Tillage Tools and Practices in Organic Farming Systems

Limiting Soil Disturbance to Build Soil Health in Organic Cropland

Introduction

Organic farmers consider healthy living soil the foundation of successful production and resource stewardship. They implement multiple practices that reflect the four NRCS principles of soil health management:

- ☑ cover the soil,
- ☑ maintain living roots,
- ☑ enhance biodiversity, and
- ☑ minimize disturbance.

These practices include:

- Diverse crop rotations and cover crops to keep soil covered, maintain living roots, and enhance below-ground biodiversity.
- Organic amendments of plant and animal origin to build soil organic matter (SOM), to provide food and habitat for soil organisms, and replenish plant nutrients.
- Exclusion of synthetic fertilizers, pesticides, herbicides, and fungicides to minimize chemical disturbance to soil life.

Organic production of annual crops without the use of herbicides usually entails tillage and cultivation, which can degrade soil aggregates, damage fungal networks and larger soil organisms such as earthworms, and leave the soil vulnerable to erosion. Cognizant of these risks, organic farmers seek to implement soil-friendly tillage practices as required by the USDA National Organic Program (NOP) Standards:

§ 205.203 Soil fertility and crop nutrient management practice standard.

The producer must select and implement tillage and cultivation practices that maintain or improve the physical, chemical, and biological condition of soil and minimize soil erosion.

Organic farmers and researchers across the US are developing innovative, regionally adapted strategies to reduce tillage intensity, manage weeds with less cultivation, and maximize duration of living cover in their crop rotations. This Guidebook discusses tillage on organic farms within the broader context of building and maintaining healthy soils and features farm stories and recent advances in practical, organic, reduced-tillage cropping systems.

Modern agriculture disturbs the soil ecosystems in several ways. In addition to the direct physical disruption of tillage and cultivation, operations that leave the soil exposed subject near-surface soil organisms to desiccation (drying out), solar ultraviolet radiation and temperature extremes, and increase the risk of soil erosion by rain and wind. Prolonged fallow periods without living cover interrupt the flow of plant root exudates, thereby cutting off a vital food source for soil life. Monoculture and low-diversity rotations such as corn-soy limit soil microbial species and functional diversity. Finally, pesticides and soluble fertilizers can alter or harm the soil biota (Ariena et al., 2015; Druille et al., 2013; Gunstone et al., 2021; Klein, 2019; Nicolas et al., 2016).

Experienced organic producers seek to limit all these soil disturbances, and to compensate for the effects of tillage through a suite of soil health practices Examples of tillage practices used by farmers highlighted in this publication include:

- Continuous (no fallow) diversified crop rotations
- Cover crops and sod crops
- Intercropping and relay planting
- Using compost and other organic amendments
- Identifying fertility needs of crops and nutrient availability in soils to avoid nutrient excesses and runoff
- Controlling traffic with strip tillage, living pathways, and permanent or raised beds
- Crop-livestock integration with managed grazing of cover crops or post-harvest residues

When and Why do Organic Farmers Till?

Organic crop farmers utilize tillage and cultivation for several purposes.

Preparing the field for seeds:

Direct-sown crops require good seed-soil contact and freedom from early season weed competition to establish successfully. When preplant herbicides are not used, farmers usually prepare the seedbed through primary and secondary tillage. Small-seeded, direct-sown crops such as carrots or salad greens may require an additional pass to create a sufficiently fine seedbed.

Stimulate microbial activity to mineralize plant nutrients from organic materials:

Organic farmers rely on soil biological activity to release plant-available nitrogen (N) and other nutrients from SOM, soil amendments, and plant residues. Some tillage may be needed to stimulate timely biological nutrient release, especially in cooler climates and heavier soils.

Mix amendments and crop residues into the soil:

Unlike soluble fertilizers that are readily carried down into the soil profile by rainfall or irrigation, most NOP-allowed nutrient sources such as compost, pelleted poultry litter, or rock phosphate have low solubility, and are most effective when mixed into the top few inches of soil. In addition, the microbial inoculant benefits of living amendments such as compost or worm castings may be lost if they are left on the surface and exposed to direct sun. Therefore, organic farmers often apply these amendments just before the final tillage to prepare a seedbed.

Remove and control weeds:

Weeds remain the leading challenge in organic crop production (Snyder et al., 2022). Organic farmers must often cultivate several times per season to keep their crops ahead of the weeds, and managing tough weed problems without herbicides can entail intensive tillage.

For example:

- When the soil's weed seed bank is large, a period of cultivated fallow is often used to germinate and destroy weeds prior to crop planting.
- Invasive perennial weed infestations require vigorous tillage followed by cultivation to deplete the weeds' underground reserves (Mohler et al., 2021).
- When a heavy weed seed "rain" occurs, moldboard plowing is sometimes done to bury weed seeds at a depth from which they cannot emerge. Traditionally, cover crops have been plowed down as green manure to provide fertility to following crops.

Terminate cover crops and sod crops:

Today, many organic farmers mow annual cover crops and work them into the top few inches with non-inversion tools, although the moldboard plow is often used to terminate the perennial sod phase of a diversified rotation. Mature, high-biomass annual cover crops can be terminated with a roller-crimper for no-till planting of production crops, but this organic no-till system requires specialized tools and skills and good luck with the weather to succeed.

Relieve compaction and crusting and improve aeration and water infiltration

Using tillage to improve aeration and relieve compaction and crusting can be a double-edged sword, since excessive or improper tillage leaves soils prone to further compaction and surface sealing that restricts gas exchange. When used with care and at the correct soil moisture levels, implements such as the broadfork, para-plow, or a narrow-point chisel plow can improve soil structure, if tillage is promptly followed by planting crops with deep, robust root systems.

The Soil Health Impacts of Tillage Tools and Methods

Conventional tillage, practiced for many decades by both organic and non-organic producers, includes familiar tools and methods such as moldboard or disk plow followed by a harrow or light disk for field crops, or a rototiller for smaller-scale specialty crop rotations.

Various cultivation tools are used to remove weeds from growing crops, and a subsoiler is used to relieve subsurface compaction. But these familiar methods have known consequences:

- deep inversion disrupts soil life by burying the most biologically active surface horizon
- disking or rotary tillage can pulverize soil aggregates
- repeated tillage to the same depth creates a subsurface hardpan
- “clean tillage” leaves the soil vulnerable to wind and water erosion and surface crusting until vegetative cover is restored.

Since the mid-20th Century, farmers and conservationists have explored ways to reduce tillage frequency and intensity. While initial research focused on no-till systems that replace steel with herbicides, many organic farmers have switched to chisel, shallow, or ridge tillage, which do less damage to soil life than annual deep plowing (Kuepper and Schahczenski, 2020; Sun et al., 2016; Zuber and Villamil, 2016).

Some lower-impact tillage tools and practices that organic farmers use include:

- High-speed disk (tractor speed 7 – 12 mph) to chop and mix residues into the top 2 – 3 inches and prepare a seedbed. It is time and energy efficient for larger acreages.
- Vertical tillage implements to work shallowly or up to 8 inches, chopping and mixing residues, and aerating the soil without inversion and with minimal lateral displacement.
- Blade plow to sever cover crops and weeds just below the surface, leaving residues on the surface and most of the soil profile undisturbed. This tool works best in drier regions.
- Strip, zone, or ridge tillage to limit soil disturbance to crop rows where weed suppression and nutrient mineralization are most needed (Figure 1 and 1b).
- Rotary harrow (power harrow) to take out small weeds, prepare a seedbed, and mix amendments and light residues into the top few inches (Figure 1c).
- Spading machines for deep, non-compacting tillage that can incorporate a mature cover crop and prepare the soil for transplants or large seeds in one pass (Figure 1d and 1e).
- Bed shapers and disk bedders to form or rebuild raised beds, concentrate soil amendments in the “grow zone,” and create a seedbed in a single pass.
- Broadfork to loosen and aerate soil to 8 – 12 inches without inverting the profile or disrupting aggregates (Figure 1F).
- Precision cultivation tools linked to computer operated optical guidance systems designed to get the most weed control for the least soil disturbance.

