Practical Conservation Tillage for Organic Farming Systems

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Presented by:
Mark Schonbeck, Research Associate, Organic Farming Research Foundation (OFRF)

Presentation Notes

Slides 1-9: Introduction.

Slide 2 – *The costs of tillage*
Slide 3 – *USDA National Organic Standards on tillage*

Most organic farmers take steps to reduce tillage intensity and frequency whenever practical to conserve soil organic matter (SOM) and protect soil health. When mainstream agricultural scientists and farmers first began researching and developing no-till methods that include herbicides for weed control, many organic farmers switched from moldboard plow-disk to less disruptive non-inversion tillage such as chisel plow or shallow (3-4”) rototilling (Kuepper & Schahczenski, 2020). A recent agricultural census revealed that similar proportions (~40%) of organic and non-organic producers practice some form of conservation tillage (Shade, 2021).

The USDA Organic Standards set a high bar, requiring certified growers to implement tillage and cultivation practices that “maintain or improve” soil condition.

Slide 4 – *Weeds and cultivation: the organic farmer’s dilemma*

Organic production of annual crops generally requires some tillage and cultivation to manage weeds, cover crops, residues, and seedbed preparation. When cultivation becomes the main tool for weed control in annual crops, the farmer often faces a tradeoff between adequate weed suppression to sustain crop yields on the one hand, and soil conservation, soil structure, and soil health on the other. Sound, ecologically based, organic weed IPM lessens the need for repeated cultivation and the associated soil health tradeoffs. This was discussed in greater depth in an earlier webinar in this series, *Beating the Weeds without Herbicides: Soil-friendly Organic Weed Management*, delivered on March 20, 2023.

Slide 5 – *What organic farmers say about tillage and soil*

Organic Farming Research Foundation (OFRF) conducted a survey of 1,059 certified organic farmers and 71 transitioning-organic farmers to identify production challenges, concerns, and technical assistance needs (Synder et al., 2022). A series of focus group discussions provided additional farmer perspectives in greater depth, including the quotes in this slide. These findings clearly illustrate that the leading production challenge identified – weeds – drives the organic sector's quest for improved tillage practices and strategies that maintain crop yields and limit weed growth while minimizing damage to soil health.

Slide 6 – *When and why organic farmers till the soil*

In the left-hand photograph, organic vegetable farmer Charlie Maloney of Dayspring Farm (Tidewater of Virginia, coastal plain loamy sand Ultisol) has broadcast rye + vetch seeds with a manual spin seeder, then set the rototiller to run just one inch deep, knocking out emerging weeds and planting cover crop seeds at the right depth. The right-hand photo shows a solid, even stand of emerging cover crop sown with this technique 11 days earlier. The rapidly growing cover crop will protect the soil surface that was temporarily left exposed by tillage and will soon begin to rebuild soil organic matter (SOM) and suppress later-emerging weeds.

Slide 7 – *Tilling for seedbed preparation*

One of the greatest challenges faced by all vegetable farmers is the vulnerable period for both soil and crop during the first few weeks after direct-seeding a small-seeded crop. Many organic farmers transplant leafy greens such as spinach and Asian greens, onions, and even round root crops like turnip or beet to give the crop a jump on weeds and shorten the period of exposed soil. Taprooted vegetables (carrot, parsnip, daikon) and mesclun salad mixes that are cut young must be direct seeded and require excellent soil tilth and low weed pressure to succeed.

Slide 8 – *Tilling to get the most from organic nutrient sources*

While conventional NPK fertilizers are soluble and can move into the root zone with rain or sprinkle irrigation after a surface application, most organic nutrient sources require biological processing to deliver their nutrients to crops. These materials work most efficiently when they are mixed into the top few inches of soil in a band close to the crop row, or across the bed top for multirow crops in narrow row spacings. In addition, the biological (microbial inoculant) benefits of finished compost, worm castings, and other living amendments can be diminished or lost in a surface application, which subjects the microbes to desiccation and solar UV radiation. Nutrient delivery from surface applied organic amendments can be especially poor in a semiarid region or in the dry summer season of a Mediterranean climate in either dryland or subsurface drip-irrigated systems.

On the other hand, high-carbon residues such as a rye cover crop, grain straw, corn stover, or chipped brush may prove most beneficial if left on the surface to protect the soil life and soil surface from direct sun and raindrop impact. Tilling these materials in can tie up N and other nutrients and reduce yields.

Slide 9 – *Tillage and cultivation for weed control*

Timely shallow cultivation can take out a lot of tiny weeds before they have a chance to get established, while disturbing only the top inch or so of the soil profile. However, if a heavy population of weed seeds in the soil necessitates repeated cultivation, surface aggregates can become pulverized, leaving the surface prone to erosion and crusting.

Creeping (rhizomatous or tuber-forming) perennial weeds like bindweed, Canada thistle, Johnson grass, Bermudagrass, and nutsedges pose the greatest weed management challenges to all farmers. One tillage pass simply propagates them as each fragment regrows. However, repeated cultivations to sever re-emerging shoots whenever they reach the 3-4 leaf stage can weaken and eventually exhaust the underground reserves (Mohler et al., 2021). The intensive tillage required to bring a severe infestation under control can be very hard on the soil, so planting an aggressive, high-biomass cover crop such as sorghum-sudangrass after the second cultivation can strengthen weed control while helping the soil recover from the impacts of tillage.

<u>Slides 10-19: Reducing Tillage Intensity and Low-Impact Tools</u>

Slide 11 – *Soil tillage intensity rating (STIR), Conservation Practice Standards, and Organic Systems*

The STIR is a NRCS tool that estimates the soil disturbance impacts of different tillage implements and other field operations. STIR integrates the intensity, depth and area (full field versus strip or zone tillage) of the disturbance. While the criteria for no-till (no full width tillage, total crop cycle STIR < 20) are challenging for organic producers to meet in annual crop production, many organic farmers use non-inversion tillage, often with a total crop cycle STIR of 80 or less. The following slides illustrate several implements that can meet the goals of tillage in various circumstances with less damage to soil life and soil structure than conventional full tillage practices such as moldboard plow followed by one or more disc passes.

The STIR values shown in this presentation were obtained from the current RUSLE2 program.

