ORGANIC FARMING RESEARCH FOUNDATION

fostering the improvement and widespread adoption of organic farming

2025 Research Summary for Cooperative Agreement on Conservation Benefits of Organic Management

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USDA Natural Resources Conservation Service

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INTRODUCTION

This document provides a summary of the latest organic agriculture research across a variety of topics, meant to provide NRCS staff, organic producers, and other interested parties with in-depth educational information on the conservation benefits of organic management. Each section provides bulleted highlights of the research, followed by a comprehensive summary. At the beginning of each section, you will also find a list of NRCS resource concerns, soil health principles, and conservation practice standards. These are meant to be generally applicable to each section and the literature contained within it. If you are interested in a copy of any of the cited papers and the resource concerns, soil health principles, and/or conservation practice standards specific to that paper, please follow up with us via email at office@ofrf.org.

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ORGANIC PEST MANAGEMENT: WEEDS, INSECTS, AND DISEASES

NRCS Resource Concerns (RCs) Addressed	NRCS Soil Health Principles Addressed	Applicable Conservation Practice Standards (CPS)
• Soil RCs: Soil erosion, Organisms and habitat, Organic matter • Plants RCs: Plant productivity and health, Plant pest pressure • Water RCs: Nutrient transport to groundwater, naturally available water use • Animals RCs: Terrestrial habitat for wildlife and invertebrates	• Minimize soil disturbance • Soil coverage • Living roots • Plant diversity	• CPS 325 High Tunnel System • CPS 328 Conservation Crop Rotation • CPS 329 No Till / CPS 345 Reduced Till • CPS 336 Soil Carbon Amendment • CPS 340 Cover Crop • CPS 386 Field Border • CPS 484 Mulching • CPS 595 Pest Management Conservation System

Highlights from Recent Research

- In more northern climates, an October-planted cereal rye cover crop responds better to roll-crimping, and permits no-till planted soybean, reduces variable costs, and increases farm net returns (Dhakal et al., 2023).
- The development of soil-biodegradable mulch films as alternatives to nonbiodegradable polyethylene materials is progressing, but uncertainties around their rates of decomposition, potential soil health impacts, and costs still need to be addressed (Shcherbatyuk et al., 2024).
- Fresh organic mulches, such as cover crop clippings, can effectively reduce Colorado potato beetle populations and foliar damage to potato crops during the critical flowering stage (Winkler et al., 2024).
- Insect exclusion netting over cucurbit mesotunnels can help reduce cucurbit yellow vine disease and the incidence of the squash bug, which transmits the disease (Pethybridge et al., 2024).
- Anaerobic soil disinfestation for disease management reduces bottom rot incidence of baby leaf lettuce by 87% and the numbers of emerging weeds, especially broadleaf species, by 50% (Vincent et al., 2024).

Cover Cropping Strategies for Weed Control

Weed management is often laborious and costly for organic producers. Cover crops can suppress weeds and disrupt weed life cycles and provide co-benefits to soil health and crop yield through continuous ground cover, nutrient provisioning through biological N fixation (legumes) and nutrient recovery (deep-rooted species), organic matter (root exudates and cover crop biomass), and habitat for beneficial species. However, cover crops are often terminated by tillage, which can compromise the positive effects of cover crops, especially when inversion tillage (moldboard plow) is used. Many row crop farmers are interested in the use of roller crimpers for cover crop termination, which allows for no-till crop planting and the retention of cover crop residue on the soil surface for weed control.

A 3-year field trial was conducted at Rodale Institute's research farm in Kutztown, Pennsylvania, to evaluate the impacts of cereal rye (*Secale cereale*) cover crop planting date and termination method (traditional plow-disk, vs. mowed, and two designs of a roller-crimper) on weed suppression and yield of organic no-till planted soybeans (Dhakal et al., 2023). While cereal rye planting date (September or October) did not affect total weed biomass, **the earlier planting date resulted in a tougher (more lignified) cover crop that was more resistant to termination by roller-crimper.** For both planting dates, cereal rye attained the desired biomass (8 Mg/ha) for weed suppression after roller-crimping in the second and third years of the trial. Farm variable costs were reduced across the no-till strategies by 14%, and net returns were increased by 19%. **The roller-crimper design, consisting of a single roller with blunt metal blades welded on in a chevron pattern, resulted in the best weed suppression and most consistent yields and net returns.** An alternative design with multiple rollers for each crop row minimized rye regrowth but allowed more weed growth in the soybean crop (Dhakal et al., 2023).

Organic grain production in the Northern Great Plains must often contend with creeping perennial weeds such as Canada thistle, field bindweed, and perennial sowthistle. Alfalfa grown for two or three years for forage (harvested at late flowering) effectively controls these weed species, but this may not be a practical option for all farmers. Diverse crop sequences that include annual cover crops could provide an alternative means to suppress perennial weeds due to the niche differentiation of plant functional groups. At two locations in North Dakota, the efficacy of various four-year crop rotations in suppressing creeping perennial weeds in dryland organic wheat production was assessed (Gramig et al., 2024). Rotations included:

- three years alfalfa – one year hard red spring wheat (HRSW);
- lentil – HRSW interseeded with sweet clover – sweet clover (left to grow after wheat harvest) – HRSW;
- nine-species cover crop mix – HRSW – 9 species cover crop mix – HRSW.

While the typical alfalfa system had greater weed control (likely due to alfalfa mowing and haying), **the two diverse rotations did not result in an increase in perennial weed biomass, and the HRSW yield in the final year of each rotation did not differ** (Gramig et al., 2024). Therefore, the more diverse rotations could be an option for farmers looking to gain the multiple benefits served by cover cropping.

Organic-Compliant Mulching

Organic vegetable crops are often grown in plastic mulch raised beds. Weed growth, soil erosion, and nutrient leaching in alleys between beds pose challenges to the efficacy of the system. Alley weeds can compete with the crop for water and nutrients, harbor pests, and promote disease by reducing air circulation. Because of this, many organic producers are interested in living cover crop mulches between beds. In Southwest Michigan, a two-year study compared the efficacy of different alley management practices in plastic-mulched organic bell pepper (*Capsicum annuum cv. Paladin*) and summer squash (*Cucurbita pepo cv. Lioness*) (Tarrant et al., 2024). Treatments consisted of:

- Living mulch of Italian ryegrass (*Lolium multiflorum*), cereal rye, or cereal rye + Dutch white clover (*Trifolium repens*), managed with mowing
- Cultivation
- Straw mulch
- Mowing ambient weeds (weedy control)

The cultivation and straw mulch treatments resulted in high levels of weed control (94% and 78%, respectively) and also reduced the weed seedbank compared to weedy control and living mulch treatments (Tarrant et al., 2024). **Live vegetation in alleys (living mulch or ambient weeds) took up leftover nitrogen (N) and thereby reduced end-of-season leachable N by 61% compared to cultivation and dead mulches.** The mulch species chosen for this trial were not suited to summer growing conditions, especially cereal rye and white clover, which are normally planted in the fall. The authors noted that, in other trials, **teff (*Eragrostis tef*) has shown greater promise as a living mulch for summer vegetables** (Tarrant et al., 2024).

Plastic film-mulched raised beds are an important part of many organic vegetable producers' systems; however, the nonbiodegradable polyethylene materials most often used raise environmental concerns, including entry of microplastics and nanoplastics into the soil and food chain. **While the US organic standards allow soil-biodegradable mulches, none of the biodegradable film mulches (BDM) that are commercially available meet NOP requirements for 100% biobased origin and 90% degradation within two years (*7 Code of Federal Regulations, section 205.2*)**. Shcherbatyuk et al. (2024) reviewed progress toward development of new water-based sprayable hydromulch, foam mulch products, and agrotextiles that meet NOP criteria and that recycle waste-stream materials. One challenge encountered has been the highly variable rates of BDM decomposition realized in the field depending on soil conditions, often considerably longer than rates measured in the laboratory.