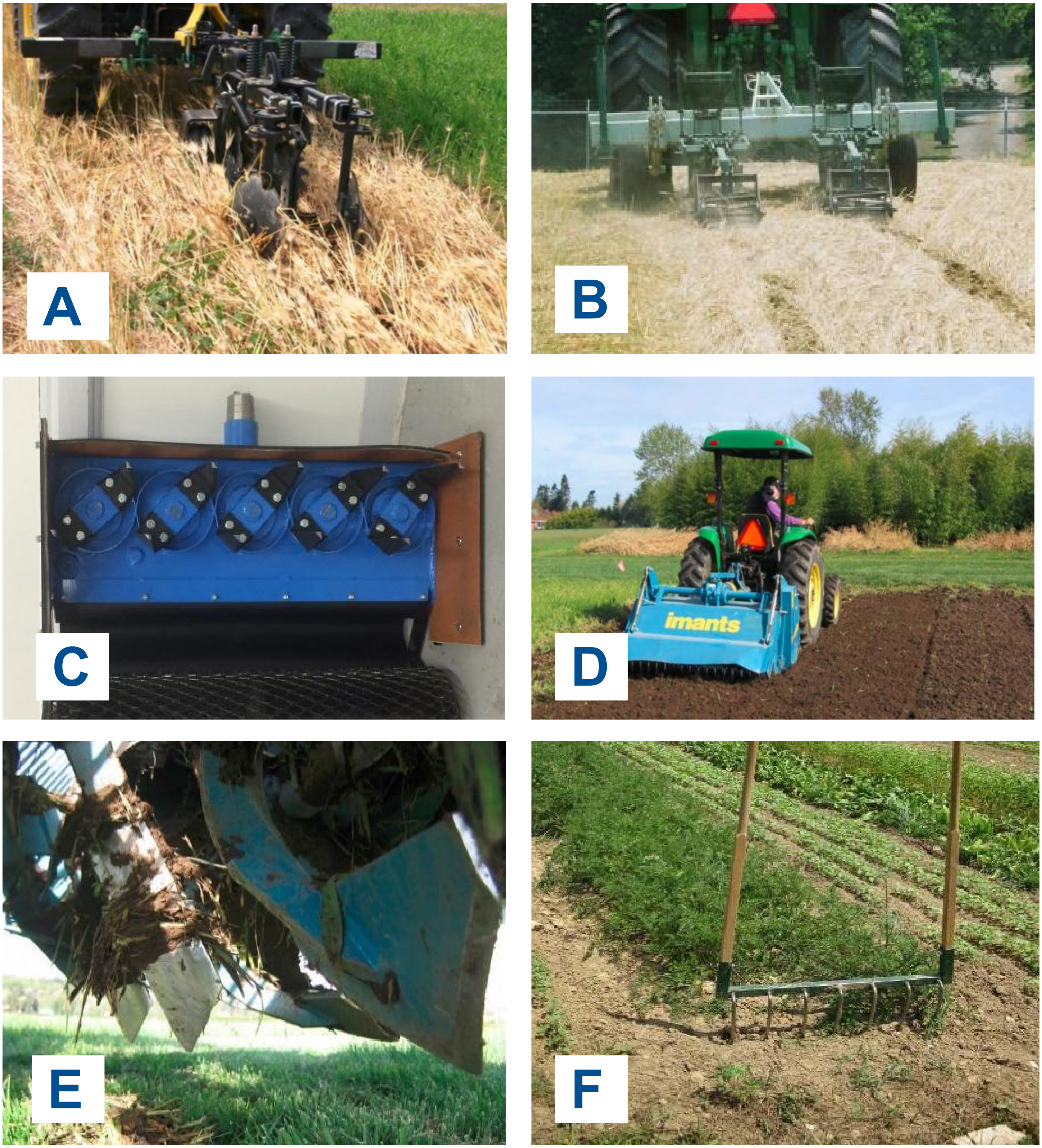

Figure 1. Some tools that organic farmers use to reduce intensity of soil disruption while getting the job done include strip tillers that leave 70-80% of the soil surface undisturbed (A, B), rotary harrow used to work the top 1 – 3 inches (C), reciprocating spader for deep non-compacting tillage (D, E), and broadfork, a manual tool used in small scale operations to loosen bed tops (F).

Monitoring Soil Health

Soil Tillage Intensity Rating (STIR) estimates physical soil disturbance associated with various tillage and other field operations, with values based on the type, area, depth, and intensity of soil disturbance (Table 1).

Total STIR for a crop cycle is calculated by adding the values for all field operations conducted from just after harvest of the preceding crop through harvest of the current crop.

The USDA's Natural Resource Conservation Service (NRCS) has defined several 'Conservation Practice Standards' (CPS's), and determining STIR values is one way to evaluate how field operations might meet goals for soil health.

For example, fields managed without full-width tillage and crop cycle STIR values of 20 or less meet the criteria for CPS 329 Residue and Tillage Management – No Till. Fields managed with only non-inversion tillage and crop cycle STIR values of 80 or less meet the criteria for CPS 345 Residue and Tillage Management – Reduced Till. Many low-tillage systems developed by organic producers meet the criteria for CPS 345.

The Soil Conditioning Index (SCI) estimates the total impact of a cropping system on net soil organic matter (SOM) accrual or loss (USDA, NRCS, undated).

The SCI is calculated as part of the Revised Universal Soil Loss Equation (RUSLE2) and is comprised of three factors:

1. Organic Matter (OM) accounts for organic materials returned to the soil including crop residues, cover crops, and organic amendments, minus expected losses through SOM decomposition. Estimates are based on expected yields of each crop in the rotation, and site factors regulating SOM decomposition such as climate, soil type, and soil texture.

2. Field Operations (FO) accounts for all field operations that affect the rate of SOM decomposition and is related to average STIR value over the crop rotation.

3. Erosion (ER) accounts for the loss of SOM through sheet, rill, and wind erosion, which is affected by inherent soil (erodibility), site (topography, slope), and climate (rainfall intensity) factors as well as management practices that affect erosion rates.

In conventional tillage (left), a winter rye cover crop has been mixed with the soil, while in strip tillage (right), the rye residue is left on the soil surface. Photo by David Bosc

NRCS Conservation Practice Standard 345

Residue and Tillage Management - Reduced Till

Definition: Managing the amount, orientation, and distribution of crop and other plant residue on the soil surface while limiting soil-disturbing activities used to grow and harvest crops in systems where the field surface is tilled prior to planting.

Table 1. Current Soil Tillage Intensity Rating (STIR) for tools and field operations often used in organic farming systems.

Primary tillage	Moldboard plow, 8 in deep	65
	Chisel plow, straight point, to 7 in depth	45.5
	Disk plow, heavy offset or tandem	39
	Chisel plow, 12-16 in low-crown sweeps, 3-4 in depth	25.02
	Spader (reciprocating)	18.2
	Rototiller, full field	18.2
	Para-plow, deep, shanks 30 in apart, <30% of surface disturbed	17.55
	Sweep plow (blade plow), 20 to 40 in wide	9.75
Secondary tillage	Disk, tandem, secondary with rolling basket	41.03
	Cultivator, field, shovel or spike point	31.2
	Disk, light finishing	19.5
	Bed shaper with drip irrigation installation	19.5
	Harrow, springtooth or spiketooth	15.6
	Harrow, rotary	10.24
Cultivation	Rod weeder	17.06
	Rotary hoe	16.57
	Cultivator, row, 1-inch ridge	14.63
	Rototiller, interrow cultivation	11.6
	Cultivator, high residue	8.13
	Manual cultivation, hoe, full field	3.9
Planting, manure application	Planter, potato	28.66
	Planter w/ in-row subsoiler, strip till coulter & roller	26.2
	Drill or air seeder, hoe/chisel openers	23.4
	Drill or air seeder, double disk opener	6.34
	Manure injector, low disturbance, 15-inch spacing	4.68
	Drill or air seeder, single disk opener	2.44
	Planter, double disk opener, fluted coulter	2.43
	Planter w/ in-row subsoiler, <10% of surface disturbed	2.34
	Broadcast seeder with pack roller	0.98
	Spreading manure on surface	0.2
Harvest and other field operations	Root crop harvest, mechanical, residue left on surface	13.75
	Root crop harvest, manual	4.16
	Plastic mulch or weed barrier application	1.56
	Harvest aboveground crops with no root disturbance	0.15
	Shredding, mowing, flame weeding	0.15
	Roller, crimp cover crop	0.1

Taken from the June, 2021 database utilized for RUSLE2 and SCI, and rounded to nearest 0.01 unit. Values updated annually based on new research findings, and therefore subject to change.

A Broader Perspective on Soil Disturbance in Organic Systems

Organic farmers are leaders in soil health practices. For example, three out of four organic farmers in the Corn Belt plant cover crops regularly, compared to just 10% of conventional farmers (Snyder et al., 2022).

Nearly all organic farmers rotate crops, and many expand the traditional corn-soy rotation to include corn, winter cover, soy, winter cereal grain overseeded with perennial legume or legume-grass sod, hayed or pastured for one or more years before rotating back to corn. Some organic vegetable growers rotate their fields into sod for one or more years to restore soil health and reduce weed pressure after several years' intensive cropping.

Thus, while organic farming entails more physical soil disturbance than no-till with herbicides to manage weeds and cover crops, reduced chemical disturbance and enhanced soil health practices can yield soil health benefits commensurate with no-till conservation agriculture (Table 2).

Table 2. Levels of physical, chemical, and biological soil disturbance and soil health practices in different crop production systems.

	FARMING PRACTICE		
	Best organic management	*Conservation agriculture*	*Conventional agriculture*
SOIL DISTURBANCE			
Tillage intensity	Low to moderate	None or minimal	Low to high
Unplanted fallow	Minimal	Minimal	Often prolonged
Pesticides, herbicides	Low*	Moderate	Moderate to high
Soluble nutrients	Low*	Moderate**	Moderate to high
SOIL HEALTH PRACTICES			
Soil cover, living root	Most of the year	Most of the year	Often inadequate
Crop diversification	Substantial	Substantial	Often limited
Organic amendments	Used regularly	Used often	No or limited use

** NOP-allowed materials only. Most organic nutrient sources are of low solubility.*
*** NPK applied according to "4R's" principles (right source, right rate, right time and right place) not to exceed Land Grant University (LGU) recommendations.*

Organic No-Till

An increasing number of organic farmers terminate some cover crops without tillage by roller-crimping, flail mowing, or planting cover crops that will winterkill in the farm's locale.

Roller-crimping mature (flowering), high biomass cover crops for no-till seeding or transplanting can work well for certain crop sequences when weather, soil moisture, and cover crop biomass and maturity date are optimal.

