Sequestering Carbon, Reducing Greenhouse Gases, and Building Climate Resilience through Organic Soil Health Practices

A Webinar for NRCS
September 11, 2023

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

Presentation Notes

Slide 2 – *How climate change affects agriculture*

The impacts of climate disruptions on agriculture are becoming more obvious and intense in recent years. In addition to the direct impacts of drought, deluge, and erratic temperature extremes, changing climates are causing the life cycles and geographic ranges of weeds, pests, and pathogens to shift, bringing new pest problems into many agroecosystems. Another serious "indirect" effect is that warmer winters result in fewer chill hours that delay or disrupt flowering, fruit set, and maturation in perennial fruit and nut crops, a problem reported by fruit and nut growers in California. On the other hand, milder winters and earlier thaws in normally colder regions (e.g. mid-Atlantic or Northeast) can accelerate bud-break and flowering, leaving tree fruit crops more vulnerable to untimely spring freezes.

Slide 3 – *How Agriculture contributes to climate change*

The US Environmental Protection Agency (EPA) reported that, in 2019, "direct" greenhouse gas (GHG) emissions from agricultural operations accounted for 9.6% of the US total human-caused GHG (US EPA, 2021). The top three sources are nitrous oxide (N_2O) from fertilized or manured soils, enteric methane (CH_4) emitted by ruminant livestock, and GHG emissions during manure storage and handling, which together account for over 95% of the total. The remainder consists of CH_4 from flooded (paddy) rice production (2%) and CO_2 released after field applications of lime and urea or field burning (2%). Globally, rice production accounts for roughly 10% of direct agricultural GHG because much larger acreages of paddy rice are produced throughout Asia and some other parts of the world.

The "direct" agricultural GHG as reported by the EPA and globally by the International Panel on Climate Change (IPCC) do not include the fossil fuel consumption for farm operations nor embodied energy in fertilizers, pesticides, and other inputs (CO_2 from fuel consumed in manufacture of these inputs). These are included in other emissions categories (machinery, transportation, industrial process). Historically, discussions of GHG mitigation in US agriculture have often focused on direct and embodied CO_2 emissions, yet they comprise only about one-sixth of the total (Carpenter-Boggs et al., 2010).

Increasing use of liquid manure storage (a major source of CH_4) has been the major driver in the 17% increase in total US direct agricultural GHG emissions since 1990 (US EPA, 2018).

Slide 4 – *Actual agricultural GHG footprint*

When net losses in soil organic carbon (SOC) and plant biomass carbon are taken into account, the global GHG footprint of agriculture doubles to about 20—25% of total human-caused GHG emissions (Intergovernmental Panel on Climate Change, 2014). About half of the SOC loss (representing about 6% of total human-caused GHG) is related to wind and water erosion, which disproportionately remove soil organic matter, exposing it to oxidation to CO_2 or (when eroded sediment is submerged in water bodies) converted to CH_4 (Lal, 2003). The other half results from in-situ soil degradation from tillage, bare fallow, excessive nutrient applications, overgrazing, and other unsustainable practices; and from destruction of plant biomass related to land use changes (deforestation and land clearing for agriculture).

Slides 5-6 – *The climate change triangle*

Farming for soil health advances the goals of climate-friendly farming: carbon sequestration, reduction in greenhouse gas emissions, and improved capacity of farming operations and their surrounding communities to mitigate and adapt to the impacts of climate change.

Since CO_2 is the leading driver of global warming, and plants consume CO_2 through photosynthesis, the world's natural and agricultural vegetation represents the most "tried and true" means to remove some of the excess CO_2 from the atmosphere. Because healthy agricultural soils built through sustainable and organic farming practices can store some of this photosynthetically fixed organic carbon as stable soil organic carbon (SOC), policy makers and the public at large are turning to the farming community to help solve the climate crisis.

In addition to sequestering carbon, optimum soil management can help combat climate change by limiting emissions of the powerful greenhouse gases nitrous oxide (N_2O) and methane (CH_4) and can enhance the resilience of crops and livestock to the impacts of climate disruption. However, climate change itself can compromise the soil's capacity to maintain optimum health and mitigate net GHG emissions. Higher temperatures accelerate the breakdown of soil organic matter, and more intense rainfalls and storms increase erosion and can degrade soil structure. For example, in the PASA Soil Health Benchmark Study conducted with over 100 organic farmers in Pennsylvania, the record-breaking torrential rains of the 2018 season caused aggregate stability to decrease by more than half in cropland soils (Egan and Nawa, 2021). Better weather and diligent soil care in 2019 helped repair the damage, but the threat of future extreme rainfall events remains.

Thus, restoring soil health through best farming practices will become at once more important and more difficult in the face of climate change. An entire issue of the Journal of Soil and Water Conservation has recently been devoted to research into the challenges that climate change itself imposes on soil, water, wildlife, and other conservation efforts (Steiner et al., 2023).

Slide 7 – *Making US agriculture part of the solution* – subtitle slide

Slide 8 – *Shrinking agriculture's greenhouse gas footprint*

Improved agricultural practices and systems can reduce agriculture's net GHG impacts in two ways: by curbing direct emissions, and by restoring soil organic carbon (SOC = SOM X 0.5) and plant biomass carbon. Advanced management of crop nutrients especially nitrogen (N) and of livestock and manure can reduce direct GHG emissions. In addition, the potential to convert substantial amounts of CO_2 into SOC and plant biomass C through enhanced year-round plant cover and living root, increased biodiversity, and reduced soil disturbance (NRCS four principles of soil health, shown in green font) could make agriculture a net sink for atmospheric CO_2 and offset the remaining direct GHGs to yield a carbon-neutral footprint for US agriculture.

This has become the objective of USDA's climate in agriculture programs and strategies, including the use of supplemental conservation funding through the Inflation Reduction Act (IRA) and the Partnership for Climate Smart Commodities program as well as the department-wide climate resilience strategy. At the legislative level, the Agriculture Resilience Act (ARA), reintroduced into Congress in 2023, seeks to make US agriculture climate-neutral by 2040.

While improved management of annual crop rotations, including cover cropping, conservation tillage, diversified rotations, and no / minimal bare fallow can limit erosion and gradually rebuild SOC stocks, perennialization – agroforestry practices such as alley cropping, silvopasture, forest farming, riparian forest buffers and other perennial conservation plantings – have by far the greatest potential to sequester carbon (Biardeau et al., 2016; Chambers et al., 2016; Feliciano et al., 2018). Transitioning sloping, highly erodible land into permanent pasture and other perennial systems is especially vital for minimizing soil erosion and the associated loss of SOC, as well as for agricultural resilience to climate change.

Enteric CH_4 from livestock and emissions of the powerful GHG N_2O from soils that have been enriched in soluble N from any source – synthetic fertilizers, manure, legume green manures, or concentrated organic N fertilizers like feather meal – pose substantial challenges that require additional research to develop practical solutions. Recent research into feed additives, both chemical and biologically based (marine macroalgae or plant essential oils), to inhibit enteric methanogenic archaea and thereby reduce CH_4 emissions and improve feed efficiency have given promising initial results, though more research is needed to verify safety (Kelly and Kebreab, 2023). Organic strategies for best N management are discussed later in the webinar.

Slide 9 – *Soil and the global carbon cycle*

This simplified diagram of the global carbon cycle, based on Weil and Brady (2019), offers several key take-home messages regarding agriculture and climate:

- The soil holds twice as much organic carbon as the sum of global vegetation biomass and atmospheric CO_2-carbon. With many agricultural soils depleted in SOC to 50% or less of their native levels, a great potential exists to offset a significant percentage of CO_2 emissions through improved agricultural practices, such as organic farming.

- *Plant photosynthesis is the world's primary sustainable means of CO_2 sequestration.* The 2 billion ton/year annual imbalance between conversion of plant C into soil organic C and the loss of soil organic C as CO_2 contributes about 15% of annual net human-caused CO_2 emissions. Most of the rest comes from fossil fuel use. Simply swapping the "60" and "62" on the carbon flows into and out of the soil – by stopping erosion and reversing net soil degradation into a gradual accrual of SOC – would make the world's agricultural systems climate-neutral by offsetting the "direct" GHG emissions.
- In addition to SOC, the world's soils hold nearly 1,000 billion tons of inorganic (carbonate) carbon, mainly in prairie, semiarid, and desert regions. More research into the impacts of climate change itself and of agricultural management practices on soil inorganic carbon (SIC) is needed.
- The world's oceans are slowing climate change by absorbing 3 billion tons CO_2-C annually, but this process threatens marine ecology through acidification, and urgent action is needed to absorb excess atmospheric CO_2 through living vegetation and to curb emissions through decarbonization of the economy.
- This diagram does not account for the conversion of biomass C into CO_2 through deforestation and wildfires. Climate-related intensification of wildfires threatens the planet' capacity to absorb and sequester C through photosynthesis and forest cover.

Slide 10 – *Four NRCS principles of soil health*

Practices that build soil health simultaneously contribute to climate mitigation by building soil organic matter (SOM = carbon sequestration) and improving nutrient cycling (potentially reducing N_2O emissions), and to agricultural resilience to the impacts of climate disruption.

The four NRCS soil health principles, *keep soil covered, maintain living root, diversify crops,* and *minimize disturbance* were established by NRCS scientists in about 2010 at the beginning of the agency's Soil Health Initiative. They have been abundantly validated through research in both organic and non-organic cropping systems and can provide a roadmap to climate-friendly and climate-resilient agriculture.

Photo credits: Korey Erb (diverse vegetable field), Washington State University (roller-crimper).

Slide 11 – *How soil sequesters carbon: an ancient partnership*

Plant photosynthesis is the ultimate source of organic carbon in agriculture and in natural land plant communities. This is why "keep soil covered" and "maintain living root" are two of the NRCS principles of soil health management, and why living plants play a central role in climate mitigation and climate resilience in farming systems.

Plant nutrition is a two-way exchange, in which photosynthesis provides nourishment for the soil life, in the form of root exudates. In addition to the "bread and butter" of sugars, amino acids, and other soluble organic substances, the roots of each plant species secrete other substances that act as specific chemical signals to stimulate and host those soil organisms most beneficial to that plant. In turn, the resulting root zone microbiome facilitates uptake of the nutrients the plant needs to thrive. This relationship evolved some 450 million years ago when plants and their mycorrhizal fungal symbionts first colonized the land and began converting gravel, sand, silt, and clay into living soil (Weil and Brady, 2017).

Slide 12 - *Optimizing Earth's carbon pipeline*

In an extensive review of agricultural conservation and soil health research, Prescott et al (2021) identified three management strategies that enhance plant root exudation and thereby feed soil microbes and support the formation of stable, *mineral-associated organic carbon* (MAOC).

Going just a little "lean" on water and fertilizer, especially plant-available N and P, will slow aboveground growth a bit, yet without adversely affecting photosynthetic rate and with little effect on yield or quality. This results in a surplus of organic carbon, which the plant sends into the root system, stimulating both root growth and root exudation, which in turn feeds soil microbes and enhances MAOC formation and long-term SOC sequestration.

