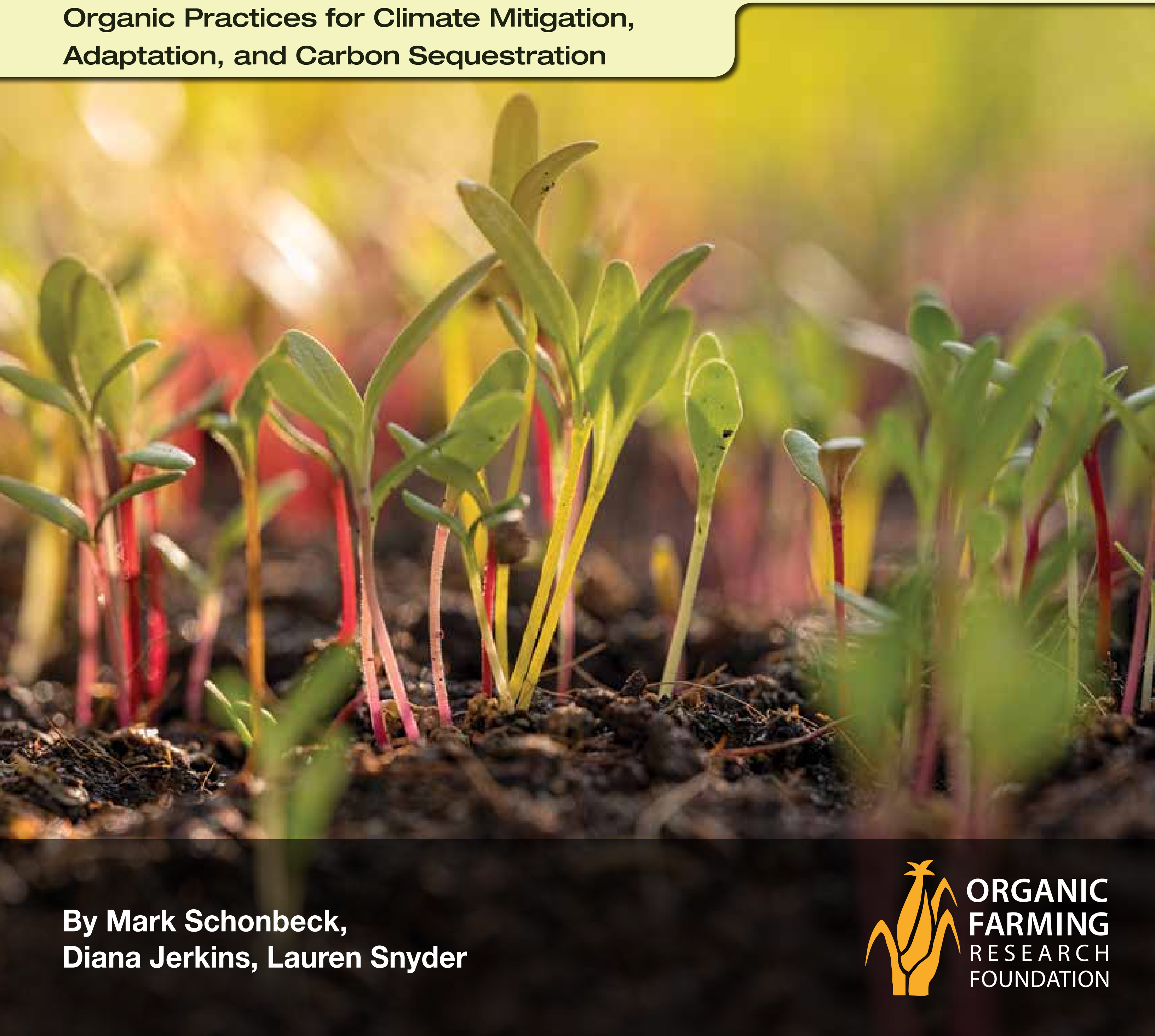
Soil Health and Organic Farming

Organic Practices for Climate Mitigation, Adaptation, and Carbon Sequestration



By Mark Schonbeck,
Diana Jerkins, Lauren Snyder

ORGANIC FARMING RESEARCH FOUNDATION

SOIL HEALTH AND ORGANIC FARMING

ORGANIC PRACTICES FOR CLIMATE MITIGATION, ADAPTATION, AND CARBON SEQUESTRATION

An Analysis of USDA Organic Research and Extension Initiative (OREI) and Organic Transitions (ORG) Funded Research from 2002-2016

Thank you to

National Co+op Grocers

for supporting this project.

ORGANIC FARMING RESEARCH FOUNDATION

Table of Contents

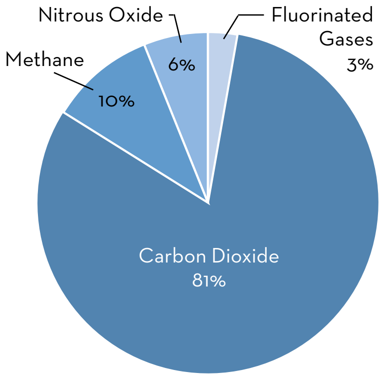
Introduction:

Climate change threatens agriculture and food security across the U.S. and around the world. Rising global mean temperatures have already intensified droughts, heat waves, and storms, and altered life cycles and geographical ranges of pests, weeds, and pathogens, making crop and livestock production more difficult. Intense rainstorms aggravate soil erosion and complicate water management, and higher temperatures accelerate oxidation of soil organic matter. Warming climates modify crop development regulated by growing degree-days or "chill hours," and threaten production of perennial fruit and nut crops that have strict chilling requirements to initiate growth and fruit set. Thus, agricultural producers have a major stake in efforts to curb further climate change, as well as improving the resilience of their farming and ranching systems to the impacts of climate disruption.

Today's climate changes are driven largely by three greenhouse gases (GHG): carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). Prior to the industrial era, the world's vegetation, soil life, and fauna mediated a vitally important balance between emissions and uptake of atmospheric CO_2, CH_4, and N_2O. Modern industrial civilization has upset this balance, resulting in a sharp rise in atmospheric concentrations of all three GHG since 1850, leading to the onset of global climate change in the late 20th century. Agricultural activities affect climate through direct GHG emissions and impacts on the soil and plant biomass components of the global carbon (C) cycle (Cogger et al., 2014; Harden et al., 2018).

The USDA Natural Resources Conservation Service (NRCS) defines *soil health* as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans." Healthy soils host a diversity of beneficial organisms, grow vigorous crops, enhance agricultural resilience (crop and livestock ability to tolerate and recover from drought, temperature extremes, pests, and other stresses), and help regulate the global climate by converting organic residues into stable soil organic matter (SOM) and retaining nutrients, especially nitrogen (N) (ITPS, 2015; Moebius-Clune et al., 2016). **Thus, building soil health through sustainable organic management practices can mitigate GHG emissions and lessen the impacts of climate change on production.**

Although CO2 accounts for the largest percentage of GHG emissions, N2O and CH4 are much more potent greenhouse gases. Methane has roughly 20 times the global warming potential (GWP) of CO2, and N2O has about 310 times the GWP of CO2. The GWP of a given gas is a function of how long it remains in the atmosphere and its ability to absorb energy. Therefore, while cutting carbon emissions is an important part of combatting climate change, we also need to develop organic practices that reduce N2O and CH4 emissions.



U.S. Greenhouse Gas Emissions in 2016 (EPA 2016)

Direct Greenhouse Gas Emissions in Agriculture

In addition to fossil-fuel-related CO_2 emissions from field operations and embodied in fertilizers and other inputs, agricultural operations emit N_2O and CH_4, whose 100-year global warming potentials (GWP) are about 310 and 21 times that of CO_2, respectively (IPCC, 2015)*.

Most agricultural N_2O is emitted during denitrification and other microbial transformations of soluble N in cropland and grassland soils that have been fertilized with synthetic N and/or manure (Burger et al., 2005; Charles et al., 2017; Cogger et al., 2014). Major sources of CH_4 emissions include "enteric CH_4" released by ruminant livestock, and anaerobic microbial metabolism in flooded paddy rice soils (IPCC, 2014). Manure storage facilities (especially liquid manure systems such as lagoons) and inadequately aerated composting operations can emit both CH_4 and N_2O (Richard and Camargo, 2011).

The International Panel on Climate Change (IPCC) estimated that direct agricultural GHG emissions accounted for 12% of total global anthropogenic (human caused) GHG emissions (IPCC, 2014). These emissions were attributed to livestock enteric CH_4 (~35% of agricultural CO_2-Ceq), N_2O from fertilized or manured soils (~35% of agricultural CO_2-Ceq), CH_4 from rice cultivation (~10%) and manure storage (~8%), and CO_2 from biomass burning, cultivation of peat soils, and other sources (12%) (Tubiello et al., 2013; IPCC, 2014).

---

* Throughout this Guide, figures for GHG emissions and their impacts are discussed in terms of their carbon dioxide carbon equivalents (CO_2-Ceq), based on IPCC estimates of 100-year GWP, Thus, 1 lb N emitted as N_2O = 133 lb C emitted as CO_2 (or CO_2-Ceq), and 1 lb C emitted as CH4 = 7.6 lb CO_2-Ceq.

In the U.S., the Environmental Protection Agency estimated that, in 2016, direct agricultural GHG emissions account for 8.6% of the nation's total anthropogenic GHG (EPA, 2018). Soil N_2O emissions accounted for 50.4% of agricultural GHG (reflecting heavier use of N fertilizers in the US, livestock enteric CH_4 for 30.2%, manure management facilities 15.2%, rice cultivation 2.4% (relatively low rice acreage in US), and CO_2 from field burning and from lime and urea applications 1.7%. Total direct agricultural GHG emissions have increased 17% since 1990, driven largely by increased use of liquid manure management systems, resulting in a 68% increase in manure facility GHG emissions (EPA, 2018).

The global IPCC report and U.S.-focused EPA analysis do not include CO_2 emissions from farm machinery and embodied energy in fertilizers and other inputs; these were subsumed under the categories of energy for transportation, machinery, and industrial processes. In a Washington State University analysis that categorized these CO_2 emissions as agricultural, N_2O (from all sources) accounted for 57% of direct U.S.agricultural GHG, CH_4 for 26%, and CO_2 for just 17% (Carpenter-Boggs et al., 2016). In conventional agriculture, N fertilizer accounts for a substantial part of the CO_2 emissions, since industrial N fixation releases about 4 lb CO_2 per lb fertilizer N (Khan et al., 2007).

Soil, Agriculture, and the Global Carbon Cycle

Plant photosynthesis, the foundation of all life on Earth, converts atmospheric CO_2 into organic (carbon-based) compounds, which are retained in plant biomass and delivered to the soil in plant residues and root exudates. As the soil life digests plant residues, about 15-35% of the annual plant carbon input remains in the soil beyond the current season as *soil organic carbon (SOC)*, the "backbone" (58% by weight) of soil organic matter (SOM) (Brady and Weil, 2008). Thus, in all natural and agricultural ecosystems, *the living plant is the primary source of SOC, and the soil life mediates soil C sequestration*.

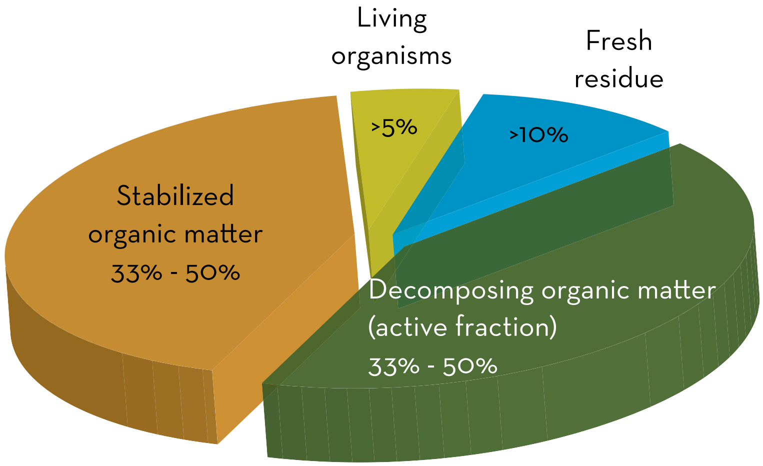
The SOC is comprised of several components, including *microbial biomass carbon* (MBC), *active* or *labile SOC* (readily decomposed by soil life, with a residence time in the soil of a few weeks to a few years) and *stable SOC* (resistant to or protected from decomposition, residence time of decades to millennia). Soil micro- and macro-organisms (collectively known as the *soil food web* or *soil biota)* play a central role in two vital processes in the soil C cycle: *mineralization,* in which active SOC is decomposed to release CO_2 and plant nutrients, and *stabilization*, in which active SOC is converted to stable forms that are protected within soil aggregates,

Mineralization *is the process by which soil organisms consume active SOC as their "food," thereby decomposing it into CO2 and plant nutrients.*

Stabilization*, also mediated by soil life, converts active SOC to more stable forms that are physically protected within soil aggregates, strongly adhered to soil minerals, or chemically resistant to decomposition.*

adhered to clay and silt particles, or chemically resistant to decomposition. Both processes help regulate climate, as mineralization is vital for ongoing plant nutrition and growth (formation of new organic C), while stabilization directly sequesters SOC.

Figure 1. Components of soil organic matter (SOM)



Soil life processes fresh organic residues into SOM, converting 10-40% of the carbon in the residues into SOC. While active SOC turns over relatively rapidly, more stable fractions can remain sequestered for decades to millennia. More than half of the world's SOC occurs below the plow layer, where it is less subject to decomposition. Most of this deep SOC is derived from plant roots; thus, including crops with deep, extensive root systems in the rotation play an important role in SOC sequestration.

Agriculture exerts multiple impacts on the global C cycle. Harvest removes a significant portion of crop-fixed C, leaving less for the soil. Tillage and overgrazing accelerate decomposition of SOM, and expose the soil to wind and water erosion, which remove SOM-rich soil particles and cause major SOC losses (Lal, 2003; Olson et al., 2016; Osmond et al., 2014; Teague et al., 2016).

Clearing land for agriculture is especially destructive to SOC and plant biomass C. Historically, deforestation and other land use changes accounted for 30% of total anthropogenic GHG emissions between 1750 and 2011. These losses have slowed in recent decades and now represent 8-12% of total emissions (IPCC, 2014; Tubiello et al., 2013). Converting temperate forest or prairie to cropland can degrade 30-50% of native SOC over a 50-year period, and clearing tropical forest can destroy 75% within 25 years (Brady and Weil, 2008; Lal, 2016; Olson et al., 2016, 2017). Since the dawn of agriculture 10,000 years ago, land use conversion has oxidized some 516 billion tons** of biosphere C (SOC, vegetation, wetlands) to CO2 (Lal, 2016), equivalent to 34 years' worth of total global GHG at current emissions rates.