Slide 12 – *Shallow noninversion tillage: power harrow*

Often, a shallow tillage can meet weed control or soil preparation needs while leaving the deeper parts of the soil profile intact, thereby avoiding subsurface compaction and reducing harm to earthworms and other soil life. Several conventional tools (light disk, field cultivator, springtooth harrow, rototiller) can be adjusted to till shallowly (1 to 4 inches); the challenge is to avoid pulverizing surface aggregates, which can lead to crusting or erosion.

Newer tools such as the power harrow have been designed specifically to till the soil shallowly and conserve aggregates.

Meta-analyses of multiple studies indicate that shallow tillage has less negative impact on soil life and soil health than deep inversion tillage (moldboard plow or heavy disk), and that shallow tillage in conjunction with organic practices can enhance SOM (Cooper et al., 2016; Zuber and Villamil, 2016). In a long term (21 yr) trial in Germany, “minimum tillage” (3 inches) and organic practices together improved SOM and microbial biomass more than either one alone (Sun et al., 2016), and a 15-year organic systems trial in Switzerland accrued 25% higher SOC in shallow noninversion tillage than moldboard plowing (Krauss et al., 2020). In the Netherlands, reduced tillage did not hurt yields of various grain, root, and vegetable crops with the exception of carrot, which requires a fine, low-residue seedbed and showed a 14% yield reduction related to spotty stand establishment (Van Balen et al., 2023).

In a recent meta-analysis comparing soil microbial (fungal + bacterial) biomass under conservation versus conventional tillage (moldboard plow 8-10 inches plus secondary tillage), reduced tillage (defined as noninversion and <6 inches) supported double the microbial biomass while strict no-till increased fungal biomass by only 25% and bacterial biomass not at all over conventional tillage (Morugán-Coronado et al., 2022). The authors attributed this finding to higher soil bulk density and restricted gas exchange under no-till; other factors could include increased dependence on herbicides or a lack of winter cover cropping in the no-till systems.

Slide 13 – *Shallow noninversion tillage: high-speed disk*

While this tool has a considerably higher STIR (41) than either the power harrow (21) or rototiller (18) several organic farmers interviewed by the presenter find that this new disk design leaves surface aggregates more intact than either the rototiller or older designs of disk harrow.

Vertical tillage describes various tools designed to minimize horizontal movement of soil, and to mix residues and amendments vertically into the soil without inversion. Many of these tools consist of coulters oriented along the line of travel (zero offset angle) alone or combined with a shank or a spike harrow to prepare planting rows. The STIR values are quite low for these tools.

Slide 14 – *Shallow noninversion tillage: blade plow*

The blade plow, sweep plow undercutter, or Noble plow, is a valuable low-impact tillage tool for organic dryland production in regions with limited rainfall. The photos were taken from a U Nebraska Lincoln article on stubble mulch tillage at https://cropwatch.unl.edu/tillage/stubble. In Nebraska, an early spring cover crop of legumes + mustard terminated by blade plow conserved moisture, reduced weeds, and improved yields of soybean and corn by 23% and 17% compared to a no-cover control, respectively, while the same cover crop terminated by disking promoted soil moisture loss and reduced soybean yields by 14% (Wortman et al., 2016).

In the Columbia plateau (annual precipitation <12 inches), managing wheat stubble and weeds during the summer fallow period with the blade plow significantly reduced wind erosion, compared to disking. The trials were done on silt loam soils with 1% SOM (Sharratt and Feng, 2009).

The blade plow requires just the right soil moisture conditions (moderately dry, below field capacity but above the permanent wilting percentage) to work well, and may not function properly in wet or very dry conditions (Doug Crabtree, pers. commun.).

Slide 15 – *Deep noninversion tillage for small scale: broadfork*

Some form of deep tillage or "subsoiling" is sometimes needed if the soil has a naturally compaction-prone horizon (e.g, the E horizon of a sandy Ultisol) or if the use of plow, disk, or rototiller to the same depth year after year has created a "tillage pan" (management caused hardpan) that restricts rooting depth. The broadfork offers a soil-saving and ergonomically friendly alternative for small scale operations such as a high tunnel or market garden. The broadfork is used to loosen the soil to a depth of 8 to 12 inches without inversion. Broadforking improves drainage and aeration and facilitates manual removal of weeds. In conjunction with permanent raised beds with traffic limited to alleys, the broadfork can help maintain good physical condition (aggregation) and prevent compaction, especially when its use is followed by deep rooted cover or production crops.

At a larger scale the chisel plow provides a non-inversion approach to deep tillage that is less likely to cause subsurface compaction than moldboard plow or disk plow. A meta-analysis of multiple tillage studies showed that, despite its high STIR value, chisel plowing may also have less adverse effects on soil biological activity than inversion tillage (Zuber and Villamil, 2016).

Slide 16 – *Moderate-impact deep tillage: spading machine*

The spading machine is highly versatile and many vegetable producers report that it can incorporate a high biomass cover crop or even sod, and create a seedbed suitable for transplanting or large-seeded crops in a single pass, while doing less damage to soil life and soil aggregates than plow-disk or rotary tillage. It does require a slow tractor speed, and thus may be most practical for smaller scale horticultural crop production.

Researchers at Washington State University have found that, compared to "conventional" tillage of moldboard plow, disk, and rototiller, the spader substantially reduces compaction at 5-12 inches below the surface, and sometimes improves crop yields (Cogger et al., 2007, 2012, and 2013). In more recent studies, the team has adopted the spader as the "conventional" (full field) tillage treatment against which to compare no-till and strip-till treatments for vegetable production.

Slide 17 – *Tilling part of the field: Strip tillage*

Strip tillage works a narrow strip of soil to facilitate seed-soil contact, crop establishment, and N mineralization in and close to the crop row, while leaving 70-80% of the field area undisturbed. For more information on strip tillage and various strip tillage tools, see Cornell (2018).

Slide 18 – *Crops thriving in strip-tilled soil*

After mowing a winter rye cover crop, organic CSA farmer Polly Hieser of Floyd County, VA used a walk-behind rototiller to establish 20-inch-wide tilled grow zones for tomatoes in rows 5 feet apart (center to center). This left 2/3 of the field in undisturbed rye, which was maintained by periodic mowing. This prevented erosion, protected soil quality, and provided mud-free access for harvest.

The peanut crop canopy has spread out from the strip-tilled planting rows, maintaining nearly weed-free conditions for a crop notoriously susceptible to weed competition.