Examples include:

- ☑ soybean after winter rye,
- ☑ corn after hairy vetch + rye,
- ☑ tomato family vegetables transplanted after a winter legume-cereal mix, and
- ☑ fall head brassicas after a summer mix of millet and southern pea.

Organic no-till planting into roll-crimped cover crops can be quite challenging to manage. Yield reductions can occur if cover crop residues interfere with planting, slow soil warming and N mineralization, or fail to control weeds adequately.

Organic farmers need a viable "plan B" in case a poor or weedy cover crop, excessively wet or dry soil conditions, or other problems arise.

This system is often called "rotational no-till" because some post-harvest tillage is often performed to prepare the seedbed for the next cover crop. Some innovative farmers have extended the no-till period over several successive crops.

However, creeping perennial weeds and (in conventionally managed fields) herbicide-resistant weeds make truly continuous no-till impractical, and nearly all "no-till" farmers must till occasionally to keep these weeds at bay.

Small-scale specialty crop farmers have several additional tools to make organic no-till practical:

- Occultation – placing opaque landscape fabric or silage tarp over a mowed or roll-crimped cover crop for a few weeks to ensure termination and reduce weeds.
- Supplemental organic mulch or plastic film over the cover crop residue.
- Periodic broadforking to relieve compaction without damaging soil aggregates.
- Manual removal of weeds.

Best Tillage Practices for Soil Health in Organic Systems

Experienced organic producers develop innovative and site-adapted strategies that put into practice the four NRCS principles of soil health:

1. cover the soil,
2. maintain living root systems,
3. enhance biodiversity, and
4. minimize disturbance.

These strategies build and maintain healthy living soils even in the context of some routine tillage. In the following pages of this guidebook, farm stories and select Resources (listed on page __ of this publication) will provide examples and applications of the overarching principles of best soil and tillage management practices on organic farms.

- ☑ Implement a suite of practices to build and protect soil health (all farm stories; Resources 2, 3, 6, 8, and 9)
- ☑ Know the reasons to till, your desired outcome, and how to choose the best tool for the job (all farm stories, Resources 1, 2a, 3, 7)
- ☑ Adjust and operate tools correctly for greatest efficacy and least harm to the soil (Hager, Felker, Bell, Martens, Crabtree)
- ☑ Rotate tillage tools and depths to maintain soil structure and avoid hardpan (Crabtree)
- ☑ Plant the next crop without delay after tilling (all farm stories)
- ☑ Reduce tillage frequency and intensity to the extent practical for the operation (all farm stories, Resources 1, 2a, 2d, and 7)
- ☑ Use ecologically based weed IPM (Integrated Pest Management) and non-soil disturbing tactics (flaming, mowing, mulching, grazing, etc.) to reduce the need for cultivation (Frost, Hager, Willey, Crabtree, Resource 2b)
- ☑ Select and combine cultivation tools to get the most weed control for the least soil disturbance (Resources 4 and 5)
- ☑ When weed pressure necessitates aggressive tillage, plant fast-growing, high biomass cover crops to restore soil and enhance weed suppression (Rich, Martens, Resource 2)
- ☑ Implement strategic crop rotations and relay planting to thwart weeds, minimize bare soil, and reduce need for tillage (Bell, Willey, Martens, Crabtree)
- ☑ Utilize scale-appropriate techniques to manage weeds and cover crops without tillage (Frost, Hager, Resources 3 and 8)
- ☑ Take an adaptive approach to tillage based on current weather and soil conditions – especially important as climate change makes weather more erratic (Martens, Crabtree)
- ☑ Plant sloping, highly erodible, or otherwise fragile land in permanent pasture, orchard, agroforestry, silvopasture, or native perennial vegetation. Limit annual crop rotations to the least erodible parts of the farm (Bell, Resource 2d)

Table 3.Farm Stories Illustrating Challenges, Opportunities, and Innovative Strategies for Soil and Tillage Management in Organic Systems

Farm story (# as they appear, farmer name, farm name, state)	Crop acres	Production system	Site challenges	Innovative strategies
1) Frost, Rough Draft Farmsetad, Kentucky	1	Vegetables	Small acreage, intensive production	Living mulch in paths No-till w/ intercropping
2) Hager, Crager Hager Farm, Georgia	2	Vegetables Strawberries	Small acreage with history of soil loss	No-till system with landscape fabric tarps
3) Felker, Mattawoman Creek Farm, Virginia	11	Vegetables	Sandy, low-SOM Ultisol soils	Powered-down rototiller Controlled traffic
4) Rich Burnt Rock Farm, Vermont	35	Vegetables	Sandy soil, short growing season	Intensive cover cropping High-speed disk
5) Bell, Elmwood Stock Farm, Kentucky	200	Vegetables, feed grains, livestock	Weed pressure	Crop-livestock integration Low-till sod term,ination
6) Willey, et al, California	295-1,700	Vegetables, specialty grains	Mediterranean climate, dry summer	NRCS collaborative project on organic reduced tillage
7) Martens, Martens Organic Farm New York	1,900	Grains	Silty soils prone to sealing	Strategic rotation, Extended no-till
8 – Crabtree, Montana	19,500	Dryland grains, pulses, oilseeds	Semiarid climate, climate change	Strategic rotations, Rotate tillage tools

Farm Story 1: Minimizing Soil Disturbance in a Commercial Market Garden

Jesse Frost and Hannah Crabtree, Rough Draft Farmstead, Lawrenceburg, KY

How can one build healthy soil in a market garden where limited acreage necessitates frequent "bed flips" to grow two or more high value crops each year? Jesse Frost, an organic vegetable farmer, author, consultant, and podcast host, described his approach at a conference in 2022.

"The soil is like a giant battery, living plants are the solar panels, and the soil life transforms plant root exudates into soil carbon," Jesse began. Once the soil battery is "full," its microbial activity supports larger organisms, including food crops and farm animals. However, "if the soil is not fed, it will feed on itself," leading to soil depletion and difficult farming.

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. Embracing all four NRCS soil health principles, they place top priority on keeping the soil planted to feed soil life and recharge the soil battery, and they minimize physical disruption as much as possible within the context of the farming operation. Crops are grown in two diversified rotations:

1. 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.
2. 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.

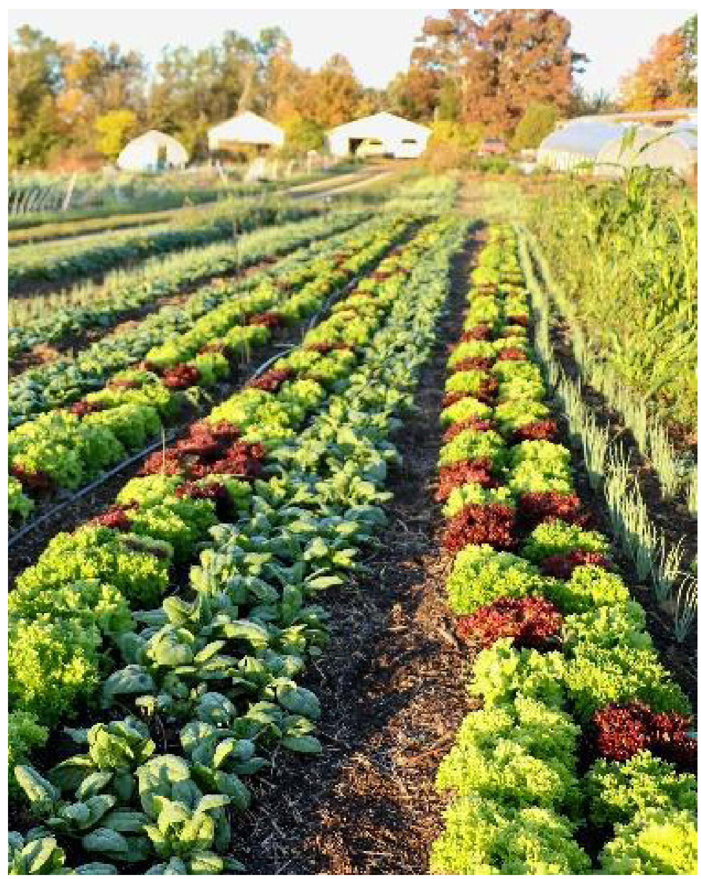

Figure 2: Intercropping, with two or more unrelated crops set out together in the same bed, enhances biodiversity, soil coverage, and soil health at Rough Draft Farmstead.

Soil management practices utilized at Rough Draft Farmstead include:

- ☑ Using a broadfork to open and loosen the soil without inversion, which improves root penetration, plant growth, and microbial activity. "Some disturbance can be beneficial," Jesse noted. "Our 'no till' does not mean no engagement with the soil at all." Beds are broadforked only when they seem compacted, usually no more than once per season.

- ☑ Cutting crops at time of bed turnover. Because uprooting vegetable plants after harvest can steal 40 lb or more of soil and roots per 100 ft bed, they cut plants at or just below the surface, remove weeds, spread amendments (compost, seaweed, biochar, humic acid), broadfork if needed, rake amendments in, then plant the next crop.

- ☑ Living pathways between beds. When intense rainfalls washed woodchip mulch away from paths on their sloping land, Jesse and Hannah planted low-growing grasses, clovers, thyme, and chamomile and maintained paths with a 17-inch electric mower and an edger to keep the perennial sod from overgrowing bed tops. Living paths enhance soil health while cultivated bare paths would erode and degrade soil and destabilize raised beds.