The soil plays a central role in the global C cycle, and the capacity to absorb and hold C is a vital function of healthy soil. Total SOC held in the world's soils (~ 1,650 billion tons) is nearly 30% greater than the *sum* of C in all living organisms plus atmospheric CO2 (Carpenter-Boggs et al., 2016; Lal, 2015). The SOC turns over (is degraded to CO2) at about 66 billion tons annually (Brady and Weil, 2008). Most of the SOC is replenished through photosynthesis, but net losses have been estimated at about 2 billion tons C per year, half of which results from soil erosion (Brady and Weil, 2008; Harden et al., 2018; Lal, 2003). When these SOC losses are added to direct agricultural GHG emissions, agriculture and land use account for about 25% of global anthropogenic GHG (IPCC, 2014; Teague, 2018).

Improved farming and land management practices can reverse this trend, resulting in *carbon sequestration*, a net conversion of CO2-C into SOC. For example, organic cropping systems often accrue more SOC than conventional systems in long-term trials (Delate et al., 2015b; Cavigelli et al., 2013; Rodale Institute, 2015). While individual practices such as cover cropping and no-till can sequester some C, integrated systems such as conservation agriculture, regenerative cropping, agroforestry, and adaptive multipaddock grazing (AMP) show much greater C sequestration potential (Table 1). Planting depleted or marginal cropland to perennial sod or trees also stores substantial C in soil and plant biomass (Feliciano et al., 2018; Jones, 2010). Cropland soils adjacent to tree lines (boundary plantings or alley crops) benefit from leaf litter, which enhances SOC and fertility up to a distance equal to tree height (Pardon et al., 2017).

**Throughout this Guide, the English system of units is used; literature reports in metric are converted to English system. One ton (2,000 lb) = 0.908 metric ton (Mg) = 908 kilograms. One acre (43,560 sq ft) = 0.405 hectare.

The potential to design farming practices for C sequestration has drawn public attention to organic and sustainable agriculture as part of the solution to the global climate crisis (Ohlson, 2014). In 2015, the USDA announced ten *Building Blocks for Climate Smart Agriculture and Forestry*. The NRCS Conservation Stewardship Program includes GHG mitigation as a component of the air quality resource concern (USDA, 2016; USDA NRCS). In December 2015, the Paris Climate Summit (Conference of Parties) launched the "4 per Thousand Initiative" to absorb 25% of total annual global GHG emissions by increasing global SOC stocks in the top 16 inches of the soil profile by an average of 0.4% per year (Lal, 2015). This would approximately offset the world's annual agricultural GHG emissions.

USDA Building Blocks for Climate Smart Agriculture and Forestry.

Building Block	NRCS Lead/Member	GHG Reduction by 2025 ($MMTCO_2e$)[1]
Soil Health	Bianca Moebius-Clune	4-18
Nitrogen Stewardship	Norm Widman, Chris Gross, Dana Ashford-Kornburger	7
Livestock Partnerships	Glenn Carpenter	21.2
Conservation of Sensitive Lands	Mike Wilson	.8
Grazing and Pasture Lands	Joel Brown, Sid Brantly, Dana Larsen	1.6
Private Forest Growth and Retention	Eunice Padley, Dan Lawson	4.8
Stewardship of Federal Forests	----------	2.5
Promotion of Wood Products	----------	19.5
Urban Forests	----------	0.1
Energy Generation and Efficiency	Rebecca MacLeod	60.2
Metrics and Quantification	Adam Chambers, Mike Wilson, Katie Cerretani	Total = 122-136

[1]$MMTCO_2e$ refers to metric tons of CO_2 equivalent.

This plan is designed to help farmers, ranchers, forestland owners, and rural communities respond to climate change. The ten "building blocks" include a range of technologies and practices to reduce greenhouse gas (GHG) emissions, increase carbon storage, and generate clean renewable energy:

Conservative estimates of potential climate mitigation through sustainable farming range from reducing U.S. agriculture's GHG footprint by a few percent (Galik et al., 2017; Powlson et al., 2011) to cutting it by half (Chambers et al., 2016). Reported SOC gains from conservation practices such as no-till or surface residue retention vary widely and often occur near the surface where the accrued SOC is vulnerable to future mineralization (Powlson et al., 2016). Based on these considerations, Powlson et al., (2011, 2016) recommend that mitigation efforts focus on soil and nutrient management to minimize emissions of the more powerful GHG, CH_4 and N_2O.

In contrast, other analyses suggest that widespread adoption of integrated systems can make U.S. agriculture carbon-negative (Harden et al., 2018; Teague et al., 2016), and even offset all anthropogenic GHG emissions (Rodale Institute, 2014). However, when soil stewardship improves, SOC levels rise steadily for several years or decades, then level off as soil C dynamics reach a new steady state (Brady and Weil, 2008; Lugato et al., 2018). Such "SOC saturation" has been observed in long term organic farming systems trials (Rodale Institute, 2015, Carpenter-Boggs et al., 2016), and after cropland conversion to pasture (Jones, 2010; Machmuller et al., 2015). Lal (2016) estimated that SOC levels in managed lands that currently average 55% of their native levels, could be restored to 80% through known best practices, and potentially to 100% or higher through future innovations. Overall, findings to date suggest that widespread implementation of today's best soil management practices could achieve the goal of the 4 per Thousand Initiative announced at the 2015 Paris Climate Summit (Table 1).

Table 1. Per-acre annual C sequestration rates required to achieve three GHG mitigation goals.

Global GHG Mitigation Goal	SOC seq. lb/ac-year[1]	References
Offset direct agricultural GHG emissions	325[2]	Richard & Camargo, 2011
Offset 25% human-caused GHG emissions thru 4 per Thousand Initiative	660[2]	Lal, 2016
Offset all human-caused GHG emissions	2,470[2]	Teague et al., 2016

[1]Carbon sequestered as SOC

[2]Based on C sequestration on the world's ~12.2 billion acres of agricultural lands, including 3.51 billion acres cropland and 8.65 billion acres grazing lands.

Table 2. SOC accrual rates estimated for various farming systems and practices		
Practice: cropland	**SOC seq. lb/ac-year**	**References**
Organic system (vs conventional), long-term field crop farming systems trials	400-600[1]	Coulter, 2012; Delate et al., 2015b; Cavigelli et al., 2013; Rodale, 2015
Continuous no-till	510	West and Post, 2002
Diversified crop rotation (e.g., 4 year 4 crops versus 2 year corn-soy)	180-470	West & Post, 2002; Alhameid et al., 2017; Lehman et al., 2017
Cover crop (NRCS practice[2])	135-195	Chambers et al., 2016
Cover crop with no-till	440-800	Lal, 2015
Conservation Agriculture[3]	600– 1,000	Lal, 2016
Regenerative cropping system[4]	2,400	Aguillera et al., 2013, Gattinger et al., 2012, Teague et al., 2016
Practice: grazing lands		
Prescribed grazing (NRCS practice[2])	150-400	Chambers et al., 2016
Adaptive multipaddock grazing (AMP)	2,400	Machmuller et al., 2015; Wang et al., 2015; Teague et al., 2016
Practice: Perennial conservation plantings		
Field border, filter strip, other herbaceous perennial conservation planting (NRCS[2])	375-850	Chambers et al., 2016
Converting cropland to grassland/prairie	≥ 2,000	Jones, 2010
Conservation Reserve Program (NRCS)	3,600[5]	Manale et al., 2016
Agroforestry, tropical region[6]	6,320[5]	Feliciano et al., 2018
Agroforestry, temperate region[6]	3,700[5]	Feliciano et al., 2018
Agroforestry, arid to semiarid regions[6]	2,400[5]	Feliciano et al., 2018

[1]Based on differences in total SOC between organic and conventional farming systems.

[2]For NRCS Conservation Practice Standards, visit: https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/technical/cp/ncps/?cid=nrcs143_026849.

[3]Conservation agriculture integrates diversified crop rotation, high biomass cover crops, no-till, organic soil amendments, and limited use of synthetic inputs.

[4]Regenerative cropping is similar to conservation agriculture, and includes "biotic fertilizer" to feed the soil biota, strong emphasis on legumes and other organic N sources, and crop-livestock integration.

[5] Soil + aboveground biomass C sequestration.

[6] Based on a review of various agroforestry practices such as silvopasture, alley cropping, permaculture home gardens, and transitioning cropland or degraded land to woodlot or forest

Organic Agriculture, Soil, and Climate

The USDA National Organic Program (NOP) Standards mandate best conservation management practices, including diversified crop rotation, cover cropping, careful nutrient management, and other practices to build SOC and protect soil health (USDA National Organic Program Final Rule). The main difference between organic and conventional approaches to soil conservation, SOC, and climate mitigation is that organic farming excludes the *chemical* disturbance of synthetic fertilizers and pesticides, but allows judicious tillage; while non-organic conservation agriculture seeks to eliminate the *physical* disturbance of tillage, but allows judicious use of synthetic fertilizers, herbicides, and other crop protection chemicals when necessary. Extensive research indicates that the organic approach has potential to sequester C and mitigate GHG emissions, but that further research and development is needed to fully realize this potential (*see Concept #1 on page 10*).

In addition to sequestering C and mitigating GHG emissions, building soil health can contribute to the resilience of the production system to abiotic stresses, including those related to climate change (Blanco-Canqui and Francis, 2016; Lal, 2016). Organic systems tend to give somewhat lower yields than conventional (Ponisio et al., 2014), yet yield *stability* (resilience) may be improved. For example, the organic system in a Rodale long term trial has sustained corn yields in drought years when conventional corn yields were reduced (Rodale Institute, 2014). In another instance, regenerative range management helped a Texas ranch maintain its herd through the extreme drought of 2012 that forced other ranchers to sell livestock (Lengnick, 2016).

Estimating the Climate Mitigation Potential of Organic Farming

Organic farming practices can enhance the soil's capacity to sequester carbon. However, assessments of the overall climate impacts of organic farming range from substantial net GHG mitigation (Rodale Institute, 2014; Scialabba, 2013), to a net increase in agricultural GHG emissions as the organic industry has grown in the U.S. (McGee, 2015). There are concerns that lower crop yields in organic production reduce crop residue returns to the soil and increase GHG emissions *per unit output* (Lorenz & Lal 2016); greater reliance on tillage to manage weeds and cover crops degrades SOM (USDA, NRCS, 2011), and SOC gains from off-farm organic inputs do not represent net C sequestration (Gattinger et al., 2012).

One valuable tool for resolving this question is to conduct a *meta-analysis*, a quantitative review of multiple studies across diverse regions, climates, and soils. Highlights from recent meta-analyses, reviews, and large-scale studies include:

- Soil samples from 659 organic fields and 728 conventional fields across the U.S. showed 13% higher total SOM and 53% higher stable SOM ("humic substances") in organically managed soils compared to conventional (Ghabbour et al., 2017).
- In 56 studies in humid-temperate, arid, and tropical regions on six continents, organic systems averaged 19% higher total SOC, 41% higher microbial biomass C, and 32-84% higher levels of several enzymes important to nutrient cycling (Lori et al., 2017).
- In 20 studies across five continents, organic systems accrued an average of 490 lb C/ac-yr compared to just 80 lb C/ac-yr for conventional systems (Gattinger et al., 2012).
- In six long-term farming systems trials in CA, IA, MD, MN, PA, and WI, organic systems accrued more SOC than conventional (Delate et al., 2015b). Organic systems with tillage outperformed conventional no-till in the MD trial (Cavigelli et al., 2013).
- In a meta-analysis of 38 studies, organic N sources lost about 0.57% of their N content as N_2O, compared to 1.0% or more for synthetic N fertilizers (Charles et al., 2017).
- Based on 12 studies, organically managed soils emitted significantly less N_2O and absorbed slightly more CH_4 per acre than conventional soils; however soil GHG emissions per unit output were slightly higher for organic systems (Skinner et al., 2014).

- Organic systems showed lower total GHG emissions per unit output than conventional in 72 out of 121 direct comparisons, while the remaining 49 comparisons showed similar or greater GHG emissions in the organic systems (Lee et al., 2015).
- A review of 115 studies with over 1,000 observations found organic yields averaging 19% lower than conventional yields (Ponisio et al., 2014). *See Concept #2 on page 22 for more.*
- Statistical analysis of U.S. agriculture indicates that the growth in USDA certified organic acreage has correlated with an *increase* in agricultural GHG emissions, likely because many organic farms have not adopted integrated, sustainable, SOC-building systems (McGee, 2015). *See Concept #3 on page 27 for more.*

BOTTOM LINE

Best organic management practices can build SOC and soil health, and potentially reduce GHG emissions. However, further research, development, demonstration, and adoption of *sustainable* organic systems is needed to optimize net climate impact.

Challenges in Carbon Sequestration and Greenhouse Gas Mitigation in Organic Farming Systems

Throughout the history of organic agriculture, practitioners have emphasized environmental stewardship. In a recent national survey, more than 86% of 615 participants in the NRCS Environmental Quality Incentives Program (EQIP) Organic Initiative cited "concerns about environment" as a reason for adopting organic practices, compared to just 61% motivated by business opportunities offered by organic markets (Stephensen et al., 2017).

Carbon sequestration

Organic producers face several challenges in assessing and optimizing the impacts of their practices on SOC and the farm's net carbon balance.

1. Total SOC, which usually accounts for about 58% of SOM, changes slowly in response to management and climate factors, making it difficult to assess short term (<10 years) trends in soil C sequestration. Several indices of biologically active SOC respond more rapidly to management, but they are not yet widely available through standard soil test labs. Of these, permanganate oxidizable carbon (POXC) reflects SOC stabilization processes, the Solvita soil respiration test (which measures potentially mineralizable carbon or PMC) reflects SOC mineralization, and both SOC stabilization and mineralization are positively correlated with crop yields (Hurisso et al., 2016). Field measurement protocols have been developed for both indices (Moebius-Clune et al., 2016). However, further research is needed to develop region- and soil-specific guidelines for interpretation of results (Roper et al., 2017).