Slide 19 – *Tilling part of the field: soil functional zone management*

The advantage of zone tillage methods, including ridge till (shown here) and strip tillage, is that these practices spatially differentiate two key functions of healthy soils: *mineralization*, in which soil organisms release crop available nutrients by consuming active organic matter; and *stabilization,* in which the soil life converts active organic matter to long-lived SOM (Williams et al., 2017). Tillage favors mineralization, and soil functional zone management practices such as ridge till limit this disturbance to crop rows, where nutrients will be utilized most efficiently, while between-row areas are left undisturbed to facilitate stabilization and protect soil health.

Planting nitrogen-rich legume or brassica cover crops in future crop rows or grow zones and high biomass, carbon-rich grasses in alleys also contributes to this differential function.

In ridge tillage, the soil functional zone management aspect is enhanced by the rebuilding cultivation, in which residues and severed weeds from alleys are moved into crop rows, thereby enhancing ridge top SOM, feeding within-row soil life, and contributing slow-release nutrients to the developing crop (Williams et al., 2017). Ridge tillage has shown promise in Cornell organic vegetable cropping systems trials (Drinkwater et al., 2014).

Full URL for the USDA photograph:
https://www.nrcs.usda.gov/Internet/FSE_MEDIA/nrcs144p2_026395.jpg.

Slides 20-27 – Organic rotational no-till systems

Slide 21 – *Step 1: grow high-biomass cover crops to maturity*.

In rotational no-till systems, a high biomass cover crop is grown to a reproductive stage at which it can be killed mechanically without tillage, usually full bloom to early seed development (before seeds are viable); at or after pollen shed for cereal grains and other grasses. The cover crop must attain high biomass (3 to5 tons aboveground dry weight per acre) with uniform, relatively weed-free stands that will provide a thick, even mulch after rolling or mowing.

While conventional crops can be produced no-till without cover crops, a high biomass cover crop plays a central role in organic no till systems, providing weed suppression as well as building soil health and fertility.

Slide 22 – *Step 2: terminate cover crop without tillage or herbicides*

The roller-crimper crushes cover crop stems to prevent regrowth, leaving stems otherwise intact to create a long-lived weed-suppressive mulch, and orients residues to facilitate mechanical no-till planting. Cover crop maturity is critical, as many cover crops will stand back up and resume growth if roll-crimped before full bloom. In addition, some cultivars may be more amenable to roll-crimp termination than others; for example, 'Purple Bounty' hairy vetch is more reliably killed by the roller-crimper than most other strains.

Flail mowing can also terminate certain cover crops, although others such as sorghum-sudangrass may regrow with renewed vigor. A row cleaner may be needed for no-till planting, and the finely chopped residue breaks down faster than roll-crimped covers, which can shorten the period of effective weed suppression. Supplemental weed control with high-residue cultivators may be easier in flail-mowed than in roll-crimped residues.

Non-hardy cover crops can be reliably terminated by freezing temperatures regardless of growth stage, which may allow for no-till planting of early spring vegetables or spring-sown cereal grains. However, a high biomass residue is essential to prevent late winter and spring weed growth from interfering with no-till planting or crop establishment.

Note that residues left by winterkill or by sicklebar or rotary mowers are randomly oriented and may interfere with mechanical no till planting. Rolling a non-hardy cover crop when falling temperatures have stopped its growth can orient the winterkilled residues.

Slide 23 – *Step 3: no-till planting of the production crop*

No-till drills and planters are used for field crops such as this soybean crop in roll-crimped cereal rye.

For organic no-till vegetable planting, the subsurface tiller-transplanter, developed by Dr. Ron Morse and colleagues at Virginia Tech in the late 1990s includes a coulter to part residues followed by a shank to open a slot in the soil, a transplanter wheel, a tank to water starts with liquid fish fertilizer, and closing press wheels. Similar no till transplanting equipment has been developed by other researchers, farmers, and agricultural engineers around the US.

Another approach is to use a "no-till planting aid" that parts residues and prepares a narrow slot in the soil for mechanical or manual transplanting with standard equipment.

Slide 24 – *Step 4: manage weeds*

Weeds are perhaps the greatest challenge to successful organic no-till systems. Even a high biomass cover crop residue may suppress weeds only for a couple of months after planting the cash crop. Some later-season weeds are likely to break through, although a vigorous cash crop with a heavy canopy can hinder their growth and reproduction. Cereal grains such as rye provide more persistent mulch than legumes, crucifers, or multispecies mixes, and an all-grass cover crop "mops up" excess soluble N from the soil, thereby slowing the growth of nitrogen-responder weeds like pigweeds, lambsquarters, or foxtails.

A strongly N-fixing cash crop like soybean can thrive and give full yields in no till terminated cereal rye whereas N demanding crops like corn or most vegetables would suffer yield reductions from N deficiency (Barbercheck, 2016; Barbercheck et al., 2014; Caldwell et al., 2016; Clark, 2016).

It is common to need some weed control during cash crop production in rotational no-till. Some cultivation tools are designed to work in the presence of substantial crop residues, without burying the residues themselves. Heavy duty finger weeders work better in residue than light torsion or tine weeders. Sweep undercutter tools set to work between and near crop rows can also remove weeds without burying residues.

After harvest, some tillage is usually needed to prepare the field for planting the next cover or production crop in the rotation, although if weed suppression has been good, minimum-till or no-till planting may be practical.

Slide 25 – *Conditions in which organic no-till may fail*

Organic rotational no-till systems can be challenging to manage and may fail for any of several reasons. Careful planning is needed to ensure that the cover crop can be grown until mature enough to terminate without herbicides or tillage without unduly delaying planting of the cash crop. In northern regions with short growing seasons, this constraint can make no-till based on roller-crimped cover crops difficult or infeasible for longer-season crops such as grain corn.

Weeds are the biggest challenge with organic rotational no-till. This system is most suitable for fields with low to moderate weed population dominated by small-seeded annuals, whose seedlings are substantially hindered by cover crop residues. Perennial weeds such as nutsedge and johnsongrass will easily break through the residue, and a heavy weed seedbank of vigorous summer annuals like pigweed can result in excessive weed competition against the cash crop.

If the cover crop has not achieved at least 3 tons/ac aboveground dry weight and does not cover the ground completely when viewed from above, its roll-crimped residue may not adequately suppress weeds. In warm, rainy climates, higher cover crop biomass may be needed. For example, in North Carolina, organic soybean planted no-till into roll-crimped rye with a 4.5 ton/ac biomass remained nearly weed-free and gave top yields, whereas a 3 ton/ac rye biomass resulted in reduced soybean yield because of weed competition (Reberg-Horton, 2009).