- ☑ Intercropping two or more crops in a bed (Figure 2). Low-growing basil, onions, greens, and beets thrive between taller crops like tomato. 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 with continuous vegetative cover and living roots.

Jesse outlined how he has adapted this system to different climates, soil types, and scales of operation, in his consulting with other organic farmers across the US:

- Cover crop system: Cover crops are grown to hold, aerate, and feed the soil, then mowed or knocked down with a heavy implement with the power off, followed by tarping; or by winterkill for direct-seeded spring crops. This system works well at medium to larger scale, on most crops, soils, and climates except for regions with very low rainfall.

- Deep compost mulch system: Cardboard is laid on the ground with 4 – 8 inches of compost on top. This system is practical for small scale high value crops when affordable high-quality compost is readily available. It works best on medium to heavy textured soils in cooler climates with low to moderate rainfall.

- Light-colored carbonaceous mulch no-till: Straw or hay mulch is used to block weeds, conserve moisture, and protect the soil surface. This system works well for small and -medium- scale production of long-season crops, especially in warm and semiarid regions, and where nearby grain or forage production makes these mulch materials available.

- Low mulch no-till system: A heavy compost application is mixed into the top few inches to provide soft, rich soil near the surface. This system is well-suited for baby greens and other direct-seeded crops, especially in high tunnels, and is handy when mulching materials are not available. It works for all soil types but may not be practical in fields subject to heavy weed pressure, intense rainfall, or strong winds.

In these systems, when the unavoidable soil disturbances of planting and managing vegetable crops stimulates respiration, Jesse noted, living plants utilize much of that extra CO_2 for more photosynthesis, growth, yield, and food for the soil life. His recent book and regular podcasts provide a wealth of practical information on organic no-till market gardening (see Resource 3).

Farm Story based on a presentation at the 2022 NOFA Vermont Winter Conference and follow-up e-mail conversation in March 2022.

Farm Story 2: Landscape Fabric for Organic No-till Vegetables and Strawberries

Crager Hager Farm, Bremen, Georgia

Farmer Bryan Hager has developed a minimum-till system utilizing landscape fabric to manage weeds and cover crops for organic vegetable and strawberry production in the Piedmont region of Georgia (Figures 3 and 4). Bryan is working on old farmlands where most of the topsoil was washed to the Gulf of Mexico decades ago. He lays heavy black fabric (3.0 oz/sq yd) with UV block to terminate cover crops and block weeds during production of above-ground (leaf, head or fruit) specialty crops. This material effectively kills cover crops and controls most weeds except for nutsedge and Bermuda grass. Unlike silage tarps, the landscape fabric “breathes” and allows rainfall to reach the soil.

Bryan uses a plywood jig and propane torch to prepare rolls of landscape fabric with planting holes for a range of crops (one to three rows, 9-36 inch in-row spacing), and uses blank fabric (no holes) for fallow periods. A typical schedule for field operations is:

- After harvest, apply lime and manure as indicated by soil test, broadcast cover crop seed, and pack with tractor-drawn rototiller with PTO off. Cover crops include ryegrass + ladino clover over winter, buckwheat (for short windows) or sorghum-sudan with iron and clay peas in summer, and oats or forage radish in fall ahead of an early spring crop.
- If cover crop planting is delayed, cover beds with blank fabric 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 lay blank fabric.
- One day before planting, remove fabric, apply fertilizers if 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.

Cover crops are managed with minimal disturbance. “In the hoophouses I use a weed wacker or a manual push mower to cut the cover crop, and a stirrup hoe or a small electric cultivator to work it in. I broadfork the hoophouse beds each year,” Bryan said.

Figure 3. For labor-efficient laying and pick up of the landscape fabric, Bryan uses a simple homemade fabric reel. Six-ft wide fabric is laid on raised beds spaced 5 feet center to center, overlapping in alleys and anchored with 8-inch metal staples. Photo credit: Bryan Hager.

Figure 4. Landscape fabric for strawberries (left) and high tunnel tomatoes (right). Photo credit: Bryan Hager.

For densely planted leafy greens, he uses a flame weeder just before planting. In the field, cover crops are mowed and, if needed, tilled shallowly with a BCS (2-wheel tractor) tiller.

The decomposing residues and roots "attract a lot of worms who loosen the soil well." Digging potatoes and sweet potatoes is "the most significant soil-disturbing activity" in the rotation. Immediately after potato harvest, he plants cover crops.

Bryan has found this system practical and highly cost-effective for his ~2-acre operation. The sturdy fabric lasts for more than five years and pays for itself in reduced weeding labor within a year or two. A few pros and cons include:

- Intense heating of the soil surface under black fabric during summer kills emerging weeds and can also hurt young crops. Sprinkling hay mulch around newly transplanted or emerging crops prevents heat damage.
- Intense rainfalls can puddle on the fabric, and raised beds minimize the problem.
- The fabric provides habitat for both beneficial organisms (earthworms) and pests (mice, fire ants, rolly pollies). The ants rarely cause major problems; if they do, he treats mounds with NOP-allowed soap and pyrethrum insecticide.

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

- In the field, a four-year rotation of brassicas, then mixed summer vegetables, then potatoes or sweet potatoes or corn with winter cover crops and one full year in cover.
- In hoophouses, two to four crops per year, and a cover crop every other year, chosen for high biomass, deep roots, nematode and disease suppression, and easy termination. These include buckwheat, oats, corn, sorghum, southern pea, ryegrass, marigolds, and rye.
- All vegetable residues are returned to the soil immediately or after decomposing in a pile. "I am trying to spread my rotation schedule so I can throw the old crops on an adjacent bed and cover with blank fabric to decompose."
- Organic mulches, including a heavy hay mulch on white and sweet potatoes, partially decomposed wood mulch in hoophouses before cover crop planting, and tree leaves in lieu of landscape fabric on some crops to add nutrients and cool the soil.

These practices maintain high fertility and SOM levels in the 5 – 8% range.

Farm Story based on telephone and e-mail conversations with Bryan in September 2020 and April

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 (coarse-loamy Ultisols) 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.

The cover crop is planted over the entire field (beds and alleys) to maximize biomass. After mowing, Rick uses a front-mounted disk bedder to pull cover crop and other vegetative matter up onto the bed top for the rear-mounted tiller to chop and mix during the first pass (Figure 5 left).

Beginning this year, he is managing the cover crop differently ahead of later-planted vegetables. Just before the rye sheds pollen, the cover crop is flail-mowed at a foot above the bed top and allowed to regrow. The vetch regrows vigorously without setting seed (Figure 5 right).

Figure 5. A mature cover crop of winter rye and hairy vetch has been flail-mowed, then moved into bed tops with a front-mounted disk bedder and tilled in shallowly in one pass (left). For later-season vegetables, vetch is allowed to regrow after flail mowing to produce additional biomass and fixed nitrogen (right).

For transplanted crops, Rick uses a bed shaper 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, he now omits the bed shaper 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 farmers in the region rototill with the PTO on high gear and a forward speed of about 1.0 mph, which leaves a fine, fluffy seedbed that readily crusts over, erodes, and loses SOM).
- In 2005, the farmers implemented a controlled-traffic system so that the grow-zones of beds receive no traffic, thereby avoiding soil compaction.
- 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. In addition, subsurface drip avoids watering near-surface, within-row weed seeds.
- 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.
- While their nine high tunnels (total 0.35 ac) are cropped more intensively (winter greens in lieu of the winter cover crop), beds are mowed, amended as needed, shallow-tilled, and replanted promptly after the preceding crop is finished, often on the same day.
- All crop residues are returned to the soil. Heavy residues like tomato are flail-mowed before tilling.
- Cover crops provide the primary source of organic carbon and nitrogen, and applied nutrient sources are used in moderation. This has maintained optimum (not excessive) soil phosphorus levels and has prevented salinization of high tunnel soils.
- Their soil health program plus deer fence installed in 2017 to protect 22 acres have greatly improved yields, so that they rarely have to double-crop outdoor beds and can rest some beds each year under season-long cover crops.

Farm story 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, a phone interview with Rick in September 2020, and an update in May 2022.

Farm Story 4: Maintaining Healthy Soil for Organic Vegetables under Full-width Tillage

Justin Rich, Burnt Rock Farm, Huntington, Vermont

How does an organic farmer maintain healthy soil when growing low-residue, weed-prone vegetable crops on a sandy loam soil that does not hold much organic matter, at a scale that makes organic no-till with applied mulch or tarps impractical, and in a cold climate with a short growing season?

During a soil health panel presentation at the 2022 Northeast Organic Farming Association (NOFA) Vermont conference, USDA certified organic farmer Justin Rich described how he evolved his strategy for his 35-acre organic vegetable farm in northern Vermont.

“Vegetables are hard on the soil, and potatoes are especially tillage-intensive,” Justin noted. When he explored no-till weed control options, he found that “our scale is difficult for tarping, and with our high rainfall, the tarps would make excessively wet areas along the edges. Mulching with compost overloads phosphorus and threatens water quality and would be prohibitively expensive at our scale.”

Then he invested in a modern high-speed disk, which he found less disruptive to soil structure than other tools such as the rototiller (Figure 6).