2. Soil samples to determine total SOM (e.g., standard soil tests), or active SOC are normally taken from the surface to a depth of 6 inches (Moebius-Clune et al., 2016). Although biological activity is greatest near the surface, 53% of the world's SOC is located from 12 to 39 inches below the surface (Lal, 2015) where SOC residence time is much longer (Lehmann and Kleber, 2015). Root-derived SOC can play a key role in long term SOC sequestration, provided that rotations include crops with deep, extensive root systems and soil conditions favor their full development (Kell, 2011; Rosolem et al., 2017). Deep rooted cover crops such as forage radish or cereal rye can relieve hardpan and enhance rooting depth

and yield of future crops (Gruver et al., 2016; Marshall et al., 2016). Gypsum applications can ameliorate root-inhibiting excesses of soluble aluminum (Al) in certain highly weathered soils (Rosolem et al., 2017). Standard soil tests can track long term (>10 year) trends in topsoil SOC, but do not reflect the efficacy of crop rotation and soil management in building deeper SOC.

3. The long term fate of newly-generated SOC is difficult to predict and monitor. Relationships among organic C input, soil biological activity, and long-term C sequestration are complex. Fresh organic residues undergo a dynamic process of decomposition and transformation by the soil life. Half or more of the added C is converted back to CO_2 via microbial respiration, and the balance becomes microbial biomass C and SOC (Grandy and Kallenbach, 2015), some of which turns over within a few years, while the rest remains sequestered for decades to millennia. Many factors—quality of organic inputs, management practices, species composition and activity of the soil food web, soil type and texture, soil moisture, climate, and weather extremes—influence SOC sequestration (McLauchlan, 2006). For example, much of the SOC gained during no-till accrues within aggregates near the soil surface, and is readily destabilized by a single tillage pass (Grandy et al., 2006; Kane, 2015). Generally, more plant root biomass C (35-40%) becomes stable SOC than shoot biomass C (15-20%) (Brady and Weil, 2008; Rasse et al., 2005). Diverse organic inputs with varying C:N ratios tend to build more SOC than single-source materials with low C:N (e.g., poultry litter) or high C:N i (e.g., corn residues) (Cogger et al., 2013; Fortuna et al., 2014; Grandy and Kallenbach, 2015).

4. While plants sequester SOC as they grow and die in situ, SOC from compost and other amendments from off-farm sources represents imported, not sequestered, C (Powlson et al., 2011). In a review of multiple studies, Gattinger (2012) found that, although organic systems tend to have higher SOC than conventional systems, imported C may account for 40% of the SOC increase measured in organic systems. Therefore, although organic systems have higher SOC, a substantial portion does not contribute to carbon sequestration.

Soil analyses for various soil carbon fractions help tell how much carbon plants have pulled from atmospheric Co2 and stored in soil organic matter. USDA ARS

Yet, depending on how it is managed, compost can help stabilize SOC (Bhowmik et al., 2017; Reeve and Creech, 2015). Compost and cover crops together build stable SOC while cover crops alone yield more active SOC that is readily mineralized through microbial respiration (Hurisso et al., 2016). In several field trials, cover crops with manure or compost application have accrued more SOC than either practice alone (Delate, et al., 2015a; Hooks et al., 2015). A single compost application to depleted rangeland in California boosted plant productivity and sequestered more C than was present in the compost itself (Ryals and Silver, 2013). Thus, judicious use of compost, manure, and other organic amendments may play an important complementary role with in situ plant growth in SOC sequestration.

The net climate impact of utilizing off-farm organic materials depends in large part on their alternative fate. Diverting food waste and yard waste from landfills or animal manure from lagoons to amend cropland, converts these materials from major GHG sources into valuable soil amendments. A life cycle analysis of applying composted manure and plant residues to grazing lands indicated a large negative GHG footprint (net mitigation), primarily through avoided CH_4 emissions, and secondarily through enhanced forage biomass and SOC on acreage receiving the compost (DeLonge et al., 2013). Carbon emissions during materials transport, and GHG emissions during the composting process, were small relative to this offset. Careful management of compost windrows to maintain aerobic conditions and avoid excessive moisture and N in the mix minimizes GHG emissions (Brown et al., 2008; DeLonge et al., 2013).

Other opportunities to avoid GHG emissions and build soil by composting organic "wastes" abound. For example, Dr. Girish Panicker (2017) states:

> *"[A]ccording to EPA, we throw away 24 million tons of dried [tree] leaves into the landfills every year … This is the greatest gift of nature, which contains thousands of tons of macro and micro nutrients for the succeeding plants. It is the food of our Mother Earth. It can conserve soil and water. EPA states that Americans pay $65/ton to put it in the landfill."*

Conversely, harvesting plant biomass to make compost or other organic amendments can deplete the "donor" field. Removal of crop residues (e.g., corn stover) from fields can severely compromise SOC and soil health (Andrews, 2006), and intensify wind and water erosion (Blanco-Canqui et al., 2016a, 2016b). Similar concerns apply to biochar, a soil amendment created by pyrolysis of organic residues, which can help stabilize SOC, improve soil structure, and reduce N_2O emissions (Blanco-Canqui, 2017; Cai et al., 2016 Mia et al., 2017). However, the pyrolysis process releases GHG, plant biomass is consumed as pyrolysis feedstock rather than returning to the soil *in situ*, and some biochar enterprises remove forest or other native plant biomass at unsustainable rates to make the product (North, 2015).

Finally, organic farmers can face tough choices between sequestering C and maintaining crop yields and net economic returns. Organic production relies on sufficient SOC mineralization to provide crop nutrients, which, at first glance, seems to contradict the goal of long term SOC sequestration. Hurisso et al., (2016) state:

> *"Soil organic matter levels are the balance of C inputs to soil (through crop residues and amendments) and losses via mineralization (i.e., CO_2 respiration). These dynamics (stabilization vs. mineralization) are mediated through the soil food web, which plays a large role in SOM decomposition and supports crop nutrition. Growers have a vested interest in both processes because they rely on mineralization for short-term crop productivity, but also strive for stabilization to build soil resilience, tilth, and quality."*

Compared to conventionally managed soils, organically managed soils typically have higher microbial respiration rates (PMC) and higher levels of active (POXC), stable, and total SOC, indicating that SOC miner-

Tips to enhance carbon sequestration

- *Implement conservation practices, such as diversified crop rotations and reduced tillage.*
- *Consider regenerative cropping systems that integrate multiple conservation practices with judicious use of compost or other organic amendments.*
- *Incorporate agroforestry practices, such as silvopasture, alley cropping, and hedgerows.*
- *Implement management intensive rotational grazing systems.*
- *Plant marginal cropland to perennial sod or trees.*
- *Plant deep-rooted cover crops, such as forage radish or cereal rye, to enhance root biomass.*
- *Diversify crop rotations by adding deep-rooted and perennial crops.*
- *Use diverse organic inputs that vary in their C:N ratio.*
- *Combine the use of compost and cover crops.*
- *Divert food and yard waste from landfills to amend cropland.*

alization and stabilization can be enhanced simultaneously (Hurisso et al., 2016; Lori et al., 2017).

Tillage and cultivation present a tougher challenge, as they accelerate SOC oxidation and sometimes erosion. Cover crop-intensive, organic no-till systems that maximize SOC often entail substantial yield tradeoffs, especially in the colder climates of the northern half of the U.S. (Barbercheck et al., 2008; Delate, 2013, Larsen et al., 2014). Thus, farmers often struggle to find the right balance between crop production and long term SOC retention.

Conservation agriculture is a system that aims to achieve this balance by integrating diversified rotations, cover crops, legumes, organic soil amendments, crop-livestock integration, and continuous no-till with limited synthetic inputs to maintain high yields, build soil health, and sequester C (Delgado et al., 2011; Teague et al., 2016). Best sustainable organic practices differ from conservation agriculture primarily in the complete *non*-use of synthetic inputs including herbicides, which protects soil life (Rose et al., 2016), but makes continuous no-till infeasible for annual crops. However, organic systems that reduce tillage intensity, maximize crop biomass and diversity, and use organic amendments can build more SOC than continuous conventional no-till (Cavigelli et al., 2013; Dimitri et al., 2012; Kane, 2015). Practical organic conservation tillage strategies include ridge or strip tillage, which release nutrients in crop rows and build SOC between rows (Williams et al., 2017), and implements such as spaders, rotary harrows, and sweep plow undercutters, which destroy less SOC and leave soil in better condition than plow-disk or rototiller (Schonbeck et al., 2017).

Crop diversification is another practice that generally enhances SOC, especially when perennial and deep rooted crops are added to the rotation, and this SOC accrual may be more stable than that achieved through no-till (Cavigelli et al., 2013; Kane, 2015; Powlson et al., 2016; Wander et al., 1994). Increasing crop diversity also enhances soil microbial biomass, biodiversity, nutrient cycling, and other soil food web functions, (King and Hofmockel, 2017; McDaniel et al., 2014; Tiemann et al., 2015. However, adding new crops to the system can entail acquiring new production tools and skills, market research for new products, and/or reduced revenues resulting from unharvested cover or sod crops.

Nitrous oxide, methane, and total greenhouse gas “footprint” of the farming system

Nitrous oxide (N_2O) emissions from fertilized soils account for about half of direct GHG emissions in U.S. agriculture (EPA, 2018), and result from microbial transformations of soluble nitrogen in the form of ammonium (NH_4) and nitrate (NO_3) into N_2O. The IPCC has estimated that on average about 1% of applied fertilizer is emitted as N_20 (emission factor, EF). However, actual EF values for organic N sources can vary from nearly zero to as high as 7% depending on the N source and its C:N ratio, soil texture and drainage, and seasonal rainfall (Charles et al., 2017). In a meta-analysis of multiple studies, organic amendments with a high C:N ratio (e.g., crop residues, paper mill sludge, etc.) or well-stabilized N (finished compost) had low EF (0-0.3%), while solid manures ranged from 0.3-1.0%, and liquid manure slurry and biogas digestate averaged 1.2% (Charles et al., 2017). Although a 1% loss from a 150 lb/ac N application has little economic impact on the farm, this loss in the form of N_2O negates about 200 lb C sequestration.

In conventional farming systems, N_2O emissions show direct relationships with N application rates and methods. Reliable, research-based nutrient management protocols for reducing N_2O emissions by 50% or more have been developed for field crops (Eagle et al., 2017; Millar et al., 2010). While organic N sources have a mean EF of 0.57%, and organic practices can mitigate N_2O (Cavigelli, 2010; Charles et al., 2017; Reinbott, 2015), the dynamics of N_2O emissions in organic systems are complex and challenging to manage, making it difficult to develop nutrient management protocols for organic systems. Brief, intense N_2O “spikes” can occur when high soil moisture levels and limited oxygen coincide with an abundance of readilydecomposable organic C and N; for example, when N rich organic fertilizers (e.g., poultry litter) or legume green manures are tilled into moist soil (Baas et al., 2015; Bhowmik et al., 2015; Cavigelli, 2010; Han et al., 2017).

Annual cover crops usually reduce N_2O losses while they are growing (by taking up N), but may stimulate emissions after termination, especially when all-legume covers are tilled in higher-rainfall climates (Basche et al., 2014; Li et al., 2009; Rosolem et al., 2017). A recent European modelling study indicated that adding clover cover crops (terminated by tillage) to existing crop rotations would boost N_2O emissions to result in large net GHG emissions by the year 2100 (Lugato et al., 2018).

In colder climates, spring thaw/snowmelt is a high-risk time for N_2O (Thies, 2007), especially after a fall alfalfa plowdown has released an abundance of soluble N into the soil (Westphal et al., 2018). Other risk factors include soil compaction, which impedes aeration and promotes denitrification when soil moisture levels are high; and fine-textured (clayey) soils, in which EF values for organic N sources averaged 2.8 times those for sandy soils (Balaine et al., 2016; Charles et al., 2017).

The soil microbial community plays a central role in regulating the conversions of soil N among organic, soluble, and volatile forms, and thereby modulates N_2O emissions. Among the many benefits of arbuscular mycorrhizal fungi (AMF) are their capacity to limit N_2O emissions and build stable SOC (Hu et al., 2016, Rillig, 2004). While organic practices and reduced tillage can enhance AMF activity, heavy compost use may inhibit AMF by building up high soil P levels (Gottshall et al., 2017; Hu et al., 2016; Van Geel et al., 2017).

Agricultural methane emissions are related primarily to livestock and rice production. Livestock-related GHG emissions include enteric CH_4 and GHG released during manure storage. Pasture-based systems reduce the need for manure storage, yet 100% grass-fed cattle emit more CH_4 than animals that receive concentrates because the former diet is higher in fiber and lower in protein (Manale et al., 2016; Richard and Camargo 2011). Pastured dairy systems also create N_2O "hotspots" in areas of high stocking density where manure is concentrated, and soil becomes compacted (Luo et al., 2017).

However, life cycle analyses of management-intensive rotational grazing systems (MIG) have shown that they can sequester sufficient SOC to offset enteric and manure GHG emissions, and may reduce enteric CH_4 by ~30% through improved forage quality (Kittredge, 2016-17; Manale et al., 2016; Stanley et al., 2018; Teague, 2016-17; Wang et al., 2015)). MIG systems divide grazing lands into multiple paddocks, each grazed intensively for 0.5-3 days at high stocking rates, followed by sufficient recovery periods for the sod to regrow fully (Kittredge, 2014-15). Life cycle analyses on MIG systems in Texas, Michigan, and South Carolina showed a net negative GHG footprint (ie. mitigation), though the investigators caution that the rapid SOC accruals over the initial 5-10 years level off thereafter (Machmuller et al., 2015; Stanley et al., 2018; Wang et al., 2015).

Well-drained agricultural and grassland soils generally do not release CH_4, and may absorb small amounts of this GHG, whereas water-saturated rice paddy soils release considerable CH_4 (Richard and Camargo, 2011; Thakur et al., 2016; Topp and Pattey, 1997). Terminating cover crops in rice paddies just before flooding intensifies emissions, whereas draining rice fields for part of the season can reduce them (Dou et al., 2016; Oo et al., 2018; Tariq et al., 2017). The System of Rice Intensification (SRI), which integrates improved crop establishment techniques, compost for fertility, and non-flooded field management, can enhance soil and crop root health, improve yields, curb CH_4 emissions, and reduce total GHG emissions per ton of grain by 60% (Thakur et al., 2016).

