the soils have more clay content and we are a little cooler, but numbers of RKN can still get very high with continuous vegetable production, especially in high tunnels,” Elizabeth noted. “In southern Georgia, where soils are very sandy, RKN severely limits organic production.” When working with vegetable growers, she often recommends “some good publications on cover crops and integrated management of nematodes from Florida, where RKN problems are even worse.” (See **Resources 20 a-c**, page 69.)

When I asked about RKN-non-host rotation crops, Elizabeth said that nearly all vegetables are susceptible to varying degrees though some crucifer greens show partial resistance. “The problem with long season summer crops like tomato or pepper is that by the end of a season several generations have occurred, resulting in severely galled roots and high populations of RKN in the soil. The summer vegetables may be productive but subsequent susceptible cool season crops such as carrots and beets are damaged.” RKN-non-host cover crops include most grasses (winter cereal grains, millets, sorghum-sudangrass), Iron Clay southern pea, sunn hemp, and possibly sesame. Velvetbean, marigold, indigo, and castor bean also show RKN resistance but may not be practical choices at a multi-acre scale.

The high tunnel environment exacerbates RKN problems by maintaining warmer temperatures and facilitating year-round multicropping. In the Georgia Piedmont, high tunnels may be planted to four high-value, RKN-susceptible crops per year. Few growers are willing to forego this income potential by rotating into non-host cover crops for the requisite period to control RKN. In addition, while optimum SOM levels (about 5% in Piedmont soils) help limit RKN populations, the *very* high SOM levels in some organically managed high tunnels can “contribute to [RKN] problems due to the lighter texture of the soil.”

Some high tunnel growers use non-host cover crops to a limited degree, and/or solarize their soil for five or six weeks during summer. While either practice denies RKN a host for its duration, Elizabeth suggested that “the non-host crop keeps the soil healthier.” Cover crops are often terminated about six weeks after planting because older, bulkier cover crops are difficult to manage in the high tunnel, and because growers are reluctant to take the high tunnel out of production for longer periods. However, "longer periods away from susceptible crops are needed to break the RKN lifecycle and reduce populations. More research is needed on optimizing the length of time for taking high tunnels out of production to reduce RKN numbers while maintaining productivity and net economic returns."

Moveable high tunnels can facilitate effective rotation, but this strategy requires a level site, entails smaller high tunnels that may not meet grower needs, and requires more land area and labor for a given level of production.

Research into improved cropping sequences and integrated organic management strategies against RKN continues.

This story is based on an e-mail exchange in September, 2020 with Dr. Elizabeth L. Little, Associate Professor, Department of Plant Pathology, University of Georgia.

Cover Crop Based Organic No-till and Reduced Tillage Systems

Researchers and farmers continue their efforts to overcome barriers to organic no-till planting into roll-crimped cover crops. While planting delays, cold wet soils under residues, and inadequate N mineralization commonly restrict organic no-till yields in colder climates, intense weed pressure poses the greatest problem in these systems in the South.

Organic no-till research findings:

- Roll-crimped cover crops build soil health, but weed challenges remain.
- Cover crops must be high biomass (4+tons/ac) to suppress weeds.
- Soybean after rye and fall crops after sunn hemp show promise.

Organic no-till summer squash, bell pepper, and broccoli performed well in Virginia and Georgia except when weed control was insufficient. A winter-killed cover crop provided inadequate mulch to suppress weeds, leading to poor spring broccoli yields, while fall broccoli gave high yields in roll-crimped summer cover crops. Zone-planting (soybean on bed top, foxtail millet on sides and alleys) enhanced N availability to broccoli, giving good yields with 60 lb/ac fertilizer N, which is less than half the recommended rate (Morse, ORG 2003-04625 and SARE LS03-149).

An organic grain farmer in Virginia tried planting corn and wheat into roll-crimped cover crops, adapting equipment on hand to do the job. He found that fescue grows through the rolled cover, that rye ahead of corn ties up N, and that rye knocked down by wildlife becomes too tangled for mechanized no-till planting. An oats + vetch cover in which the oats winterkilled proved more manageable for no-till corn (Yowell, SARE FS08-231).

Winter rye + crimson clover produced 8,000 lb biomass and 130 lb N per acre and were either roll-crimped or soil-incorporated in two years of trials in Clemson, South Carolina. Soil soluble N levels and organic tomato and squash yields were similar in tilled and no-till treatments, and total labor costs were greater for the tilled system (Robb, SARE GS13-126).