Hydromulches based on cellulosic materials such as recycled paper and cardboard, crop residues, and wood chips, plus plant-derived tackifiers have shown promise for moderating soil temperature and retaining moisture in hot, semiarid regions, can suppress most weeds, but require specialized equipment for application. Seaweed-based mulches show similar efficacy against weeds, offer some of the benefits of seaweed-based organic fertilizers, can be made from invasive seaweed species removed from impacted ecosystems, and can be applied with standard spray equipment. Additional research is needed to assess hydromulch impacts on soil health during decomposition, and to develop formulations for different purposes, including raising soil temperature for warm-season crops (Shcherbatyuk et al. 2024). Foam mulches under development can be sprayed on the soil surface or on plants as protectants, and have given weed control similar to black polyethylene mulch. Biofabrics (biobased agrotextiles) based on polylactic acid (PLA) suppress weeds, conserve moisture, allow gas exchange, and last longer than film BDMs, which is desirable for long-season crops or double crops. Researchers have had success sowing narrow-spaced crops like carrots in growing media on top of PLA biofabric, which allows crop roots to penetrate yet blocks weed emergence. However, biofabrics tend to cool the soil (unlike black film mulches) and PLA-based biofabrics do not decompose rapidly enough in soil to meet NOP requirements, and must be removed and composted (Shcherbatyuk et al. 2024). **Remaining challenges and questions to address for biobased mulches include higher costs to the farmer and cost-share programs based on the ecosystem service of reducing plastic waste and pollution, impacts on soil health and soil biology during decomposition, farmer perceptions of mulch esthetics, and uncertainties about their impacts in organic production (Shcherbatyuk et al., 2024). This review could serve as a helpful resource as these technologies develop.**

Organic mulches, primarily living and/or dead plant materials, can also be useful for insect pest management. **Mulches can provide habitat for beneficial insects (i.e., predators), and may also impede pest movement into the foliage of the cash crop.** The Colorado potato beetle (CPB; *Leptinotarsa decemlineata*) is found across the country as well as in Europe and Asia, and they have the capability to overwinter in soil near crop fields, although they do not travel far distances once adults emerge in the spring. In Germany, three research station trials and on-farm trials were conducted to determine if organic mulches (fresh triticale-vetch cover crop clippings, fresh grass-clover clippings, dry straw, or grass silage) could effectively reduce CPB populations and foliar damage to potato crops during the critical flowering stage when CPB feeding tends to be at its highest and has the greatest impact on crop yield (Winkler et al., 2024). **Compared to bare soil, the mulches reduced CPB numbers and damage by 30% at the research stations and 40% at the on-farm locations. Additionally, the mulches significantly boosted potato yield in three of the six trials.** The authors suggest that mulching should not be the sole technique used for CPB control, but the other benefits of these mulches (i.e., soil health, nutrient retention, etc.) make them economically attractive to growers (Winkler et al., 2024).

Other Organic Methods for Pest and Disease Control

The seedcorn maggot (*Delia platura*) is another prevalent insect pest, particularly in organic corn and soybean. The adult stage of this species is drawn to decomposing plant residues for their oviposition (egg laying), which for organic growers can pose a challenge as cover crops, other plant residues, and organic soil amendments are often worked into the topsoil by tillage. In Central Pennsylvania, researchers examined the effects of planting date, cover crops, and tillage on seedcorn maggot in organic corn and soybean (Regan et al., 2024). Seedcorn maggot flies were six times as numerous in corn as in soybean, though **delaying corn planting 1-2 weeks reduced fly numbers. Seedcorn maggot flies were 15 times as numerous when a cover crop was tilled into the soil as when the cover crop was roller-crimped for no-till cash crop planting, and fly numbers were found to be negatively related to cover crop legume proportion** (Regan et al., 2024).

Some plant diseases are transmitted by arthropod vectors and require an integrated approach to pest and pathogen management in organic operations. Cucurbit species are susceptible to bacterial wilt (*Erwinia tracheiphila*), which is transmitted by spotted and striped cucumber beetles (*Diabrotica undeimpunctata howardi* and *Acalymma vittatum*, respectively). Insect-excluding row covers are often used to prevent bacterial wilt in cucurbits by excluding cucumber beetles. However, melon and other cucurbits require bee pollination to set fruit, and weed growth is harder to manage if the crop remains covered through the season. Field trials in Iowa evaluated different methods to allow pollination in organic muskmelon (*Cucumis melo*) while excluding pests with net-covered mesotunnels (3.5 ft), and to manage alley weeds between plastic-mulched crop rows (Mphande et al., 2024). Three pollination methods were compared: 1) Keeping mesh covers on all season and installing one bumblebee hive for each subplot (3 rows by 150 ft); 2) Opening ends of mesotunnels for two weeks during flowering; and 3) Removing nets entirely for two weeks during flowering. **Season-long coverage resulted in higher marketable muskmelon yields, reduced incidence of cucumber beetle and bacterial wilt, and enhanced net returns by 29% over the on-off-on method and by 45% over the open ends method. Seeding alleys with teff at the time of muskmelon transplanting then mowing three weeks after teff seeding reduced alley weed biomass by 84-98% and resulted in melon yields nearly as high (9-16% reduction) as landscape fabric between rows. Planting alleys with teff and not mowing, or leaving alleys unplanted and uncovered with or without mowing reduced melon yields by 30-50%, likely due to teff or weed competition with the crop for moisture.** In addition, the living mulch added organic matter and improved soil structure in alleys, and seeding the teff cover was less expensive than the landscape fabric, making net returns for mowed teff competitive with landscape fabric (Mphande et al., 2024).

Similarly, exclusion netting can also be effective for insect and disease management in organic acorn squash. Recently, organic cucurbit production has faced the emergence of cucurbit yellow vine disease (CYVD), caused by the bacterium *Serratia marcescens* and transmitted by the squash bug (*Anasa tristis*) (Pethybridge et al., 2024). Trials in New York evaluated insect exclusion netting over a mesotunnel and alley cover crops (ryegrass or ryegrass + clover) for insect, disease, and weed control for organic acorn squash. **The mesotunnel with netting reduced incidence of squash bug and CYVD but did not reduce common diseases including downy and powdery mildews and *Alternaria* leaf spot. Alley cover crops reduced weed pressure overall, and while treatments did not significantly affect numbers of marketable squash, mesotunnels reduced the incidence of soft or sunburned fruit** (Pethybridge et al., 2024).

Anaerobic soil disinfestation (ASD) is another tool for organic growers in managing diseases. This process is an alternative to chemical fumigation and involves the addition of readily decomposable organic carbon (C) amendments, followed by irrigating the soil to saturation under an airtight tarp, which results in a burst of anaerobic microbial activity. During this anaerobic phase, soil microbes decompose the C amendments, resulting in metabolites like fatty acids and volatile compounds, which can help decrease the viability of pathogens and weed seeds. In Florida, researchers examined the effect of ASD (using molasses as a C source) versus compost or a control treatment (neither ASD nor compost) on weed density, bottom rot incidence (caused by *Rhizoctonia solani*), and crop yield and quality in several cultivars of romaine and oakleaf lettuce direct seeded in organically managed high tunnels and harvested as baby leaf lettuce (Vincent et al., 2024). All treatments received poultry litter fertilizer (3-3-3) at 200 kg/ha. **The ASD treatment reduced bottom rot incidence by 87% and the numbers of emerging weeds, especially broadleaf species, by 50% compared to the control.** In contrast, the compost treatment tended to increase bottom rot incidence and weed populations. While treatment effects on crop yield were not statistically significant, yields in the ASD treatment were numerically higher than in the compost or control by about 25% in the spring trial and nearly double in the fall planted trial (Vincent et al., 2024)

ORGANIC FERTILIZERS AND SOIL AMENDMENTS

NRCS Resource Concerns (RCs) Addressed	NRCS Soil Health Principles Addressed	Applicable Conservation Practice Standards (CPS)
● Soil RCs: Organic matter, Soil organisms, Aggregate stability ● Plant RCs: Plant productivity and health	● Soil coverage ● Living roots ● Plant diversity ● Minimize soil disturbance	● CPS 317 Composting Facility ● CPS 336 Soil Carbon Amendment ● CPS 528 Grazing Management ● CPS 590 Nutrient Management

Soluble, inorganic fertilizers such as ammonium nitrate, Chilean nitrate, urea, superphosphate, potassium chloride, and potassium sulfate are often attractive to farmers because they contain high levels of readily available NPK that can be quickly taken up by plant roots. However, soluble fertilizers can also be lost quickly from the soil via leaching or runoff, resulting in N and P pollution of surface and ground waters, and denitrification that converts N into N_2O (discussed in more depth below). Often, soluble N is applied two or three times during the growing season (split applications) in an effort to compensate for and mitigate these losses. Organic fertilizer sources, such as bone or blood meal, compost, and manure, may have lower concentrations of NPK that are released more slowly, but they also offer a wider range of essential crop micronutrients and can provide other benefits to soil and plant life.