Researchers are attempting to develop realistic models and decision tools for estimating the carbon balance and overall GHG "footprint" of a farming operation (Baas et al., 2015; Jones, 2010; Wander et al., 2014). The USDA has developed GRACEnet, a field chamber protocol for monitoring CO_2, N_2O, and CH_4 emissions in different cropping systems, thereby providing data for construction of predictive models (Parkin and Venterea, 2010). COMET Farm and COMET Planner are online tools designed to help producers in this complex task, and to identify management changes that could reduce emissions or sequester SOC. Models were initially developed for conventional production of commodity crops. Additional refinement to address minor and specialty crops and other farming systems including organic are underway. OFOOT is another tool under development by the Center for Sustaining Agriculture and Natural Resources at Washington State University, designed to help organic producers understand and improve the net GHG footprint of their farms (Carpenter-Boggs et al., 2016).

Positive feedback and the vital role of climate adaptation

Climate change itself can render C sequestration and GHG mitigation more difficult. Rising temperatures are expected to accelerate the oxidation of SOC (ITPS, 2015; Kell, 2011, Petit, 2012). Warming-related SOC losses will be especially pronounced in cold-temperate climates and in regions where permafrost thawing occurs (Harden et al., 2018; Kirschbaum, 1995). Warmer, drier winters and springs in the U.S. Corn Belt may complicate crop establishment and leave tilled soils more prone to wind erosion (Daigh and DeJong-Hughes, 2017). N_2O emissions also increase with soil temperature (Ball et al., 2007), and with mean summer temperatures (Eagle et al., 2017). Finally, rising atmospheric CO_2 levels may also stimulate N_2O formation by soil fungi (Zhong et al., 2018).

These trends highlight the urgent need to strengthen the resilience of agricultural systems to climate disruptions already underway. As noted earlier, the deeper, more biologically active soils of mature organic systems that have higher SOC can improve crop and livestock resilience to drought and other weather extremes. The soil benefits of organic practices appear especially pronounced in tropical climates (Lori et al., 2017), and thus may become more important in temperate regions as mean temperatures increase.

New risks, learning curves, and other barriers to climate-friendly organic farming

Adding new management practices to make a farming system more climate-friendly and climate resilient can initially increase financial risks as producers must acquire new knowledge and training, and often new equipment and infrastructure. The knowledge-intensive and site specific nature of organic farming is accentuated when C sequestration and climate mitigation and adaptation are added to the producer's goals. For example, a cover crop-intensive organic minimum-till system that works well in the Southeast may lead to crop failures in a colder or drier region.

Crop diversification requires careful business planning and market research to ensure sustained profitability.

For example, adding a specialty grain or legume crop to a corn-soy-wheat rotation may require new market venues for the new crop. Integrating a sod crop into the rotation builds SOC but often entails foregone income, and may be infeasible for a small-acreage market garden.

While the benefits of building soil health and sequestering SOC can lead to improved yields or yield stability in organic systems, the financial returns may not be realized for several years. In the meantime, organic producers encounter economic, infrastructural, social, and policy barriers to the adoption of climate friendly and climate resilient farming systems, including:

- Upfront costs and delayed benefits of adopting new practices.
- A steep learning curve and lack of qualified technical assistance to help producers identify and adopt the best suite of practices for their farm.
- A historical under-investment in organic agriculture research, which has contributed to the "yield gap" between organic and conventional systems (*see Concept #2 on page 22)*.
- A lack of crop cultivars adapted to sustainable organic production systems.
- An agriculture and food system infrastructure that perpetuates unsustainable production systems.
- Government agricultural policies and programs that create dis-incentives to crop diversification, cover cropping, and other conservation practices.
- The lack of viable carbon markets for climate-conscious producers.
- The current lack of political support for addressing climate change at a societal level.
- Social or cultural pressures that deter adoption of organic or climate friendly practices.

The bottom line is that farmers—organic or otherwise—need to make a living; thus, any management changes to sequester C or mitigate GHG emissions must also maintain or improve the farmer's net returns. If the farm goes out of business and the land undergoes commercial or residential development, its net per-acre GHG emissions may soar. For example, one study in Yolo County, California estimated that urban areas emitted *70 times* the GHG (in CO_2 equivalents) as irrigated cropland (Jackson et al., 2012). Thus, farmland preservation in itself can be seen as a climate-mitigating endeavor. In addition, our society must provide farmers with the technical, economic, infrastructure, and social support to adopt optimal soil-building, climate-friendly, and profitable systems for their farming or ranching operations.

Closing the organic *versus* conventional yield gap

One challenge that organic farmers face as they strive to improve their environmental stewardship *and* stay in business is the "yield gap." Given the lower yields often associated with organic production, the GHG footprint of organic food in carbon dioxide carbon equivalents (CO_2-Ceq) *per unit output* is not as small as might be expected based on CO_2-Ceq *per acre in production*. In addition, concerns have been raised that lower-yielding organic systems would require more acres of native vegetation to be cleared to meet humanity's food and fiber needs, which would further increase the GHG footprint of organic production.

For grain crops, the mean yield shortfall for organic production has been estimated at 19%, based on studies in 38 countries (Ponisio et al., 2014). In comparisons of organic systems with a diversified crop rotation or multicropping system versus a conventional monoculture or low-diversity rotation, the yield difference diminished to 8-9%. However, in comparisons in which *both* organic and conventional systems were diversified, the yield gap remained at 21%.

Much of the yield gap can be attributed to low investment in organic research and plant breeding for organic systems. Since 2002, the USDA Organic Research and Extension Initiative (OREI) and Organic Transitions Program (ORG) have begun to address this need (Schonbeck et al., 2016). Yet, only 1.5% of USDA research dollars currently go into organic systems, lagging behind the 5% market share for organic food. Ponisio et al., (2014) add:

> *"Given that there is such a diversity of management practices used in both organic and conventional farming, a broad-scale comparison of organic and conventional production may not provide the most useful insights for improving management of organic systems. Instead, it might be more productive to investigate explicitly and systematically how specific management practices (e.g., intercrop combinations, crop rotation sequences, composting, biological control, etc.) could be altered in different cropping systems to mitigate yield gaps between organic and conventional production.*
>
> *"Further, many comparisons between organic and conventional agriculture use modern crop varieties selected for their ability to produce under high-input (conventional) systems. Such varieties are known to lack important traits needed for productivity in low-input systems, potentially biasing towards finding*

lower yields in organic versus conventional comparisons. By contrast, few modern varieties have yet been developed to produce high yields under organic conditions; generating such breeds would be an important first step towards reducing yield gaps when they occur."

BOTTOM LINE

Today's climate and food security crises make research into sustainable organic systems more urgent than ever. The potential of plant breeding for soil health and economic viability of organic farms and ranches is discussed in the companion Guide, *Soil Health and Organic Farming: Plant Genetics, Plant Breeding and Variety Selection*.

Best Management Practices and Information Resources for Carbon Sequestration and Net Greenhouse Gas Mitigation in Organic Farming

The first steps toward creating a climate-resilient and climate-friendly farm or ranch ecosystem are to:

- Clarify your objectives and priorities.
- Inventory farm resources including soil, water, crops and livestock, infrastructure, expertise, and labor.
- Evaluate your current production practices and their potential impacts on GHG emissions and the resilience of your farming system.
- Identify opportunities to improve your operation's climate and environmental impacts while maintaining or enhancing your bottom line.
- Outline your overall strategy to achieve your objectives.

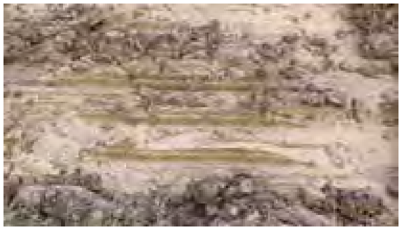
Gather the information you need on current and potential new practices or components, their C sequestration or GHG implications, and their direct costs and benefits to your operation. For example, diversifying your crop rotation can enhance SOC sequestration and reduce GHG; it also presents marketing and management challenges and an opportunity to evaluate and compare net returns of your current crops and new crops under consideration. Some valuable resources for this part of the process include enterprise budgets, business planning templates, and market information on organic farm products, available online or as Extension bulletins.

Consider seeking technical assistance from NRCS field staff or independent consultants with a commitment to agricultural sustainability and expertise in organic systems, soil health, climate in agriculture, and agricultural economics. These professionals can help you clarify goals and develop a practical and site specific strategy for your operation. NRCS has developed a nine-step comprehensive conservation planning process in which their field staff or a technical services provider works on the ground with farmers to clarify objectives, inventory resources and concerns, develop and implement a strategy, and evaluate outcomes (USDA NRCS, 2014). In addition, the Conservation Stewardship Program (Resources, item 23) offers high level conservation strategies that can mitigate GHG and improve resilience to weather extremes.

Factors to consider and their GHG and resilience impacts (listed in parentheses) include:

- Your soil type(s), including texture, mineralogy, profile, depth, drainage, topography, inherent strengths and constraints, and risk factors for soil erosion or degradation. NRCS Web Soil Survey (Resources, item 22) provides this information.
- Management history and current condition (fertility, tilth, vegetative cover) of the soil in each field or pasture.
- Tillage practices and other field operations (*CO_2 from fuel, loss of SOC, soil erosion*).
- Cover crops (*C sequestration, N uptake, reduced input needs*), termination of legume and other low C:N cover crops (*N_2O emissions*).
- Compost and other organic amendments, on- or off-farm sourcing (*soil health, SOC stabilization, nutrient cycling, soil nutrient balance, GHG impacts of manufacture and transport versus GHG offsets for materials diverted from landfill or lagoon*).
- Nitrogen applications such as poultry litter or livestock manure (*N_2O*).
- Critical times in the season or crop rotation when high levels of soil moisture and soluble N may occur together (*N_2O*).
- Flooded field production systems, e.g., rice (*CH_4*).
- Livestock nutrition, forage quality, grazing and pasture/range management (*enteric CH_4 and its mitigation, N_2O "hotspots," C sequestration*).
- Manure storage facilities and composting operations (*CH_4 and N_2O*).
- Opportunities to increase plant cover (days per year), biomass, and depth and extent of living roots in the farm's cropland, pasture, or range (*enhanced C sequestration and resilience to drought, temperature extremes, and other stresses; reduced soil erosion*).
- Opportunities to diversify the crop rotation and farm enterprises (*C sequestration, resilience, including economic resilience to crop failure or market fluctuations*).
- Opportunities to plant trees, shrubs and other perennials, including orchard and other perennial crops; windbreaks, hedgerows, alley crops, silvopasture, and other agroforestry; restoration of native plant communities or wildlife habitat (*C sequestration, erosion control, resilience*).
- Opportunities to tighten nutrient cycles, such as crop-livestock integration (*N_2O mitigation, resilience*).

As you fine-tune your organic production system for soil and climate stewardship, keep in mind that adopting new crops or practices entail a learning curve and new potential risks, as well as benefits. Add one or two practices or components at a time, trying them out on a small scale first, then integrate those that support the farm's economic viability while advancing your soil health and climate mitigation/adaptation goals.



Clay soil

Sandy soil

Silty soil

Remember also that no single practice or new crop will be a "silver bullet" solution for soil health, climate, or profit. Your long term goal is to develop an integrated systems approach, which is the essence of organic farming (*see Concept #3 on page 27).*

See Resources, items 1-5, 8, 9, 12, 14-18, 21, 22, 24 and 25 for resources to help identify and estimate GHG impacts of your farming system and practical strategies for mitigation and adaptation.

Organic is More than Renouncing Synthetics and GMOs

How full implementation of NOP Standards can sequester carbon, limit greenhouse gas emissions, and build agricultural resilience

> *"Organic agriculture is defined as having no synthetic inputs, but organic farms may or may not practice the full suite of cultivation techniques characterizing sustainable agriculture."* (Ponisio et al., 2014).

In order to become part of the climate solution, organic producers and certifiers have been urged to move beyond a narrow focus on "input substitution" (McGee, 2015) and to fully implement NOP requirements to protect natural resources, wildlife, and biodiversity (Wild Farm Alliance, 2017). The NOP Rules provides a clear roadmap to resilient, climate-friendly farming. Note, these rules are subject to change.

§ 205.2 Definitions:

"Organic Production: a production system that is managed … to respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity."

§ 205.202 Land Requirements:

"[F]ield or farm parcel … must have distinct, defined boundaries and buffer zones … to prevent the unintended application of a prohibited substance …"

- Tree and shrub plantings to meet this requirement also sequester C.

§ 205.105 Allowed and Prohibited Substances:

"[Organic] product must be produced … without the use of synthetic substances…"

- Non-use of synthetic N stabilizes SOC, enhances microbial function, and reduces N_2O.
- Non-use of synthetic crop protection chemicals protects soil organisms that build SOC.

§ 205.203 Soil fertility and crop nutrient management practice standard:
"[T]illage and cultivation practices [must] maintain or improve physical, chemical, and biological condition of soil, and minimize erosion."

- Tilling with care and reducing tillage when practical protects SOC and soil health.

§ 205.203 Soil fertility and crop nutrient management practice standard:
"[M]anage crop nutrients and soil fertility through rotations, cover crops, and the application of plant and animal materials …"

§ 205.205 Crop rotation practice standard:
"[I]mplement a crop rotation including … sod, cover crops, green manure crops, and catch crops that … maintain or improve SOM, provide for pest management, manage deficient or excess plant nutrients, and provide erosion control."

- Diversified crop rotations build microbial biodiversity and biomass, and total SOC.
- Cover crops and rotation reduce the need for applied N, and thus reduce N_2O risks.
- Cover crops, sod crops, and diversified rotations build yield stability and resilience.
- Judicious use of compost and other organic inputs stabilizes SOC and enhances soil life.

§ 205.240 Pasture practice standard
"The producer … must [have] a functioning management plan for pasture… to annually provide a minimum of 30 percent of a ruminant's dry matter intake …"

- Management intensive grazing can build SOC, distribute nutrients, and foster resilience.

In selecting management practices, consider the following detailed lists as menus of options from which to choose. Some of the recommendations are well researched and widely applicable, while others are more specific to certain regions, soils, or production systems, and may or may not be the right choice for you. A few of the practices listed are noted as experimental; while they have shown promise, they are also potentially risky in certain circumstances.

Sequestering and conserving carbon in the soil

Extensive research has illustrated the central role of living vegetation in restoring and maintaining SOC, and has validated the four NRCS principles of soil health management as guidelines for C sequestration and resilience of the farming system. These principles are:

- Keep the soil covered year round.
- Maintain living roots throughout the soil profile as much of the year as practical.
- Minimize soil disturbance – tillage, compaction, overgrazing, chemicals.
- Energize the system with biodiversity.

The following practices and strategies can build SOC and agricultural resilience.