If the cover crop is planted immediately after breaking sod, residual grass clumps therefrom are likely to grow through a mowed or roll-crimped cover crop. Problems can also arise if the cover crop itself becomes overmature and self-seeds. For example, in a Virginia Tech field trial near Blacksburg, VA, organic summer squash planted no-till into roll-crimped barley + crimson clover became overwhelmed by self-seeding barley and clover, while squash thrived and yielded well in an adjacent plot with roll-crimped rye + vetch, neither of which self-seeded. The key difference was maturity date of the cover crops.

Cover crop residues slow soil warming and drying, which can delay cash crop planting, hinder crop establishment, and slow biological N mineralization. Reduced tillage cover crop management without supplemental applied N often results in N deficiencies in cooler climates (Carr et al., 2020). In multiple long term farming systems trials across the North Central and Northeast regions, organic rotational no-till with roll-crimped winter cover crops gave the best soil health outcomes but slashed grain yields in organic corn and oats by 63% because of N limitation and weed pressure (Delate, 2013). Soybeans, which fix their own N, suffered a smaller (31%) yield loss in the organic no-till systems in northern locations, and gave high yields in warmer regions including MO, MD, and NC (Barbercheck, 2016; Clark, 2016; Delate, 2013; Reberg-Horton, 2009). Snap bean and dry common bean (*Phaseolus vulgaris*) have more limited N fixing capacity and can be adversely affected by tie-up of soil N under a grass cover crop residue, as shown in the slide.

Moisture consumption by the cover crop prior to termination can help remove excess soil moisture in wet seasons, but can also leave the soil too dry in limited-rainfall regions or dry seasons.

Slide 26 – *Organic no-till challenges in a Mediterranean climate*

In 2018, several organic farmers and researchers received a NRCS Conservation Innovation Grant to develop strategies to reduce tillage in midscale organic vegetable production in California. Participants included:

- Scott Park and Brian Park, Park Farming Organics in Sutter Co., 1,700 ac.
- Paul Muller and Andrew Brait, Full Belly Farm inYolo Co., 400 ac.
- Phil Foster, Pinnacle Organically Grown Produce in San Benito Co., 295 acres
- Tom Willey, T&D Willey Farms, consultant and former organic farmer in CA.
- Jeff Mitchell, University of California at Davis Plant Sciences
- Cynthia Daley, Center for Regenerative Agriculture, California State University Chico

In addition to the no-till challenges discussed above, California's organic vegetable farmers face additional hurdles, including:

- Difficulty gauging the best timing to roll-crimp covers and plant cash crops during the transition from rainy winter to dry summer in a Mediterranean climate.
- A nearly rainless growing season, which slows decomposition of surface residues, nutrient mineralization, and nutrient transport to the crop root zone.
- Need for rapid and timely nutrient release for short season (60-90 day) crops.

- Trouble with roller-crimped covers regrowing or delaying soil warming.
- A lack of locally available tools and knowledge for no-till vegetable systems.

Tom Willey, who grew vegetables in California's San Joaquin Valley for 40 years and has since provided consulting for other farmers, joined three other leading farmers and several university and Extension professionals in a collaborative effort to overcome these challenges. Driven by a shared understanding of the central role of soil biology in successful organic farming and concern about the adverse effects of tillage, the project has become a learning community committed to the effort for the long haul.

All three farms implement advanced soil health systems including cover crops, compost, and livestock-crop integration. During the CIG project, they increased the amount and diversity of cover crops in their rotation (using mixes of up to 12 species) and took steps to reduce tillage, including roll-crimped cover crops (Full Belly Farm), reduced tillage frequency and intensity (Pinnacle Organic), and goat grazing and shallow (3-inch) tillage to terminate cover crops (Park Farm).

All three farmers observed soil health benefits in their field trials: more earthworms, better water infiltration, and structure so mellow they can dig the soil with their hands. Yet, reducing tillage significantly reduced yields of tomato and other crops. Apparently, leaving compost and residues on the surface in the hot dry central California summer hindered the mineralization and delivery of nutrients to crop roots. Efforts to move nutrients into the root zone by sprinkler irrigation caused crop disease problems. Plastic film over drip irrigation restored yields, but the farmers disliked having to landfill petroleum-based plastic waste each year.

The farmers recognize that it could take several years under organic minimum-till to realize optimal soil biological function and crop nutrition. "There's emerging scientific evidence that diverse soil microbial communities can deliver never-imagined levels of nutrients to crops if our farming practices facilitate, rather than interfere with, their ability to do so," Tom noted in a 2021 interview (Wozniacka, 2021). Conversely, overapplication of nutrients from any source, even compost, can make the soil life "lazy" and less efficient in nutrient cycling. Since many vegetable crops need their nutrients over a short period of time, the tradeoffs between meeting this need and building the soil's capacity to mineralize nutrients in a low-till system in a Mediterranean climate can be challenging to navigate.

The farmers are experimenting with several additional strategies:

- Biodegradable plastic mulch, removed and composted after harvest.
- Aerated subsurface drip irrigation to stimulate microbial activity and N mineralization in the root zone.
- Small-scale trials to evaluate individual components of their soil health systems.

Slide 27 – *When organic no-till is most likely to succeed*

In warm, rainy regions with long growing seasons, it is easier to ensure sufficient time and resources for both cover and cash crop. No-till yields are often equal or better than after cover crops are tilled in, especially when a combination of hot rainy climate and sandy soil might mineralize N too quickly after a cover crop is tilled in. For example, in Hawaii, green onions planted no-till into mowed sunnhemp yielded better and had fewer pests than onions planted in bare ground or black plastic mulch after the sunnhemp was tilled in (Chen et al., 2015).

As noted earlier, organic soybeans planted no-till into roll-crimped rye gain a selective advantage over N-responder weeds and can give excellent yields (Caldwell et al., 2016; Clark, 2016; Reberg-Horton, 2009). Other strong N fixers such as southern pea or lima bean might also do well in a rolled cereal grain cover crop.

Slides 28-33 – Soil Disturbance: a Broader Perspective

Slide 29 – *Types of soil disturbance*

Physical disturbance – tillage – is only one of several ways in which agricultural practices impact soil health. Biological disturbances that can degrade soil health include overgrazing or poorly managed continuous grazing, invasions by exotic noxious weeds whose root exudates harm the indigenous soil microbiome, and the microbial famine that occurs when a prolonged unplanted fallow period cuts off the daily supply of plant root exudates.