Highlights from Recent Research

- Either organic or soluble fertilizers can enhance grassland biomass production (Shi et al., 2024).
- Soluble fertilizer reduces grassland biodiversity while organic fertilizer does not (Shi et al., 2024).
- Organic fertilizer builds SOC, especially in grasslands in warmer climates (Shi et al., 2024).
- Aerobic composting substantially enhances the benefits of manure for building SOC and soil microbial activity and carbon use efficiency (Krause et al., 2022).
- Manure-based and plant-based organic fertilizers provide distinct and potentially complementary benefits for soil microbial community structure and function (Yu et al., 2024).

Organic vs. Inorganic Fertilizers

Prior research has shown that inorganic fertilizer application to grasslands can lead to increased plant biomass but reduced plant biodiversity, likely due to species-specific responses to fertilizer, which can cause interspecific competition for nutrient and water uptake. A global meta-analysis by Shi et al. (2024) examined 537 experiments to determine possible impacts of organic (derived from animal or plant sources) versus inorganic fertilizers (chemically synthesized) on plant biomass, plant biodiversity, and soil organic carbon (SOC) in grassland and cropland ecosystems. **Overall, organic fertilization increased grassland aboveground biomass by 56% and SOC by 19% without affecting two parameters of biodiversity: species richness (number of species) or evenness (relative abundance across species present). Inorganic fertilizer increased grassland aboveground biomass by 42% and SOC by 2%, but decreased species richness by 18% and evenness by 6%.** Direct comparisons of organic versus inorganic fertilizer showed 10% higher species richness and evenness and 15% higher SOC for organic fertilizers. SOC increases were greatest for higher organic fertilizer use rates, higher C:N organic nutrient sources, and soils with lower initial SOC levels (further below their saturation level). When studies were grouped by climate, an interesting trend emerged: in cooler climates (mean annual air temperature ≤ 15℃), organic fertilizer increased SOC by 32% in croplands and only 14% in grasslands, whereas in warmer climates (>15℃), organic fertilizer increased cropland SOC by 34% and grasslands by 62%.

In discussing their findings regarding biodiversity, the authors noted that **organic fertilizer builds SOC, cation exchange capacity, and water-holding capacity, and also provides a wider range of macro- and micro-nutrients, and may thereby support microbial diversity** (Shi et al., 2024). These soil health benefits may mitigate the negative impact of moisture competition on plant biodiversity.

Plant vs. Animal Fertilizer Sources

The NOP Standards require organic producers to utilize plant and animal materials as nutrient sources. Recent research on organic fertilizer type (i.e., plant versus animal) provides greater insight into their effects on soil microbial communities, nutrient cycling, and plant growth. Yu et al. (2024) analyzed the microbiomes (from 16S rRNA gene amplicon sequencing) in 637 samples of soils amended with commercial plant-based (fermented tree leaves or "tea slag") or animal-based organic fertilizers (fermented pig or poultry manure) and evaluated impacts on plant growth (using pac choi as a test crop), soil microbial communities and C and N cycles, and "ecological risks" including heavy metal contaminants, antibiotic-resistance genes, and pathogenic viruses. **Overall, plant-based fertilizers enhanced carbon cycling, plant root and foliar biomass, and microbial community stability, while animal-based fertilizers enhanced nitrogen cycling, microbial community diversity, and plant root growth** (Yu et al., 2024). Microbial communities and metabolic functions that developed in soil with manure-based or plant residue-based fertilizers differed substantially from the unfertilized control and from each other. **Plant fertilizers resulted in slightly lower abundance of antibiotic-resistant genes and potentially hazardous viruses, and the authors suggest they may be more suitable for long-term applications.** However, with the two types of organic fertilizers enhancing different key functional components of the soil microbiome (e.g., carbon and nitrogen cycling), additional research is needed to explore and develop:

- The potential benefits of using both fertility sources together (e.g., compost derived from manure or poultry litter mixed with straw bedding, tree leaves, yard trimmings, and/or food processing waste).
- Livestock farming and animal health practices that prevent or minimize the evolution of antibiotic resistance genes.
- Composting methods to enhance the safety of manure-based organic fertilizers.

Fertilizer Effects on Soil Biology

The long-term effects of fertilizers on soil health are also important to consider when selecting amendments. A 42-year trial in Northwestern Switzerland examined the impact of different fertility inputs on SOC and soil biology, including treatments of composted manure, aged manure, fresh manure plus soluble fertilizer, soluble fertilizer only, and an unfertilized control (Krause et al., 2022). Application rates for all manure treatments were equivalent to 1.4 animal units per hectare; thus, the amount of manure carbon was higher for fresh manure than the other treatments, which had undergone some microbial respiration and associated carbon loss as CO_2 during aging or composting.

All treatments were applied to a diverse, seven-year rotation of corn, soy, wheat, barley, and vegetables (potato, beet, cabbage), all receiving tillage to a depth of 20 cm. Two "catch crops" were included per cycle, followed by two years in grass-clover (red and white clovers, fescue, ryegrass, orchardgrass, timothy). The catch crops were a highly diverse mix of berseem clover, common vetch, phacelia, mustard, and *Guizotia abyssinica*, an Ethiopian oilseed crop in the composite (sunflower) family. Soil samples were taken and tested for SOC (0-20 cm) every two years through six rotation cycles (42 years), and total N, microbial respiration, and microbial biomass were measured at the end of the sixth cycle. **Composted manure was the only treatment with a substantial SOC gain (1.5 g/kg over 42 years, a 10% increase). Aged manure yielded a 0.4 g/kg increase over 42 years, while fresh manure + soluble fertilizer added only 0.07 g/kg SOC.**

All other treatments saw SOC losses of 1.1-1.6 g/kg, except the unfertilized treatment, which lost 3.9 g/kg SOC, or about 27% of the initial level. **Soil microbial biomass was highest for composted manure > aged manure > fresh manure + soluble NPK > soluble NPK only > unfertilized.** Microbial respiration was also highest with composted manure followed by aged or fresh, and lowest in the unfertilized treatment; however, the "metabolic quotient" (mg C respired/g microbial C-hr, an indicator of microbial stress) was lowest for composted manure and highest for unfertilized or soluble fertilizer alone (Krause et al., 2022). Complete aerobic composting over a longer period improved the quality of manure organic carbon so that this treatment built more SOC despite the loss of some manure organic C during composting. **This outcome shows the value of composting for improving both SOC sequestration, soil biological activity, and microbial growth efficiency.** Soil respiration was highest in treatments with the most SOC accrual, demonstrating that soil microbial activity plays a central role in conversion of organic input C into stable SOC.