Unlike soluble N from conventional fertilizers, legumes supply N in organic forms (amino acids), which, combined with sugars, provide a particularly nourishing root exudate for optimum microbial growth and function.

In rotational grazing, allowing the forage to recover completely and go through most of its rapid growth phase (during which root exudation is greatest) before grazing again can optimize the SOC accrual benefits of livestock grazing systems. Grazing too soon (incomplete recovery) or too late (overmature forage) reduces net annual exudation and MAOC formation.

Slide 13 – *Inflation Reduction Act (IRA) of 2022*

The Inflation Reduction Act provided a total of $20 billion during 2022-26 in supplemental conservation funding to support climate-smart agricultural systems and practices through:

- CSP $3.25B
- EQIP $8.45B
- RCPP $4.95B
- ACEP $1.4B
- Conservation technical assistance $1B.

NRCS has posted a full listing of climate mitigation activities to be supported by IRA funds at: https://www.nrcs.usda.gov/sites/default/files/2023-01/CSAF%20Mitigation%20Activities_2023.pdf.

For additional analysis, see blog posts by National Sustainable Agriculture Coalition (NSAC):

- August 2022: IRA investment in climate and agricultural conservation.

- February 2023: IRA and water conservation in Western region.
- February 2023: IRA rollout.

Slide 14 – *Partnership for Climate Smart Commodities*

The USDA's new Partnership for Climate Smart Commodities invited proposals during 2022, funded 70 large ($5M – 95M) and 71 smaller (<$5M) proposals, launched the implementation phase in spring of 2023, and establsihed a Partnership Network to facilitate mutual learning and information exchange among project teams.

Blog posts by NSAC:

- December 2022: announcement of PCSC awards including many with organic or sustainable agricultural NGOs as lead or major partners.
- June 2023: preliminary analysis of PCSC awards.

Slide 15 – *Agriculture Resilience Act*

Reintroduced in both chambers of Congress in 2023 as a marker bill for the 2023 Farm Bill, the Agriculture Resilience Act (ARA) provides a roadmap toward a climate-neutral and climate-resilient agricultural system for the US. It includes substantially increased investments in USDA research and conservation programs specifically focused on climate in agriculture, including:

- Soil health systems and practices.
- Support for State and Tribal soil health programs.
- Conversion of livestock production to pasture-based systems and advanced grazing management.
- Alternative manure management - composting and other solid manure management systems versus liquid / slurry systems, which emit larger amounts of GHG and do not produce as beneficial a soil amendment as compost.
- Building community food systems, reducing food waste, and composting unavoidable food waste.

Slide 16 – *Organic agriculture as a climate solution: opportunities and challenges* –subtitle slide

Slide 17 – *Agricultural greenhouse gas emissions and NOP Rules*

The National Organic Standards do not directly require certified organic farmers to help solve the climate crisis, yet they do address practices that can reduce the GHG footprint of organic agriculture in each of the five sectors of the pie chart of direct and indirect agricultural GHG emissions. Preventing erosion, building soil organic matter (SOM) and improving the physical chemical and biological condition of the soil would eliminate the left-hand side of the GHG footprint (indirect emissions related to soil conservation and soil health) and potentially render it negative, thereby offsetting at least some of the direct GHG emissions (right-hand side).

Embodied energy (CO2) in inputs (gray slice of pie chart) are generally lower in organic systems than in conventional production, since synthetic N fertilizer is fairly energy intensive. Reducing N_2O and CH_4 emissions related to soil, nutrient, and livestock management pose challenges for all farmers, and promising research-based guidelines will be discussed later in this Webinar.

Slide 18 – *Six organic principles of soil health*

Throughout its history, the organic method has emphasized soil health as described in the four NRCS principles, plus two additional principles: integration of crop and livestock production, and return of all organic residues (manure, grain straw, etc) to the land, either directly or after composting. First stated and promoted by Sir Albert Howard (1947) and other early leaders in the organic movement, the Law of Return states that farmers must replenish both nutrients removed in harvest and organic matter consumed in production, in order to maintain soil fertility.

Early leaders of the movement also emphasized the value of integrating livestock with crop production for a more balanced agroecosystem that cycles nutrients and other resources more efficiently and thereby reduced dependence on inputs from off-farm sources. A recent modeling study conducted in China indicated that integrating livestock and crop production could substantially reduce the net GHG footprint of food production, largely through more efficient local/regional cycling of nutrients and other resources (Chen et al., 2023)

Photo credits: National Center for Appropriate Technology (livestock), Korey Erb (diverse vegetable field), Washington State University (roller-crimper).

Slide 19 – *What organic farmers say about climate change*

The Organic Farming Research Foundation (OFRF) conducted a survey of 1,059 certified organic farmers and 71 transitioning-organic farmers and reported findings in its National Organic Research Agenda (NORA) 2022 (Snyder et al., 2022). Survey participants identified their soil health and resource stewardship practices and their leading production challenges, concerns, and technical assistance needs. More than one-third of respondents considered climate change a substantial challenge for their own operations, and slightly over one-half expressed concern about how they will adapt to climate change. High percentages reported implementing several of the key climate-smart practices identified by NRCS as priorities for IRA conservation funding (slide 13 above).

Slide 20 – *Organic advantages and challenges*

The organic method offers some important advantages over other approaches to climate mitigation in agriculture. With its priority emphasis on healthy, living soils, organic agriculture utilizes biological (plant or animal based) sources of nutrients, and otherwise manages soils to build and maintains high soil organic matter (SOM) levels. Increases in SOM represent, at least in part, SOC sequestration. In addition, healthy soil makes crops and livestock more resilient to stresses, including weather extremes related to climate change.

Exclusion of synthetic biocides and limited use of natural-mineral fungicides or botanical pesticides protects aboveground and belowground biodiversity throughout the agroecosystem, especially the soil microbiota on which SOC sequestration, nutrient cycling, and other vital soil functions depend. In addition, non-use of herbicides facilitates crop diversity and allows tight rotations that include prompt planting of cover crops after harvest, relay planting of cover crops into cash crops prior to harvest, and other intercropping strategies. In conventional systems, herbicide residues often necessitate a waiting period (from a few weeks to a year or more) before following one crop with other crops from unrelated plant families.

A recent global meta-analysis comparing production systems has shown that crop diversification enhances soil microbial biomass, and that the use of compost and other organic nutrient sources can maintain twice the microbial biomass as either conventional fertilizer or no fertilizer (Morugán-Coronado et al., 2022). Since the soil microbial community plays a central role in the conversion of plant root exudates and plant residues into MAOC, organic systems that build soil microbial abundance will generally enhance SOC sequestration (Prescott et al., 2021).

Organic farmers face three challenges related to soil health and climate. First, without herbicides, organic annual cropping systems generally rely on tillage and cultivation to manage weeds and cover crops, and to prepare seedbeds. Tillage breaks up soil aggregates and fungal networks, can harm larger soil organisms including earthworms, and accelerates the decomposition of SOM that has been so carefully built through cover cropping, compost, organic mulch, and other organic practices. Shallow cultivation leaves most of the soil profile undisturbed, but repeated passes can pulverize near-surface aggregates, oxidizing aggregate-protected SOM, and increasing the risk of surface crusting and erosion by untimely downpours or windstorms.

The second challenge is that organic nutrient sources, especially compost, manure, and poultry litter, tend to provide nitrogen (N), phosphate (P_2O_5) and potash (K_2O) in roughly a 1:1:1 ratio, while crops utilize (and harvests remove) roughly three pounds each N and K_2O for every pound of P_2O_5. As a result, relying on compost, manure, and/or poultry litter fertilizers to meet crop N and K needs will eventually build surplus P in the soil. As soil test P level rises above optimum ("high") into the "very high" range, plant-symbiotic arbuscular mycorrhizal fungi (AMF) go dormant and cease to colonize plant roots (Hamel, 2004). While crops may not need the mycorrhizal partnership for P uptake when soil test P levels are ample, other vital functions of mycorrhizal fungi are lost, including SOC sequestration, improved crop moisture uptake and drought resilience, micronutrient uptake, and suppression of soilborne plant pathogens.

The third challenge is that, while organic sources of nitrogen (N) support much greater soil microbial growth, activity, functional biodiversity, and carbon sequestration than conventional N fertilizers, organic N can be more challenging to manage. Research has documented great potential for organic soil and nutrient management to meet crop N needs while minimizing N leaching and N_2O emissions (Bowles et al., 2015). Yet, other studies have shown that concentrated organic N such as poultry litter or all-legume green manures can result in large bursts of N_2O emissions when heavy rainfall creates wet soil conditions shortly after amendments and/or legumes are tilled in (Baas et al., 2015; Davis et al., 2019; Han et al., 2017).

Conservation agriculture is another integrated approach to climate friendly and climate resilient farming. Conservation agriculture aims to eliminate tillage (*physical* soil disturbance) and allows judicious use of agricultural chemicals, especially herbicides and fertilizers (*chemical* soil disturbance) as needed to sustain yields and control weeds. The organic method excludes synthetics, thereby minimizing chemical soil disturbance, while allowing some physical disturbance (tillage and cultivation) within the context of NOP requirements that tillage practices must improve or maintain soil condition.

These two approaches to annual cropping systems show roughly equal potential to sequester carbon in SOM. Experienced organic farmers continually seek new ways to further reduce tillage intensity and frequency, as covered in the webinar, *Practical Conservation Tillage for Organic Cropping Systems* given on July 17, 2023. The best conservation farmers often reduce total agrochemical applications to one per year or less, and a few have been able to phase them out altogether.

The good news from meta-analysis is that reducing tillage to a degree that is practical for organic crop production (e.g., shallow, full-field, non-inversion tillage) enhances soil microbial biomass (over deeper inversion plow-disk tillage) more effectively than continuous no-till, which is often considered by conservation professionals to be the "gold standard" of cropland soil health management (Morugán-Coronado et al., 2022). The authors suggested that soil compaction and surface sealing under long-term continuous no-till may restrict microbial growth but did not address the possible impact of greater dependence on herbicides for continuous no-till systems on the microbial community.

Slide 21 – *Does organic agriculture sequester more carbon?*

A global meta-analysis found an average of 19% higher total SOC in organic vs conventional systems, with larger differences in functional indicators of soil biological activity such as microbial biomass and enzyme activities (Lori et al., 2017). Enhanced soil microbial function and soil health may contribute to climate resilience in organic agricultural systems.

Recent research indicates that the "humic substances" (fulvic and humic acids) reported in the Ghabbour et al. (2017) study are mainly artifacts of the alkaline extraction methods used to analyze SOM, and that formation of stable SOC is primarily mediated by microbial processes (Dynarsky et al., 2020; Grandy and Kallenbach, 2015; Lehmann & Kleber, 2015). Yet, the substantially higher percentages of humic substances formed during extraction of organically managed soils may reflect a qualitative difference in the organic matter pools, and soil microbial functions.