Figure 6. For most tillage operations, Burnt Rock Farm uses a 2.5 meter (8 ft) Farmet Softer high-speed disk equipped with independently sprung, compound-angled, notched disks and a depth-setting rolling basket in the rear. Working 3-4 inches deep at a forward speed of 7-8 mph, the disk chops and incorporates flail-mowed cover crops (left) and makes a satisfactory bed for transplanting in two passes 10 days apart. Winter-killed cover crops require only one pass (right). Because the disk works best in moist soil, Justin incorporates mid-summer covers after a rainfall.

Figure 7. A midsummer cover crop of sorghum-sudangrass, Japanese millet, peas, and oats had reached a height of more than 5 feet when it was flail-mowed in late August, 57 days after planting. Justin is planting this nutrient-depleted hayfield to a series of high-biomass cover crops to restore fertility for organic vegetable production.

In a cropping system that depends on full-field tillage, "we must prioritize cover crops. We aim to keep something growing all the time, except for short fallows for weed control or to let incorporated residues decompose."

Drawing on a toolbox of about eight different cover crop species, Burnt Rock Farm uses living plants to feed the soil life year-round, and rotates 10 of the 35 acres into full season cover each year.

Some cropping sequences used at Burnt Rock Farm include:

- Winter rye, flail-mowed and disked at the pre-boot stage (to avoid N tie-up), followed two weeks later by sweet corn. Within two days after corn harvest is complete, corn stalks are flailed, disked once, and followed with a fall cover crop of oats and peas.
- Early spring vegetables followed by a high biomass summer cover crop (Figure 7).
- 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.

Justin's integrated strategy of diversifying crops, maximizing living cover and roots, and shallow full-width tillage maintains soil health and fertility for a productive and profitable organic farm.

Farm story based on a presentation at the February 2022 Northeast Organic Farming Association (NOFA) Vermont Conference and a follow-up conversation with Justin Rich.

Farm Story 5: Reducing Tillage on a Mid-size Organic Crop and Livestock Farm

John Bell, Elmwood Stock Farm, Georgetown, Kentucky

John Bell, Ann Bell, and Mac Stone of Elmwood Stock Farm produce 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 200 acres, the most level and least erosion-prone land, in a rotation of three years in 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 cropping systems rely on off-farm organic nutrient sources.

In the past, the farmers moldboard plowed and disked the perennial sod, and disked winter cover crops to prepare fields for annual crops. Soil health studies on their system conducted by University of Kentucky scientists showed that the five years in undisturbed sod restored the soil microbial community to a condition similar to their permanent pasture and helped to replenish active and total SOM and soil organic N (Lin et al., 2020). However, plowing and disking led to rapid bursts of SOM mineralization and greenhouse gas emissions (Shrestha et al., 2019).

Based on the research and their own observations, the farmers had several concerns:

- Plowing to break sod undoes some of the soil health benefits of five years' pasture.
- Producing vegetables or grains only three years out of eight decreases revenue and subjects more acres to periodic tillage.
- Long rest periods in the grazing rotation optimize soil health but allow perennial weeds like Johnsongrass to set seed and become a problem in subsequent crops.

Beginning with the 2019 growing season, Elmwood Stock Farm has taken a different approach to terminating sod and cover crops. Late in the fall of the fifth year, the perennial sod is grazed severely, then rototilled shallowly (2-3 inches) in late February or early March before active growth resumes. "I run the tiller with the tailgate open at a forward speed of about 3 mph so that the soil is not beaten so hard," John said. "If I see viable chunks of grass come off the tiller, I slow down a little to be sure that the sod is properly broken."

A second shallow rotary tillage in April prepares the field for laying drip tape and black plastic mulch for planting long-season, nutrient-demanding crops including tomato, pepper, eggplant, Brussels sprouts, and double-cropping of shorter-season crops. "Crops have done just as well as in the past, and we get no sod regrowth," John observed, adding that it would be especially helpful to have University of Kentucky researcher Kristi Jacobsen or her grad students conduct additional research to evaluate how the new system affects soil health and greenhouse gases.

Over the past several years, John has begun roll-crimping cover crops for no-till feed grain planting in lieu of disking the cover crops. "It is a learning curve, and success has varied, but it is awesome when it works." Soil moisture at time of termination appears critical, as either wet or dry soil conditions can interfere with no-till planting (Figure 8(.

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Figure 8. Crop-livestock integration at Elmwood Stock Farm includes rotation of annual cover/ forage crops (left). John is experimenting with roll-crimping cover crops for no-till feed grain planting (right) in lieu of disking the cover crops. "It is a learning curve, and success has varied, but it is awesome when it works." Soil moisture at time of termination appears critical, as either wet or dry soil conditions can interfere with no-till planting.

Finally, the farmers are experimenting on a small scale (two fields totaling 11 acres) with an alternative two-year rotation consisting of a succession of annual cover / forage crops followed by a vegetable or feed grain.

In 2020, summer plantings of green beans, dry beans, and winter squash were followed by no-till drilled rye, winter pea, vetch, and radish. This cover crop was grazed twice in spring 2021, rototilled shallowly in early June, and followed by a summer mix of German millet, rye, southern pea, soybean, sunn hemp, radish, and valencia clover.

After grazing this crop mix twice, the field was no-till drilled with rye, which John plans to combine in June of 2022, though it could also be roll-crimped for no-till planting of another production crop.

Advantages of this rotation include faster-growing, nutritious forages, a food or feed crop every other year (versus three crops in eight years), and less soil disturbance. The tradeoff, John notes, is that "we do give up the benefits of deep perennial roots." Comparing the soil health benefits of the two rotations would be another great project for

Farm story based on a tour of the farm in 2017 and follow-up conversations with John Bell in August 2020 and April 2022.

Farm Story 6: NRCS Conservation Innovation Grant: Reducing Tillage in Larger-scale Organic Vegetable Production

Scott Park and Brian Park, Park Farming Organics, Meridian (Sutter Co.) CA, 1,700 acres

Paul Muller and Andrew Brait, Full Belly Farm, Guinda (Yolo Co.) CA, 400 acres

Phil Foster, Pinnacle Organically Grown Produce, Hollister and San Juan Bautista (San Benito Co.) CA, 295 acres

Tom Willey, T&D Willey Farms, consultant and former organic farmer in Madera Co., CA

Jeff Mitchell, University of California at Davis Plant Sciences

Cynthia Daley, Center for Regenerative Agriculture, California State University Chico

Organic no-till farming at a mechanized scale requires mature, high-biomass cover crops that can be terminated by mechanical means to create a weed-suppressive mulch, no-till planting equipment that can set seeds or transplants through the mulch at the right soil depth, and soil conditions that allow sufficient and timely nutrient release to the production crop.

Controlling weeds in a non-disturbance environment without herbicides can be difficult, and California's organic vegetable farmers face additional challenges, including:

- Difficulty gauging best timing for cover crop termination and cash crop planting during the transition from rainy winter to dry summer in a Mediterranean climate.
- Little or no rainfall during the summer growing season, which slows decomposition of surface residues and nutrient mineralization and transport to the crop root zone.
- Need for rapid and timely nutrient release for short season (60-90 day) vegetable crops.
- Trouble with roller-crimped cereal grains regrowing or keeping the soil too cold in spring for early crops.
- A lack of locally available tools and knowledge for no-till vegetable systems.

Farmers working with limited moisture often hesitate to plant cover crops; however, studies in the Central Valley of California showed no net soil moisture depletion from winter cover crops. (https://calag.ucanr.edu/archive/?article=ca.2022a0001).

Tom Willey, who grew conventional and organic vegetables in California's San Joaquin Valley for 40 years, and has since provided consulting for other farmers, described earlier attempts at organic no-till as "so disappointing, we gave up."

In 2018, he joined three other leading farmers and several university and Extension professionals in a collaborative effort, funded through an NRCS Conservation Innovation Grant (CIG) to develop workable minimum-till systems for larger-scale organic vegetable production in California. 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 farmers have long-integrated cover crops, compost, and diversified rotations to build healthy, living soils, and continually seek ways to reduce tillage. The Parks normally combine winter vetch cover crops, chicken litter compost at 3-5 tons/ac, and a disk designed to work their raised beds to a depth of 6 inches before planting, with a yield goal of 55 tons/ac for canning tomatoes.

Phil Foster makes compost on farm, grows high biomass winter cover crop mixes, mows the cover crop and usually prepares for vegetable planting with either strip tillage or shallow vertical tillage. At Full Belly farm, Paul Miller and Andrew Brait have integrated a flock of 200 sheep into the rotation, grazing cover crops and vegetable residues in a management system that meets the requirements for food safety certification.

As part of the collaborative CIG project, all three farms increased the amount and diversity of cover crops in their rotation (using mixes of up to 12 species) and took additional steps to reduce tillage. Full Belly Farm is using the roller crimper, Phil has reduced tillage frequency and intensity, and Scott aimed to maximize soil health with two successive multispecies cover crops, goat grazing to terminate the second cover, and running his bed disk only 3 inches deep.

Meanwhile, university researchers tested a wide range of cover crop species, varieties, and mixtures for biomass, N, maturity date, and efficacy of termination by roller-crimper

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 transport of nutrients from the organic materials to crop roots.

When they used sprinkler irrigation to move nutrients into the soil, it caused disease problems in fruiting vegetables. Laying drip irrigation lines beneath plastic film mulch after mowing cover crops gave the best results, improving nutrient availability and supporting no-till watermelon yields similar to the standard tilled treatment in two successive years. However, project participants disliked having to landfill petroleum-based plastic waste at the end of each season.