Grow and sequester carbon in place:

- Maintain plant cover, biomass, and living roots as much of the year as practical; avoid or minimize bare fallow periods.
  - In regions with sufficient rainfall, implement "tight" crop rotations after each harvest or cover crop termination; plant the next crop as soon as practical.
  - In semiarid conditions such as dryland grain production, grow one cash or cover crop per year to maintain SOC and soil health. If extended fallow is needed to store soil moisture, keep surface covered with plant residues.
- Diversify the crop rotation. Adding just one new crop can enhance SOC and soil health.

- Grow high biomass, multi-species cover crops in rotation with production crops.
- Include a perennial sod phase (1-3 years) in the rotation, if economically feasible.
- Close time and space gaps between crops in the rotation whenever practical. Some advanced techniques for maximizing year round living cover include:
  - Interseed or overseed cover crops into standing grain, row, or vegetable crops. Interseed cover crops into corn at the V5-V6 (~knee high) stage.
  - Roll-crimp, mow, or ridge-till cover crops before planting cash crop *(may be risky, especially in colder regions; experiment first on small area).*
  - Seed row crop into standing cover before roll-down if soil moisture is ample and good seed-soil contact can be achieved for the row crop *(may be risky; experiment first on small area).*
  - Plant intercrops of dissimilar but complementary species, for example
    - "Three sisters": corn (tall, erect, N demanding), pole beans (climbing, N fixing), and winter squash (covers ground, tolerates part shade).
    - Alternate rows of tomato (tall, need good air circulation and full sun) with beds of salad greens (low growing, appreciate light shade in summer).
- Manage for high crop root biomass and deeper root growth:
  - Include deep rooted crops (cash, cover, or sod) in the rotation.
  - Choose crop varieties with greater root mass and depth.
  - Avoid "spoon-feeding" soluble N; use slow-release fertility sources.
  - Relieve hardpan using deep-rooted cover crops (subsoil first if necessary).
  - If subsoil acidity and high Al constrains root depth, apply gypsum.
- Keep orchard and vineyard floor, and berry crop alleys covered in living vegetation. Perennial sod maintained by periodic mowing works well for established fruit crops.
- Install windbreaks, hedgerows, silvopasture, alley cropping, and other functional agroforestry plantings as appropriate to your operation.
- Convert highly erodible cropland to orchard, other perennial crops, or permanent pasture.
- Restore degraded lands, marginal cropland, and riparian or other ecologically sensitive areas to forest or prairie, with emphasis on native perennial plants and wildlife habitat.

Use organic amendments to supplement and enhance *in-situ* plant based C sequestration:

- Apply compost, manure, or other amendments. Start with on-farm or nearby sources.
- Adjust manure and compost use rates to maintain moderate soil P levels; avoid excess P.
- Combine low and high C:N cover crops and organic inputs.
- If additional organic materials from off-farm sources are needed, choose materials that would otherwise "go to waste," e.g., autumn leaves or food waste headed to landfills, or manure that would otherwise be stored in a lagoon or unmanaged heap.
- Avoid inputs whose "harvest" depletes SOC on other lands (e.g., corn stover biochar).
- Commercial microbial soil inoculants may be valuable when rebuilding depleted soils.
- Mycorrhizal inoculants can be valuable, especially for woody perennial crops.

Conserve soil carbon:

- Prevent or remedy soil erosion—it is an infamous SOC thief.
  - Reduce tillage whenever practical.
  - On sloping fields, lay out raised beds or ridges approximately on contour, with gradual (0.5-1%) row grade down toward one or both edges of field. Use contour buffer strips (sod), terraces, or other soil conservation measures as warranted.
  - Put steeper, highly-erodible lands in permanent cover—pasture, silvopasture, forest, orchard with sod understory, native plants, wildlife habitat, etc.

Slow-release Fertility Sources

- **Finished compost**
- **Legume-grass cover crop residues**
- **Alfalfa meal**

UC Davis

- Avoid breaking perennial sod, and especially native forest, prairie, wetland, or other natural ecosystems, for annual crop production.
- Avoid harvesting or "baling-off" crop residues such as corn stover or mature cover crops, especially for fuel or off-farm use. Leave residues on soil surface as long as practical.
- Carefully managed *grazing* of crop residues or cover crops as part of a crop-livestock integrated system can be compatible with soil health and SOC sequestration.
- Terminate cover crops by mowing, roll-crimping, tarping (occultation), winterkill, undercutting, or shallow tillage that leaves most of the root mass undisturbed in the soil profile *(note that no-till cover crop management can be challenging in organic systems)*.
- Use ridge tillage or strip tillage to promote nutrient release in crop rows while leaving between-row soil undisturbed to maximize SOC accrual (*experimental for organic systems, has shown promise in research trials)*.
- Avoid overapplying plant-available N, which can "burn up" SOC. On fertile soils, simply replenish N removed by harvest, ≤50 lb/ac for most vegetables (Wander, 2015).

For more on building SOC and soil health, see Resources, items 2, 5, 6, 7, 9-13, 19-21, 23-25, and the other guides in the *Soil Health and Organic Farming* series.

Minimizing nitrous oxide (N_2O) and methane (CH4) emissions from cropland soils

Although abundant soil moisture and organic C and N during spring thaw or after green manuring have been identified as risk factors for N_2O emissions, more research is needed to better understand and minimize pulses of N_2O emissions from fertile, biologically active soils. However, the following strategies can reduce annual total N_2O emissions in organic crop production:

Know your soil properties and plan moisture management accordingly:

- Identify soil type, texture, and drainage properties to better understand N_2O risks:
  - Heavy (clay, clay loam, silt loam) soils have two to three times the N_2O "emissions factors" for organic N inputs as light (sandy loam) soils.
  - Floodplains, depressions, soils with naturally occurring hardpan ("fragipan" or "duripan"), and areas with naturally slow drainage ("moderately well drained" to "poorly drained") are likely N_2O hotspots in the farm landscape.
  - Sodic (high-sodium) soils, which occur in low-rainfall regions such as interior parts of the western US, often have poor, compacted structure and drain slowly.
- Remedy moderate drainage/aeration issues with deep rooted cover crops, inputs to build SOC and tilth, graded raised beds (sloping at 0.5-1% grade to field edge), or tile drains.
- Plant wetter, high-risk areas in unfertilized perennial vegetation such as grass sod, edible perennial landscape, or native woodland or wetland plant communities.
- Prevent and remedy soil compaction with deep rooted cover crops, diversified rotation, controlled traffic, and soil health building practices. For severe compaction, subsoil or chisel plow just before planting deep rooted crops.
- On irrigated crops:
  - Manage water applications to avoid prolonged periods of excessive soil moisture.
  - Monitor fields for ponding in low spots or tailwater collection areas—these can be major N_2O hotspots especially in high SOC soils.
  - In sodic soils, gypsum applications can relieve compaction, improve water relations, and prevent waterlogging during irrigation.

Manage soil nitrogen to minimize nitrous oxide emissions:

- Aim to meet most of crop N needs through the action of the soil food web on SOM and slow-release N sources, such as legume-grass cover crop residues.
- If "quick" N is needed, use concentrated N sources such as poultry litter, blood meal, manure slurry, and Chilean nitrate in moderation, perhaps 50 lb N/ac.

- Ration applied N to meet, but not exceed crop N needs.
  - Conduct simple N rate trials to assess crop response.
  - On biologically active soils, crop N need may be well below amounts recommended on a standard soil test.
  - Measure in-season soil or crop tissue nitrate-N (e.g., pre-sidedress nitrate test for corn at 12-inch height), to determine if more N is needed.
- Match timing of plant-available N with crop N demand, which usually peaks during the period of most rapid growth, such as the V9-V10 stage for corn.
  - Split applications of more concentrated N, such as feather or blood meal, *or*
  - Use in-row drip irrigation to deliver a little N each week to the crop.
- Monitor and "mop up" excess soluble N.
  - Measure soil nitrate-N after harvest. Send soil samples to a laboratory or use an in-field test kit.
  - If surplus soluble N (≥30 ppm nitrate-N) is found or expected to remain after harvest, plant a high biomass, N-demanding cover crop immediately. Intercrop or overseed before harvest, if practical.
- Avoid adding manure or other concentrated N sources or turning under succulent, high-N cover crops (green manure) when soil is wet or heavy rainfall is likely.
- For the perennial sod phase of a rotation, plant a mix of legumes with grasses and other non-legumes to minimize risk of N_2O emissions after plowdown.
- Manage for mycorrhizal fungi and other soil organisms that promote tight N cycling:
  - Avoid excess soil P and soluble N levels.
  - Monitor P levels in compost and manure, adjust application rates accordingly.
- Use mycorrhizal fungal inoculum to help restore depleted soils with low P.

Mitigate GHG risks in organic rice production and composting:

- Use the non-flooded System of Rice Intensification (SRI) .
- If your rice production system includes periodic flooding, time cover crops so that the paddy is not flooded when large amounts of fresh residue are present.

- Make compost from a diversity of organic materials with an overall C:N ratio between 25:1 and 40:1, and maintain aerobic conditions (e.g., turn windrows).

See Resources, items 1-5, 14, 15, 18, 24, and 25 for tips on mitigating N_2O and CH_4 emissions from cropland; item 6 for on-farm propagation of mycorrhizal inocula; and item 11 for SRI production methods. For more on managing N in organic systems, see *Soil Health and Organic Farming: Nutrient Management for Crops, Soil, and Environment.* For more on water management, see *Soil Health and Organic Farming: Water Management and Water Quality.*

Minimizing methane (CH_4) and net total GHG emissions in livestock operations

Although grass-fed ruminants emit more enteric CH_4 than grainfed (Manale et al., 2016), management-intensive rotational grazing (MIG) systems may sequester sufficient SOC to offset CH_4 and N_2O emissions, and higher forage quality may reduce enteric CH_4 (Wang et al., 2015; Rowntree et al., 2016; Stanley et al., 2018).

To mitigate net GHG emissions during organic livestock production:

- Maximize time on pasture and minimize time spent in confinement (reduces need for manure storage).
- Implement mob grazing, holistic management, adaptive multipaddock (AMP), or other MIG system, adapted to your region, climate, soils, pasture resources, livestock species and breeds, and farming or ranching system.
- Ensure sufficient rest periods for full recovery of pasture or range before re-grazing. *This is critical for C sequestration, soil health, forage quality, and livestock nutrition.*

- Monitor and manage pasture/range for forage quality and livestock nutrition; modify grazing schedule and/or overseed desirable species as needed to improve forage quality.
- Arrange paddocks, watering areas, and rotation schedule to distribute manure evenly and minimize N_2O hotspots.
- Eliminate manure lagoon storage if possible.
- Compost or dry stack manure with sufficient dry, high-carbon bedding (straw, wood shavings, etc.) to achieve an initial C:N ratio of 25:1 or higher; turn windrows as needed to maintain aerobic conditions.
- If liquid manure storage is unavoidable, install a facility to capture CH_4 for use as fuel, or at least "flare" it (controlled burn) for release as less-harmful CO_2.
- Spread manure when soil is well drained and aerobic, not while saturated, frozen, or snow-covered.
- Apply manure at rates consistent with sound nutrient management, based on soil tests.

See Resources, items 7-10, 14, 16, 17, 19-21, and 23-25 for more information on estimating and managing GHG emissions in organic livestock production. Items 10, 19, 21, and 25 provide case studies of successful MIG systems from different regions across the U.S.

Building soil health for climate adaptation and agricultural resilience

Practices that enhance soil food web function, build SOC throughout the soil profile, or enhance nutrient cycling and nutrient efficiency, tend to improve crop and livestock resilience to pests, diseases, and abiotic stresses such as drought and unpredictable frost dates. So, don't wait for the farm GHG models to become more accurate or for carbon trading markets to open. Climate-friendly soil-building practices can help your farming system adapt to climate changes already under way, and may improve your economic bottom line in the long run.

See Resources, items 7, 19-21, and 23 for an overview of farm management strategies for climate adaptation, including farm stories that illustrate successful strategies.

Resources

1. **Greenhouse Gases and Agriculture: Where does Organic Farming Fit?** (Lynne Carpenter-Boggs, D. Granatstein, and D. Huggins, 2016). In-depth webinar on agricultural GHG emissions and opportunities for mitigation. http://articles.extension.org/pages/30835/greenhouse-gases-and-agriculture:-where-does-organic-farming-fit-webinar

2. **Impact of Organic Grain Farming Methods on Climate Change** (Webinar by M. Cavigelli, USDA ARS Beltsville, MD, 2010). http://articles.extension.org/pages/30850/impact-of-organic-grain-farming-methods-on-climate-change-webinar

3. **Why the Concern about Nitrous Oxide Emissions?** (C. Cogger and D. Collins, Washington State University, and A. Fortuna, North Dakota State University, 2014).