Gattinger et al. (2012) point out that not all of the SOM increment in organically managed systems that import compost or other organic amendments represent *in-situ* sequestration. Across the 20 studies in their meta-analysis, they estimated that about 40% of the SOC was imported and 60% sequestered *in situ*. If compost is made from manure and plant biomass that would have otherwise returned to the soils in their acres of origin, this carbon accrual represents carbon depletion of the donor acres ("robbing Peter to pay Paul"). However, if compost is made from organic refuse such as food scraps, yard trimmings, autumn leaves, or manure that would otherwise have "gone to waste" in landfills or manure lagoons (where they would have emitted a lot of CH_4), this represents a substantial net reduction in GHG emissions.

Slide 22 – *Does tillage negate C sequestration?*

Soil organic carbon (SOC) becomes stabilized in three ways:

- Physically protected within soil aggregates.
- Tightly bound to soil minerals (especially clay and silt) (MAOC).
- Deposited deeper in the soil profile where lower microbial activity and lower oxygen levels lengthen its half-life.

Continuous no-till systems and perennial systems allow particulate SOC to accrue in near-surface aggregates, which play an important role in certain aspects of soil health, especially permeability to rainfall. SOC accrual rates through no-till can reach 500 lb/ac-year for the first ten years until the topsoil reaches a new "saturation point" after which SOC levels hold steady (West and Post, 2002). However, most no-till farmers growing annual field or vegetable crops must till or subsoil occasionally to deal with perennial or herbicide-resistant weeds or to relieve compaction (Grandy et al., 2006; Kane, 2015). The near-surface, physically protected SOC is highly vulnerable to oxidation, even after a single shallow tillage pass (Ibid.).

Research has demonstrated that the largest and most stable fraction of SOC – the MAOC – is derived from microbial processing of root exudates and other organic materials (Dynarsky et al., 2020; Kallenbach et al., 2016). In deep, biologically active, well "fed" soils, soluble organic substances can leach into subsoil horizons where they are converted into long-lived MAOC, so that more than half of the soil's stable SOC occurs at depths below 12 inches, out of the reach of most tillage operations (Dynarski et al., 2020). Even within the A horizon, MAOC stocks are less vulnerable to oxidation by tillage, especially in organic systems that implement shallow non-inversion tillage and other reduced-intensity tillage strategies, as described in greater depth in the recent webinar *Practical Conservation Tillage for Organic Cropping Systems,* given July 17.

Slide 23 – *Long-term agroecological research findings*

In the US, results of six long-term farming systems trials show that organic crop rotations that include legume cover or sod crops, organic nutrient sources (compost or manure), and routine tillage accrue significantly more SOC than conventional corn-soybean rotations (Delate et al., 2015b). The perennial legume or legume-grass sod phase in organic systems increases the depth, biomass, and duration / continuity of living roots, and thus plays a major role in SOC accrual in these systems (Rodale, 2014; Wander et al., 1994). For example, researchers at University of Minnesota have found that 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 and reduces weed pressure (Moncada and Sheaffer, 2010).

In the Beltsville, MD trial, SOC levels (measured from surface to 39-inch depth) at the end of 13 years were 2.5 tons/ac higher in organic rotations with cover crops, light applications of poultry litter (0.7 – 1.3 t/ac annually), and some routine tillage each year, than in a conventional no-till system, and 3.9 tons/ac higher than in a tilled conventional rotation (Cavigelli et al., 2013). Other trials also suggest gains of 400 – 600 lb SOC/ac-year for organic systems.

Slides 24 and 25 – *Organic practices build resilience*

Best organic practices that build soil health also improve agricultural resilience to the impacts of climate change, particularly the impacts of drought and deluge. In California, winter rains infiltrate into cover cropped fields and either pond or run off from unplanted fallow, leaving less moisture in the soil profile for the next production crop. In the Rodale long term farming systems trials, organically managed soils stored more moisture and sustained corn crops better through drought than the conventional treatment (Rodale, 2015).

Organic producers must often work with depleted soils when transitioning a field from conventional to organic production. Skillful use of compost, organic fertilizers, and other natural amendments, combined with favorable weather, can sustain good yields. However, the high production costs of input-intensive organic production can approach or even exceed gross proceeds, resulting in significant financial risk to the farm. In addition, soils in compromised health show much less resilience to the impacts of drought or excessive rainfall, as illustrated in the real-life examples in Slide 24 as well as the hypothetical example of production records over a six year period (Slide 25).

As soil condition improves, transitioning to a soil health management strategy with lower inputs and greater emphasis on grown-in-place fertility (cover crops, intercrops, etc) can reduce costs and improve net returns. While the high input system may slightly out-yield the soil health system in favorable weather years, healthy soil conditions will minimize losses to drought and flood, lower input costs, enhance net returns, and reduce financial risk in most years.

Slide 26 – *Best practices for carbon sequestration* - Subtitle slide

Slide 27 – *C sequestration from different farming practices*

Continuous no-till by itself can accumulate 510 lb SOC/ac-yr (West and Post, 2002), mostly in near-surface aggregates where it is subject to rapid re-oxidation after a single tillage pass. In practice nearly all “continuous no till” farmers need to till every few years to combat perennial or herbicide-resistant weeds or break up surface crust or subsurface hardpan. A recent global meta-analysis confirmed that no-till mainly builds SOC near the surface, and the authors concluded that no-till can help maintain soil health and crop productivity, yet it plays only a minor role in carbon sequestration and GHG mitigation (Mondal et al., 2023).

No-till without winter cover crops (cash crop residues only) may not fully protect the soil surface from compaction by heavy rainfall, and the absence of living root can diminish the benefits of no-till for soil structure. Leaving the soil surface undisturbed under a substantial residue of roll-crimped or mowed cover crop maintains soil structure more effectively.

The cover crop practice is estimated to sequester about 150 lb C/ac-yr (Chambers et al., 2016). A recent meta-analysis of 49 studies in the Americas and in Europe on the impacts of cover cropping on different soil carbon fractions showed significant increases in active particulate organic carbon (POC) of 15% and in stable MAOC of 5.5% (Wooliver and Jagadamma, 2023). Both SOC fractions were directly and strongly related to cover crop aboveground biomass. A global meta-analysis of 93 studies comparing cover crop and bare fallow showed very similar trends, including 12% higher total SOC, 15% higher POC, and 7% higher MAOC with cover crops. The MAOC response increased with duration of the trial (Hu, 2023).

Cover crop termination by plowing, spading, or heavy disking may stimulate microbial respiration and mineralization of much of the cover crop biomass. Combining the cover crop with no-till termination can enhance both the quantity and stability of sequestered SOC, providing both near-surface POC protected in aggregates and long-lived MAOC throughout the rooting depth (Lal, 2015). In an organic system, rotational no till (tilling once a year after cash crop harvest to manage weeds and plant the next cover), can enhance SOC accrual from cover crops, especially if shallow non-inversion tillage is used.

Photo credit: cover crop rolling and no till planting in one pass from *Reduced Tillage in Organic Systems Field Day Program Handbook*, page 6.
https://rvpadmin.cce.cornell.edu/uploads/doc_699.pdf

Slide 28 – *C sequestered in diversified crop rotation*

Adding a cereal grain interseeded with a perennial legume such as alfalfa or red clover to the traditional corn-soy rotation substantially increases biomass production per year, and duration, depth, and diversity of living roots, resulting in greater SOC accrual throughout the soil profile. Diversifying a rotation from two to three or more different crops has been estimated to build about 180 lb SOC/ac annually over a 40-year period, and this SOC accrues throughout the rooting depth and is more stable than that accrued by no-till alone.

Even when crop intensity (average annual plant biomass production, percentage of the year in living cover) is unchanged, adding one or two new crops to a low diversity rotation has been found to enhance active and total SOM, soil biodiversity, and net C sequestration (Lehman et al., 2017; Tiemann et al., 2015). In addition, a review of multiple studies showed that corn grown in diverse crop rotations (three or more crops) showed greater resilience to drought and other weather extremes, and showed a rising yield trend over time, compared to corn monoculture or corn-soy rotations (Bowles et al., 2020). A recent meta-analysis showed small but significant increases in SOC and aggregation with rotational diversity, especially in systems with residues returned to the soil and reduced N fertilization rates (Zheng et al., 2023).

Slide 29 – *In annual cropping systems, plant a cover crop the day after harvest – or sooner!*

Bare soil is hungry and will lose SOM even in a no-till system. The weeds – pioneer plants – can be seen as the soil's way of feeding itself if we do not do so.

Whenever the soil lacks living vegetation, the staple food pipeline for soil life – plant root exudates – is cut off. Plant residues (on the surface or tilled in) can sustain soil organisms during short intervals between crop harvest or cover crop termination and establishment of the next cover or cash crop. However, during prolonged fallow without living cover, soil biological activity and soil health decline, and sequestration of MAOC ceases. If the soil surface is exposed (no residue cover), SOM losses may be accelerated, especially if the soil microbiome is further stressed by tillage, excess nutrients, or agrochemicals.

In most regions, prompt cover crop planting whenever the season's production is finished is a top priority for soil health and climate friendly farming. In dryland farming on limited rainfall (20 inches annually or less), care must be taken to ensure sufficient moisture for the next production crop. Shallow-rooted, low-moisture-demand cover crops, managing cover crops and weeds in a timely manner to allow soil moisture recharge for the next crop, and using no-till or shallow undercutter (sweep plow) termination methods that leave residues on the surface can protect SOM and soil health in these circumstances.

Slide 30 – *Terminate cover crops with less tillage*

Plowing an all-legume cover crop such as hairy vetch (shown here) or a perennial sod like red clover or alfalfa can meet the full N requirement of heavy feeders like corn or head brassicas. However, plowing also "turns the house upside down" for soil life and stimulates rapid decomposition of residues, which can consume SOC and release so much N that much of it leaches to groundwater or denitrifies into N_2O before the next crop can utilize it. A grass-legume mix is less likely to cause massive N_2O emissions. However, if excessive rainfall follows plowing-under of any cover crop, the buried residues can undergo anaerobic decomposition forming breakdown products that are somewhat toxic to plant roots and beneficial microbes.

Flail mowing followed by shallow tillage to mix residues into the soil surface is less disruptive to the soil profile. If the cover crop has a balanced carbon-to-nitrogen (C:N) ratio (e.g., cereal grain + legume), this practice can yield a slow, steady release of plant nutrients. The high-speed disk, rotary harrow, or sweep plow undercutter (best for lower-rainfall regions), can do the job with less damage to soil aggregates than a rototiller run at full PTO (rotary) speed. Some oxidation of near-surface SOC and surface crusting can still occur. However, shallow tillage can sustain soil biological activity and will not reverse the soil carbon sequestration from cover crop root exudates and MAOC formation throughout the soil profile.

The best choice for soil health is no-till termination of a mature cover crop using a roller crimper, followed by no-till or strip till planting of the next crop. This system can be challenging to manage in organic systems because of slower N mineralization and weed pressure.

Slide 31 – *Additional strategies to keep the soil covered*

In photo A, winter rye cover crop was strip tilled with a walk-behind rototiller for tomato planting, and alleys were maintained by mowing. Rye growth slows or dies back in the heat of summer, which facilitates management of this system.