An organic vegetable farmer dealing with a slow-draining soil near the South Carolina coast purchased a roller-crimper designed for raised beds and used occultation (silage tarp) to enhance cover crop termination and weed control. Despite drought followed by torrential hurricanes during both years of the project, the rolled cover and tarping created excellent seedbeds and doubled summer squash yields compared to preceding years (Connor, SARE FS16-288).

An organic crop rotation of winter wheat, soybean, rye + crimson clover, and sunflower in Georgia developed heavier weed pressure under no-till management than where the cover crop and wheat residue were tilled in. No-till cut sunflower yield by 70% but did not significantly harm wheat or soybean yield (Tillman, SARE LS10-232).

In Alabama, organic pepper and tomato planted into rolled winter rye with supplemental in-row compost mulch produced yields similar to the same crops in tilled raised beds in one out of two sites. However, in a follow-up study with five organic farmers, cover crop residues decomposed too quickly to suppress weeds in the wide spaces between crop rows. The team concluded that, with current equipment options, organic no-till is not practical for summer vegetables in the Gulf Coast states. They explored no-till planting of fall kale and winter cereal grain into roll-crimped sunn hemp with more promising initial results. In another SARE project in Alabama, no-till collards in fall after a soybean cover crop required additional mulch (wheat straw, lespedeza, or mimosa prunings) to suppress weeds and sustain crop production (Kloepper, OREI 2005-04494 and SARE LS09-218; Mulvaney, SARE GS05-049).

Four systems of sweet potato production were compared over three seasons at CEFS: conventional, organic without cover crop, organic with rye + vetch tilled in, and organic with rye + vetch no-till. Flail-mowed cover did not provide adequate weed suppression the first year, and a roller-crimper was used in subsequent trials. The no-till plots required hand weeding and gave yields similar to tilled treatments in two years out of three. (Treadwell, SARE GS00-006).

In eastern North Carolina, bulb onions are fall-planted near the frost date (~ Nov 1) which makes no-till planting into a frost-tender summer cover crop feasible. Organic onions planted no-till after southern pea required manual weeding but gave yields similar to the tilled treatment. Foxtail millet residues suppressed weeds but depressed onion yield, and a millet-pea mix gave intermediate results. (Vollmer, SARE GS07-058).

Organic soybean sown no-till into high biomass (≥ 9,000 lb/ac) rolled cereal rye cover crops at two sites in North Carolina emerged well, remained nearly weed-free during the critical crop establishment period, and gave yields equivalent to a tilled treatment. Corn gluten, sometimes marketed as an organic herbicide, slightly reduced soybean yield, and flail-mowed rye did not suppress pigweed as effectively as the roll-crimped residue. At a third site with lower rye biomass (6,000 lb/ac), weeds reduced soybean yield (Reberg-Horton, SARE OS08-042). Organic no-till soybean has also yielded well in roll-crimped rye in Missouri, the mid-Atlantic, and New York. N immobilization by the rye suppresses "N-responder" weeds like pigweed, lambsquarters, ragweed, and foxtails, while the legume fixes sufficient N to sustain production (Barbercheck et al., OREI 2010-03391; Caldwell et al., 2016; Clark, OREI 2014-05341).

Organic corn and edamame soybean grown in no-till terminated winter cover crops at one site in central North Carolina became overwhelmed by weeds and failed in three successive seasons. Low rye cover crop biomass (~ 2,000 – 4,000 lb/ac) proved inadequate mulch, and crimson clover and subterranean clover (~3,000 – 5,000 lb/ac) decomposed too quickly to suppress weeds. Inadequate cover crops and intense weed pressure dominated by purple nutsedge and curly dock at this site created a "perfect storm" for a no-till failure and even thwarted production in conventional and tilled organic plots (Baldwin, SARE LS02-132).

In a long-term trial in North Carolina, microbial biomass and active and total SOM were highest in organic minimum till (cover crop roll-crimped), intermediate in conventional no-till or organic full till, and lowest in the conventional full tillage system. However, the organic minimum till system suffered severe crop losses to weed competition. A low diversity rotation of sweet corn and crimson clover every year may have contributed to weed pressure (Osmond et al., ORG 2009-05488).