Prolonged unplanted fallows are common in the Corn Belt and the Great Plains, where the standard corn-soy and wheat-fallow rotations are implemented without cover cropping over a vast majority of cropland acreages. Recent findings that the cover cropping practice gradually builds all fractions of soil organic matter (SOM) regardless of tillage intensity (Peng et al., 2023)) suggest that the combination of tillage and prolonged bare fallow is what has exhausted SOM reserves in many cropland soils. Even without tillage, the wheat-fallow system without cover crops can degrade semiarid region soils (Halvorson et al., 2002). Similarly, removal of crop residues (for use as bedding or biofuel) from field cropping systems is destructive to soil health, promotes erosion, and depletes SOM to a far greater degree than plowing-in the residues (Andrews, 2006; Blanco-Canqui, 2016a, 2016b; Zhang et al., 2023)

Chemical soil disturbances can occur when herbicides, insecticides or other crop protection chemicals are applied to or washed into the soil. A growing body of research indicates that all classes of crop protection chemicals can exert adverse effects on all major taxonomic groups of beneficial soil organisms (Ariena et al., 2015; Druille et al., 2013; Gunstone et al., 2021; Klein, 2019; Nicolas et al., 2016). Pesticide impacts on soil bacterial, fungal, nematode, and earthworm populations and communities may be greater than those of tillage (Pelosi et al., 2014; Puissant et al, 2021; Vahter et al., 2022; Walder et al., 2022). NOP-allowed crop protection substances such as vinegar-based herbicides and copper-based fungicides can also hurt soil life and should be used with care (Atthowe, 2010; Klein, 2009). In addition, as noted earlier, shallow non-inversion tillage may support substantially higher microbial populations and maintain better soil health than either full till (moldboard plow + secondary tillage) or no-till with conventional inputs and no or inadequate cover cropping.

Research findings and scientific opinions vary widely on whether conventional soluble NPK fertilizers can enhance soil health by stimulating more vigorous crop growth (and hence organic matter inputs to the soil) or whether they degrade soil health by upsetting the soil microbiome and promoting a more rapid consumption of active SOM. Soils that receive organic nutrient sources may support up to twice the microbial biomass as soils fertilized with conventional soluble fertilizers, and the former also accrue larger reserves of SOM and mineralizable organic N (Franzluebbers et al., 2020; Morugán-Coronado et al., 2022). High levels of soluble N and phosphorus (P) in the soil, *regardless of source* (synthetic or concentrated organic fertilizers like poultry litter) compromise soil biological function and hinder the accrual of SOM, in large part because these surpluses limit crop root development and root exudation (Bhowmik et al., 2016, 2017; Prescott et al., 2021).

Unlike the soil health threat posed by direct toxicants especially xenobiotic (synthetic and foreign to life) crop protection chemicals, the issue with soluble fertilizers appears to be one of balance, and what a conventional fertility program lacks rather than what it contains. Providing nutrients in either all-organic form or a combination of organic and soluble sources substantially improved SOM and soil organic N accrual over soluble fertilizers alone (Young et al., 2021).

Slide 30 – *USDA National Organic Standards on tillage and soil health.*

The USDA National Organic Program (NOP) sets a high bar for organic soil and weed management. The NOP standards require tillage and cultivation practices to "maintain or improve soil condition," and outline a preventive approach to weeds, as well as a list of several non-soil-disturbing control measures in addition to mechanical cultivation. The standards also set physical soil disturbance in a wider context of integrated soil health practices that include cover crops, green manures, sod crops, catch crops (to scavenge leftover soluble nutrients), a crop rotation designed to build SOM and prevent erosion, and the use of plant and animal materials to return nutrients and organic matter to the soil.

Slide 31 – *Three components of the soil conditioning index (SCI)*

The NRCS Soil Conditioning Index (SCI) recognizes and integrates three key components of soil health: the net balance between sources of organic matter inputs into the soil and SOM losses to decomposition, the physical disturbance impacts of all field operations, and SOM losses to erosion, based on inherent soil properties, topography, climate (rainfall intensity) and management impacts on erosion. Thus, implementation of soil health practices such as diverse rotation, cover crops, no or minimal unplanted fallow, and organic amendments can yield a positive SCI value in a cropping system with tillage, especially when lower impact and non-inversion tillage implements are used.

Organic farming systems are characterized by higher diversity rotations, regular use of cover crops, and application of compost, manure, and other organic amendments (Snyder et al., 2022). In six long-term agroecological research (LTAR) trials in CA, IA, MD, MN, PA, and WI, organic crop rotations that include legume cover or sod crops, organic amendments, and routine tillage accrued more SOM than the conventional corn-soy rotations (Delate et al., 2015b). In the Beltsville, MD trial, soil organic carbon levels (SOC ~SOM X 0.5) after 13 years in the organic systems were 2.5 tons/ac higher than for conventional no-till and 3.9 tons/ac higher than tilled conventional (Cavigelli et al., 2013; Delate et al., 2015b). Organic amendments such as compost play an important complementary role with the living roots of diverse rotations and high biomass cover crops in building active and stable SOM, thereby making soils less vulnerable to adverse effects of tillage (Bhowmik et al., 2017; Delate et al., 2015a; Hurisso et al., 2016).

Slide 32 – *Crop rotation and residue return in long-term trials*

One of the main differences between the organic systems and the conventional systems in LTAR trials is that the organic systems include longer term, more diverse rotations with a greater percentage of the year in effective living vegetative cover. Cover crops and especially the perennial forage phase of organic rotations add to the organic matter inputs from both living roots and aboveground residues (Wander et al., 1994). A corn-soy rotation without cover crops leaves the soil fallow, unfed, and at risk from erosion as much as eight months of the year, and even when managed organically, leads to soil degradation and increased weed pressure, whereas the more diverse rotations build and maintain soil health (Moncada and Sheaffer, 2010).

Slide 33 – *Comparison of soil disturbance in three cropping systems*

When implemented with best regenerative practices that address all four NRCS principles of soil health management, organic agriculture and conservation agriculture offer two promising approaches to restoring and maintaining healthy soils. Conservation agriculture virtually eliminates physical soil disturbance and allows judicious use of soluble fertilizers and synthetic herbicides (which can entail some chemical disturbance to soil life). Organic agriculture minimizes chemical disturbances by permitting only natural fertility and crop protection inputs that are allowed under the NOP standards and allows judicious tillage (physical disturbances) with the requirement that the overall soil management system improves and maintains the physical, chemical, and biological condition of soil.