Tomatoes and greens were planted together in the high tunnel (photo B). The greens are nearing harvest ready just as the tomatoes begin to occupy the whole bed. Straw mulch (photo C) does not provide living root; however, it protects the soil surface, feeds near-surface soil organisms, and improved moisture retention.

In the relay planting example from central Vermont (USDA hardiness zone 4), author Eliot Coleman sowed the clover between brassica rows when the latter were just getting established; after vegetable harvest, the clover is ready to grow and cover the ground (photo D).

Slide 32 – *C sequestered by improved grazing management*

C accrual through the NRCS conservation practice "prescribed grazing" has been estimated at 400 lb/ac-yr (Chambers et al., 2016). Management-intensive rotational grazing (MIG) systems, variously called "mob grazing," "adaptive multipaddock" (AMP), "holistic management," or "regenerative" grazing and now offered as a CSP Enhancement for prescribed grazing, have been adapted to regions as diverse as upstate New York and New England, the Gulf Coast, and the Great Plains. In addition to enhanced soil, forage, and livestock health, success stories report initial C sequestration rates of one to three tons per acre for the first five to 10 years (Machmuller et al., 2016; Teague et al., 2016; Wang et al., 2015).

By combining cropping practices that reflect the four NRCS principles of soil health with MIG, rancher and author Gabe Brown (2018) rebuilt 5,000 acres of rangeland soil from a severely depleted state (2% SOM) to near optimum health (7% SOM) over a 20-year period – on just 16 inches of moisture per year. This 5-point increase in SOM represents an average annual sequestration of about 2,500 lb/ac, or 125,000 tons of C for the 5,000-acre ranch over 20 years.

Other estimates of SOC sequestration under advanced grazing management have shown smaller and more variable benefits (Byrnes et al., 2018; Mosier et al., 2021). Grazing schedules, stocking rates, rest periods, forage mix, and other management factors must be adapted both to locale and to fluctuating weather conditions. The primary mechanism of SOC and soil organic N accrual under best rotational grazing consists of mineral association, which is optimized by timing grazing to occur late in the rapid growth phase of forage development (Mosier et al., 2021; Prescott et al., 2021).

Slides 33 and 34 – *C sequestered by perennial plantings*

Among agricultural conservation practices, *perennial plantings* have the greatest per-acre C sequestration potential, as carbon accrues both in undisturbed soil profiles and in perennial plant biomass. Biardeau et al. (2016) estimated C sequestration in herbaceous perennial conservation plantings at 800 lb/ac-yr, and 1,000-1,500 lb/ac-yr for woody perennial plantings such as hedgerow or riparian forest buffer. Converting highly erodible, depleted, or marginal cropland; and riparian or other ecologically sensitive areas to forest, prairie, or permanent pasture can sequester a ton of carbon or more annually in SOC + plant biomass, compared to 400 – 600 lb SOC/acre-year for either organic or conservation agricultural systems (Chambers et al., 2016, Feliciano et al., 2018). The highest C sequestration rates were observed in silvopasture and installing intensive permacultural home gardens in previously underutilized land.

Perennial agricultural systems such as forest farming and permaculture will also play a vital role in adapting to the impacts of climate change, as they offer diversified enterprises and income streams and can support improved diets and community food security. In addition, windbreaks, hedgerows, silvopasture, alley cropping, and other agroforestry plantings accomplish multiple conservation objectives, including nutrient retention and cycling and water conservation to wildlife habitat and biodiversity conservation C sequestration.

A recent estimate of the potential for improved management of cropland and grazing lands to absorb CO_2 between now and the end of the 21st Century came to 38 – 120 billion tons C removed. However, adding reforestation of degraded and abandoned lands; shelterbelts, riparian woodland, and other conservation forest plantings; community reforestation projects; urban permaculture and green belt plantings, and wetland restoration raises this potential to 209 – 458 billion tons sequestered, which, (for the median value of 333 billion tons) would reduce end of century atmospheric CO_2 by some 156 ppm (Lal et al., 2018).

Slide 35 – *Stacking practices to build SOC and enhance resilience*

Organic amendments, especially finished compost, can work in a complementary and synergistic manner with living plants (cover crops, tight diverse crop rotations, etc) to build SOM and soil health (Delate et al., 2015a; Hooks et al., 2015; Hurisso et al.,2016). The compost adds stable SOM and may help stabilize the SOM deposited by crop roots. Light applications of compost that do not aggravate P surpluses may be sufficient to provide this synergistic benefit. Reducing tillage can further enhance outcomes. Integrated systems of practices generally yield greater benefits than single practices such as compost without cover crops or vice versa. As noted above, organic rotations that integrate multiple soil health practices have sequestered significantly more SOC than conventional rotations in long-term farming systems trials cross the US (Cavigelli et al., 2013; Delate et al., 2015b).

In a recent meta-analysis of 36 studies comparing organic systems using different practices and inputs, Crystal-Ornelas et al (2021) found statistically significant increases in SOC from organic amendments or conservation tillage. Eight of these studies compared systems with vs. without cover crops and showed a gradual increase in SOM over multiple seasons with cover cropping.

While continuous no-till is not feasible for organic producers, many other techniques exist that can reduce the SOC costs of necessary tillage. These include strip tillage (photo on slide), ridge tillage, spading machine (deep, non-inversion primary tillage), rotary harrow (shallow tillage), and even a rototiller – with the PTO slowed down and tractor forward speed increased to avoid pulverizing surface aggregates (Schonbeck et al., 2017).

Slice 36 – *Avoid nutrient surpluses to sequester more soil carbon*

Providing more plant-available N and P from any source (soluble fertilizers, manure, other organic amendments) substantially alters the soil microbiome in ways that reduce net SOC accrual, promote N_2O emissions, deter mycorrhizal activity, and thus perpetuate reliance on concentrated nutrient inputs (Davis et al., 2019; Hamel, 2004; Prescott et al., 2021).

Standard soil test recommendations, even those that comply with the NRCS Conservation Practice Standard 590 Nutrient Management, do not fully account for the capacity of soil life to deliver plant-available N, P, and other nutrients through mineralization of organic residues and soil organic matter. In a biologically active soil under good organic management, the soil life can meet 50 – 100% of the crop's N requirement. Recent studies in a wide range of soil types show that actual N need reliably decreases with increasing "Soil Test Biological Activity" (STBA, a simple lab procedure to measure soil respiration over a three-day period). In the southeastern US, the Economic Optimum N Rate (EONR) reached *zero* in 12 out of 36 trials with corn grain, 6 out of 11 for corn silage, and 21 out of 57 for fescue forage (Franzluebbers, 2018; Franzluebbers et al., 2018). These soils were under organic or sustainable reduced-tillage management and were in much better health than research station soils. Greatly reduced NPK needs have been reported in organically managed soils in cooler climates as well (Kloot, 2018).

In addition, supplying ample N, P, and water to crops maximizes top growth but reduces production of root exudates, which results in less "food" for microbes and less formation of stable MAOM in the root zone (Prescott et al., 2021).

Slide 37 – *Balance input C and N to build SOC*

A research team at Washington State University compared the crop and soil impacts of two nutrient sources in organic vegetable production in a maritime soil in Washington State: on-farm mixed compost made from dairy manure and bedding and yard waste (C:N ~20) at rates of 6 to 8 tons/ac annually, and composted poultry litter (C:N ~7) at 1.8 – 2.6 tons/ac annually. The total N amounts applied in the two treatments were similar. Crop yields, soil physical, chemical, and biological properties, and potential N_2O emissions were monitored over an 11-year period.

The higher C:N compost improved overall soil health, with substantially higher levels of active and total SOM, and microbial activity. Crop yields in the two treatments were generally similar.

Slide 38 – *Tips for carbon sequestration and agricultural resilience in organic systems*

Summary slide, self-explanatory.

Slide 39 – *Best organic practices for greenhouse gas mitigation* – subtitle slide

Slide 40 – *The denitrification process*

Nitrous oxide (N_2O) is formed during microbial transformations of soluble inorganic N in the soil, primarily reduction of nitrate-N (denitrification). Conditions that promote N_2O emissions include high soluble N levels in the soil, wet soil conditions with limited but not zero oxygen, and sufficient decomposable organic C to support microbial activity (Cai et al., 2016). Under fully anaerobic conditions, denitrification produces harmless elemental N_2 gas, but significant CH_4 emissions from anaerobic decomposition of organic carbon may occur.

In conventional agriculture, N_2O emissions predictably occur when periods of high moisture (high rainfall and or slow soil drainage) follow fertilizer N applications, or during wet spells later in the season if N applications have exceeded crop needs. Total annual N_2O emissions rise exponentially as N use rates exceed crop need (Eagle et al., 2017; Millar et al., 2010). Best nutrient management protocols can cut these emissions by half. Regardless of management system, N_2O emissions become minimal when soil moisture drops below "field capacity" (~ 50 – 60% water-filled pore space) or when soil nitrate-N drops below 6 ppm (Cai et al., 2016; Thomas et al., 2017).

The Intergovernmental Panel on Climate Change (IPCC, 2014) estimates that, in conventionally managed soils, about 1% of applied fertilizer N is converted to N_2O *in situ*, and an another 0.75% of N that leaches is converted to N_2O. For example: if a conventional corn crop receives 200 lb N/ac and half of it eventually leaches to groundwater, an estimated total of 2.75 lb N will be emitted as N_2O, which would negate 366 lb SOC sequestration.

Slide 41 – *Do organic systems emit less N_2O?*

Comparisons of N_2O emissions from organic vs non-organic production systems have given mixed results. Although one meta-analysis has shown a trend toward lower emissions for organic (Skinner et al., 2014), a recent review of multiple meta-analyses found that organic N sources can increase by about 25% (Young et al., 2022). While most organic N sources do not elevate soil nitrate-N as much as conventional soluble N fertilizers and have lower estimated emissions factors (Charles et al., 2017), most organic systems provide an abundance of two other ingredients for N_2O emissions: ample active (decomposable) organic matter, and abundant and active soil microbiomes. N_2O emissions increase about 24% for each 1% increase in total SOC

(Eagle et al., 2017), and emissions from clay loam can be two or three times those from sandy loam because of slower gas diffusion in finer soils (Balaine et al., 2016; Charles et al., 2017).

A recent meta-analysis of 134 studies comparing poultry litter (PL) to meet crop N requirement versus synthetic N for cotton production found that the PL enhanced SOC, CEC, P, K, and some key micronutrient levels. However, PL doubled N_2O emissions over synthetic N, reflecting the stimulating effect of co-occurring high levels of soluble N and labile organic C on emissions of this GHG (Lin et al., 2022). Many organic farms currently use PL or pelleted PL fertilizer products as their "go to" fertilizer, and this may contribute to the trend toward higher N_2O emissions from organic versus conventionally fertilized cropping systems.