The farmers recognize that it could take several years under 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. For example:

- high levels of soluble nitrogen (N) reduce microbial N fixation and N cycling,
- while high phosphorus (P) reduces the activity of mycorrhizal fungi, prized by farmers for their multiple benefits to soil and crops.

“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 Willey, consultant and organic farmer

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.

During the 2022 season, the farmers are experimenting with several additional strategies: Biodegradable plastic film mulch, which will be removed and composted after harvest to meet NOP requirements.

Aerated subsurface drip irrigation to stimulate microbial activity in the root zone.
Small-scale trials to evaluate individual components of Scott Park’s soil health system.

Despite the tough learning curve and initial setbacks, the farmers remain determined to continue their on-farm trials and innovations in pursuit of viable organic minimum-till systems that optimize the plant-soil-microbe symbiosis and thereby sustain yields.

Farm story based on a series of e-mail and phone conversations with Tom Willey in 2021-2022. For more information, see slides and transcript of Tom Willey’s pre-conference presentation, To Till, Or Not To Till, given at the Organic Growers’ Summit in Monterey, CA on December 2021. http://creativecopy.net/ttontt/.

Farm Story 7: A Strategic Approach to Reducing Tillage and Improving the Health of Silty Soils in Organic Grain Rotations

Klaas Martens, Martens Organic Farm, Penn Yan, New York

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 also operate Lakeview Organic Grains, a farmers' cooperative providing feed grains and forages for organic dairies in the region. 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.

"The first step is to clarify the reasons why we use tillage to grow crops, and to identify the services that tillage provides," Klaas said. These include:

- ☑ Stimulate biological N mineralization and optimize its timing relative to crop need.
- ☑ Loosen the soil for better root penetration, water infiltration, and aeration.
- ☑ Reduce weed competition against crops.
- ☑ Provide a favorable environment for seeds, including correct depth and seed-soil contact.
- ☑ Warm the soil early in the season.
- ☑ Manage pests and pathogens.

Understanding that tillage is expensive, time consuming, and hard on the soil, and that it can make the soil too hot for optimum plant growth, Klaas asks, "can we accomplish these same services without tillage?"

In addition to protecting the soil, advantages of not tilling include:

- Avoiding stimulating certain weed seeds to germinate.
- Protecting beneficial soil fungal networks and larger organisms such as earthworms.
- Leaving residues and stubble that create a favorable microclimate for emerging seedlings.

In developing organic reduced-tillage strategies, Klaas draws guidance from the work of several 20th and 21st century agricultural leaders in Germany, including Jan-Hendrick Cropp, whose book on organic no till will soon be published in an English translation.

When tillage is necessary, Klaas notes, the key is to find the right tool and use it correctly. For example, "we still use our European moldboard plows and keep them set shallow and correctly adjusted when we have heavy residue to incorporate. Run that way, they don't fully invert the soil and the result has been a big improvement in soil health. The rule is that horizontal tillage should never go deeper than the depth to which the soil is well aggregated. That is usually 4 to 6 inches."

The moldboard plow has gotten a bad name because modern plows are too large and heavy, poorly designed, and are generally used incorrectly. "Deep full inversion buries the organic matter and biology in an anerobic zone, and brings unstable, unaggregated soil to the surface," Klaas explained.

"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.

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Many of the soils in the Finger Lakes region are silt loams, with more than 50% silt. When unaggregated silt is present at the surface due to improper plowing or inadequate soil biology, the silt leaches down during rainfall, clogging soil pores and creating a water-impermeable subsurface layer. Roots cannot penetrate deeply, and no-till crops commonly fail in drought years.

When these conditions necessitate mechanical soil loosening, Klaas's tool of choice is a subsoiler with narrow shanks set 30 inches apart and running just deep enough to penetrate the silt-deposit hard layer. The roots of forage rape seeded into the slots creatd by subsoiling enhance soil aggregation to a 12-inch depth.

"We use a narrow chisel to avoid lateral force that shatters hardpan – this can disrupt soil capillaries so water cannot go in, while the narrow slots allow both downward and upward transfer of water and improves cover crop germination."

"High silt soils can become 'addicted' to tillage," Klaas added. "Deep plowing is done to loosen them and to break up the layers that have become plugged with silt. Plowing brings unaggregated silt to the surface. Rain then moves it back into the deeper layers where it again plugs pores and capillaries."

For secondary tillage to prepare a seedbed, Klaas uses either a rotary harrow or a speed disk. These tools loosen and mix the top two inches of soil without pulverizing aggregates and are less likely to form a secondary tillage hardpan than a standard disk or rototiller.

For the past 25 years, Klaas has studied the ecological roles of weeds, soil microbial communities, and the positive and negative interactions among different crop species and varieties.

With this information in hand, he works backward in time to identify crop sequences that promote the desired conditions while reducing weed pressure and other problems that are commonly addressed through tillage.

Figure 9. Winter rye + Austrian winter pea no-till drilled into sorghum-sudangrass stubble. Although planted two weeks later than optimum, the cover crop has established well in the microclimate provided by stubble (left). Chickweed and henbit have filled in the gaps and will contribute organic carbon along with the cover crop (right).

Strategic crop diversity is key. For example:

- Red clover and canola promote soil aggregation through root exudates that support rhizosphere biological activity.
- Terminating red clover by shallow undercutting that leaves residue on the surface creates “pasture for earthworms.” Together, the worms, roots, and microbes “biotill” the soil.
- Heavy growth of chickweed, deadnettle, and henbit over winter, or galinsoga (annual weed) in summer indicate a loss of soil carbon due to excessive tillage or soluble N. The winter weeds tend to die back in late spring, making organic no-till corn or even spring wheat feasible.
- Adding mustard or buckwheat to a rotation of grasses and legumes can reduce root rot in dry bean and wild mustard weed pressure in wheat.
- Canada thistle and perennial sowthistle commonly infest organic corn-soy-wheat-red clover rotations in upstate New York. Adding winter barley followed by buckwheat or dry bean reduces thistle populations because the timing of barley harvest corresponds to the thistles’ most vulnerable stage of development.
- Sorghum-sudangrass loosens soils and suppresses pest nematodes, and the brown midrib (BMR) forage cultivars produce high volumes of valuable forage for dairy operations.
- Adding a winter grain to a corn-soy rotation makes the field less favorable to velvetleaf, turning this aggressive weed into a weak, disease-prone plant with stunted roots.
- Planting Austrian winter pea with rye stimulates rye growth by providing N, creating a heavier, more weed-suppressive roll-crimped cover for organic no-till soybean.
- No-till planting winter peas and rye into sorghum-sudangrass stubble protects the emerging crop from wind, desiccation, and winterkill, resulting in good stands (Figure 9).

Flexibility in crop selection for each phase of the rotation and using tillage tools correctly when needed makes for a viable system that protects soil health and crop yields.

- A winter grain broadcast-seeded into soybeans at the first yellow leaf stage of maturation works well, as soybean leaf fall covers the seed and promotes germination.

“We have had a lot of success with crop sequence that greatly improve yield, plant health, and ease of controlling weeds by making our crop the best adapted species for the soil conditions,” Klaas noted.

“An example of this is: winter barley/ no-till doubled cropped with sorghum-sudan or buckwheat, 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.”

Things don’t always work out optimally for a long no-till sequence, especially as climate change brings more extreme and erratic weather patterns. Flexibility in crop selection for each phase of the rotation and using tillage tools correctly when needed makes for a viable system that protects soil health and crop yields.

For example, when soybean is no-till planted into rye, the rye residue may be too thick for no-till broadcast seeding, so shallow tillage may be used to incorporate the rye. Klaas looks forward to participating in additional University and on-farm research into crop sequences and strategies to advance the cutting edge of organic minimum-till systems.

Farm story based on a telephone interview in April, 2022.

Farm Story 8: Diversifying Crops and Tillage Methods to Build Healthy Soil in Organic Dryland Grain Production

Doug and Anna Crabtree, Vilicus Farms, Havre, Montana

Can one grow organic wheat, specialty grains, pulses, and oilseed crops in a cold-temperate climate on just 11 inches of natural moisture annually? Yes. Can it be done no-till? Not easily. Can an organic farmer maintain soil health and productivity while tilling as needed to manage weeds and prepare seedbeds for a highly diversified rotation? You bet!

Doug and Anna Crabtree, with help of several skilled farm employees, are doing just that on 12,509 acres (350 owned, the rest leased) in Hill County in north-central Montana. They maintain soil health through crop diversification, green fallows, organic amendments, and alternating tillage methods based on current soil conditions and the needs of the next crop.

Vilicus Farms uses the following seven-year, flexible rotation on most of its acreage:

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 from a nearby feedlot is applied at a rate sufficient to replenish phosphorus (P) removed through harvests over the seven-year rotation, 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. Doug includes oats in this block because "it has a beneficial effect on the soil ecosystem, very different from other cereals."

Year 5: Pulse crop:

pea, lentil, or chickling vetch for seed, sown in spring.

Year 6: Oat, broadleaf, or light-feeding grain:

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 were planted in Year 2), or annual legumes or mix (if sweetclover was grown in Year 2). Terminated in June.

Vilicus Farms participates in the Conservation Stewardship Program (CSP), with a contract that supports this diverse, resource-conserving crop rotation and maintenance of extensive field borders for biodiversity and pollinator habitat (Figure 10).