Both organic and conservation agricultural systems maintain soil coverage, living root, and farming system diversity (which in turn supports aboveground and belowground biodiversity), and supplement these practices with organic soil amendments. As a result, they tend to support a positive SCI and healthy soils. In contrast, conventional agricultural rotations often include extended unprotected fallow periods, utilize limited or no organic amendments, rely more heavily on synthetic inputs, and sometimes on tillage, a suite of practices likely to result in a negative SCI.

<u>Slides 34-53: Reducing tillage intensity in organic systems: examples from working farms</u>

Slides 35 and 36 – *Tips for a site-specific, soil-friendly tillage strategy.*

Soil and tillage management decisions must take a site-specific approach based on production system, climate, soil type (inherent properties), current soil condition (including past management impacts on dynamic properties), and available resources. This webinar cannot provide a formula for best organic tillage decisions; however, it provides examples from innovative working organic farms of creative strategies to optimize soil health within the context of organic production of annual crops with varying degrees and forms of tillage.

One guideline that applies to most circumstances is to plant the next cash or cover crop as soon as possible after tillage. For intensive crop rotations such as a high tunnel or a small-scale market garden, many organic specialty crop farmers aim to "flip a bed" on the same day as the final harvest, performing tillage and amendment applications as needed, and planting the next production or cover crop before the sun goes down. In dryland grain production when limited rainfall may necessitate time intervals between harvest or termination of one crop and attempting to grow the next, tillage is either postponed or conducted in such a manner as to leave the surface protected by residues (e.g., sweep plow).

In ecological weed management, organic farmers do not simply substitute the "big hammer" of tillage for the "big hammer" of herbicides; they use "many little hammers," to keep weeds below economically damaging levels (Liebman and Gallandt, 1997). The "little hammers" of organic Integrated Weed Management (IWM) aim to:

- Keep the soil occupied by desired vegetation.
- Disrupt weed life cycles with diverse rotations and varied timing of field operations.
- Prevent weed propagation.
- Kill weeds without harming soil life.
- Cultivate strategically to get the most weed control with the least soil disturbance.

These tactics were discussed in greater detail in an earlier webinar, *Beating the Weeds without Herbicides: Soil-friendly Organic Weed Management*, presented on March 20, 2023.

> Note that each of the farm stories summarized in the following slides is written up in greater depth in the NRCS Guidebook, *Tillage Tools and Practices in Organic Farming Systems: Limiting Soil Disturbance to Build Soil Health in Organic Cropland*

Slides 37-38 – *Minimizing soil disturbance in a one-acre market garden*
Jesse Frost and Hannah Crabtree, Rough Draft Farmstead, Lawrenceburg, KY

Jesse and Hannah grow vegetables intensively on one acre, including one 24 X 96 ft high tunnel and two 15 X 50 ft caterpillar tunnels. They place top priority on *keeping the soil planted* to keep the soil life well fed. They implement two diversified rotations:

- The "high rotation" beds are planted to a succession of short-season crops (60 days or less) including green onions, beets, arugula, spinach, carrots, lettuces, and an occasional cover crop, with no individual crop occurring more than once in a 12-month period.

- The “slow rotation” beds are planted in long-season crops such as potatoes, sweet potatoes, garlic, and tomatoes with cover crops; for example, cover crop □ summer tomatoes □ garlic □ winter squash □ cover crop □ popcorn, etc.

Soil management practices include:

- Using a broadfork to open and loosen the soil without inversion, which improves root penetration, plant growth, and microbial activity. Beds are broadforked only when they seem compacted, usually no more than once per season.
- *Cutting crops at time of bed turnover*. Because uprooting plants after harvest can steal 40 lb or more of soil and roots per 100 ft bed (~ two tons/ac), they cut plants at or just below the surface, remove weeds, spread and rake-in amendments, and plant the next crop.
- *Living pathways between beds.* When intense rainfalls washed woodchip mulch away from paths, Jesse and Hannah planted low-growing grasses, clovers, thyme, and chamomile, mowing as needed. They find that living paths enhance soil health while cultivated bare paths erode and degrade soil and destabilize raised beds.
- *Intercropping* two or more crops in a bed. Low-growing basil, onions, greens, and beets thrive between taller crops like tomatoes. Differing root depths minimize competition for nutrients, and diverse root exudates support microbial biodiversity.
- *Relay planting* short- and long-season, such as radish with summer squash, green onions after radish, and later, napa cabbage after squash, yielding four marketable crops in one growing season with continuous vegetative cover and living roots.

The farmers also do consulting to help other farmers establish organic minimum-tillage production systems, adapting their approach according to farm scale, climate, and soil types.

Slides 39 and 40 – *Landscape fabric for organic no-till vegetables*
Bryan Hager, Crager Hager Farm, Bremen, Georgia

Bryan has developed a tarping system for minimum-till organic specialty crops, using heavy black fabric (3.0 oz/sq yd) with UV block to terminate cover crops and control weeds during production of above-ground (leaf, head, or fruit) specialty crops. This material effectively stops most weeds except nutsedge and Bermuda grass. Unlike silage tarp, the landscape fabric “breathes” and allows rainfall to reach the soil. A typical schedule for field operations is:

- After harvest, apply lime and manure as indicated by soil test, broadcast cover crop seed, and pack. Cover crops include ryegrass + ladino clover over winter, buckwheat or sorghum-sudangrass + southern peas in summer, and oats or forage radish in the fall.
- If cover crop planting is delayed, cover beds with fabric to suppress weeds.
- One month before vegetable planting, mow the cover crop and lay fabric (no holes).
- One day before planting, remove fabric, apply fertilizers if needed, mix shallowly.
- Lay drip tape and fabric with planting hole spaced according to the crop, then plant.
- One month after planting, remove any weeds emerging through planting holes.

Bryan has found this system practical and highly cost-effective for his 2-acre operation. The sturdy fabric lasts for more than five years. A few pros and cons include:

- Intense heating under the fabric during summer kills emerging weeds and can also hurt young crops. Sprinkling hay mulch near the crops prevents heat damage.
- Heavy rainfall can puddle on the fabric. Raised beds minimize the problem.