In addition, the complex dynamics of soil organic carbon and nitrogen in organically managed soils can result in brief spikes in N_2O emissions that can be difficult to predict, detect, or control. For example, one trial in Michigan documented five-fold greater annual N_2O in the organic system, resulting from intense bursts of N_2O when excessive rain immediately after poultry litter + cover crop plowdown created a "perfect storm" of high moisture and soluble N with ample decomposable organic C and high biological activity (Baas et al., 2015). Significant N_2O emissions commonly occur when the perennial legume sod phase of organic field crop rotations is terminated by plowing, especially when moist to wet soil conditions follow the plowing (Han et al., 2017). A grass-legume mixture may emit less N_2O after plowing.

In California, organic broccoli production reached an economic optimum at 220 lb N/ac from organic sources; however this treatment also resulted in losses of 11 – 27 lb N/ac as N_2O, a GHG impact equivalent to loss of 1,400 to 3,400 lb SOC/ac (Li et al., 2009).

In addition, all farms face increasing challenges related to untimely and unpredictable excessive rainfalls due to climate change itself.

Slide 42 – *Balance input C and N to mitigate N_2O emissions.*

In the Washington State University trials, the compost-amended treatment showed higher levels of soil enzymes involved in nutrient cycling and a more balanced nematode community than the poultry litter treatment (Bhowmik et al., 2016, 2017; Cogger et al., 2013). Notably, the compost amended soil showed both a greater capacity to mineralize N for crop production and to immobilize excess soluble N. This suggests that reliance on concentrated, low C:N inputs like poultry litter may shift the soil microbiome in a way that weakens N cycling and provisioning, thereby perpetuating reliance on these inputs and increasing the risk of spikes in N_2O emissions if wet conditions follow cover crop termination or amendment application.

Slide 43 – *Tightly coupled N cycling can reduce N_2O emissions*

In a study of 13 organic tomato fields in central California, four fields under the best management showed "tightly coupled N cycling" and sustained top tomato yields while soil nitrate-N levels remained at or below 5 ppm. This level is known to minimize leaching and N_2O

emissions but is usually associated with crop N deficiency. The “tightly coupled” soils had high levels of active and total SOC, microbial activity, and microbial and plant root enzymes that facilitate N mineralization and uptake (Bowles et al., 2015; Jackson and Bowles, 2013). While crops received some in-row soluble N as fish emulsion or Chilean nitrate, the bulk soil was amended with a yard waste compost with a moderate C:N ratio (15-18:1), and the crop derived most of its N from biological mineralization from compost and active SOM.

Seven “N-saturated” fields also sustained high yields but had somewhat lower active and total SOC, high microbial activity but with greater SOC-consuming enzyme activity and less N-cycling enzymes. Nitrate-N levels were at or near the accepted sufficiency level (16 ppm), a level that can also result in leaching or denitrification to N_2O if wet soil conditions occur. Two “N-deficient” fields failed to support good organic tomato yields because of low active and total SOC, low biological activity, and fall manure application that did not match crop uptake timing.

Slides 44-45 – *Tips for limiting N_2O emissions in organic production*

High levels of N mineralization from SOM and low to zero Economic Optimum N Rate (EONR) for corn and fescue in soils with high Soil Test Biological Activity (STBA, Franzluebbers, 2018, Franzluebbers et al., 2018) indicate that organic crops growing in fertile, biologically active soils may need little or no concentrated organic N (feather meal, poultry litter, etc) to achieve satisfactory yields. Cutting back on these inputs will reduce the farm’s GHG footprint, protect water quality, and save money. If the crop receives more N and P than it needs, N_2O emissions rise sharply and the soil’s capacity to provide N through biological mineralization of SOM can diminish, thereby perpetuating dependence on more concentrated N and P sources (Bhowmik et al., 2016, 2017; Davis et al., 2019; Li et al., 2009).

Mycorrhizal fungi can reduce N_2O emissions, but this benefit can be lost if soil test P rises into the “very high” range and inhibits the plant-mycorrhizal symbiosis (Hamel, 2004; Hu et al., 2016).

While cover crops have slight and inconsistent impacts on *direct* N_2O emissions (from the field itself), they reduce *indirect* emissions by recovering nitrate-N from the subsoil (Basche et al., 2014). Deep-rooted crops can scavenge most of the nitrate-N throughout the top 5 -7 feet of the soil profile (Rosolem et al., 2017). Of these, pearl millet, sorghum-sudangrass, and some other crops release natural nitrification inhibitors that further mitigate both leaching and N_2O emissions (ibid.).

The challenge for organic producers is to find the “sweet spot” between too little N (crop deficiency and yield reduction) and too much N (increased N_2O emissions and compromised soil microbial functions). Using concentrated N in small, weekly, within-row doses (e.g. via drip fertigation) when crops need a boost (a few lb/week, total 20 -50 lb/ac for a cropping cycle) shows promise as a win-win strategy. Some of the “tightly coupled N cycling” sites in the tomato study used Chilean sodium nitrate, the one form of soluble N allowed under the National

Organic Program (maximum 20% of total crop N requirement) to provide this within-row weekly N boost.

Researchers are developing practical tools to help organic farmers discern whether and how much applied N their crops are likely to need. Scientists at Pennsylvania State University and farmers in the Pasa Sustainable Farming network have developed a decision support tool that estimates how much N the soil will release to an organic corn crop, based on soil texture, soil organic matter, and the biomass, species composition, and C:N ratio of the preceding cover crop (). While the STBA (3 day soil respiration test) has not yet been released for widespread routine soil testing, findings to date indicate that even heavy N feeders may not need applied N fertilizer on healthy soils under best management, especially in warmer climates of the southern half of the US. The NRCS Comet Planner tool estimates that replacing all applied N with soil-derived N can reduce N_2O emissions equivalent to 1,080 lb C/ac-year, compared to just 120 lb C/ac-year for implementation of the general criteria for CPS 590 Nutrient Management.

Slide 46 – *Climate impacts of livestock production*

In anaerobic conditions such as within the rumen of ruminant animals, certain microbes called *methanogens* convert organic carbon into CH_4, which then escapes to the atmosphere. Dairy cattle have been estimated to release 450 – 570 lb enteric CH_4 per animal annually, equivalent in global warming potential (GWP) to a loss of 2560 – 3270 lb C as CO_2.

Pastured livestock can emit more enteric CH_4 than grainfed, since a 100% grass diet is often higher in fiber and lower in protein than diets that include grains and high-protein concentrates. One study found organic 100% grassfed dairy cattle emitted about 30% more CH_4 per animal than grainfed animals (Richard and Camargo, 2011)

Pastures can develop N_2O "hotspots" in areas of high stocking density and soil compaction (e.g. a watering area or shady spot in a continuously grazed pasture, where cattle congregate) (Luo et al., 2017). Management intensive rotational grazing (MIG) systems that move cattle to new paddocks every 12-72 hours can improve manure distribution and minimize N_2O hotspots.

Slide 47 – *Climate-friendly livestock production*

When Richard and Camargo (2011) re-estimated the *total* GHG footprint for different dairy production systems, assuming that well-managed pasture sequesters 890 lb C/ac-yr, the 100% grassfed organic milk GHG footprint decreased to only 80% that of conventional confinement dairy milk.

Rotational grazing under regionally tailored best management can further enhance SOC sequestration and forage quality (Beetz and Rinehart, 2010). The SOC sequestration (~1 ton C/ac-yr) and enteric CH_4 reductions (30%) from switching from a continuous grazing system to a

MIG rotational grazing system were equally evident in studies in Michigan and Texas and rendered livestock production net GHG-mitigating (Stanley et al., 2018; Wang et al., 2015).

Slide 48 – *Recent research findings on farming practices and climate* – subtitle slide.

Slide 49 – *Agroforestry: #1 climate mitigation strategy*

Riparian forest buffers, alley cropping, and other agroforestry practices provide many ecosystem services including greatly enhanced carbon sequestration and nutrient cycling and preventing soil erosion, and have been recommended as a leading GHG mitigation strategy (Ogg, 2022; Udawatta and Galtzer, 2022).

Recent research findings confirm that perennial cover sequesters far more SOC and greatly reduces N leaching compared to annual crop rotations. In North Carolina, the "root zone enrichment of SOC" (attributed to plant biomass as determined by land use and management) increased from about 5 tons/ac under tilled annual rotation to 9.5 tons/ac for no-till and 17 tons/ac for woodland (Franzluebbers, 2023). In the Midwest, N leaching under perennial vegetation was reduced by some 85% compared to fertilized annual crops (Shrestha et al., 2023). Woody perennial plantings implemented under the Conservation Reserve Program (CRP) have been estimated to sequester three to >10 times as much carbon as practices such as cover cropping, conservation rotation, and conservation tillage (Moore et al, 2023).

Conversely, the conversion of expiring CRP acreage back to annual crop production causes an increase in microbial respiration per unit microbial biomass and a rapid loss of SOC, leading to a strong recommendation that CRP acres remain in perennial vegetation whenever possible (Li et al., 2022). In South Asia, deforestation of the Himalayan foothills has left the Indo-Gangetic Plains (home to 900 million people and one of the most intensively farmed regions of the world) especially vulnerable to extremes of drought and flood, now intensified by climate change (Lal, 2022). Reforestation of the Himalayan foothills is urgently recommended to rebuild SOC stocks (sequestering carbon) and make the entire region more resilient to the impacts of climate change.

NOP standards require organic producers to protect the natural resources of their operations, including soil, water, wetlands, woodlands, and wildlife. Thus, perennial crops, perennial conservation buffers, and natural areas with woody perennial vegetation commonly play a significant role in organic farming systems, where they provide additional ecosystem services such as habitat for natural enemies of crop pests.

Slide 50 – *The dryland SOC challenge.*

Dryland grain farmers face a tough tradeoff between maintaining living cover and living roots to build SOC and ensuring sufficient moisture for their cereal grain cash crop. In regions with very low annual rainfall (~10-15 inches), the standard practice has become a two-year wheat-fallow system, which aims to store two year's rainfall for one grain crop. However, even under no-till management, the wheat-fallow system depletes SOC, whereas growing a cover crop, oilseed, or pulse in lieu of fallow gradually builds SOC (Halvorson et al., 2002: West and Post, 2002). Producers must choose a low water use, short season crop, and terminate cover crops sufficiently early to avoid soil moisture depletion that can threaten the next year's wheat yields. Thus, options for SOC sequestration appear limited.

Slide 51 – *Compost builds dryland soil carbon and fertility.*

Compost can play a vital role in building SOC and sustaining yield in semiarid regions by stimulating plant growth and hence organic carbon inputs to the soil. Researchers at Utah State University found that a single application of composted beef manure + bedding at 22 tons/ac can double topsoil SOC levels and dryland wheat yields for at least 15 years, with substantial benefits continuing for 26 years and counting (Reeve and Creech, 2015; Reeve et al., 2022). During 2020-22, extreme heat and drought related to climate change severely impacted field trials, yet one-time 22 t/ac compost applications one to five years prior to the extreme weather events improved crop resilience to the drought and enhanced SOC and soil structure to a depth of 35 inches. Apparently, the compost promoted crop growth and root development, which, in turn, built SOC throughout the rooting depth and, of course, improved yields.