SOIL ORGANIC CARBON

NRCS Resource Concerns (RCs) Addressed	NRCS Soil Health Principles Addressed	Applicable Conservation Practice Standards (CPS)
● Air RCs: Emissions of greenhouse gases (GHG) ● Soil RCs: Organic matter, Compaction, Soil organisms, Aggregation ● Plant RCs: Plant productivity and health ● Water RCs: Naturally-available water use efficiency	● Living roots ● Minimize disturbance ● Soil coverage ● Plant diversity	● CPS 311 Alley Cropping ● CPS 327 Conservation Cover ● CPS 328 Conservation Crop Rotation ● CPS 329 No Till / CPS 345 Reduced Till ● CPS 332 Contour Buffer Strip ● CPS 336 Soil Carbon Amendment ● CPS 340 Cover Crop ● CPS 379 Forest Farming ● CPS 380 Windbreak / Shelterbelt ● CPS 381 Silvopasture ● CPS 390 Riparian Herbaceous Cover ● CPS 391 Riparian Forest Buffer ● CPS 422 Hedgerow ● CPS 512 Pasture and Hay Planting ● CPS 528 Prescribed Grazing ● CPS 550 Rangeland Planting ● CPS 590 Nutrient Management ● CPS 612 Tree and Shrub Planting

Highlights from Recent Research

- Management practices affect SOC levels to a depth of 50 cm (20 in) (Skadell et al., 2023).
- Regular use of organic fertilizers and soil amendments enhances SOC by 30-35% (Beillouin et al., 2023).
    - When feedstocks for organic inputs are diverted from waste streams (landfill, burn pile, manure lagoon) a large net GHG mitigation is realized.
- Enhanced plant biomass and duration through cover crops or diverse rotations builds SOC gradually over time (Prairie et al., 2023).
- Annual cover crop planting increases SOC by an average of 12% (McClelland et al., 2021a; Schipanski et al., 2024).
    - High biomass, multispecies, or long-duration cover crops can build SOC by 30%.
- No-till or reduced tillage increases SOC levels by 9-12% (Beillouin et al., 2023).
- Implementing agroforestry on cropland or silvopasture on grassland enhance SOC levels by 20-26% (Beillouin et al., 2023).
- Converting forest, wetland, or grassland to crop production entails severe losses of SOC (Beillouin et al., 2023).

    - Converting natural areas to agroforestry is less destructive to SOC than conversion to annual crop rotations.
- The ‘priming effect” in which fresh residues stimulate microbes to consume organic matter with a net SOC loss, occurs mainly when a succulent, low-biomass (<1 Mg/ha) cover crop or residues of very low or very high C:N ratio are tilled into the soil (Liang et al., 2023).

Various Management and Land Use Effects on SOC

Beillouin et al. (2023) conducted an extensive second-order global meta-analysis of land use and management impacts on soil organic carbon (SOC). The analysis integrated 230 first-order meta-analyses representing over 25,000 primary studies and 190,000 individual comparisons of SOC levels (concentration in g/kg soil or SOC stock in Mg/ha) with versus without a given practice or land use change. **This large compilation of data provides robust estimates of the efficacy of land restoration and management practices on SOC, soil health, and carbon sequestration.** Data were presented as the mean and 95% confidence interval (CI) of % change in SOC levels with versus without a particular practice. **Some key findings for individual practices include:**

- Organic soil amendment on cropland (n ~ 940): +29%
- Organic soil amendment on grassland (n ~ 230): +34%
- Organic sources for some or all nutrients vs soluble, cropland (n ~ 730): +34%
- Biochar on cropland (n ~ 880): +67%
- Biochar on grassland (n < 100): +34%
- Cover crop (n ~ 2,900): +12.0%
- Retention of crop residues +13%
- Conservation tillage (n ~ 7,000): +9.3%
    - No-till +9.3%
    - Reduced tillage +12%
- Soluble fertilizer vs unfertilized on cropland (n ~ 3,300): +9.4%
- Soluble fertilizer vs unfertilized on grassland (n ~ 650): +3.6%
- Agroforestry (all forms) on cropland (n ~ 2,000): +20%
    - Alley cropping +21%
    - Hedgerows +17%
- Silvopasture on grassland +26%; number of comparisons not shown.

The literature search revealed only a few meta-analyses that evaluated systems of multiple practices (e.g., conservation agriculture combining reduced tillage, residue retention, and crop diversity). **Another noteworthy aspect of the outcome of this meta-analysis is that retention of crop residues in the field, cover cropping, and conservation tillage each provide significant SOC benefits of similar magnitude. The results also show that reduced tillage may be as effective as no-till.** Regarding organic agriculture, the authors found a large effect on SOC of +35% (Beillouin et al., 2023). **These findings suggest that the use of organic fertilizers and soil amendments is the main driver in the higher SOC under organic systems. Regarding the large SOC responses to off-farm carbon inputs, the authors emphasize the importance of responsible sourcing of feedstocks to reduce waste and make organic amendments such as compost, biochar, or organic mulch.**

Conversion of forest or wetland to cropland entailed a loss of SOC of - 25% while conversion of grassland to cropland reduced SOC -16%. Because studies spanned a few years to a few decades, while SOC changes in response to land use change can require 80 years to reach a new equilibrium, these figures may underestimate the total SOC losses resulting from such land use changes. Converting forest to cropland with agroforestry practices or perennial crops caused much smaller SOC losses (-12% and -7%, respectively) than converting to annual cropping (-32%); grassland conversion showed similar patterns. Converting cropland back to forest or grassland boosted SOC by + 57% and +26%. Since cropland starts with much lower SOC stocks, this may fall short of full recovery of SOC to levels in virgin forest or prairie (Beillouin et al., 2023). **These findings illustrate the importance of preserving forestland and grassland to maintain carbon sequestration. In addition, agroforestry practices sequester C primarily when implemented on cropland.** See the Diversified Organic Cropping Systems section (below) for additional research on agroforestry systems.

Building SOC in the Soil Profile Beyond 20 cm

Many studies of management effects on SOC focus on the top 10-20 cm (4-8 inches) of the soil profile, yet at least 50% of SOC stocks (in Mg C/ha) occur between 30-100 cm (12-40 in) depth (Lal, 2015). Cropping systems that promote deep root development can build stable SOC in this part of the soil profile (Cavigelli et al., 2013; Wander et al., 1994). In a recent study of management impacts on SOC, soil cores were taken from surface to 100 cm from different treatments in 10 long-term farming systems trials in Germany (Skadell et al., 2023). Cores were divided into 0-30 cm, 30-50 cm, and 50-100 cm depths and analyzed for total SOC (0-12, 12-20, and 20-40 in depths, respectively). Treatment comparisons included with and without soluble fertilizers, manure, straw return, cover crop, irrigation, and reduced (vs full) tillage. **On average, 78.6% of management effects on SOC stock took place at 0-30 cm, another 18.7% at 30-50 cm, and 2.8% at 50-100 cm. The authors recommended sampling from the soil surface to 50 cm (20 inches) to capture most of the management impacts on SOC.**

Cover Crop, Tillage, and Rotational Diversity Effects on SOC

Two major components of SOC are particulate organic carbon (POC) and mineral-associated organic carbon (MAOC), which have different soil health functions. POC is the more active (decomposable) fraction, whose consumption by soil microbes releases (mineralizes) nitrogen (N), phosphorus (P) and some other nutrients in crop-available form. POC can become partially stabilized when protected within soil aggregates. MAOC is the most stable form of SOC, as it is tightly adsorbed to silt and clay soil particles. In addition to long-term carbon sequestration, MAOC enhances the soil cation exchange capacity (CEC), or ability to hold potassium (K), magnesium (Mg), calcium (Ca), ammonium nitrogen (NH_4-N), and other positively charged nutrients in plant-available form.