In addition to minimal tillage, Bryan uses a suite of soil health practices, including:

- In the field, a four-year rotation of three years in diversified vegetables with winter cover crops and one full year in cover.
- In hoophouses, two to four crops per year, and one cover crop every other year.
- All vegetable residues are returned to the soil and covered with fabric to decompose.
- Organic mulches, including hay mulch on white and sweet potatoes (which cannot easily be grown with landscape fabric), and partially decomposed wood chip mulch or tree leaves in lieu of fabric on some crops to add nutrient and cool the soil.

Slides 41 and 42 – *Gearing down the rototiller to restore sandy soil*
Rick and Janice Felker, Mattawoman Creek Farm, Cape Charles, VA

Outdoor crops are grown in rotation with a winter rye + hairy vetch cover crop, which is planted over the entire field (beds and alleys) to maximize biomass. In spring, the cover crop is mowed, pulled onto bed tops with a front-mounted disk bedder and mixed in shallowly with a rear mounted tiller. For transplanted crops, Rick follows this operation with a bed shaper that lays subsurface drip tape and shapes the bed. After the cover crop has decomposed for a few weeks, he adds organic nutrient sources according to crop need, and works bed tops 3-4 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. Many farmers operate their tillers at maximum PTO speed with a forward speed of 1 mph, which creates a finely pulverized seedbed that crusts over and erodes easily.

For later-planted vegetables, the cover crop is mowed to a higher (1 ft) stubble height and allowed to regrow, thereby enhancing biomass and N fixation by the vetch.

Despite annual rotary 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%, 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." He attributes this success to several management factors:

- Lower-intensity rototilling.
- Controlled traffic with permanently positioned beds.
- Subsurface (3-4 inches) drip irrigation to encourage deeper rooting.
- Tight, diverse rotations with same-day bed flips.
- Returning all crop residues to the soil.

Slides 43 and 44 – *Maintaining healthy soil under routine tillage*
Justin Rich, Burnt Rock Farm, Huntington, VT

Organic vegetable farmer Justin Rich faces multiple challenges: a suite of low-residue, weed-prone vegetable crops, a sandy soil that does not hold much organic matter, a cold-temperate climate with a short growing season, and a farming scale (35 acres) that makes organic no-till with applied mulch or tarps impractical. In addition, compost use is constrained by State regulations on phosphorus (P) nutrient loading as well as the costs of meeting nutrient needs of multi-acre vegetable crops with compost. He responded to these challenges with intensive cover cropping, and by investing in a modern high-speed disk, which he finds less disruptive to soil structure than other tools such as the rototiller.

Burnt Rock Farm uses living plants to feed the soil life year-round and rotates fields into a full-season cover crop one year out of four. Some cropping sequences include:

- Winter rye, flail-mowed and disked at the pre-boot stage (to avoid N tie-up), followed two weeks later by sweet corn. Immediately after harvest, corn stalks are flailed, disked, and followed with a fall cover crop of oats and peas.
- Early spring vegetables followed by a high biomass multispecies summer cover crop.
- Spring planting of oats and red clover, oats mowed at heading and clover allowed to grow until the following spring, then terminated to plant potatoes, winter squash, or onions.

Slides 45-47 – *Integrating crops and livestock for soil health*
John Bell, Ann Bell, and Mac Stone, Elmwood Stock Farm, Georgetown, KY

Elmwood Stock Farm produces certified organic beef, pork, lamb, chicken, turkey, eggs, and mixed vegetables for an 800-family CSA and other markets. Their 550-acre operation includes 350 acres permanent pasture, and the most level 200 acres in a rotation of three years vegetables or feed grains with winter cover crops, followed by a perennial alfalfa-grass mix under rotational mob grazing for five years.

Crop-livestock integration and selling only edible portions of farm products optimizes within-farm nutrient cycling, minimizes fertilizer costs, and avoids nutrient imbalances that can develop when organic crop production depends on off-farm sourced compost and manure. Their annual off-farm inputs, including soil amendments and livestock feed supplements amount to less than 1 lb/ac each N and P, and 4 lb/ac potassium (K), plus mineral supplements for livestock.

University of Kentucky scientists have studied the integrated farming system at Elmwood Stock Farm and found that the five-year sod phase under rotational grazing restores SOM and microbial community to close to that of their permanent pasture (Lin et al., 2020). However, when the sod is broken by moldboard plow and disk to resume crop production, a burst of SOM oxidation and N_2O emissions occurs (Shrestha et al., 2019). The farmers have the following additional concerns with the current system:

- Plowing to break sod undoes some of the soil health benefits of five years' pasture.
- Growing cash crops only three years out of eight requires more acres in tilled rotations.
- Perennial weeds like Johnsongrass build up during the five years in pasture.

Beginning in 2019, the farmers are experimenting with new approaches to address these concerns, including:

- Terminating the sod phase by grazing severely in fall of the fifth year, followed by shallow tillage in lieu of plowing and disking. The tillage is done with a rototiller with the tailgate open and tractor speed around 3 mph, adjusted up or down to take out the sod with least damage to soil structure. *Results thus far:* sod effectively terminated, and no decrease in yields of long-season, heavy feeding crops.
- Terminating winter cover crops with a roller-crimper for no-till feed grain plantings. *Results thus far*: mixed success, learning curve, soil moisture conditions are critical for no-till planting, "awesome when it works."
- A small-scale experiment with an alternative crop rotation of one vegetable or feed grain crop every two years, and the rest of the time in annual multispecies cover/forage crops rotationally grazed. In 2020, summer vegetables were followed by no-till drilled rye, winter pea, vetch, and radish, grazed twice in spring 2021, rototilled shallowly in early June, and followed by a summer mix of German millet, southern pea, soybean, sunn hemp, radish, and valencia clover. After grazing this crop mix twice, the field was no-till drilled with rye, either for grain harvest or roll-crimping for the next vegetable crop. *Results thus far:* faster-growing, more nutritious forages, less soil disturbance.

The farmers would like to have University of Kentucky scientists study the new rotation and address the possible soil health tradeoffs associated with not having any perennial crops in the rotation.

Slides 48-50 - *Strategic rotations for minimum-till organic grains in upstate New York.*
Klaas and Mary Howell Martens, Martens Organic Farm, Penn Yan, NY

Klaas and Mary Howell Martens grow certified organic feed grains, sorghum-sudangrass forage, dry beans and peas, and vegetables on 1,900 acres in the Finger Lakes region of upstate New York. They collaborate extensively with researchers at Cornell University and University of Wisconsin in two Long Term Agroecological Research (LTAR) trials to tackle the challenges of tillage, soil health, crop nutrition, and weed control in organic farming systems. Their research and practice focus on two priorities:

- Choosing the best tillage tool for the job and using it correctly.
- Developing strategic crop rotation sequences that minimize the need for tillage and build multicrop organic no-till sequences.