4. **Management to Reduce N_2O Emissions in Organic Vegetable Production Systems**. (A. Fortuna, D. Collins, and C. Cogger). Webinars 1 and 2 at: http://articles.extension.org/pages/70280/two-part-webinar-series-on-greenhouse-gas-emissions-and-soil-quality-in-long-term-integrated-and-tra

5. **Soil Microbial Nitrogen Cycling for Organic Farms** (Louise Jackson, University of California, Davis, 2010). Describes how soil organisms regulate soil N retention, crop N nutrition, and N_2O emissions. http://articles.extension.org/pages/18657/soil-microbial-nitrogen-cycling-for-organic-farms

6. **Soil Fertility in Organic Farming Systems: Much More than Plant Nutrition** (Michelle Wander, University of Illinois, 2015). N cycling and practical organic nutrient management. http://articles.extension.org/pages/18636/soil-fertility-in-organic-farming-systems:-much-more-than-plant-nutrition

7. **On-farm Production and Utilization of AM Fungus Inoculum** (David Douds, Jr., USDA Agricultural Research Service, 2015). How to introduce and foster mycorrhizal fungi in organic fields. http://articles.extension.org/pages/18627/on-farm-production-and-utilization-of-am-fungus-inoculum

8. **New Times, New Tools: Cultivating Climate Resilience on Your Organic Farm** (L. Lengnick, 2016). Climate change adaptation, including adaptation stories from leading organic farms across the US. http://articles.extension.org/pages/73466/new-times-new-tools:-cultivating-climate-resilience-on-your-organic-farm

9. **Greenhouse Gas Emissions Associated with Dairy Farming Systems** (Tom Richard and Gustavo Camargo, Pennsylvania State University, 2011) Webinar comparing organic grass, organic grass/crop, conventional grazing, and confinement systems, and strategies to mitigate GHG. http://articles.extension.org/pages/32626/greenhouse-gas-emissions-associated-with-dairy-farming-systems-webinar

10. **Carbon Farming**. Special supplement to The Natural Farmer, Winter 2016-17, 32 pp. Practical C sequestration strategies that organic farms in New England utilize, including cover cropping, rotational grazing, and reduced tillage in small scale vegetable production. http://thenaturalfarmer.org/issue/winter-2016-17-carbon-farming/

11. **Grazing**. Special supplement to The Natural Farmer, Winter 2014-15, 32 pp. In-depth how-to information on management-intensive rotational grazing systems that sequester SOC and build soil, pasture, and herd health. Articles include Mob Grazing, Allen Savory's Holistic Management system, and several farmer articles on organic dairy cattle and lamb grazing systems. http://thenaturalfarmer.org/issue/winter-2014/

12. **Crop Intensification**. Special supplement to *The Natural Farmer*, Winter 2013-14, 32 pp. Describes the System of Rice Intensification (SRI), a non-flooded approach to high-yield organic rice production developed in Madagascar in the 1980s, and implemented successfully in the U.S. and elsewhere. Compared to paddy rice, SRI builds soil and crop health, and sharply reduces CH4 emissions. http://thenaturalfarmer.org/issue/winter-2013/

13. **Biochar in Agriculture**, special supplement to the Fall, 2015 issue of The Natural Farmer includes a number of articles on the history, science, practical applications, potential C sequestration benefits, and eco-social pros and cons of biochar as a soil amendment. http://thenaturalfarmer.org/issue/fall-2015/

14. **Rodale Institute's Farming Systems Trial,** https://rodaleinstitute.org/our-work/farming-systems-trial/

    a. *Farming Systems Trial Brochure. Summary after 35 years. 2015, 2 pp.* http://rodaleinstitute.org/assets/FST-Brochure-2015.pdf

    b. *The Farming Systems Trial, Celebrating 30 Years. 2011, 21 pp.* http://rodaleinstitute.org/assets/FST-bookletFINAL.pdf

    c. *Regenerative Organic Agriculture and Climate Change: a Down to Earth solution to Global Warming. 2014, 16 pp.* White paper based on Rodale's farming systems trial and other farming systems trials around the world. https://rodaleinstitute.org/assets/RegenOrgAgricultureAndClimateChange_20140418.pdf

    d. *Reversing Climate Change Achievable by Farming Organically***.** Blog post at https://rodaleinstitute.org/reversing-climate-change-achievable-by-farming-organically/

15. **Denitrification-Decomposition (DNDC) Calculator**, developed by Institute for the Study of Earth, Oceans, and Space at University of New Hampshire, includes modules for estimating GHG emissions in farming systems across the U.S. (US-DNDC Model), in livestock production (Manure-DNDC Model), and in forestry (Forest-DNDC Model). Models are updated periodically. http://www.dndc.sr.unh.edu/

16. **Organic Farming Footprint (OFoot),** developed by Center for Sustaining Agriculture and Natural Resources at Washington State University, aims to provide organic farmers, certifiers, and carbon traders with a scientifically sound yet simple estimate of C and N sequestration and net GHG balance for a given organic cropping scenario. Tool is available at https://ofoot.wsu.edu/, with additional information at http://csanr.wsu.edu/organic-farming-footprints/. The project has also updated the CropSyst model to support water and nutrient management of 28 additional crops. http://sites.bsyse.wsu.edu/cs_suite/cropsyst/documentation/articles/description.htm

17. **Shades of Green Dairy Farm Calculator** (Charles Benbrook, The Organic Center, 2014). Webinar offers instruction on the use of this GHG footprint calculator for dairy farms, and discusses the reasons for wildly inconsistent outcomes of GHG studies. http://articles.extension.org/pages/31790/shades-of-green-dairy-farm-calculator-webinar

18. **Northeast Dairy Emissions Estimator (NDEE)**, is an on-line tool to help dairy producers in New York and New England estimate GHG emissions from all parts of the farm operation, and evaluate tactics to reduce GHG. http://nedairy.ags.io/

19. **GoCrop** is an online nutrient management planning tool developed by University of Vermont. http://gocrop.com/. University of Illinois is refining modules for estimating plant available nitrogen and GHG emissions for organic systems.

20. **Two Percent Solutions for the Planet: 50 low-cost, low-tech, nature-based practices for combatting hunger, drought, and climate change** (Courtney White, Quivira Coalition, www.quiviracoalition.org. 2015. Chelsea Green Publishing, White River Junction VT, 227 pp.). Farmers, ranchers, conservationists, and food system activists share their stories and practical solutions to mitigate climate change, sequester carbon, and build resilient and abundant agricultural and food systems.

21. **The Soil will Save Us: how scientists, farmers, and foodies are healing the soil to save the planet** (Kristin Ohlson, 2014. Rodale Press, http://rodalebooks.com, 242 pp). Journalist Kristin Ohlson interviews leading scientists in sustainable agriculture and presents the science of soil C sequestration and soil health in plain English.

22. **Soil Health, Water & Climate Change: a Pocket Guide to What You Need to Know.** (Land Stewardship Project, October 2017, http://landstewardshipproject.org/smartsoil, 51 pp). Although not specifically geared towards organic systems, this Pocket Guide offers valuable practical information on conservation agriculture and management intensive rotational grazing practices for soil health, water quality, and C sequestration in the Midwest. The Guide also discusses impacts of climate disruption on agriculture and the urgent need—and opportunities—to build system resilience to weather extremes.

23. **NRCS Web Soil Survey,** https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm. Enter your full mailing address to locate your fields and identify your soil types and their properties including texture, depth, profile, drainage, topography, production capability, and constraints.

24. **NRCS Conservation Stewardship Program (CSP),** https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/csp/. The CSP offers technical and financial support for farmers and ranchers in adopting a whole-farm approach to resource stewardship that can enhance productivity and build resilience to weather extremes. CSP offers a menu of conservation enhancements including many that enhance SOC accrual, and some that are designed specifically for organic systems.

25. **Organic Agriculture Resource Area on the Extension website** http://articles.extension.org/organic_production. Articles, webinars, videos, courses on many aspects of organic vegetable, grain, and dairy production and marketing, developed by the eOrganic Community of Practice.

26. **ATTRA – National Sustainable Agriculture Information Service,** https://attra.ncat.org/ Offers publications, videos, and webinars on a wide range of topics; an Ask an Ag Expert service by phone or online; breaking research news and new information resources; and a search function that facilitates information retrieval on topics such as organic no-till or enterprise budgets. Some topic areas with substantial offerings include:

    a. Organic farming https://attra.ncat.org/organic.html

    b. Marketing, business, and risk management https://attra.ncat.org/marketing.html

    c. Urban agriculture https://attra.ncat.org/urban_ag.html

    d. Soils and compost https://attra.ncat.org/soils.html

Organic Farming, Soil Health, Carbon Sequestration, and Greenhouse Gas Emissions: A Summary of Recent Research Findings

Research continues to validate the four NRCS principles of soil health as guidelines for SOC sequestration, climate mitigation and adaptation. The National Organic Standards require organic producers to implement these principles *(see Concept #3 on page 27)*, using practices to *keep the soil covered, maintain living roots*, and *increase biodiversity* that non-organic conservation farmers also use routinely. As noted earlier, organic producers must take a different approach to the fourth principle to *minimize soil disturbance,* as the Organic Standards exclude synthetic fertilizers and herbicides, and require the use of organic and natural mineral nutrient sources.

Following are a few highlights from recent research findings on organic and sustainable agriculture, soil health, C sequestration, and climate mitigation and adaptation.

Agricultural carbon sequestration and climate mitigation

- Protecting the world's agricultural soils from erosion would reduce GHG emissions by ~ 1.1 billion tons CO_2-Ceq per year, or 7% of humanity's *total* annual GHG (Lal, 2003).
- Worldwide implementation of NOP requirements to "maintain or improve soil organic matter" would check the net decline in global SOC pools and thereby save 2 billion tons C/year, about 12% of total annual GHG (Harden et al., 2018).

Growing SOC in place: diversifying and intensifying the crop rotation

- In long-term trials, organic grain rotations have accrued 400-600 lb SOC/ac-year more than conventional grain rotations, primarily through *higher crop diversity* (e.g., three annual grains and a perennial forage *versus* corn-soy, Cavigelli et al., 2013; Delate et al., 2015b), and *greater mean duration of living plant cover* (e.g., 72% vs 42% of the calendar year, Wander et al., 1994).
- Organic orchards managed with living orchard floor cover have double the SOC levels of orchards maintained by clean tillage or herbicide fallow (Lorenz and Lal, 2016).
- Removing annual crop residues (e.g., corn stover for biofuel) severely depletes SOC and increases erosion risks (Blanco-Canqui et al., 2016a, 2016b)

- In semiarid regions, alternate year fallow (e.g., in dryland wheat) causes significant losses of SOC, even under no-till management, whereas planting one crop per year can sustain SOC levels (Halvorson et al., 2002; West and Post, 2002).

Growing and holding SOC in place: the central role of soil life:

- Organic practices that build soil microbial activity and biodiversity, generally enhance POXC (index of SOC stabilization) and PMC (SOC mineralization). POXC and PMC are better predictors of crop yields than other SOC fractions (Hurisso et al., 2016).

- Short-term increases in microbial biomass, microbial activity, and active SOC generally foretell longer-term increases in total SOC (Ghabbour et al., 2017; Lori et al., 2017).
- Cover crops with compost or manure applications may build more SOC and microbial functional biodiversity than either practice alone (Delate et al., 2015a, Hooks et al., 2015).
- As crop diversity increases from monoculture or corn-soy to four or five crops, microbial biomass, and functional diversity increase substantially (Tiemann et al., 2015).
- Reduced tillage (shallow ~ 3 inches, or non-inversion chisel plow) can improve microbial biomass and function in organic systems (Sun et al.,2016, Zuber and Villamil, 2016).
- Increased microbial respiration *per unit microbial biomass* (metabolic quotient) may indicate stresses on the soil biota, such as bare fallow, intensive tillage, or excessive soluble N (Fauci and Dick, 1994; Lori et al., 2017; Zuber and Villamil, 2016).
- Plant root symbiotic arbuscular mycorrhizal fungi (AMF) play a major role in nutrient cycling and transmuting plant organic C into stable SOC (Hamel, 2004; Rillig, 2004).

- Many cover crops, including oats, rye, sorghum, sunnhemp, and bahiagrass, host AMF and increase soil AMF populations (Douds, 2015; Duncan, 2017; Finney et al., 2017).
- AMF are deterred by tillage, fallow periods, and excessive soil P levels, which may occur with heavy use of compost or manure (Rillig, 2004).
- In-row subsurface drip irrigation can enhance water use efficiency and yield in organic tomato in low-rainfall regions, but leaving interrow soil unwatered can reduce microbial activity and SOC sequestration (Schmidt et al., 2018).

Sequestering C in perennial conservation plantings

- The NRCS Conservation Reserve Program (CRP), which converts degraded, marginal, or environmentally sensitive cropland to perennial grass or woodland has been estimated to sequester 3,200 lb C/ac annually in SOC and aboveground biomass (Manale et al., 2016).

- Permaculture home gardens planted on previously “under-utilized” land, and replanting degraded cropland to forest can accrue over 3,000 lb SOC/ac-year (Feliciano et al., 2018).

SOC saturation: how much C can the land hold?

- Restoration of global SOC to pre-agriculture levels (~ 8,000 BC) may be achievable with further advances in soil health management, and would absorb about 34 years’ worth of total global human-caused GHG emissions at current rates (Lal, 2016).

Looking below the surface: the hidden value of deep roots

- While most soil biological activity and nutrient release occurs in the top 12 inches, at least one-half of all SOC exists *below* 12 inches (Brady and Weil, 2008; Lal, 2015).
- Deep SOC is deposited mainly by plant roots, and long-term SOC accrual correlates closely with root biomass (Brady and Weil, 2018; Kell, 2011; Rasse et al., 2005).
- Many crops send roots 4 to 8 feet deep if soil conditions allow it. Cover crops such as pearl millet, sorghum-sudangrass, sunflower, sunnhemp, radish, and winter rye penetrate subsurface hardpan and facilitate deep rooting by subsequent crops (Rosolem et al., 2017).
- Organic practices can enhance cereal grain root biomass up to 60 percent (Hu et al., 2018).
- Managing for deep, extensive root systems, including plant breeding, may be a major opportunity for SOC sequestration, climate mitigation, and resilience (Kell, 2011).

Soil inorganic carbon: an important unanswered question

- Soils of prairie, semiarid, and arid regions hold 20-90% of their total carbon in the form of carbonates (soil inorganic carbon or SIC) (Brady and Weil, 2008).
- Recent research has documented significant management impacts on SIC, including SIC losses in organic systems in three out of seven organic-conventional comparisons.
- More research on SIC management in drier regions is needed (Lorenz and Lal, 2016).

Reducing soil disturbance: tillage

- Organic rotations with cover crops, compost or manure, and routine tillage often sequester as much C as conventional no-till (Syswerda et al., 2011; Wander et al., 2014).
- In one long term trial, the organic system accrued 400 lb/ac-year *more* SOC than continuous conventional no-till (Cavigelli et al., 2013).
- Practical reduced-till options for organic producers include ridge tillage, spading machine, chisel plow, rotary harrow (shallow till), and sweep-plow undercutter to terminate cover crops (Schonbeck et al., 2017).
- Compared to plow-disk or rototiller, terminating cover crops with spader or undercutter can reduce compaction and improve yields (Cogger et al., 2013; Wortman et al., 2016).

Reducing soil disturbance: organic versus conventional inputs

- Long-term use of soluble NPK fertilizers has depleted deep (12-18 inch) SOC and total soil N in the 100+ year Morrow Plots (University of Illinois) and many other long term trials around the world (Khan et al., 2007).
- Regular or heavy use of inorganic N can reduce microbial biomass, increase metabolic quotient, and compromise nutrient cycling and soil food web function (Fauci and Dick, 1994).
- Organic nutrient sources supported greater SOC accrual and AMF activity than inorganic (soluble) fertilizers (Zhang et al., 2016).

Compost, manure, and other organic amendments

- In a meta-analysis of 74 farming system studies, crop-livestock integrated organic systems that use on-farm manure and compost accrue ~240 lb SOC/ac-year) without relying on imported organic inputs (Gattinger et al., 2012).
- The percent of applied organic C retained as stable SOC is generally greatest for finished compost, followed by solid manure, uncomposted plant residues, and liquid manure (slurry) or liquid biogas digestate (in that order). (Cogger et al., 2013; Hurisso et al., 2016; Sadeghpour et al., 2016; Wuest and Reardon, 2016).