Prairie et al. (2023) conducted a global meta-analysis of 139 studies that included 1,250 individual treatment comparisons to evaluate the efficacy of regenerative agricultural practices in building POC, MAOC, and total SOC. The analysis focused on no-till, crop-livestock integration, and four types of crop intensification:

- Moving from a crop-fallow system (one crop every two years) to one crop per year
- Moving from one crop per year to more than one crop per year (double cropping)
- Adding a cover crop to an annual crop rotation

- Adding a perennial crop to an annual crop rotation

Most management effects on SOC were observed in the topsoil (0-20 cm / 0-8 in). **Some studies of crop intensification, especially those that introduced perennials into the crop rotation, showed a substantial increase in POC in the subsoil (below 20 cm), likely related to rhizodeposition from the deeper-rooted perennials** (Conant et al., 2017; Guo and Gifford, 2002; Ledo et al., 2020; Ogle et al., 2005). POC comprised an average of 17% of total SOC and showed larger % responses to management practices than MAOC. Thus, while the % increase in POC in response to a practice was generally higher than MAOC, the actual change in Mg C/ha was sometimes greater for MAOC. **Responses of both fractions as well as total SOC develop gradually over time; thus, trials lasting <6 years showed statistically non-significant responses, while trials conducted for ≥6 years showed significant increases**.

The authors also found that no-till increased topsoil SOC by an average of 11.3%, ranging from just 2% for trials <6 years in duration to 13% for 6-12 years and 14% for >12 years, suggesting that SOC accruals under no-till reach a plateau within 12 years (Prairie et al., 2023). Trends for POC and MAOC were very similar. Converting from a system with multiple tillage passes per year to no-till enhanced SOC more (16%) than from once-a-year tillage to no-till (9%), and the difference was driven mainly by a larger MAOC response to the shift from frequent tillage to none. SOC response to no-till was greater in systems with one annual crop per year (14%) than with double crop or cover crop (6-7%); in this case, the difference was related almost entirely to POC, which increased with no-till only in the single crop systems. **These findings suggest that keeping the ground in living cover most of the year through either cover cropping or double cropping mitigates the adverse effects of tillage on POC and total SOC, and that tilling once per year has less severe impacts on MAOC (though not on POC) than multiple tillage passes.**

Crop rotation intensification accrued topsoil POC, MAOC, and total SOC over time, with SOC increases of 5.5% in trials <6 years in duration, 12.3% for 6-12 years and 17.6% for > 12 years. Shifting from a two-year crop-fallow system (common in dryland grains in semiarid regions) to one crop per year boosted SOC by 14%, mainly through a 57% increase in POC. Adding cover crops to annual crop rotations enhanced SOC by 13%, while shifting from one production crop per year to two or more production crops did not. Adding a perennial crop to an annual crop rotation increased topsoil SOC by 16% and some studies also showed increased subsoil POC. **Overall, crop rotation intensification enhanced total SOC more in tilled systems (16%; average tillage depth across studies = 20 cm) than in no-till systems (10%), which again illustrates the value of increased duration of living cover and living root in mitigating the adverse effects of tillage on SOC and soil health (Prairie et al., 2023).**

Integrating livestock into cropping systems enhanced SOC by about 9% mostly through an increase in POC. When no-till and crop-livestock integration were adopted together, SOC increased by 29%, somewhat more than the additive effect for the two individual practices. **Combining crop-livestock integration with crop rotation intensification resulted in a markedly synergistic enhancement of MAOC with a 33% increase with cover crops and 53% increase with perennial crops, compared to just 8% increase in MAOC with crop intensification alone and very little change in MAOC for crop-livestock integration alone**

(Prairie et al., 2023). These patterns suggest that the three types of regenerative farming practice have different effects on SOC fractions and their associated functions, and that systems of multiple practices, such as conservation agriculture or organic farming, can yield greater soil health benefits than individual practices.

Studies showing that fresh residues can induce a "priming" effect that stimulates microbial breakdown of existing SOC have led some researchers to question the value of cover crops for C sequestration (Chaplot and Smith, 2023). However, an experiment conducted in an agricultural research field in Denmark showed that **net loss of SOC through priming occurred only when cover crop residues are mixed with topsoil at rates equivalent to ≤ 0.7 Mg/ha biomass, whereas the same residues mixed into soil at 1.1 Mg/ha or higher result in net SOC accrual** (Liang et al., 2023). The authors concluded that, in long-term farming systems trials at this site, cover crops have failed to build SOC because cover crop biomass often fell below 1 Mg/ha in the cold-temperate climate of this location. Similarly, recent studies conducted to update the DayCent process model used in the COMET Farm tool identified a minimum cover crop biomass of ~1 Mg/ha to realize net SOC accrual (McClelland et al., 2021a; Schipanski et al., 2024). **While cover cropping enhanced SOC by an average of 12% in the trials reviewed for the model calibration, high biomass cover crops (>7 Mg/ha) with a long growing time window increased SOC by 30%. Combining legumes with grasses in cover crop mixes can also enhance SOC accrual**. A meta-analysis of 81 individual treatment comparisons found a 22% increase in SOC for grass-legume mixtures compared to 11% for legumes alone and 13% for grasses alone (Muhammad et al., 2019). In a laboratory study, residues of rice straw, groundnut, and both crops together were incubated with soil for 112 days to document priming (consumption of existing SOC) and conversion of residue C into new SOC. The mixture showed less priming, lower respiration, and higher conversion of residue C into SOC than either rice straw alone (C:N = 96:1) or groundnut residues alone (C:N = 30:1) (Pingthaisong et al., 2024).

DIVERSIFIED ORGANIC CROPPING SYSTEMS

NRCS Resource Concerns (RCs) Addressed	NRCS Soil Health Principles Addressed	Applicable Conservation Practice Standards (CPS)
● Air RCs: Emissions of greenhouse gases ● Soil RCs: Soil organism habitat, Organic matter, Aggregate stability, Soil erosion ● Plant RCs: Plant community structure and composition, Plant productivity and health, Plant pest pressure ● Water RCs: Nutrients transported to groundwater or surface water, Naturally available water use ● Animal RCs: Livestock feed and forage balance	● Soil coverage ● Living roots ● Plant diversity ● Minimize soil disturbance	● CPS 311 Alley Cropping ● CPS 328 Conservation Crop Rotation ● CPS 340 Cover Crop ● CPS 379 Forest Farming ● CPS 380 Windbreak ● CPS 381 Silvopasture ● CPS 391 Riparian Forest Buffer ● CPS 422 Hedgerow ● CPS 511 Forage Harvest Management ● CPS 512 Pasture and Hay Planting ● CPS 528 Grazing Management ● CPS 550 Range Planting ● CPS 590 Nutrient Management ● CPS 595 Pest Management Conservation System ● CPS 612 Tree and Shrub Planting

Highlights from Recent Research

- Organic agroforestry systems provide greater atmospheric carbon dioxide (CO_2) sequestration in woody biomass as well as in soil organic carbon (SOC) stocks (Aaron et al., 2024; De Stefano & Jacobson, 2017).
- Alley cropping and hedgerows can increase SOC sequestration rates while providing other ecosystem services (Biffi et al., 2025; Mayer et al., 2022).
- Careful selection of a mix of functionally diverse native plant species can maximize the potential carbon sequestration in conservation and land restoration plantings (Yang et al., 2019).
- The perennial grain Kernza produces substantial amounts of forage, opening an opportunity for dual use (harvesting of the grain and forage) - fall forage harvest can increase grain yield, and harvesting forage in the spring and summer optimizes the nutritive value of the forage (Culman et al., 2023).

Agroforestry Systems

The National Organic Standards (NOP) mandate the use of practices to promote biodiversity, protect natural areas, including woodlands, wetlands, and wildlife habitat, and provide buffers or diversions to protect organic production areas against exposure to NOP-prohibited substances. Agroforestry systems combine annual crops and livestock grazing with trees and shrubs to enhance and integrate production and conservation activities and provide multiple ecosystem services.