A few landowners from whom the Crabtrees rent cropland have expressed hesitation about such a long and complex rotation. On these acres the rotation has been simplified to the first five years shown above, which maintains diversity and provides a cash crop four years out of five.

These rotations stand in sharp contrast with the dominant practice in Hill County, which consists of a two-year wheat-fallow no-till system in which fallow is maintained with herbicides. Research has shown that this system degrades SOM and soil health

Figure 10. The blade plow or sweep plow undercutter terminates cover crops and weeds by severing root crowns just below the surface, leaving residues in place and most of the soil profile undisturbed. This tool requires just the right soil moisture level, as wet conditions allow the vegetation to regrow, while very dry conditions prevent the tool from penetrating sufficiently to kill the cover crop. "It works about 50% of the time for terminating the green fallow," Doug said. "My fallback option is the speed disk." Photos by Drew Lyon, U. Nebraska.

(Halvorson et al., 2002). Although more farmers are adding pulse and oilseed crops to their rotation, at least two-thirds of cropland in Hill County remains in wheat-fallow, which leaves the soil bare and "inert of life" from harvest in July until the next crop is planted – more than 18 months for spring wheat.

Climate change has impacted farming practices in the Crabtrees' region in a couple of ways. Historically, farmers in this part of Montana grew only spring wheat, but with warmer temperatures and earlier springs, about half of the county's acreage is now planted to winter wheat, which enhances duration of living cover and reduces the fallow period to 12-14 months. On the other hand, Doug noted that four out of the past five years (2017-2021) have had significantly below-average precipitation, which restricted plant growth, crop production, and net return of organic residues to the soil, making it more difficult for all farmers to maintain SOM.

Doug has developed a tillage strategy to keep weeds in check, manage cover crops, and prepare seedbeds while protecting soil health. Stubble and residues are left in place over winter, and most tillage occurs seven to 10 days prior to planting each crop. Their seeder is equipped with sweeps to take out small weeds that germinate during this interval. Pre-plant tillage tools are chosen based on the needs of the crop to be sown:

- Speed disk, which works the top 2-3 inches of soil without inversion.
- Chisel plow with wide sweeps to lift and loosen the top 3-4 inches, followed by a coil packer to firm the soil and make weeds emerge so that planter sweeps can take them out.
- Moldboard plow working 6-8 inches deep to bury weed seeds, followed a week later by speed disk. Doug uses this strategy for the least weed-competitive crops (flax, oats), and only once in each seven-year rotation cycle.

"I have seen a tremendous advantage to rotating type and depth of tillage," Doug noted. I never use the same tool in the same field two years in a row."

Doug noted that it is important to terminate cover crop green fallow at just the right time – late enough to develop meaningful biomass and fixed nitrogen (N), yet early enough to avoid depleting soil moisture and reducing yield of the next crop. Most years, the "sweet spot" is close to July 1;

Figure 11. Unlike the region's dominant wheat-herbicide fallow system, Vilicus Farms keeps all their acreage covered by living vegetation or residues year-round. Examples include overseeded legume green fallow visible after grain harvest (left) and native perennial conservation buffers that hold soil and host beneficial organisms and wildlife (right).

unfortunately, current crop insurance program rules mandate a June 1 termination date.

Over the past few years, Vilicus Farms has begun to integrate livestock into their crop rotation. "Our operations foreman, Paul Neubauer, has a custom grazing business, and began grazing beef cattle on our land three years ago," Doug said. "We expect to host at least 400 head between June and October of this year. Paul developed a method to utilize grazing in lieu of tillage to terminate the green fallow. Cover crops are cut with a swather, then grazed for two or three days. I really like this system, as it effectively terminates the cover crop, and the manure stimulates soil biology."

Inspired by this success, Doug has acquired a small herd (12 head) of Scottish Highland cattle, which he plans to expand for a future new enterprise in grass-fed beef.

In 2021, the Crabtrees acquired a compost turner and started composting the manure they use for the heavy-feeding grain. Composting with bio-inoculants and water as needed stabilizes nutrients and enhances soil health benefits. Researchers in Utah reported that a single heavy application (22 tons dry weight/acre) of composted beef manure doubled near-surface SOM and dryland organic wheat yields for the next 15 years (Reeve and Creech, 2015).
Doug observed that "with livestock now on our land, we can reduce our dependence on imported manure, though we may not be able to eliminate it entirely."

In conclusion, Vilicus Farms protects the soil resource in a cold-temperate semiarid climate through integrated organic farming practices that exemplify NRCS principles of soil health:

- ☑ A highly diversified crop rotation.
- ☑ Living plant cover each growing season.
- ☑ Tillage tools and timing that maintain residue cover when living cover is not present.
- ☑ Rotating tillage methods and depth to avoid creating hardpan.
- ☑ Organic methods that exclude synthetic agrochemicals.
- ☑ Use of organic amendments to maintain but not exceed desired nutrient levels.
- ☑ Integration of crops and livestock to enhance nutrient cycling and soil biology.
- ☑ Wide prairies strips to reduce wind erosion and support biodiversity.

Farm story based on telephone and e-mail conversations in March 2022.

Resources

1. **Reducing Tillage Intensity in Organic Production Systems** by George Kuepper and Jeff Schahczenski. 2020. ATTRA Bulletin, 12 pp, National Center for Appropriate Technology. https://attra.ncat.org/product/reducing-tillage-intensity-in-organic-production-systems/.

2. **Guidebooks on Soil Health and Organic Farming** Organic Farming Research Foundation https://ofrf.org/research/reports/ including:
   a. Practical Conservation Tillage
   b. Weed Management: An Ecological Approach
   c. Understanding and Optimizing the Community of Soil Life
   d. Building Healthy Living Soil for Successful Organic Farming in the Southern Region

5. **The Living Soil Handbook: The No-till Grower's Guide to Ecological Market Gardening** by Jesse Frost. 2021. Chelsea Green Publishing, White River Junction, VT, 290 pp. Also, The No-till Market Garden Podcast. https://www.notillgrowers.com.

6. **Cultivating Partnerships: In-row weed control options for farmers large and small** Michigan State University video. 2018. NC SARE-funded on-farm research and demonstration of flex tine cultivator, finger weeder, and torsion weeders widely used by organic farmers. https://www.youtube.com/watch?v=UUt7egqexVA.

7. **Physical Weed Control Forum** Videos and technical information on organic weed IPM and advanced cultivation tools for precise weed control in vegetables. Eric Gallandt (U Maine) and Daniel Brainard (Michigan State U). https://forum.physicalweedcontrol.org/.

8. **The Dirt on Organic Farming** a 2021 podcast series hosted by Mallory Krieger & Nate Powell-Palm of the Organic Agronomy Training Service (OATS). https://www.organicagronomy.org/the-dirt-on-organic-farming. Podcast 1, Moldboards and Dust Clouds: Organic Has a Tillage Problem. Farmers and scientists from New York, Montana, and the Corn Belt discuss tillage and soil health in organic systems.

9. **Reduced Tillage in Organic Systems Field Day Program Handbook** Willsboro Research Farm, Cornell University, Willsboro, NY, July 31, 2018. 108 pp. https://rvpadmin.cce.cornell.edu/uploads/doc_699.pdf.

10. **Growing for Market** has published multiple farm stories on no-till and minimum-tillage systems and tools for small-scale organic production of vegetables and other specialty crops. Recent articles in Vol 28 (2019) No 1; Vol 29 (2020) No 1, 2, 4, 5, 7, 8, and 10; Vol 30 (2021) No 2 and 3. https://growingformarket.com/.

11. **Soil Health Benchmarks 2021 Report** Franklin Egan and Sarah Bay Nawa, Pasa Sustainable Agriculture, https://pasafarming.org/soil-benchmarks-2021. Documents excellent soil health in no-till, reduced-till, and full-till vegetable and field crop rotations.

Additional Research Findings on Tillage on Organic Cropping Systems

Maintaining and improving soil health in tilled organic cropping systems

Organic cropping systems that maintain soil cover, living root, and crop diversity in conjunction with judicious full-field tillage can sustain soil health. In six long-term farming systems trials in CA, IA, MD, MN, PA, and WI, organic crop rotations that included legume cover or sod crops, organic amendments, and routine tillage accrued more soil organic carbon (SOC ~ SOM X 0.5) than the conventional corn-soy rotations (Delate et al., 2015b).

In the Beltsville, MD trial, SOC levels 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). Crop diversity and living cover are vital, as a two-year organic corn-soy rotation can degrade soil health and invite weed problems, while a four-year corn-soy-cereal-alfalfa rotation improves soil condition (Moncada and Sheaffer, 2010). Organic amendments such as compost play a key complementary role with living roots in building active and stable SOM, thereby making soils less vulnerable to adverse effects of tillage (Bhowmik et al., 2017; Hurisso et al., 2016).

Many of the tillage implements that are gaining popularity among organic producers appear gentler on soil life and soil health than moldboard plow, disk, and rototiller. Multiple studies have shown that chisel tillage or shallow (~3 inches) noninversion tillage (e.g., rotary harrow or high-speed disk) maintain greater soil microbial activity and functional diversity than deep inversion tillage (Sun et al., 2016; Zuber and Villamil, 2016).