Vegetables grown in roll-crimped sunn hemp yielded well in a sandy soil in Florida, while vegetables did poorly in roll-crimped rye + vetch in fertile soil in Iowa. The combination of cover crop, composted manure, and reduced tillage enhanced soil structure, active and total SOM, and soil organic N at both sites (Delate et al., ORG 2010-03956). In another Florida study, strip till vegetable planting into rolled cover crops enhanced SOM and water holding capacity and maintained good yields two out of three years (Anderson et al, ORG 2010-03958).

Ensuring full termination of the cover crop can also pose a challenge. In summer cover crop trials in North Carolina in the 1990s, mowing killed mature broadleaf cover crops but not grasses, and rolling was not effective (roller-crimper designs have since improved). Undercutting, which disturbs just the top two inches of soil to sever root crowns, effectively terminated most cover crops (Creamer, 1998. OFRF project).

In the U.S. Virgin Islands, sunn hemp was effectively terminated by roller-crimper, but its fibrous stems tangled in a rotary mower or disk. Southern pea and lablab were readily terminated by disk but not roller-crimper. Roll-crimping killed sunn hemp, sunflower, and sesame 90 days after planting, while velvetbean and pigeon pea regrew. In an on-farm trial, sunn hemp sown in April and grown through the dry season (June-July) generated high biomass and suppressed weeds after roll-crimping. Trials with peppers in Florida, Puerto Rico, and the Virgin Islands had good results with roll-crimped sunn hemp, but additional hay mulch or landscape fabric was needed to suppress weeds adequately to maintain pepper yield (Weiss, SARE projects OS11-062, and LS12-252).

Research projects in progress on organic no-till systems include:

- Farmer trials with summer cover crops (sunn hemp, soybean, buckwheat, Japanese millet) for no till organic fall broccoli in South Carolina (Belk, SARE FS20-326).
- Comparison of soil carbon and nutrient cycling and GHG emissions in four organic grain rotations from full tillage to minimum tillage (Jagadamma, ORG 2020-02390).
- Working with farmers to adapt cover crop termination and organic no-till methods to small scale operations (McSwain, SARE OS19-129).

Soil-friendly Organic Weed Management

Weed pressure can pose a huge barrier to organic transition in the South and has caused crop failure in some trials. Organic management of nutsedges and other stubborn weeds can entail intensive tillage that hinders efforts to build healthy soils (Henley and Henley, SARE FS08-225; Baldwin, SARE LS02-132; Chase, SARE LS05-170).

RESEARCH NEED:

- *Develop effective, soil-friendly organic weed management strtegies.*
- *Develop weed- and disease- resilient crop cultivars.*

One Georgia organic vegetable farmer faced with a Bermuda grass infestation in a Fuquay loamy sand (very low SOM) compared intensive repeated tillage ("mechanical" strategy) versus cover crops of buckwheat followed by pearl millet + southern pea with fewer and lighter tillage passes (biological). Mechanical weed control reduced Bermuda grass more quickly than biological, and the latter allowed some increase in yellow nutsedge. However, the biological strategy protected soil health and improved subsequent vegetable yields by 11% (onion) and 70% (kale) (Taylor, SARE FS13-267).

Flame weeding gave better weed control and higher yields than mechanical cultivation in organic cotton, popcorn, and soybean in the North Carolina coastal plain. Researchers used flame successfully to terminate a January-planted rye cover crop for no-till planting (Heiniger, 1998). Flaming was also more effective than either early season cultivation or red plastic mulch against an aggressive weed flora in Louisiana, though not as effective as a five-inch mulch of bahiagrass hay (Poudel, 2003).

In the coastal plain of Virginia, soil solarization for three weeks prior to strawberry planting in September reduced weed growth in the crop, while soil amendments with mustard seed meal, corn gluten meal, or paper pulp meal did not affect weeds (Das, SARE GS15-150).

Weed seed consumers such as ground beetles, field crickets, and field mice can reduce soil weed seed populations. In the CEFS farming systems research, providing field border habitat for these organisms did not increase cropland weed seed predation. However, maintaining fall vegetative cover in the crop field itself by planting the next crop promptly after summer harvest enhanced their activity, while leaving the soil bare after harvest maximized weed seed survival (Fox, SARE GS10-091).