Aaron et al. (2024) conducted a systematic review of studies comparing organically managed agroforestry systems with conventional agroforestry or with organic or conventional production of a perennial crop monoculture (e.g., coffee, cocoa, olive, or tree fruit) or annual crop rotation without an agroforestry component (collectively referred to as "monoculture"). Their analysis showed that organic agroforestry enhances the ecological, agronomic, and socioeconomic sustainability of farming systems. **Organic agroforestry systems reduced net greenhouse gas footprint and nutrient impacts on water quality, especially in comparison with monocultures under organic or conventional management. Organic agroforestry improved soil nutrient cycling, fertility, and SOC, especially in comparison with conventional agroforestry or monoculture systems.** In regards to weeds, pests, diseases, soil microbial communities, and overall biodiversity, most comparisons showed a neutral effect. In the minority of studies finding significant differences, organic agroforestry outperformed the other three systems more often than the reverse. This suggests that organic agroforestry systems entail few trade-offs for their multifunctional ecosystem benefits (Aaron et al., 2024). While the review did reveal that yields of primary crops in agroforestry systems were often lower than the same crops in conventional monoculture, the four studies that evaluated total system yield found higher yields in agroforestry. **In comparison with organic or conventional monoculture, organic agroforestry showed socioeconomic benefits (labor productivity, people fed per hectare, net profit, community social resilience)** in the vast majority of studies, and also outperformed conventional agroforestry in five out of 13 studies (Aaron et al., 2024). Agroforestry systems may also provide greater atmospheric carbon dioxide (CO_2) sequestration in woody biomass as well as in SOC stocks.

De Stefano and Jacobson (2017) performed a meta-analysis of 53 studies to examine SOC stock changes at various soil profile depths across various land-use changes (when cropland, grassland, or forest was converted to agroforestry). Overall, the authors found that **converting from treeless cropland or pasture to agroforestry built SOC, and converting from natural forest to any form of agroforestry is likely to cause a loss of SOC, especially at 0-30 cm / 0-12 in).** This was likely due to the fact that natural forests are more diverse and accrue more near-surface SOC than grasses, which deposit more SOC at depth through root exudates. **"Agrosilvopastoral" systems that integrated trees, arable crops, and perennial forages offered high diversity and built SOC in different and complementary ways. It was also noted that site preparation for tree planting can entail a short-term SOC loss due to soil disturbance.** The authors summarize that SOC stock increases largely came from less complex to more complex land use (De Stefano & Jacobson, 2017). These findings corroborate outcomes of the second-order meta-analysis discussed above (Beillouin et al., 2023).

Alley Cropping, Hedgerows, and Silvopasture Systems

A meta-analysis by Mayer et al. (2022) examined soil organic carbon (SOC) stocks in various diversified cropping systems, including alley cropping (n = 25), hedgerows (n = 26), and silvopasture (n = 10), and compared these to the SOC stocks of adjacent treeless areas. The analysis revealed that **SOC sequestration rates (surface to 40 cm / 15 in) for alley cropping averaged 490 kg/ha-year, 600 kg/ha-year for hedgerows, and a *loss* (– 220 kg/ha-year) for silvopasture systems.** The "controls" for silvopasture studies were grasslands with a smaller "SOC saturation deficit" than the arable croplands that served as controls for the alley crop and hedgerow systems (Mayer et al., 2022). **The authors note that SOC losses can occur as a result of soil disturbance when establishing such systems, which can even out over time while providing other ecosystem services such as preventing wind and water erosion and a habitat for beneficial species.**

The United Kingdom (UK) and the European Union (EU) committed to extensive hedgerow plantings as part of the 2015 Paris climate agreements. SOC stocks (0-50 cm depth) were measured within 46 hedgerows of varying ages in five pedo-climatic regions across the UK (Biffi et al., 2025). Hedgerow SOC fractions [MAOC, "light" or free particulate organic carbon (POC,) and "heavy" or aggregate-occluded POC] were compared with adjacent grassland fields. **C sequestration rates were high in the early years after hedgerow planting and decreased rapidly thereafter, with SOC stocks reaching a steady state of ~40 Mg C/ha above adjacent grassland, which represented a 40% increase. Young hedgerows (up to 10 years) rapidly accrued SOC in the top 20 cm while older hedges (>20 years) began to build SOC at 20-40 cm (7-15 in)** (Biffi et al., 2025). Most of the SOC sequestered by hedgerows was free POC, likely derived from surface litter and root exudates (Biffi et al., 2025). C sequestration rates and SOC totals were similar across climates (Cumbria, Yorkshire, West Sussex) and soil types (sandy loam to clay loam), which suggests that hedgerows might perform similarly in the Northeast and North Central US. **These findings show the importance of planting new hedgerows for rapid SOC sequestration and of conserving existing hedgerows, since free POC would be lost rapidly after hedgerow removal.**

Restoration with Perennial Vegetation

Restoration of degraded or abandoned cropland with perennial vegetation offers an important opportunity to sequester carbon in soil and plant biomass while providing other conservation benefits, including wildlife and pollinator habitat, water quality protection, erosion control, and buffers between organic and non-organic production areas. Trials were conducted in the prairie region of Minnesota to document SOC and plant biomass C sequestration in native prairie plantings on degraded soil over a 22-year period. Treatments consisted of monocultures and mixes of 2, 4, 8, or 16 species selected from four plant types: C3 grasses, C4 grasses, legumes, and non-legume broadleaf species, and C sequestration rates were compared with 21 nearby abandoned fields that had undergone secondary succession for 4-74 years (Yang et al., 2019). **All treatments sequestered SOC and the 2, 4, 8, and 16 species mixes accrued an average of 60%, 115%, 115%, and 178% more SOC than monocultures, respectively.** Root biomass showed a similar trend. Mixes that included one or more C4 grasses (which develop high root biomass) and one or more legumes (which enhance plant and microbial growth) sequestered the most carbon. **During years 13-22 of the trial, C sequestration rates in the 4, 8, and 16-species mixes accelerated to two to three times that of natural secondary succession in abandoned fields** (Yang et al., 2019). This trial shows that careful selection of functionally diverse native plant species can maximize the potential carbon sequestration in conservation and land restoration plantings.

Integrating Poultry and Cover Crops

The integration of cover crops in a crop rotation also offers a way to diversify the operation while providing several ecosystem services. One such service is the ability to sequester nutrients or provide them through plant biomass, but organic farmers must often supplement crop nutritional needs with organic fertilizer sources. The integration of poultry into cover-cropped systems may decrease fertilizer requirements and increase on-farm nutrient cycling. Poultry also feed on weeds and insects, thereby contributing to pest and weed control (Carey et al., 2025). A study conducted in Iowa evaluated soil health, nutrient cycling, crop production, and weed management benefits of integrating poultry (broiler chickens) into an organic vegetable production system with cover crops. In a three-year trial (2021-2023), the following treatments were compared:

- control (vegetable double crop – winter cover crop)
- V-P-CC (spring vegetable crop – poultry – cover crop)
- V-CC-P (spring vegetable – summer cover crop – poultry – winter cover crop).

Spinach, leaf lettuce, and broccoli were used as the spring vegetables, and the summer vegetables in the control treatment were butternut squash, bell pepper, and sweet potato. The summer cover crop consisted of cowpea (*Vigna unguiculata*) plus teff (*Eragrostis tef*), while the winter cover crop contained cereal rye (*Secale cereale*) plus Austrian winter pea (*Pisum sativum*). **Poultry integration, regardless of timing in the rotation, increased spring plant available N, P, and K by 88%, 30%, and 29%, respectively (Carey et al., 2025). Poultry also enhanced earthworm populations by 109%, and infiltration rate (measured as hydraulic conductivity) by 108-148%, although soil microbial biomass and soil aggregate stability were not different across treatments. While spinach and broccoli yields were similar across treatments, lettuce yields were 86-96% higher when poultry was included in the rotation** (Carey et al., 2025). Poultry integration into cover-cropped organic vegetable systems provides a promising way for farmers to see the benefits of different ecosystems services, but the authors do note that **there may be some concern for excess nutrient levels and that future research is needed that carefully monitors and manages nutrients.**