Compared with disking, terminating cover crops with a sweep plow improved moisture retention, weed control, and subsequent crop yields in Nebraska (Wortman et al., 2016) and reduced wind erosion in the interior Pacific Northwest (Sharratt & Feng, 2009). In organic vegetables, the spading machine prevented subsurface compaction and sometimes improved yields over plow-disk or rotary tillage (Cogger et al., 2007).

One challenge that organic farmers face in maintaining soil and environmental health in an annual/perennial rotation is the burst of SOM oxidation and greenhouse gas emissions that can occur when a legume or legume-grass sod is plowed to resume annual crop production (Han et al., 2017; Shrestha et al., 2019). Some farmers are exploring alternatives to moldboard plowing to retain more of the soil benefits of these rotations (see Farm Story 5).

In the most recent agricultural census conducted by USDA National Agricultural Statistics Service (NASS), similar percentages (~39%) of organic and conventional producers use some form of conservation tillage (Shade, 2021). Although continuous no-till is considered more practical for conventional systems than organic, the ongoing evolution of herbicide resistant weeds has forced more conventional farmers to “buy steel” for weed control (see Resource 6).

Benchmark Study Finds Healthy Soil in Tilled Fields

“Many farms that rely on tillage for controlling weeds and preparing fields are still able to achieve optimal soil health by balancing tillage with a holistic soil health management strategy” (Egan and Nawa, 2021).

Key elements of this strategy include cover crops, full season green fallows, maintaining living vegetative cover for most of the year, and carefully timed tillage. Soil health in tilled systems did not appear to depend on heavy use of compost and other organic amendments, as many of the farms used only light applications.

A recent meta-analysis compared microbial biomass in no-till, “reduced tillage” (full field shallow non-inversion tillage with disk or rotary harrow), and “conventional tillage” (moldboard plow 8 inches or deeper followed by secondary tillage). Reduced till doubled fungal and bacterial biomass over plowing, while no-till only yielded a small increase in fungal biomass (Morugán-Coronado et al., 2022). The authors attributed this finding to compaction, reduced porosity, and surface sealing during long-term continuous no-till, which can restrict gas exchange, promote waterlogging, and thereby limit microbial activity.

Conversely, lower-intensity full-width tillage can promote aeration and microbial activity while doing less damage to fungal networks than plow-disk tillage. Soil microbes play central roles in formation of stable organic matter and nutrient cycling (Franzluebbers, 2018; Prescott et al., 2021), which suggests that organic reduced tillage systems may enhance these vital functions.

A recent review of nearly 400 studies showed that insecticides, fungicides, herbicides, and other agrochemicals do significant harm to soil invertebrates including earthworms, mites, springtails, beetles, and other arthropods (Gunstone et al., 2021). These organisms play vital roles in maintaining soil structure, cycling nutrients, and building SOM; thus organic farming systems protect soil biological function by excluding the use of synthetic agrochemicals.

Ongoing research related to soil health and tillage in organic systems includes:

- ☑ Soil health and grain yields under full tillage, shallow till (high-speed disk), and reduced-frequency tillage, and observational study of soil health and tillage on 25 organic grain farms in the PASA Soil Health Benchmark Study (Wallace and Barbercheck, 2021).
- ☑ Efficacy of organic amendments in mitigating the effects of tillage on soil biota and soil health in semiarid regions (ID and eastern WA) (Johnson-Maynard, 2021).
- ☑ Effects of different cover crops, poultry litter, and strip till vs full till on soil health, nutrient cycling, and yields in southeastern US Ultisols (Ye, 2021).
- ☑ Effect of four levels of tillage intensity and off-farm inputs on soil health, nutrient cycling, and yields in an organic corn-soy-wheat rotation in TN (Jagadamma, 2021).
- ☑ Effect of three levels of tillage and inputs on soil health, nutrient cycling and yields in organic grains in coarse and fine texture soils on Delmarva peninsula (Weil et al., 2021).

Organic minimum tillage systems for field crops

Rotational organic no-till in which production crops are planted into roller-crimped cover crops improves soil health outcomes over either conventional continuous no-till or organic with routine tillage but can sharply reduce yields especially in colder climates (Barbercheck et al., 2008; Curran et al., 2014). In a study at 11 sites in five northern tier states (IA, MI, ND, WI, PA), this no-till system reduced organic corn and oat yields 63% and soybean 31% (Delate, 2013).

Organic no-till has also faced challenges in semiarid and Mediterranean climates, including aggressive perennial weeds like Canada thistle, slow nutrient release from surface residues, and reduced yields (Menalled, 2019; Norton et al., 2014; Wozniacka, 2021).

Rotational no-till appears more practical in warmer climates with moderate to high rainfall, especially for N-fixing cash crops. In the mid-Atlantic region, yields of organic soybeans planted no-till into roller-crimped vetch-cereal covers equaled or exceeded soybean yields in the tilled treatment, while no-till corn still showed a significant yield reduction (Barbercheck, 2016; Barbercheck et al., 2014).

Organic soybean no-tilled into roll-crimped high-biomass cereal rye has also done well in NC, MO, and NY (Caldwell et al., 2016a; Clark, 2019; Reberg-Horton, 2009). The rye ties up soluble N, which hinders nitrogen-responder weeds like pigweeds, ragweed, foxtails, and lambsquarters without hurting the N-fixing soybean; in addition, rye mulch reduces white mold in organic soybean and dry bean (Pethybridge & Ryan, 2021).

Another strategy for reducing tillage is relay planting or overseeding cover crops into standing production crops, which extends the cover crop's growing period, provides continuous soil cover, and eliminates post-harvest tillage. Overseeding ryegrass and clover into corn at the 5 – 7 leaf stage, or ryegrass into soybean has worked well in NY (Caldwell et al., 2016b). In PA, overseeding timothy and red clover into spelt improved subsequent corn yields by 11 bu/ac compared to planting annual cover crops after spelt harvest (Barbercheck, 2016).

Some current research efforts in organic minimum-till field crop production include:

- Farmer-participatory research to develop extended organic no-till crop sequences and an adaptive management decision tool (Ryan et al., 2021, see also Farm Story 7).
- Perennial dual-use grain/forage crops (kernza, perennial cereal rye) with interplanted legumes for reduced till organic field crop rotations (Culman et al., 2021)

Organic minimum tillage systems for vegetable crops

Organic minimum-till vegetables have yielded well in warmer climates. Examples include strip till sweet corn in MD and no-till green onion in mowed sunn hemp in HI (Chen et al,., 2015), summer squash and bok choy in roll-crimped sunn hemp in FL (Delate, 2015a), and summer squash and tomato after rye + crimson clover in SC (Robb and Zehnder, 2016).

Covering mowed or roll-crimped cover crops with opaque plastic tarps or landscape fabric for a few weeks (see Farm Stories 1 and 2) can ensure termination, reduce weed pressure for several weeks after the tarp is removed, and improve yield by warming the soil (Brust, 2015; McSwain, 2021; Rangarajan, 2021; Rangarajan et al., 2016). In a cold-temperate climate (ME), solarizing (transparent) tarps applied for 10-30 days after terminating rye + vetch suppressed weeds and sustained high organic cabbage yields (Smith, 2021).

Organic vegetable farmers and researchers are exploring minimum-till strategies to deal with climate disruption that has made timely tillage and planting difficult. In a SARE producer grant project in coastal SC, terminating cover crops with a roller-crimper designed for raised beds followed by tarping for no-till planting doubled organic squash yields despite extreme and erratic rainfalls alternating with drought (Connor, 2018). Other farmer-participatory teams are exploring no-till raised beds with compost, cover crops, and tarping to grow organic vegetables despite extreme spring rainfalls in IA (Scheibel, 2022), and cover crop based reduced till systems to enhance resilience to extreme rainfall events in WI (Genger, 2021).

Organic weed IPM: getting the best weed control for the least soil disturbance

Weed management remains a top research priority and technical assistance need for organic producers (Snyder et al., 2022). Current efforts to develop innovative organic weed IPM strategies and tactics to improve efficacy and reduce reliance on cultivation include:

- Cellulose-based biodegradable hydro-mulches for weed suppression in market vegetables, strawberry, and blueberry (Gramig et al., 2021).
- Organic carrots and greens direct-sown on top of biobased biodegradable fabric mulch and covered with compost (Wortman, 2021).
- Electric weed control in lieu of intensive alley tillage in organic orchard and bushberry crops (Moretti et al., 2021).
- High-residue cultivator, electric weed zapper, and interrow mowing to enhance weed control in organic no-till soybean planted into roll-crimped rye (Ryan et al., 2021).
- A farmer-designed between-row mower has provided sufficient weed control to sustain no-till organic soybean yields (Clark, 2019; Los, 2020).

- Perennial cover crops in travel paths between vegetable beds to reduce need for tillage for weed control and improve soil health (Hurisso et al., 2021; see also Farm Story 1).
- NOP-allowed herbicide (caprylic and capric acids) and sensor-guided selective herbicide application in organic no-till dryland wheat/winter pea rotation (Carpenter-Boggs, 2021).
- Integrated biocontrols (thistle rust fungus and bindweed gall mite), cover crops, strategic crop rotation and harvesting, and limited strategic tillage in lieu of intensive tillage to control field bindweed and Canada thistle in organic dryland grains (Carr et al., 2021).
- “Stacking” multiple cultivation tools (sweeps, spyders, flextine, torsion, finger, whisker weeders, etc) to enhance within-row weed control (Gallandt and Brainard, 2021).

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