Vigorous, resilient crop cultivars play a vital role in organic weed management. A network of plant breeders and farmers has developed new weed-competitive lines of soybean and wheat, and has made significant progress toward disease-resistant peanut. In soybean, large seed, rapid early growth, and wide leaflets confer weed competitiveness through early canopy closure and possibly through vigorous, competitive root systems. Similarly, plant height, vigor, and canopy density correlate with weed competitiveness in wheat cultivars, while allelopathic activity in lab tests does not (Reberg-Horton et al., OREI 2009-01333 and 2012-02236; Place, SARE GS08-073; Worthington, SARE GS12-115).

Clemson University researchers are developing disease resistant, high yielding winter pea cultivars as a production crop in rotation with sorghum (Thavarajah et al, OREI 2018-02799).

Several rice cultivars have shown desirable traits for organic production. 'Jasmine 85', 'PI312777', 'Rondo', 'TH683', 'Tesanai 2', 'XL723' and 'XL753' grew tall, tilled strongly, outcompeted weeds, and yielded well. All but PI312777 showed resistance to *Cercospora* narrow brown leaf spot (Zhou, OREI 2015-07384).

Soil Health in Perennial Systems

- **Perennial systems build more SOM than annual crop rotations.**
- **Annual covers or organic mulch work with perennials to improve nutrient cycling and weed control.**

While grazing and hay land is normally maintained in perennial sod, some livestock producers utilize annual forage crops alone or interplanted into perennials to enhance forage quantity and quality. Researchers at University of Tennessee have compared forage productivity and soil health in annual (winter wheat with crimson clover, followed by sorghum-sudangrass), perennial (tall fescue with red and white clovers), and perennial/annual systems (red clover overseeded with crabgrass in summer). All three systems produced similar forage yields, with little weed biomass in the annual rotation. Weeds comprised about 25% of plant biomass in the perennial forage and more than 50% (not counting crabgrass) in the annual/perennial system. However, SOM declined in the annual rotation while it increased in the other two systems (Butler, SARE OS11-057).

Starting with an extremely poor soil from which over 100 years of intensive production had eroded the entire A horizon leaving exposed red clay B horizon, researchers at University of Georgia compared soil-improving rotations with or without rows of a woody leguminous perennial (*Albizia julibrissin*, sometimes called mimosa) spaced 16 feet apart and cut one to three times annually to provide mulch. All systems were planted to two successive cover crops (sunn hemp followed by rye + vetch + crimson clover) roll-crimped, then strip tilled for organic cotton and vegetables. Within seven years, SOM doubled, and organic N increased 90% in the alley crop system, largely from root sloughing from the perennial (Jordan, SARE LS06-190).

In Florida, sunn hemp and lupine were planted in citrus orchards in November to suppress weeds and terminated six to ten weeks later to provide N for the spring growth flush (Treadwell, SARE OS10-056).

In Puerto Rico, one advantage of shade-grown organic coffee production is that the shade tree (*Inga* sp., a legume that grows to about 50 feet) suppresses weed growth. Early in plantation establishment, perennial peanut (*Arachis pintoi*) cover crops reduce weeds more effectively than line trimmer or NOP-allowed herbicides (Ramos, SARE LS10-231).

Different organic mulches had contrasting effects on apple orchard establishment in field trials in Arkansas. Wood chips gave the best tree growth overall. A municipal green compost mulch accrued the highest SOM but mineralized too much N, resulting in excessive late season vegetative growth and increased weed pressure. Mowing alleys and blowing clippings into crop rows did not provide sufficient nutrients to the crop, and shredded paper mulch tied up N and stunted tree growth (Rom, SARE LS04-167 and LS05-176; OREI 2008-01251).

Rabbiteye blueberry (*Vaccinium virgatum*) is native to southern Georgia and northern Florida and is well adapted to the region's climate and soils. A research project in 2006-10 developed guidelines for organic production and found that mulching with pine straw or pine bark enhanced crop vigor compared to woven fabric mulch (Anderson et al., OREI 2006-04971).

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NOTE: for project summaries and final reports on SARE, OREI and ORG-funded research, see links at Resources 31 and 32, page 69.

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FARMING
RESEARCH
FOUNDATION

P.O. Box 440
Santa Cruz, CA 95061
831.426.6606
info@ofrf.org
www.ofrf.org