Perennial Grains – Kernza

Annual crops require repeated tractor passes for field prep, nutrient amendment incorporation, and weed management via cultivation. Incorporating perennial crops into a rotation can reduce these field passes and benefit soil health by reducing soil disturbance and compaction, enhancing living cover duration, and providing deeper root systems. The perennial grain Kernza (intermediate wheatgrass or IWG; *Thinopyrum intermedium*) was developed to maintain living cover and minimize the need for tillage in grain production. Grain yields tend to decrease sharply in the second and third seasons, but the crop produces substantial amounts of forage, opening an opportunity for dual use (harvesting of the grain and forage). Field trials were conducted at nine sites across the US over three years to evaluate the impact of different timings and frequencies of forage harvest on Kernza grain and forage production and quality (Culman et al., 2023). **Results showed that fall forage harvest can increase grain yield, and harvesting forage in the spring and summer optimized the nutritive value of the forage but somewhat decreased grain yield. Overall, dual use of intermediate wheatgrass shows promise for improving productivity and profitability** (Culman et al., 2023). There is also the potential to interseed a cover crop in Kernza, thereby providing more ecosystem services. A 3-year field trial was conducted in New York to compare Kernza with annual plantings of winter wheat for grain production, straw production, and the effects of a red clover (*Trifolium pratense* L.) interseeded cover crop (Law et al., 2021). Wheat yields were considerably higher than Kernza, and the latter yields declined in the second year. **However, higher and gradually increasing Kernza straw production supports the potential for dual use of the perennial crop. Red clover interseeding reduced weed biomass and weed species richness, increased total Kernza forage biomass, and likely improved forage quality** (Law et al., 2021).

PRODUCTION OF ORGANIC VEGETABLE TRANSPLANTS

NRCS Resource Concerns (RCs) Addressed	NRCS Soil Health Principles Addressed	Applicable Conservation Practice Standards (CPS)
• Plant RCs: plant productivity and health	• N/A	• CPS 325 High Tunnel System • CPS 595 Pest Management Conservation System

Highlights from Recent Research

- Cucumber and bell pepper emergence can be delayed in soil blocks compared to cells.
- Bell pepper “starts” show greater biomass, height, and stem diameter in soil blocks; cucumber starts show the opposite.
- More research is needed to adjust blocking methods to optimize bulk density and aeration, to optimize growing conditions (e.g., temperature), and to document year-to-year variation in nutrient content of commercial organic growing media (Carey et al., 2024).

Flats vs Soil Blocks for Organic Vegetable Starts

Recent research has addressed a vital and historically under-researched challenge for organic specialty crop farmers: production of vigorous "starts" for vegetables and other annual horticultural crops using NOP-allowed organic materials and methods (Carey et al., 2024). Greenhouse trials were conducted in Iowa in 2022 and 2023 to compare performance of pepper and cucumber starts grown in four NOP-approved commercial mixes and one in-house mix:

- Purple Cow Organics "Seed Starter Mix" (Middleton, WI) ("Purple")
- Cowsmo, Inc. "Green Potting Soil" (Cochrane, WI) ("Cowsmo")
- Beautiful Land Products "Soil Blocking Mix" (Tipton, IA) ("BLP")
- Vermont Compost Company "Fort Vee" (Montpelier, VT) ("VCC")
- Sphagnum peat, compost, vermiculite, perlite at a 4:2:1:1 ratio ("Lab")

Seedlings were grown in 50-cell flats and in unenclosed blocks made with a soil blocker. The soil block method, used by some growers, is claimed to reduce transplant shock by air-pruning roots so that root circling does not occur. The flat cell volume was 141 cm^3, while blocks were 87 cm^3. Compression during block making increased bulk density by 137-237% compared to media in cells. However, block bulk densities (0.21-0.46) remained well below the range for mineral soils (Carey et al., 2024). Soil mix nutrient contents, salinity (electrical conductivity or EC), and other properties were monitored weekly, seedling emergence was recorded, and plant height, stem diameter, dry weight, and root surface area were measured 22 days after sowing (DAS) for cucumber and 50 DAS for pepper.

Cucumber emergence from blocks was reduced (compared to cells) in 2022 but not 2023, and pepper emergence from blocks was somewhat delayed both years. **At 22 DAS, cucumber plants in cells had 20% (2022) and 38% (2023) more dry weight and greater height, stem diameter, and root area than plants in blocks. Pepper starts measured at 50 DAS showed the opposite trend in 2022 with 50-130% higher biomass, 47-74% greater height, and 26% larger stem diameter in blocks than in cells.** Pepper starts grew well in both systems in 2023, with a trend toward better growth in blocks in 2023 (Carey et al., 2024). **Delayed pepper emergence from blocks was attributed to lower media temperatures in blocks (18.5°C) than in the black plastic flat cells (21.3°C), and to the higher media bulk density in blocks, which may have restricted aeration of the root zone.** Because cucumber emergence was counted at 10 DAS and this crop can emerge in as few as 2-3 days, delayed emergence from soil blocks may not have been detected yet and may have reduced cucumber dry weight at 22 DAS. The longer (50-day) growing period for pepper allowed block-grown seedlings to catch up and outgrow the seedlings in cells (Carey et al., 2024).

Overall, seedlings grew equally well in the Purple, BLP, and VCC mixes despite initially high EC (6-7 mS/cm), which declined into the optimum range (2-4 mS/cm) at 21-28 DAS. The "Lab" mix gave somewhat slower growth, and **plants were severely stunted in the Cowsmo mix, except for pepper in cells in 2023. N deficiency appeared to be the main limiting factor, as BLP was high in ammonium N while Purple and VCC had high nitrate-N, "Lab" had intermediate soluble N levels, and Cowsmo was lowest in both nitrate and ammonium N** (Carey et al., 2024). A media X method interaction was observed in that peppers seeded in Purple grew much better in blocks than in cells, while peppers seeded in VCC did equally well in cells and blocks. In addition, the authors cited an earlier study showing excellent growth after transplanting to the field in broccoli and tomatoes started in Cowsmo, which suggests year-to-year variability in nutrient content of media (Carey et al., 2024).

Previous research on soil blocks has focused on field performance of the transplants and the authors could find no prior studies to compare their findings on emergence and seedling growth prior to transplanting. **More research is needed to adjust blocking methods to optimize bulk density and aeration, to optimize growing conditions (e.g., temperature), to document year to year variation in nutrient content of commercial organic growing media, to assess direct and environmental costs of blocks versus plastic flats, and to follow crop performance from seeding through transplant to field harvest** (Carey et al., 2024).

NITROUS OXIDE AND ITS MITIGATION IN ORGANIC PRODUCTION SYSTEMS

NRCS Resource Concerns (RCs) Addressed	NRCS Soil Health Principles Addressed	Applicable Conservation Practice Standards (CPS)
• Air RCs: Emissions of greenhouse gases • Water RCs: Nutrients transported to groundwater • Soil RCs: Habitat for soil organisms, Compaction, Organic matter	• Soil coverage • Living roots • Plant diversity • Minimize soil disturbance	• CPS 329 No-till • CPS 336 Soil Carbon Amendment • CPS 340 Cover Crop • CPS 345 Reduced Till • CPS 590 Nutrient Management

Highlights from Recent Research

- N fertilizers boost N_2O emissions from wet soil at 80% water-filled pore space (WFPS) (Lussich et al., 2024).
- Tilling a cover crop and N fertilizer (soluble or organic) into the soil at the same time can lead to high N_2O emissions even at 50% WFPS (Lussich et al., 2024).
- Legume cover crops terminated by tillage sharply increase N_2O emissions (Muhammad et al., 2019).
- Non-legume and mixed-species cover crops with higher C:N (>25:1) terminated with no-till methods can reduce N_2O compared to unplanted fallow (Muhammad et al., 2019).
- Deep-rooted cover crops prevent N leaching and thereby reduce indirect N_2O emissions (Barneze et al., 2024).

- Fine-textured soils (i.e., clay loam, silty clay loam) may generate two or three times as much N_2O as sandy loams under the same crop rotation and management (Sedghi et al., 2024).
- Diverse plantings may reduce N_2O emissions compared to monoculture (Barneze et al., 2024).
- Effective, NOP-compatible N_2O mitigation strategies include biochar amendments, in-row drip irrigation (vs. full-field irrigation), and reducing N rates to match crop need (Grados et al., 2022).