- One ton of finished compost may add ~220 lb stable SOC, but GHG emissions (primarily CH_4) during compost production have been estimated at 400 lb CO_2-Ceq per ton (Carpenter-Boggs et al., 2016). This analysis did not include offsets from diverting organic materials from landfills or manure lagoons.
- A single compost application (total N 225 lb/ac) to grasslands in a California study stimulated plant production and enhanced "ecosystem C storage" (soil + biomass C) by 25-70% over a three year period (Ryals and Silver, 2013).
- A single application of composted cattle manure (22 tons dry weight/ac) to a dryland wheat field in Utah enhanced wheat yields for 15 years, at the end of which SOC in the top 4 inches was double that in an adjacent unamended field (Reeve and Creech, 2015).

Biochar

- The biochar method is based on findings that up to half of the SOC in fertile prairie soils is "black carbon" left by prairie fires, and that charcoal from indigenous peoples' cooking fires helped create the anomalously fertile *terra preta* soils in the Amazon basin, where the native soils are nutrient-poor (Kittredge, 2015; Wilson, 2014).
- Biochar can stabilize SOC, improve soil aggregation and moisture retention, enhance nutrient availability, and improve crop yields. Results vary widely, and biochar works best in conjunction with compost or microbial inoculants (Blanco-canqui, 2017; Kittredge, 2015; Wilson, 2014).
- As biochar ages for several years in the soil, it acquires cation exchange capacity, binds to soil clays, and stabilizes SOC more effectively (Mia et al., 2017).

- Sustainability concerns include removal of plant biomass to create biochar, land grabs in the Global South for biochar feedstock, and GHG emissions during pyrolysis (North, 2015).
- Annual spring burning enhanced root biomass and AMF activity in a Kansas native tallgrass prairie, suggesting that prescribed burning might yield some of the benefits of biochar without the need for off-farm inputs (Wilson et al., 2009).

Nitrous oxide emissions from cropland soils

- Soil N_2O emissions are related to soil moisture, soluble N, and labile organic C; N_2O emissions are minimal when soil nitrate-nitrogen (NO_3-N) is below 6 ppm, or soil moisture is below field capacity (Cai et al., 2016; Thomas et al., 2017).
- N_2O emissions are directly related to impeded gas diffusion through the soil, and are therefore related to high soil moisture, fine (clayey) texture, and soil compaction (Balaine et al., 2016; Charles et al., 2017).
- N_2O emissions may increase in no-till if roll-crimped covers maintain soil moisture levels above field capacity (Linn and Doran, 1984).
- In conventional corn production, N_2O emissions rise sharply as rates of fertilizer N begin to exceed crop needs (Eagle et al., 2017; Millar et al., 2010).
- Peak N_2O emissions occur when rains follow soluble N applications in conventional agriculture, and after legume-rich cover crops or sod are plowed down in organic systems (Burger et al., 2005; Han et al., 2017; Westphal et al., 2018).
  - Red clover sod can contain 300 lb N/ac, with 85% of it below ground. A legume-grass sod is recommended for grain-forage rotations because it may emit less N_2O at plowdown than an all-legume sod (Han et al., 2017).

- In a meta-analysis and modelling study including 8,000 sites throughout Europe, adding legume cover crops to existing rotations (clover planted in any fallow period ≥ 2 months) was estimated to sequester about 3 tons SOC/ac over 80 years, but also to emit twice that amount of N_2O in CO_2-Ceq (Lugato et al., 2018).

- Studies on N_2O emissions from organic systems illustrate the need for careful management of organic N, and for more research. For example:
  - In Colorado organic lettuce trials, reducing preplant N (feather or blood meal) from 50 to 25 lb/ac cut N_2O emissions by 2/3 without affecting yield. Delivering the N in five split applications via drip fertigation (fish emulsion) during crop growth eliminated N_2O emissions altogether (Toonsiri et al., 2016).
  - In California, N_2O emissions from organic tomato systems were half those from conventional tomato systems (Burger et al., 2005).
  - Some California tomato fields under long term organic management exhibit "tight N cycling," in which plant-soil-microbe dynamics and expression of plant N uptake genes maintain low soil soluble N, yet adequate plant nutrition and high yields. These fields receive diverse low- and high-C:N organic inputs, and have high active and total SOC levels (Jackson, 2013; Jackson and Bowles, 2013).
  - Organic broccoli in California and Washington required more than 200 lb N/ac for optimal yield. Providing it with legume green manure + organic fertilizers released 11-27 lb N/ac-year as N_2O, which negates 1,400-3,400 lb/ac SOC sequestration (Collins and Bary, 2017; Li et al., 2009).
  - An organic grain rotation in Michigan fertilized with poultry litter (130-200 lb N/ac-year) emitted five times as much N_2O per year as the conventional system, mostly during intense bursts after heavy rains (Baas et al., 2015).
- Indirect emissions take place when NO_3-N is leached from the soil profile and a portion (estimated by IPCC at 0.75%) is converted to N_2O off site (Parkin et al., 2016).
  - Deep rooted cover crops like sorghum, millets, radish, and chicory scavenge NO_3-N, thus curbing indirect N_2O emissions (Rosolem et al., 2017).
  - Pearl millet, sorghum, groundnut, and signalgrass, release natural nitrification inhibitors that reduce NO_3-N leaching and N_2O emissions (Rosolem et al., 2017).

- Active AMF can promote tight nutrient cycling and reduce N_2O provided that soil P levels are not excessively high (Hamel, 2004; Hu et al., 2016).
- Lab trials suggest that biochar may help curb N_2O emissions (Cai et al., 2016).

Methane emissions in rice production

- Paddy (flooded cultivation) rice can release 110 lb CH_4-C/ac per cropping cycle (~840 lb CO_2-Ceq), and emissions increase when a cover crop is terminated prior to flooding or organic N fertilizer is applied (Dou et al., 2016).
- While flooded rice shows severe root decay by the time the crop flowers, roots of SRI (non-flooded) rice remain healthy, grow larger and deeper, host AMF and beneficial soil bacteria, and enhance nutrient use efficiency (Thakur et al., 2016).

Sequestering C and minimizing GHG emissions in organic livestock production

- Higher enteric CH_4 and lower milk production in grass-fed organic dairy cows double direct GHG emissions per gallon of milk compared to conventional confinement dairy (Richard and Camargo, 2011). However, this comparison does not consider potential SOC sequestration under management intensive grazing (MIG).
- Compared to continuous grazing in the cow-calf phase of beef production in the Southern Great Plains region of Texas, multipaddock grazing enhanced SOC sequestration by 2,400 lb/ac annually for 10 years, improved forage quality, and thereby reduced enteric CH_4 about 30%, resulting in a net negative GHG footprint (Wang et al., 2015).
- In Michigan, conversion of grass-finishing beef operations from continuous grazing to adaptive multipaddock grazing sequestered 3,200 lb C/ac annually for four years, and reduced enteric CH_4 by 36%, again resulting in a net GHG sink (Stanley et al., 2018).
- In coastal South Carolina, converting depleted sandy loam (0.5% SOC) from row crops to Bermuda grass pasture under MIG accrued 6,300 lb C/ac annually during the third through sixth year, after which annual SOC accrual tapered off (Machmuller et al., 2015).
- Producer success stories with MIG abound from across the U.S.; before and after photos show dramatic soil and forage health outcomes from MIG. One farm in upstate New York documented SOC gains well over 3 tons/ac in three years through dozens of soil tests. (Kittredge, 2014-15).

- Crop-livestock integration can enhance SOC, improve nutrient cycling, and mitigate GHG emissions. While baling-off cover crops or corn residues reduces SOC and promotes erosion, these resources can be grazed without seriously compromising soil health (Blanco-Canqui et al., 2016a, 2016b; Franzluebbers and Studeman, 2015).

Breaking the vicious cycle: positive feedback between greenhouse gases and climate change

- Warming temperatures will accelerate SOC decomposition; for example, models indicate that, with continued warming, no-till corn fields in Ohio that are currently sequestering C will begin losing SOC before the end of the century (Maas et al., 2017).
- Impacts will be most severe in cold climates (a 10% SOC loss for every 1.8°F increase), and less pronounced in tropical regions (3% loss per 1.8°F) (Kirschbaum, 1995).
- Thawing of permafrost may lead to an additional 600 million tons SOC loss per year globally, a 30% increase over current net SOC loss (Hardin et al., 2018).
- Fall tillage combined with warmer, drier winters and springs leaves Corn Belt soils in an excessively “fluffy” condition that hinders seed-soil contact and stand establishment, leading to further SOC losses to erosion (Daigh and DeJong-Hughes, 2017).
- Soil N_2O emissions are directly related to soil temperature, and thus may increase as climates warm. In a meta-analysis of 27 studies across the Corn Belt, N_2O emissions increased 18-28% with every 1.8° F increase in mean July temperatures (Ball et al., 2007; Eagle et al., 2017).
- Rising atmospheric CO_2 levels may directly accelerate SOC losses. In Florida, scrub oak lands experimentally subjected to elevated CO_2 lost SOC even as tree growth increased (Petit, 2012).
- Experimental CO_2 enrichment of grazing lands increased fungal biomass and N_2O emissions, an unexpected finding given the role of mycorrhizal fungi in mitigating N_2O (Rillig, 2004; Zhong et al., 2018).
- No-till based conservation systems that store SOC near the surface may not suffice in the face of these trends; new, innovative approaches, such as integrated organic systems and deep SOC sequestration, will be needed to break the vicious cycle (Kell, 2011).

Questions for Further Research: Organic Farming Soil Carbon, Soil Health, and Climate

Findings to date suggest that widespread adoption of sustainable organic production systems could make the world's agriculture climate-neutral, and enhance the resilience of farms and ranches to the impacts of climate changes already underway. Multiple studies and meta-analyses on organic systems have validated the National Organic Standards and the NRCS Four Principles of Soil Health Management as frameworks for climate-friendly and adaptive farming and ranching. In addition, researchers have identified some promising new strategies that merit further research and development into practical guidelines for producers. However, several major hurdles to realizing the vision of soil- and climate-friendly agricultural systems remain, including:

- A need for tools to help producers and service providers translate framework principles into effective, economically viable, site-specific applications.
- A need for practical tools that farmers can use to measure SOC, estimate GHG emissions, and monitor progress toward soil health and climate goals.
- A need for crop cultivars and livestock breeds that will thrive and yield well in sustainable organic production systems.
- Knowledge gaps in areas such as soil microbial community dynamics, the nature of stable SOC, and the coupling of C and N cycles in the agroecosystem.
- A need to address economic, logistical, policy, and social barriers to farmer adoption of soil health and climate mitigation practices.

Putting principles into practice

Several pivotal strategies appear to offer substantial and fairly consistent benefits to soil health, SOC sequestration, climate mitigation, and agricultural resilience:

- Crop intensification – maximizing plant biomass and year round soil coverage.
- Maximizing living roots – root biomass, depth, duration, diverse root architecture.
- Diversified crop rotation – production crops, cover crop mixes, perennial sod phase.

- Reducing soil disturbance – physical (tillage, traffic), chemical (inputs), and biological (overgrazing, invasive exotic species).
- Integrated organic soil and crop management: diverse rotation + cover crops + organic amendments + nutrient management + soil-friendly tillage practices.
- Management-intensive rotational grazing for livestock systems.
- Crop-livestock integration.

In implementing these strategies on their farms, organic producers must learn new skills and consider new costs (e.g., cover crop seed, planting equipment for new crops), risks (e.g., weed pressure and potential yield reductions in reduced tillage systems), and income foregone (e.g., adding a sod break to an intensive vegetable rotation). There are potential economic benefits as well, ranging from new crop or livestock enterprises to long term improvements in soil health, fertility, and resilience. Farmers may have questions such as:

- What are the most cost-effective and least risky practices to increase crop biomass, soil coverage, and living roots in my crop rotation?
- How can I ensure that new crops added to the rotation will be profitable?
- What are the best cover crops for my farm and crop rotation?
- When and how should the cover crops be terminated?
- How can I minimize N_2O emissions upon plowing-down the sod phase of the rotation?
- How much compost should I apply?
- What are the most practical and least risky ways to reduce tillage intensity?

The answers to these questions depend so much upon site specific factors—climate, soil, topography, farming system, crop and livestock mix, markets, etc., that research cannot yield prescriptive answers for all producers. In addition, solutions developed in collaboration with farmers engaged as equal partners are much more readily adopted than formulae developed and delivered in a top-down manner. Research outcomes that could help organic producers implement soil-building, climate-friendly, and profitable management practices include:

- Tools to help the farmer select the best system components (crop rotation, cover crops, organic fertilizers and amendments, tillage tools and techniques, etc) for their climate, soil, production system, and market constraints and opportunities.

- A process similar to the NRCS's Comprehensive Conservation Planning that farmers and service providers can use to develop the best site-specific strategies to meet identified production, soil health, and climate mitigation/adaptation goals.
- Farm case studies and success stories in soil health, C sequestration, and climate adaptation.
- Enterprise budgets and business planning templates to help producers evaluate the economic viability of current and potential new crops in a diversified rotation.
- Economic analysis and risk management tools to help producers evaluate the potential costs and benefits of adopting a new system or practice.

Monitoring SOC, soil N, GHG, and progress toward soil and climate goals

Farmers need practical tools to monitor soil health and fertility, and the GHG footprint of their production systems. These include simple, reliable tests that can be conducted on site or by a standard soils lab for a modest fee, and user-friendly computer models and decision tools that provide output that is relevant for organic systems. Most soil test labs estimate total SOM by loss on ignition, a few labs offer POXC (index of SOC stabilization) and PMC (SOC mineralization), and several research teams have developed experimental protocols for estimating the release of plant-available N via SOC mineralization. Additional research is needed to:

- Develop improved sampling and testing protocols for accurate and meaningful measurement of total SOC, which usually accounts for about 58% of SOM.
- Develop practical sampling and testing protocols for monitoring subsurface SOC beyond the normal sampling depths of 6 to 12 inches.
- Develop benchmarks and realistic site-specific goals for total SOC based on climate (temperature and rainfall regimes), soil type and texture, and production system.
- Verify and demonstrate a simple in-field soil nitrate-N test as a N monitoring and management tool in organic production (Collins and Bary, 2017).
- Develop reliable, practical methods to estimate plant-available N released through SOC mineralization.
- Make practical, reliable on-farm monitoring of POXC, PMC, and other measures of soil microbial activity and SOC fractions widely available and affordable.