Similarly, a review of 27 studies (7 in the US and 20 abroad) on one-time compost applications to rangeland showed a 50% increase in SOC and 42% greater aggregate stability and 18% higher water retention related to enhanced vegetative growth that also improved forage production by 40% (Kutos et al., 2023).

Slide 52 – *Mitigating N_2O emissions with biochar and crop choices*.

In a review of global meta-analyses on soil N dynamics and management, Young et al (2022) found that biochar applications can improve crop yields, build SOC, and reduce N_2O emissions by 40%. Combining reduced fertilizer N use (70% of recommended rates), straw return, and biochar application reduced N_2O and overall GHG footprint of wheat-maize production in a semiarid region of China (Bai et al., 2023).

Currently, woody biomass that is removed from forests to reduce wildfire risk (fuel reduction) and logging slash are simply piled and burned, releasing smoke and CO_2. Instead, these woody residues can and should be converted to biochar and used to enhance SOC sequestration and mitigate soil N_2O emissions (Franco et al., 2022).

Biochar should be considered one component of the soil health and GHG mitigation system, and not as a stand-alone "silver bullet." For example, a review found that biochar by itself may not prevent soil erosion nor improve soil water holding capacity, though it can enhance SOC and fertility in sandy or depleted soils (Blanco-Canqui, 2022). The new Conservation Practice Standard 336 Soil Carbon Amendment emphasizes finished compost and biochar as amendments. Using the two amendments together and in conjunction with other soil health practices, especially cover crops and crop rotations that enhance living root, cover, and diversity may yield the greatest benefit. Additional research is needed to verify the benefits of biochar in minimizing N_2O emissions within the context of an integrated soil health program in organic production systems.

In a surprising result that merits further investigation, Liu et al. (2023) reported that a maize-garlic rotation reduced soil N_2O emissions about 40% compared to a maize-wheat rotation, and that the garlic appeared to reduce soil soluble N levels by releasing a natural urease inhibitor. Sorghum releases biological nitrification inhibitors (BNIs) that can reduce formation and emission of N_2O an effect which seems beneficial when sorghum and corn are intercropped, yielding a land equivalency ratio greater than 1.0 (Zhang et al., 2023).

Slide 53 – Avoiding chemicals may protect SOC and reduce GHG

Recent studies and literature reviews have shown that agricultural chemicals, especially insecticides, fungicides, nematicides, and herbicides, have significant adverse impacts on nearly all classes of soil micro- and marcro-organisms (Gunstone et al., 2021; Klein, 2019; Pelosi et al., 2014). Pesticide impacts on soil bacterial, fungal, nematode, and earthworm communities may be greater than those of tillage (Pelosi et al., 2014; Puissant et al, 2021; Vahter et al., 2022; Walder et al., 2022). Glyphosate herbicide used at normal rates have been shown to reduce arbuscular mycorrhizal fungal (AMF) colonization of crop roots, a symbiosis that can play an important role in SOC sequestration (Druille et al., 2013). Lettuce and carrot under organic management host more beneficial microbes that confer resilience to crop pathogens and other stresses than the same crops under conventional management (Abdelrazek, 2018; Abdelrazek and Hoagland, 2017; Ariena et al., 2015).

Studies investigating impacts of agrochemicals on soil carbon sequestration and agricultural GHG emissions are few thus far; however the commonly used soil fumigant chloropicrin has been shown to increase soil N_2O emissions by up to seven-fold (Spokas and Wang, 2003). Although this fumigant is generally thought to be short-lived in the soil, its effects on soil microbiota that mediate N_2O formation may persist up to 48 days after application (Spokas et al., 2005). Since the soil biotic community plays a central role in the processing of root exudates and organic residues into MAOC, impacts of conventional agrochemicals at normal field use rates on SOC sequestration and agricultural resilience merits further study.

Slide 54 – *Does soluble N build or "burn up" SOC?*

Debates over the soil health benefits and costs of soluble N fertilizer center on two divergent hypotheses: that best use of conventional fertilizers support SOC sequestration by stimulating crop growth and thereby root exudation, residue production, and ultimately SOC accrual; and that soluble fertilizers harm soil microbes or alter microbial community function in ways that interfere with formation of stable SOC. Citing a lack of evidence from the nation's longest running cropping systems experiment – the University of Illinois Morrow Plots – that the soluble fertilizer treatments build SOC, Khan et al. (2007) rejected the first hypothesis and conducted a review of over 60 other farming systems trials worldwide, which yielded equivocal results on the relationship between synthetic N and SOC.

More rigorous meta-analyses indicate that either organic N sources or a combination of organic and soluble N enhance SOC accrual over soluble fertilizers alone (Young et al., 2022). This suggests that the main problem with soluble N fertilizers is not what they contain (nitrate and ammonium-N, which are also gradually released from organic nutrient sources and SOM itself) but in what they lack: organic carbon. The balance between carbon and nitrogen appears critical, as SOC can be consumed and N_2O emitted whenever an overabundance of soluble N from any source is present – poultry litter, legume plowdown, or inorganic N fertilizer. Maintaining that balance is essential for soil health, SOC sequestration, and GHG mitigation in any farming system, organic or otherwise.

Slide 55 – Questions?

Thank you for participating in this webinar series. I hope you enjoyed it and found it useful.

Can you explain how the photo on the right-hand panel of this slide came about? Stumped? Contact: schonbeckmark@gmail.com.

References

Abdelrazek, Sahir. 2018. Carrot Endophytes: Diversity, Ecology and Function. PhD Thesis, Purdue University. https://docs.lib.purdue.edu/dissertations/.

Abdelrazek, S., and L. A. Hoagland. 2017. Potential functional role of carrot endophyte communities. Tri-Societies Meetings, Tampa, FL, October, 2017.

Ariena H. C. van Bruggen, Isolde M. Francis, and Randy Krag. 2015. *The vicious cycle of lettuce corky root disease: effects of farming system, nitrogen fertilizer and herbicide*. Plant and Soil 388 (1-2): 119-132.

Bai, J., et al., 2023. *Biochar combined with N fertilization and straw return in wheat-maize agroecosystem: Key practices to enhance crop yields and minimize carbon and nitrogen footprints*. Agriculture, Ecosystems, and Environment 347: article 108366.

Baas, D. G., G. P. Robertson, S. R. Miller, N. and Millar, N. 2015. *Effects of Cover Crops on Nitrous Oxide Emissions, Nitrogen Availability, and Carbon Accumulation in Organic versus Conventionally Managed System*s. Final report for ORG project 2011-51106-31046.

Balaine, N., T. J. Clough, M. H. Beare, S. M Thomas, and E. D. Meenken. 2016. *Soil Gas Diffusivity Controls N_2O and N_2 Emissions and their Ratio*. Soil Science Society of America Journal, 80 (3): 529-540.

Basche, A.D., F.E. Miguez, T.C. Kaspar, and M.J. Castellano. 2014. *Do cover crops increase or decrease nitrous oxide emissions? A meta-analysis.* J. Soil Water Conserv. 69(6): 471–482.

Beetz, A., and L. Rinehart. 2010. *Rotational Grazing.* National Center for Appropriate Technology, ATTRA bulletin, 12 pp. https://attra.ncat.org.

Bhowmik, A. A-M. Fortuna, L. J. Cihacek, A. Bary, P. M. Carr, and C. G. Cogger. 2017. *Potential carbon sequestration and nitrogen cycling in long-term organic management systems.* Renewable Agriculture and Food Systems, 32 (6): 498-510.

Bhowmik, A., A. Fortuna, L. J.Cihacek, A. I.Bary, and C. G.Cogger. 2016. *Use of biological indicators of soil health to estimate reactive nitrogen dynamics in long-term organic vegetable and pasture systems*. Soil Biology and Biochemistry 103: 308-319.

Biardeau, Léopold, Rebecca Crebbin-Coates, Ritt Keerati, Sara Litke, and Hortencia Rodríguez. 2016. Soil Health and Carbon Sequestration in US Croplands: A Policy Analysis. Goldman School of Public Policy, University of California Berkeley. https://food.berkeley.edu/wp-content/uploads/2016/05/GSPPCarbon_03052016_FINAL.pdf.

Blanco-Canqui, H. 2022. *Does biochar conserve soil and water?* J Soil and Water Conservation 77(6): 79A-84A.

Bowles, T. M., A. D. Hollander, K. Steenwerth, and L. E. Jackson. 2015. *Tightly-coupled plant-soil nitrogen cycling: comparison of organic farms across an agricultural landscape*. PLOS ONE http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0131888.

Bowles, T,. M., et al. 2020. Long-Term Evidence Shows that Crop-Rotation Diversification Increases Agricultural Resilience to Adverse Growing Conditions in North America. One Earth 2, 284–293. https://doi.org/10.1016/j.oneear.2020.02.007.

Brown, G. 2018. *Dirt to Soil: One Family's Journey into Regenerative Agriculture.* Chelsea Green Publishing, White Junction, VT. 223 pp.

Byrnes, R.C., D.J. Eastburn, K.W. Tate, and L.M. Roche. 2018. *A global metaanalysis of grazing impacts on soil health indicators*. Journal of Environmental Quality 47(4):758–765.

Carpenter-Boggs, L., D. Granatstein, and D. Huggins. 2010. *Greenhouse Gases and Agriculture: Where does Organic Farming Fit* (Webinar). https://eorganic.org/node/5617.

Cai, Z., S. Gao, A. Hendratna, Y. Duan, M. Xu, and B. D. Hanson. 2016. *Key Factors, Soil Nitrogen Processes, and Nitrite Accumulation Affecting Nitrous Oxide Emissions.* Soil Science Society of America Journal 80 (6): 1560-1571.

Cavigelli, M. A., J. R. Teasdale, and J. T. Spargo. 2013. *Increasing Crop Rotation Diversity Improves Agronomic, Economic, and Environmental Performance of Organic Grain Cropping Systems at the USDA ARS Beltsville Farming Systems Project*. Crop Management 12(1) Symposium Proceedings: USDA Organic Farming Systems Research Conference. https://dl.sciencesocieties.org/publications/cm/tocs/12/1.

Charles, A., P. Rochette, J. K. Whalen, D. A. Angers, M. H. Chantigny, and N. Bertrand. 2017. *Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis*. Agriculture, Ecosystems and Environment 236: 88-98.

Chambers, A., R. Lal, and K. Paustian. 2016. *Soil carbon sequestration potential of U.S. croplands and grasslands: implementing the 4 per Thousand Initiative.* J. Soil & Water Conserv. 71(3): 68A-74A.

Chen, X, J. Lin, K. Tan, Y, Pei, and X. Wang. 2023. Cooperation between specialized cropping and livestock farms at local level reduces carbon footprint of agricultural system: A case study of recoupling maize-cow system in South China. Agriculture, Ecosystems, and Environment 348, Article 108406.