Nitrous oxide (N_2O) is a powerful greenhouse gas with 300 times the global warming potential over a 100-year period (GWP-100) of CO_2. N_2O from fertilized, manured, or green manured soils accounts for nearly 50% of the GWP-100 of *direct* GHG emissions from agricultural operations in the US (US EPA, 2024). **One pound of nitrogen (N) emitted as N_2O negates 129 lb of carbon (C) removed from the atmosphere through sequestration in SOC or plant biomass.**

The conditions that promote denitrification and N_2O formation in soil include:

- Moderate to high levels of soluble N (nitrate-N and ammonium-N).
- Ample labile organic carbon (C) that microbes can readily consume, including C from fresh plant residues, manure, root exudates, and active SOM.
- High levels of microbial activity.
- Reduced levels of oxygen (O_2) – hypoxic but not fully anaerobic (zero O_2).

Soil releases N_2O when all the above conditions occur together (Cogger et al., 2014). N_2O emissions peak when rain or irrigation pushes soil moisture levels to about 80% water-filled pore space (WFPS) and subside when soil moisture drops below field capacity or 50% WFPS (Cai et al., 2016). **Other conditions that hinder soil aeration and gas exchange, such as clayey soil texture or soil compaction, can also promote N_2O emissions** (Balaine et al., 2016; Charles et al., 2017). Total annual N_2O emissions rise exponentially as plant-available N from any source increases beyond crop need (Davis et al., 2019; Eagle et al., 2017). In conventional agriculture, N_2O emissions predictably occur when heavy rain follows fertilizer N applications or later in the season if surplus N remains in the soil. Best N management protocols can cut these emissions by half (Eagle et al., 2017; Millar et al., 2010).

NOP-Compliant Strategies for Reducing N_2O Emissions

Managing N_2O risk in organic production systems can be especially challenging because organic soil health practices create two of the conditions for N_2O formation – labile organic C and microbial activity. Concentrated organic N sources like poultry litter or manure slurry provide labile C and N together and can promote greater N_2O emissions than soluble fertilizer at the same N rates (Baas et al., 2015; Charles et al., 2017; Davis et al., 2019). Global meta-analyses have shown that the use of organic versus soluble N fertilizers builds SOC and reduces N leaching and runoff losses by 43% and ammonia volatilization by 52%, but increases N_2O emissions by an average of 25% (Young et al., 2021). Similarly, while cover crops build SOC and greatly reduce N leaching (Beillouin et al., 2023; Brennan, 2018; Sedghi et al., 2024), they can stimulate N_2O emissions (Grados et al., 2022). Recent research has begun to identify strategies to mitigate soil N_2O emissions in both organic and conventional farming systems. In a review of meta-analyses on this topic, Grados et al. (2022) identified several effective, NOP-compliant strategies that can reduce N_2O emissions:

- **Biochar soil amendments: 26.6% reduction (mean of four meta-analyses)**
- **Optimizing N application rates (< standard rates): 31.2% reduction (one meta-analysis)**
- **Drip irrigation vs sprinkler or furrow irrigation: 26.5% reduction (one meta-analysis)**

Controlled release fertilizers, nitrification inhibitors, and urease inhibitors reduced N_2O emissions by 33-49% (Grados et al., 2022), but these synthetics are not allowed under NOP and their potential impacts on the soil microbiome should be researched. The review also found a 36.7% increase with cover cropping (based on two meta-analyses), an 18.6% increase when fertilizer is placed deeper into the soil profile to enhance nutrient use efficiency (one meta-analysis), and mixed results in comparing organic vs. synthetic fertilizers (six meta-analyses; mean effect 4.8% increase) (Grados et al., 2022).

Tilling in cover crop residues with N fertilizer (organic or synthetic) may cause N_2O emissions to spike, even if the soil is not excessively wet. In laboratory soil incubation studies, adding soluble N fertilizer (KNO_3) at a rate equivalent to 165 kg N/ha promoted N_2O emissions in soil wetted to 80% WFPS but not at 50% WFPS. However, soil incubated with the same fertilizer and cover crop (wheat or vetch) residues equivalent to 3 Mg/ha (a moderate biomass) showed equally high N_2O emissions at 50% and 80% WFPS (Lussich et al., 2024). The residues promoted a burst of microbial activity that reduced soil O_2 levels and stimulated N_2O formation at both moisture levels, and better aeration at 50% WFPS may have facilitated N_2O release into the atmosphere.

Soil Texture Influences

Soil texture strongly influences N_2O emissions from cover crops and their residues, likely through impacts on soil aeration. Cover cropping caused the largest N_2O increases in clay loam soils (+216%) followed by silty clay loam (+108%), silt loam (+56%), sandy clay loam (+32%), and sandy loam (+11%, not statistically significant) (Muhammad et al., 2019). **In the ARS long-term farming systems trials in Beltsville, MD, N_2O emissions from a silt-loam were 9-fold higher than from a sandy loam under identical crop rotations and tillage practices** (Sedghi et al., 2024). Cover crop C:N ratio and termination method play major roles in N_2O outcomes. In a meta-analysis of 48 studies, Muhammad et al (2019) found that **legume cover crops increased soil N_2O emissions 61% (n = 152 comparisons) while non-legumes decreased N_2O emissions by 37% (n = 303). Tilling cover crops into the soil caused N_2O emissions to soar 136% above the no-cover control (n = 201) while cover crops left on the surface after termination reduced N_2O emissions by 55% (n = 244).** With residues removed (harvested for animal forage), cover crops had little impact on N_2O emissions (n = 35). Across all cover crop types, **N_2O emissions decreased as residue C:N ratio increased. Cover crops with C:N>25 generally reduced N_2O emissions.** Studies conducted to update model parameters for the DayCent model and the COMET Farm tool indicated little change in N_2O emissions from cover crops terminated no-till by herbicide or roller-crimper (McClelland et al., 2021b). When tillage radish was winter killed or frost damaged in Beltsville, MD, N_2O emissions increased in proportion to the biomass of damaged tissue (Sedghi et al., 2024). However, a vigorous fall radish cover crop greatly reduced N leaching, thereby protecting water quality and curbing *indirect* N_2O emissions, which have been estimated at 0.75% of N leached (IPCC, 2014). Field trials in southwest Michigan indicated that, when soil soluble N levels are low, incorporating cover crops by non-inversion tillage (chisel plow) does not lead to sufficient N_2O emissions to be of major concern, and that chopping cover crop residues into small (1-7 cm) fragments (e.g. by flail mowing) prior to chisel plowing can further reduce emissions (Nguyen and Kravchenko, 2021).

Plant Biodiversity Effects on N_2O

Plant biodiversity may help to mitigate N_2O emissions. In a greenhouse trial, soil in pots planted with either barley or Italian ryegrass emitted significantly more N_2O during certain vegetative growth stages than soil in unplanted pots; however, **planting barley and ryegrass together in the same pot eliminated these surges in emissions, possibly due to changes in the soil-root microbiome** (Bore et al., 2024). In a field study of N_2O dynamics under six different perennial species, timothy (*Phleum pratense*), chicory (*Cichorium intybus*), and red clover (*Trifolium pratense*) gave the lowest N_2O emissions, followed by plantain (*Plantago lanceolata*), ryegrass (*Lolium perenne*), and white clover (*Trifolium repens*) in that order. Low emissions under timothy and chicory were related to their high root biomass and the two-fold difference in emissions under white versus red clovers, despite similar plant N content, was related to plant architecture. Red clover is erect with a deep taproot, while white clover spreads by rhizomes and a network of shallow roots that may deposit more plant N close to the soil surface. A mix of all six species emitted about 10% less N_2O than the mean of the six monocultures, **confirming that diverse pasture plantings may reduce emissions of this GHG compared to a monoculture of a high-emission species** like ryegrass or white clover (Barneze et al., 2024).

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