Regarding the first priority, Klaas notes that "we still use our European moldboard plows when we have heavy residue to incorporate and keep them set shallow and correctly adjusted. The shares on a European moldboard plow are smaller and are designed for partial inversion, turning the bottom layer 90 degrees while only the top two or three inches are fully inverted, so that the organic matter and biological activity remain contiguous with the surface." In contrast, modern plows are larger and designed for deep, full inversion, which "buries the organic matter and biology in an anerobic zone, and brings unstable, unaggregated soil to the surface."

In his region (Finger Lakes of New York), many soils are silt loams with more than 50% silt. When improper plowing brings unaggregated silt to the surface, subsequent rainfalls carry the silt downward, clogging soil pores and creating a subsurface compacted layer that plant roots cannot penetrate, leaving crops more susceptible to drought. When farmers attempt to relieve this compaction with additional deep plowing, they simply recreate the problem. Klaas treats this problem with a subsoiler with narrow shanks set on 30-inch centers, running just deep enough to penetrate the compacted silt layer, then sows forage rape in the slots. This crop improves soil aggregation to a depth of 12 inches.

For secondary tillage, Klaas uses a rotary harrow or speed disk working two inches deep. He finds that these tools create less tillage hardpan than a rototiller or standard disk.

Regarding the second priority, years of careful observation of interactions among different crops, weeds, pathogens, and soil health have led to strategic cropping sequences that promote soil biological activity and reduce weed pressure, thereby reducing the need for tillage. For example:

- Red clover and canola promote soil aggregation through root exudates that support microbes. Terminating red clover by shallow undercutting creates "pasture for earthworms." Together, the worms, decaying roots, and microbes "biotill" the soil.
- Sorghum-sudangrass loosens soil, suppresses crop-parasitic nematodes, and provides large amounts of excellent forage.
- Simply adding a winter cereal grain to a corn-soy rotation turns the aggressive weed velvetleaf into a "weak, disease-prone plant with stunted roots."
- Perennial thistles often infest organic corn-soy-wheat-clover rotations. Adding a winter barley/ buckwheat or dry bean double crop reduces thistle pressure because barley harvest hits the thistles at their most vulnerable stage of development.
- Heavy growth of chickweed, deadnettle, and henbit indicate depleted SOM from excessive tillage and soluble N, and because these weeds die back in late spring, organic no-till corn planting may be workable.
- Planting rye + winter peas no-till into sorghum-sudangrass stubble after an end-of-summer forage harvest gives better rye + pea stands than planting into a tilled seedbed. The stubble provides a favorable microclimate for cover crop establishment, and fall frost prevents the sorghum-sudangrass from regrowing. Mixing peas with rye enhances rye N nutrition and vigor, providing a higher biomass for roller-crimping and no-till planting.

The farm continues to work with University researchers to develop extended crop rotation sequences that can be grown without tillage when conditions are favorable. One example is: "winter barley/ no-till doubled cropped with sorghum-sudan forage, followed by a fall no-till planting of rye with Austrian winter peas, crimped down the next spring and no-tilled with soybeans, then fall no-tilled with triticale and winter peas. This is a best-case scenario when everything works." With erratic weather becoming increasingly common with climate change, Klaas is ready to pivot to a modified crop sequence and/or appropriate tillage operation to meet the challenges that arise.

Slides 51-53 – *Strategic rotations for dryland organic grains in the Northern Great Plains*

Doug Crabtree and Anna Jones Crabtree, Vilicus Farms, Havre, MT

Vilicus Farms is located in a region dominated by a no-till wheat-fallow rotation that uses herbicides to maintain fallow for 14-18 months, a practice known to degrade SOM and soil health (Halvorson et al., 2002). In contrast, the Crabtrees have developed a complex, flexible, 7-year crop rotation that maintains year-round cover (living crops or residues) and includes some 15 production crops (wheat, specialty grains, oilseeds, pulses) and 10 cover crop species:

- **Year 1 Light feeding grain**: spelt, emmer, einkorn, barley or soft wheat with lower demands for nutrients and moisture are planted April 1 – May 15. Grains are harvested in late July or August, leaving 4 – 8" stubble and straw swathed in the field.
- **Year 2 Green fallow:** annual legume or cocktail mix planted late March or early April, *or* biennial sweetclover overseeded into the preceding crop. In June, beef manure + bedding is applied, and cover crops are terminated with a blade plow (leaving 90% residue cover) (Figure 9) or a speed disk (50-60% residue cover).
- **Year 3 Heavy feeding grain**: hard red winter or spring wheat, or durum wheat. "This is our highest market-value crop, and it must be successful," Doug noted. It is planted after the manure application to ensure sufficient crop-available nutrients.
- **Year 4 Broadleaf crop or oats:** safflower, flax, mustard, camelina, hemp, or oats, are planted in May and harvested in September.
- **Year 5 Pulse crop:** pea, lentil, or chickling vetch for seed, sown in spring.
- **Year 6 Oats, broadleaf, or light-feeding grain:** A crop not grown in the field earlier in the rotation cycle is planted in spring and harvested in August or September.
- **Year 7 Green Fallow:** biennial sweetclover overseeded into the Year 6 crop (if annual covers in Year 2), *or* annual cover (if sweetclover in Year 2). Terminated in June.

Additional soil health practices include:

- Extensive use of native prairie strips and field borders for biodiversity, wildlife habitat carbon sequestration, wind protection, and erosion control.
- Leaving stubble and residue in place over winter and conducting primary tillage 7-10 days before cash crop planting.
- Rotating type and depth of tillage, never using the same tool in a field two years in a row.
- Sweeps on planters remove emerging weeds at planting.
- Careful and adaptive timing of cover crop termination: late enough to develop meaningful biomass and fixed N, early enough to avoid soil moisture depletion for the next crop. About July 1 in a year with normal rainfall.

With help from an employee skilled in grazing management, the Crabtrees are gradually integrating livestock into their rotation, terminating green fallows by grazing in lieu of tillage. Manure deposits enhance soil biology. They are also composting manure that they spread to enhance soil benefits.

Slide 54 – *Questions?*

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* For OREI and ORG project reports, see Gateway database at https://nifa.usda.gov/data/data-gateway.