Cogger, C. G. M. Ostrom, K. Painter, A. Kennedy, A. Fortuna, R. Alldredge, A.; Bary, T. Miller, D. Collins, J. Goldberger, A. Antonelli, and B. Cha. 2013. *Designing Production Strategies for Stewardship and Profits On Fresh Market Organic Farms*. Final report for OREI award 2008-51300-04460.*

Crystal-Ornelas, R., R. Thapa , and K. L. Tully, 2021. *Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: A meta-analysis*. Agriculture, Ecosystems, and Environment 312 (2021) 107356.

Davis, B. W., S. B. Mirsky, B. A. Needelman, M. A. Cavigelli, and S. A. Yarwooda. 2019. *Nitrous oxide emissions increase exponentially with organic N rate from cover crops and applied poultry litter*. Agriculture, Ecosystems and Environment 272 (2019) 165–174.

Delate, K., C. Cambardella, and C. Chase. 2015a. *Effects of cover crops, soil amendments, and reduced tillage on Carbon Sequestration and Soil Health in a Long Term Vegetable System.* Final report for ORG award 2010-51106-21857.*

Delate, K., C. Cambardella, C. Chase, and R. Turnbull. 2015b. *A review of long term organic comparison trials in the US.* Sustainable Agricultural Research 4(3): 5-14.

Druille M, Cabello MN, Omacini M, Golluscio RA. 2013. *Glyphosate reduces spore viability and root colonization of arbuscular mycorrhizal fungi*. Applied Soil Ecology 64:99–103. https://doi.org/10.1016/j.apsoil.2012.10.007.

Dynarski, K. A., D. A., Bossio, and K. Scow. 2020. *Dynamic stability of soil carbon: reassessing the "permanence" of soil carbon sequestration*. Frontiers in Environmental Science. Vol 8 (November 2020). https://doi.org/10.3389/fenvs.2020.514701.

Eagle, A. J., L. P. Oander, K. L. Locklier,J. B. Heffernan, and E. S. Bernhardt. 2017. *Fertilizer Management and Environmental Factors Drive N2O and NO3 Losses in Corn: A Meta-Analysis.* Soil Sci. Soc. Am. J. 81 (5): 1191-1202.

Egan, F., and S. B. Nawa. 2021. *Soil Health Benchmarks 2021 Report*. Pasa Sustainable Agriculture. 48 pp.

Feliciano, D., A. Ledo, J. Hillier, and D. R. Nayak. 2018. *Which agroforestry options give the greatest soil and above ground carbon benefits in different world regions?* Agriculture, Ecosystems, and Environment 254: 117-129.

Franco, C. R., D. S. Page-Dumroese, and J. Archuleta. 2022. *Forest management and biochar for continued ecosystem services*. J. Soil and Water Conservation 77(4): 60A-64A.

Franzluebbers, A. J. 2018. *Soil-Test Biological Activity with the Flush of CO2: III. Corn Yield Responses to Applied Nitrogen*. Soil Science Society of America Journal, Volume 82, Issue 3, https://doi.org/10.2136/sssaj2018.01.0029.

Franzluebbers, A. J. 2023. *Soil organic carbon and nitrogen storage estimated with the root-zone enrichment method under conventional and conservation land management across North Carolina.* Journal of Soil and Water Conservation 78(2): 124-140.

Franzluebbers, A. J., S. Pehim-Limbu, and M. H. Poore. 2018a. *Soil-Test Biological Activity with the Flush of CO2: IV. Fall-Stockpiled Tall Fescue Yield Response to Applied Nitrogen*. Agronomy Journal, Volume 110, Issue 5, https://doi.org/10.2134/agronj2018.03.0146.

Gattinger, A., A. Muller, M. Haeni, C. Skinner, A. Fliessbach, N. Buchmann, P. Mader, M. Stolze, P. Smith, N. E. Scialabba,and U. Niggli. 2012. *Enhanced topsoil carbon stocks under organic farming*. Proceedings of the National Academy of Sciences 109 (44) 18826-18231.

Ghabbour, E. A., G. Davies, T. Misiewicz, R. A. Alami, E. M. Askounis, N. P. Cuozzo, A. J. Filice, J. M. Haskell, A. K. Moy, A. C. Roach, and J. Shade. 2017. *National Comparison of the Total and Sequestered Organic Matter Contents of Conventional and Organic Farm Soils*. Advances in Agronomy 146: 1-35.

Grandy, S., and C. Kallenbach. 2015. *Microbes drive soil organic matter accumulation in organic cropping systems*. Recording from the Organic Agriculture Research Symposium, LaCrosse, WI February 25-26, 2015, http://eorganic.info/node/12972.

Grandy, A.S., G.P. Robertson, and K.D. Thelen. 2006. *Do Productivity and Environmental Tradeoffs Justify Periodically Cultivating No-till Cropping Systems?* Agronomy Journal, 98(6): 1377-1383.

Gunstone, T., T. Cornelisse, K. Klein, A. Dubey, and N. Donley. 2021. *Pesticides and soil invertebrates: a hazard assessment.* Frontiers in Environmental Science 04 May, 2021. https://doi.org/10.3389/fenvs.2021.643847.

Halvorson, A.D., B.J. Wienhold, and A.L. Black. 2002. *Tillage, nitrogen, and cropping system effects on soil carbon sequestration*. Soil Sci. Soc. Am. J. 66(3): 906–912.

Hamel, C. 2004. *Impact of arbuscular mycorrhizal fungi on N and P cycling in the root zon*e. Can J Soil Sci. 84(4):383-395.

Han, Z., M. T. Walter, and L. E. Drinkwater. 2017. *Impact of cover cropping and landscape positions on nitrous oxide emissions in northeastern US agroecosystems*. Agriculture, Ecosystems and Environment, 245: 124-134.

Hooks, C. R., K. H. Wang, G. Brust, and S. Mathew. 2015. *Using Winter Cover Crops to Enhance the Organic Vegetable Industry in the Mid-Atlantic Region.* Final report for OREI award 2010-51300-21412.*

Howard, Sir Albert. 1947. *The Soil and Health: a Study of Organic Agriculture.*

Hu, Q., et al., 2023. *Soil organic carbon fractions in response to soil, environmental and agronomic factors under cover cropping systems: A global meta-analysis*. Agriculture, Ecosystems, and Environment 355, Article 108591.

Hu, S., C. Reberg-Horton, M. Schroeder-Moreno, Y. Cardoza, J. Grossman, W. Robarge, and W. Eveman. 2016. *Assessing the Greenhouse Gas Mitigation Potential of Organic Systems in the Southeast.* Progress report for ORG award 2012-51106-20332.*

Hurisso, T. T., S. W. Culman, W. R. Horwath, J. Wade, D. Cass, J. W. Beniston, t. M. Bowles, A. S. Grandy, A. J. Franzluebbers, M. E. Schipanski, S. T. Lucas, and C. M. Ugarte. 2016. *Comparison of Permanganate-Oxidizable Carbon and Mineralizable Carbon for Assessment of Organic Matter Stabilization and Mineralization.* Soil Sci. Soc. Am. J. 80 (5): 1352-1364.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Mitigation of Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 11 Agriculture, Forestry, and Other Land Use (AFOLU), and Annex II Metrics and Methodology. Available at: https://www.ipcc.ch/report/ar5/wg3/.

Jackson, L. and T. Bowles. 2013. *Researcher and Farmer Innovation to Increase Nitrogen Cycling on Organic Farms* (Webinar). http://articles.extension.org/pages/67391/researcher-and-farmer-innovation-to-increase-nitrogen-cycling-on-organic-farms-webinar.

Kallenbach, C. M., S. D. Frey, and A. S. Grandy. 2016. *Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls*. Nature Communications, 7, Article number: 3630. https://www.osti.gov/pages/servlets/purl/1363941.

Kane, D. 2015. *Carbon sequestration potential on agricultural lands: a review of current science and available practices*. Breakthrough Strategies and Solutions. National Sustainable Agriculture Coalition. 35 pp. available at: https://sustainableagriculture.net/wp-content/uploads/2015/12/Soil_C_review_Kane_Dec_4-final-v4.pdf.

Kelly, L., and E. Kebreab. 2023. *Recent advances in feed additives with the potential to mitigate enteric methane emissions from ruminant livestock.* J. Soil and Water Conservation 78 (2): 111-123.

Khan, S. A., R. L. Mulvaney, T. R. Ellsworth, and C. W. Boast. 2007. *The myth of nitrogen fertilization for soil carbon sequestration.* J. Environ. Qual. 36:1821‑1832.

Klein, K. 2019. *Pesticides and Soil Health*. Friends of the Earth, 9 pp.

Kloot, Robin. 2018. *Using adaptive nutrient management to answer "how much fertilizer do you actually need?"* NRCS webinar May 8, 2018. Science and Technology Training Library, http://www.conservationwebinars.net/listArchivedWebinars.

Kutos, S., E. Stricker, A. Cooper, R. Ryals, J. Creque, M. Machmuller, M. Kroegar, and W. L. Silver. 2023. *Compost amendment to enhance carbon sequestration in rangelands.* Journal of Soil and Water Conservation 78(2): 163-177.

Lal, R. 2003. *Soil erosion and the global carbon budget*. Environment International 29:437-450.

Lal, R. 2015. *Cover cropping and the "4 per thousand" proposal*. J. Soil and Water Conservation 70(6): 141A.

Lal, R. 2022. *The flood-drought syndrome and ecological degradation of the Indo-Gangetic Plains of South Asia.* J Soil and Water Conservation 77(6): 85A-90A.

Lal, R., P. Smith, H. F. Jungkunst, W. J. Mitsch, J. Lehmann, P. K. R. Nair, A. B. McBratney, J. C. de Moraes Sa., J. Schneider, Y. L. Zinn, A. L. A. Skorupa, H. Zhang, B. Minasny, C. Srinivasrao, and N. H. Ravindranath. 2018. *The carbon sequestration potential of terrestrial ecosystems*. J. Soil and Water Conservation 73(6): 145A-152A.

Lehman, R. M., S. L. Osborne, and S. E. Duke. 2017. *Diversified No-Till Crop Rotation Reduces Nitrous Oxide Emissions, Increases Soybean Yields, and Promotes Soil Carbon Accrual*. Soil Sci. Soc. Am. J. 81(1): 76-83.

Lehmann, J., and M. Kleber. 2015. *The Contentious Nature of Soil Organic Matter*. Nature 528:60-68.

Li, C., J. M. Moore, V. Ascosta-Martinez, L. M. Fultz, and M, Kakarla. 2022. *Conversion of Conservation Reserve Program land back to cropland: changes in soil carbon and nitrogen dynamics during the first five years.* J. Soil and Water Conservation 77(4): 333-346.

Li, C., Salas, W. and Muramoto, J. 2009. *Process Based Models for Optimizing N Management in California Cropping Systems: Application of DNDC Model for nutrient management for organic broccoli production*. Conference proceedings 2009 California Soil and Plant Conference, 92-98. Feb. 2009. http://ucanr.edu/sites/calasa/files/319.pdf.

Lin, Y., D. B. Watts, and G. B. Runion. 2022. *Influence of poultry litter on nutrient availability and fate in plant-soil systems: a meta-analysis.* J. Soil and Water Conservation 77(3): 230-239.

Liu, D. et al., 2023. *Inhibiting N_2O emissions and improving environmental benefits by integrating garlic growing in grain production systems*. Agriculture, Ecosystems, and Environment 347, article 108371.

Lori, M., S. Symnaczik, P. MaEder, G. De Deyn, A. Gattinger. 2017. *Organic farming enhances soil microbial abundance and activity – A meta-analysis and meta-regression*. PLOS ONE | https://doi.org/10.1371/journal.pone.0180442. July 12, 2017, 25 pp.

Luo, J. J. Wyatt, T. J. van der Weerden, S. M. Thomas, C. A.M. de Klein, Y. Li., M. Rollo, S. Lindsey, S. F. Ledgard, J. Li, W. Ding, S. Qin, N. Zhang, N. Bolan, M.B. Kirkham, Z. Bai, L. Ma, X. Zhang, H. Wang, H. Liu, G. Rys, *et al.,* 2017. *Potential Hotspot Areas of Nitrous Oxide Emissions From Grazed Pastoral Dairy Farm Systems.* Advances in Agronomy 145: 205-268.

Machmuller, M. B., M. G. Kramer, T. K. Cyle, N. Hill, D. Hancock, and A. Thompson. 2015. *Emerging land use practices rapidly increase soil organic matter*. Nat. Commun. 6:6995. doi:10.1038/ncomms7995.

Millar, N., G.P. Robertson, P.R. Grace, R.J. Gehl, and J.P. Hoben. 2010. *Nitrogen fertilizer management for nitrous oxide (N2O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for U.S. Midwest agriculture*. Mitig. Adapt. Strateg. Glob. Change 15(2): 185–204.

Moncada, K, and C. Sheaffer. 2010. *Risk Management Guide for Organic Producers.* University of Minnesota Extension, 300 pp. http://organicriskmanagement.umn.edu/.

Mondal, S., D. Chakraborty, R. K. Paul, A. Mondal, and J. Ladha. 2023. *No-till is more of sustaining the soil than a climate change mitigation option*. Agriculture, Ecosystems, and Environment 352, Article 108498.

Moore, J. M., D. K, Manter, M. Bowman, M. Hunder, E. Bruner, and S.C. McClelland. 2023. *A framework to estimate climate mitigation potential for US cropland using publicly available data.* Journal of Soil and Water Conservation 78(2): 193-206.

Mosier, S., S. Apfelbaum, P. Byck, F. Calderon, R. Teague, R. Thompson, and M.F. Cotrufo. 2021. *Adaptive multi-paddock grazing enhances soil carbon and nitrogen stocks and stabilization through mineral association in southeastern U.S. grazing lands*. Journal of Environmental Management 288:112409.

Morugán-Coronado, A., P. Pérez-Rodríguez, E. Insolia, D. Soto-Gómez, D. Fernández-Calvino, and R. Zornoza. 2022. *The impact of crop diversification, tillage and fertilization type on soil total microbial, fungal and bacterial abundance: A worldwide meta-analysis of agricultural sites*. Agriculture, Ecosystems, and Environment 329, Article 107867, May 2022 (posted online in January, 2022).

Ogg, C. 2022. *Conservation programs to reduce greenhouse gases.* J. Soil and Water Conservation 77(2): 30A-32A.

Pelosi, C., Barot, S., Capowiez, Y., Hedde, M. and Vandenbulcke, F., 2014. *Pesticides and earthworms.* A review. Agronomy for Sustainable Development, 34(1), pp.199-228.

Prescott, C. E., Yi. Rui, M. F. Cotrufo, and S. J. Grayston. 2021. *Managing plant surplus carbon to generate soil organic matter in regenerative agriculture*. J. Soil & Water Conservation 76(6): 99A-104A.

Puissant, J., C. Villenave, C. Chauvin, C. Plassard, E. Blanchart, and J.Trap. 2021. *Quantification of the global impact of agricultural practices on soil nematodes: A meta-analysis.* Soil Biology and Biochemistry Volume 161, October 2021, 108383.

Reeve, J., and E. Creech. 2015. *Compost Carryover Effects on Soil Quality and Productivity in Organic Dryland Wheat*. https://eorganic.org/node/14629.

Reeve, J. R., P. M. Carr, J. B. Norton, A. R. Jacobson, U. Norton, I. C. Burke, I. M. Kim, K. Curtis, R. Larsen, M. Yost, T. R. Fortenbery, J. E. Creech, and C. A. Eberle. 2022. *From compost carryover to compost legacy: intercropping and compost effects on yield, quality, and soil health in organic dryland wheat*. OREI award 2019-51300-30476.*

Richard, T., and G. Camargo. 2011. *Greenhouse Gas Emissions Associated with Dairy Farming Systems*. https://eorganic.org/node/5737.

Rodale Institute, 2014. Regenerative Organic Agriculture and Climate Change: A Down-to-Earth Solution to Global Warming. https://rodaleinstitute.org, 16 pp.

Rodale Institute, 2015. Farming Systems Trial Brochure, 2 pp. https://rodaleinstitute.org/assets/FST-Brochure-2015.pdf.

Rosolem, C. A., K. Ritz, H. Cantarella, M. V. Galdos, M. J. Hawkesford, W. R. Whalley, and S. J. Mooney. 2017. *Enhanced plant rooting and crop system management for improved N use efficiency.* Advances in Agronomy 146: 205-239.

Schonbeck, M., D. Jerkins, and J. Ory. 2017. *Soil Health and Organic Farming: Practical Conservation Tillage.* Organic Farming Research Foundation, https://ofrf.org. 32 pp.

Shrestha, D., K. Masarik, and C. J. Kucharik. 2023. *Nitrate losses from Midwest US agroecosystems: Impacts of varied management and precipitation.* Journal of Soil and Water Conservation 78(2): 141-153.

Skinner, C., A. Gattinger, A. Muller, P. Mader, A. Fliessbach, M. Stolze, R. Ruser, and U. Niggli. 2014. *Greenhouse gas fluxes from agricultural soils under organic and non-organic management—a global meta-analysis*. Sci. Total Environ. 468–469: 553–563.

Snyder, L., M. Schonbeck, T. Velez, and B. Tencer. 2022. *2022 National Organic Research Agenda: Outcomes and Recommendations from the 2020 National Organic & Transitioning Farmer Surveys and Focus Groups*. Organic Farming Research Foundation, https://ofrf.org, 232 pp.

Spokas, K., & Wang, D. (2003). *Stimulation of nitrous oxide production resulted from soil fumigation with chloropicrin*. Atmospheric Environment, 37(25), 3501-3507.

Spokas, K., Wang, D., & Venterea, R. (2005). *Greenhouse gas production and emission from a forest nursery soil following fumigation with chloropicrin and methyl isothiocyanate*. Soil Biology and Biochemistry, 37(3), 475-485.

Stanley, P. L., J. E. Rowntree, D. K. Beede, M. S. DeLonge, and M. W. Hamm. 2018. *Impacts of Soil Carbon Sequestration on Life Cycle Greenhouse Gas Emissions in Midwestern USA Beef Finishing Systems*. Agricultural Systems 162: 249–58. https://doi.org/10.1016/j.agsy.2018.02.003.

Steiner, J. L., X. Lin, N. Cavallaro, G. Basso, and G. Sassenrath. 2023. *Climate change impacts on soil, water, and biodiversity conservation.* Journal of Soil and Water Conservation 78(2): 27A-32A.

Teague, W. R., S. Apfelbaum, R. Lal, U. P. Kreuter,J. Rowntree, C.A. Davies, R. Conser, M. Rasmussen, J. Hatfield, T. Wang, R Wang, and P. Byck. 2016. *The role of ruminants in reducing agriculture's carbon footprint in North America*. J. Soil & Water Conserv. 71(2): 156-164.

Thomas B. W., and X. Hao. 2017. *Nitrous Oxide Emitted from Soil Receiving Anaerobically Digested Solid Cattle Manure*. Journal of Environmental Quality 46 (4): 741-750.

Tiemann, L.K., A.S. Grandy, E.E. Atkinson, E. Marin-Spiotta, and M.D. McDaniel. 2015. *Crop rotational diversity enhances belowground communities and functions in an agroecosystem*. Ecol. Lett. 18(8): 761–771.

Udawatta, R. P., and C. J. Gantzer. 2022. *Soil and water ecosystem services of agroforestry*. J. Soil and Water Conservation 77(1): 5A-11A.

United States Environmental Protection Agency (EPA). 2018. Sources of Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.

United States Environmental Protection Agency (EPA). 2021. Inventory of U.S. Greenhouse Gas Emissions, 1990-2019. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019.

Vahter, T., S-K Sepp, A. Astover, A. Helm, T. Kikas, S. Liu, J. Oja, M. Öpik, P. Penu, M. Vasar, E. Veromann, M. Zobel, and I. Hiiesalu. 2022. *Landscapes, management practices and their* *interactions shape soil fungal diversity in arable fields – Evidence from a nationwide farmers' network*. Soil Biology and Biochemistry, Volume 168, May 2022, 108652.

Walder, F., M. W. Schmid, J. Riedo, A. Y. Valzano-Held, S. Banerjee, L. Büchi, T. D. Bucheli, and M. G.A.van der Heijden. 2022. *Soil microbiome signatures are associated with pesticide residues in arable landscapes*. Soil Biology and Biochemistry, Vol. 174, November, 2022.

Wander, M. M., S. J. Traina, B. R. Stinner, and S. E. Peters. 1994. *Organic and Conventional Management Effects on Biologically Active Soil Organic Matter Pools*. Soil Sci. Soc. Am. J. 58:1130-1139.

Wang, T., W. R. Teague, S. C. Park, and S. Bevers. 2015. *GHG mitigation and profitability potential of different grazing systems in Southern great plain*. Sustainability 7:13500–13521.

Weil R. R., and N. C. Brady. 2017. *The Nature and Properties of Soils*. 15th Edition.

West, T.O., and W.M. Post. 2002. *Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis*. Soil Sci. Soc. Am. J. 66(6): 1930–1946.

Wooliver, R., and S. Jagadamma. 2023. *Response of soil organic carbon fractions to cover cropping: A meta-analysis of agroecosystems C*. Agriculture, Ecosystems, and Environment 351, Article 108497

Young, M. D., G. H. Ros, and W. de Vries. 2022. *Impacts of agronomic measures on crop, soil, and environmental indicators: A review and synthesis of meta-analysis*. Agriculture, Ecosystems, and Environment 319. https://doi.org/10.1016/j.agee.2021.107551.

Zhang, M., et al., 2023. *Intercropping with BNI-sorghum benefits neighbouring maize productivity and mitigates soil nitrification and N_2O emission*. Agriculture, Ecosystems, and Environment 352, Article 108510.

Zheng, F., et al., 2023. Positive effects of crop rotation on soil aggregation and associated organic carbon are mainly controlled by climate and initial soil carbon content: A meta-analysis. Agriculture, Ecosystems, and Environment 355, Article 108600.

* Proposal summaries, progress and final reports for OREI and ORG projects available at https://nifa.usda.gov/data/data-gateway.