- Complete development of OFOOT and organic modules for tools such as DNDC and COMET-Farm, so that organic producers can estimate soil N_2O emissions, enteric CH_4, and net total GHG of their farming system, and identify mitigation opportunities.

Plant and animal breeding for SOC sequestration, GHG mitigation, and resilience in organic farming

Development and release of public crop cultivars and livestock breeds that thrive and perform well in sustainable organic production systems could enhance organic farmers' yields, and thereby reduce the GHG footprint per unit output for organic farm products. New cultivars and breeds that combine this capacity with desired market traits (flavor, nutritional quality, etc.) will improve organic producers' bottom line and increase their capacity to implement climate-friendly soil health management practices. Farmer participatory plant breeding, in which producers work with plant breeders to identify objectives, conduct on-farm breeding and selection, and produce seed, have proven cost-effective in making new, improved cultivars available to farmers (Schonbeck et al., 2016). In addition, certain plant breeding objectives based on known heritable traits can contribute *directly* to SOC sequestration, GHG mitigation, and resilience. These include:

- Nutrient use efficiency, tight N cycling, capacity to thrive in soils low in soluble N.
- Enhanced rhizosphere interaction with mycorrhizal fungi, N fixing bacteria, and other beneficial soil biota that facilitate plant nutrition, vigor, and resilience.
- Water use efficiency.
- Resilience to drought, excessive moisture, temperature extremes, and other stresses.
- Capacity to maintain normal production despite reduced or unpredictable chill-hours and frost dates resulting from climate change (perennial fruit and nut crops).
- Deep, extensive, high biomass root systems.
- Enhanced total biomass, increased plant residue return to the soil while maintaining yield, market qualities, and ease of harvest.

Climate related livestock breeding objectives might include:

- Capacity to thrive in management-intensive rotational grazing (MIG) systems.
- Reduced enteric methane production in ruminants.
- Increased resilience to heat and other weather extremes.

Developing promising leads into practical applications

Soil health research over the past ten years has identified several new strategies that show potential to enhance agricultural SOC sequestration or GHG mitigation. Some are based on one or a few studies, and merit further testing in a diversity of regions, soils, climates, and organic production systems, to evaluate their potential for practical application. Others have a more substantial track record in research, and need fine-tuning, demonstration, and outreach to facilitate more widespread and successful adoption. Promising new strategies and associated research priorities include:

- *Tight nitrogen cycling:* Identify practical methods to promote tight N cycling and N use efficiency in a wider range of organic vegetable, fruit, and grain crops, across a wider range of soils, climates, and regions (Jackson, 2013; Jackson and Bowles, 2013).
- *System of Rice Intensification:* Refine, evaluate, and demonstrate SRI for yield and GHG mitigation in organic rice in U.S. rice growing regions (Thakur et al., 2016).
- *Deep roots, soil health, and climate:* Explore the potential of deep rooted crops and organic practices to enhance deep SOC sequestration and N recovery; develop and demonstrate practical applications (Hu et al., 2018; Kell 2011; Rosolem et al., 2017).
- *Compost for grazing lands:* Determine whether the multi-year gains in forage biomass and SOC from a single compost application in California grasslands can be replicated in other regions, soils, and climates (DeLonge et al., 2013; Ryals and Silver, 2013).
- *Prescribed burning for in-situ biochar:* Conduct trials on grazing lands in different regions and climates to determine whether prescribed fire generates *in situ* biochar and benefits soil food web function and root growth as observed in Kansas (Wilson, et al., 2009).
- *Forage quality and livestock GHG mitigation:* Verify and demonstrate efficacy of MIG in reducing ruminant enteric CH_4 emissions through improved forage quality on grazing lands in different regions across the U.S. (Stanley et al., 2018; Wang et al., 2015).

Addressing key knowledge gaps

Additional research is needed to better understand soil C and N dynamics and soil-plant-microbe interactions as they influence soil fertility, C sequestration, and GHG emissions in organic systems. For example, the chemical nature and sequestration mechanisms of “stable” SOC remain unclear, and sharply contrasting conceptual models of SOC-related processes have been proposed (Ghabbour et al., 2017; Lehman and Kleber, 2015; Six et al., 2002). Similarly, since organic N sources release plant available N through biological processes, their impacts on soluble soil N levels and N_2O emissions are more challenging to predict and manage than conventional fertilizer N (Charles et al., 2017). Research-based N recommendations for organic production are not available for many crops, and research-based estimates vary from as little as 25 lb N/ac to optimize organic lettuce yields (Toonsiri et al., 2016) and 20 - 40 lb/ac to replace N removed in mixed vegetable harvests (Wander et al., 2015), to > 200 lb/ac to optimize organic broccoli yields (Li et al., 2009; Collins and Bary, 2017).

GHG impact analyses for organic practices can give widely different outcomes depending on the factors included in the analysis. For example, the composting process has been reported to emit more GHG (in CO_2-Ceq) than is sequestered as stable C in the compost itself; yet, composting can prevent much larger emissions by diverting organic materials from waste streams (Carpenter-Boggs et al., 2016; DeLonge et al., 2013). The direct GHG emissions of organic grassfed cattle have been estimated at double those from conventional confinement, yet total GHG footprint of grassfed livestock can become negative (net mitigation) based on rapid SOC sequestration during the first few years after implementation of MIG (Richard and Camargo, 2011; Stanley et al., 2018). However, composting and landfill are not the only two possible fates of organic “wastes,” and the initial rapid increase in SOC under MIG levels off after the first decade. Thus, the full climate implications of these practices merit further study.

Priorities for additional research on soil, GHG, and climate in organic production include:

- Mechanisms of SOC stabilization and de-stabilization, and potential impacts of warming climates, tillage, fertility inputs, and other management practices on long term SOC sequestration (Grandy et al., 2006; ITPS, 2015; Lehman and Kleber, 2015).
- Realistic estimates of total SOC sequestration from improved practices, taking into consideration climate, soil type and texture, and production system.
- Roles of soil bacteria, mycorrhizal fungi, nematodes, plant roots, and other soil food web components in soil C and N dynamics, SOC accrual, and GHG emissions..
- Efficacy of microbial inoculants (produced on-farm or commercial products) for soil health, climate mitigation, and adaptation.

- Impacts of inherent soil properties (soil series, texture, horizons, drainage, mineralogy, natural hardpans, etc.), on C and N cycling, soil-plant-microbe dynamics, and response of SOC and GHG emissions to organic management practices.
- Best management of organic N inputs for soil health, plant nutrition and N_2O mitigation:
  - N sources – compost, manure, organic N fertilizers, and legume cover crops.
  - Potential to mitigate N_2O emissions from green manure plowdown by using grass-legume mixtures in lieu of all-legume, and non-tillage termination methods.
  - Placement and timing – preplant broadcast or band, or in-row drip fertigation.
  - Application rates – establish optimum N rates for a wide range of crops, based on trials in organic fields in different regions, climates, and soil.
- Life cycle GHG analyses of compost production and application, including:
  - Comparison of composting with direct land application of uncomposted residues, as well as with GHG-intensive waste disposal (landfills, manure lagoons).
  - Best management practices for composting processes, and GHG impacts of variations from optimum starting C:N ratios, aeration/windrow turning schedules, and moisture management.
- Optimum compost use rates, considering soil nutrient levels, direct costs and benefits, and potential synergism between cover crops and compost on SOC seqeustration.
- Life cycle GHG analysis of biochar manufacture and use.
- Best irrigation practices, including potential tradeoffs between N_2O mitigation and reduced SOC sequestration under in-row drip fertigation (Schmidt et al., 2018; Toonsiri et al., 2016).
- Impacts of organic inputs and management practices on soil inorganic carbon (SIC) in soils of drier regions (Lorenz and Lal, 2016).
- Life cycle GHG analyses for MIG systems for organic beef, dairy, and other livestock, conducted over time spans beyond the initial period of rapid SOC sequestration after conversion from cropping or continuous grazing to MIG.
- Additional strategies to mitigate enteric CH_4 in organic livestock, including forage species composition, and NOP-allowed dietary supplements.

Overcoming socioeconomic, logistical, cultural, and policy barriers to adoption of climate-friendly organic farming practices

Farmers face significant economic, social, cultural, and policy barriers to adopting soil- and climate-friendly production systems. For example, many of the practices discussed here entail up-front costs, and economic benefits arising from improved production and resilience or reduced input needs may not begin to accrue for several years. Given the great variability in soil-crop-livestock-climate interactions, and the current lack of political support for climate mitigation, financial support through carbon markets or carbon offset payments does not appear feasible at this time.

While socioeconomic and policy issues were beyond the immediate scope of the research review on which this Guide is based, it has become clear that several key constraints and missed opportunities must be addressed before the potential for organic agriculture to mitigate GHG emissions and build agricultural resilience can be fully realized. These include:

- Lack of educational resources and qualified technical assistance to help organic farmers learn and successfully adopt new soil health and climate mitigation practices while maintaining or improving their bottom line.
- Actual and perceived risks associated with new practices, including the costs of acquiring new skills, equipment, and infrastructure, and lack of carbon markets or other cost offset for ecosystem services.
- Crop insurance and government farm policies that create disincentives to adopting conservation practices, such as cover cropping and diversified crop rotations.
- Social and cultural forces that deter adoption of new sustainable practices, including peer pressure and social norming in farming communities, as well as a pervasive political climate hostile to climate change mitigation science and action.
- Current agricultural and food system infrastructure, markets, and government policies that perpetuate the segregation of U.S. agriculture into livestock production within confined animal feeding operations (CAFOs), commodity grains (corn-soy-wheat), and specialty crops; lack of informational, market, and policy support for diversified systems.

- Society-wide waste management systems that fail to return organic residues to the land.
- Unrealized potential to expand urban agriculture, agroforestry, and permaculture practices, which are known for their high per-acre C sequestration potential.

Conclusion

A national and global investment in further research into these topics is urgently needed to enable all producers—organic, transitioning, and non-organic—to make effective contributions to climate mitigation and to enhance the resilience of their farming and ranching systems to impacts of climate change. Based on research outcomes to date, producers and society as a whole can anticipate a substantial return on investment in this field of research.

References

Aguilera, E., L. Lassaletta, A. Gattinger, and B. S. Gimeno. 2013. *Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a metaanalysis*. Agric. Ecosyst. Environ. 168, 25–36.

Alhameid, A., M. Ibrahim, S. Kumar, P. Sexton, and T. E. Schumacher. 2017. *Soil Organic Carbon Changes Impacted by Crop Rotational Diversity under No-Till Farming in South Dakota, U.S.A*. Soil Sci. Soc. Am.J. 81(4): 868-877.

Andrews, S. 2006. *Crop residue removal for biomass energy production: effects on soils and recommendations*. White Paper published for NRCS soil Quality National Technology Development Team, updated February 22, 2006. 15 pp.

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 Systems*. Final report for ORG project 2011-04952. CRIS Abstracts.*

Balaine, N., T. J. Clough, M. H. Beare, S. M Thomas, and E. D. Meenken. 2016. *Soil Gas Diffusivity Controls N2O and N2 Emissions and their Ratio* Soil Sci. Soc. Am. J. 80 (3): 529-540.

Ball, B.C., C. A. Watson, and I. Crichton. 2007. *Nitrous oxide emissions, cereal growth, N recovery and soil nitrogen status after ploughing organically managed grass/clover swards*. Soil Use. Manag. 23, 145–155.

Barbercheck, M. E., D. A. Mortensen, H. Karsten, E. S. Sanchez, S. W. Duiker, J. A. Hyde, and N. E. Kiernan. 2008. *Organic Weed Management: Balancing Pest Management and Soil Quality in a Transitional System*. Final report on ORG project 2003-04619. CRIS Abstracts.*

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.

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-M. Fortuna, L. J. Cihacek, and P. M. Carr. 2015. *Use of Laboratory Incubation Techniques to Estimate GHG Footprints from Clean and No-Tillage Organic Agroecosystems.* ASA-CSSA-SSSA Meetings Nov 15-18, 2015 Minneapolis, oral presentation. https://scisoc.confex.com/crops/**2015**am/webprogram/start.html.

Blanco-Canqui, H. 2017. *Biochar and Soil Physical Properties.* Soil Sci. Soc. Am. J. 81 (4): 687-711.

Blanco-Canqui, H., and C. A. Francis. 2016. *Building resilient soils through agroecosystem redesign under fluctuating climatic regimes.* J. Soil & Water Conserv. 71(6): 127A-133A.

Blanco-Canqui, H., A. L. Stalker, R. Rasby, T. M. Shaver, M. E. Drewnoski, S. van Donk, and L. Kibet. 2016a. *Does Cattle Grazing and Baling of Corn Residue Increase Water Erosion?* Soil Sci. Soc. Am. J. 80 (1): 168-177.

Blanco-Canqui, H., J. Tatarko, A. L. Stalker, T. M.Shaver, and S. J. van Donk. 2016b. *Impacts of Corn Residue Grazing and Baling on Wind Erosion Potential in a Semiarid Environment.* Soil Sci. Soc. Am. J. 80(4): 1027-1037.

Brady, N. C., and R. R. Weil. 2008. *The Nature and Properties of Soils,* 14th Edition. Pearson Education, Inc., Upper Saddle, NJ. 992 pp.

Brown, S., C. Kruger, and S. Subler. 2008. *Greenhouse gas balance for composting operations.* Journal of Environmental Quality 37: 1396-1410.

Burger, M., L. E. Jackson, E. J. Lundquist, D. T. Louie, R. L. Miller, D. E. Rolston, and K. Scow. 2005. *Microbial responses and nitrous oxide emissions during wetting and drying of organically and conventionally managed soil under tomatoes.* Biol Fertil Soils 42:109-18.

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.

Carpenter-Boggs, L., D. Granatstein, and D. Huggins. 2016. *Greenhouse Gases and Agriculture: Where does Organic Farming Fit* (Webinar). http://articles.extension.org/pages/30835/greenhouse-gases-and-agriculture:-where-does-organic-farming-fit-webinar.

Cavigelli, M. 2010. *Impact of Organic Grain Farming Methods on Climate Change* (Webinar) http://articles.extension.org/pages/30850/impact-of-organic-grain-farming-methods-on-climate-change-webinar.

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.

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

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

Cogger, C, A. Fortuna, and D. Collins. 2014. *Why the Concern about Nitrous Oxide Emissions?* Webinar 1 at: http://articles.extension.org/pages/70280/two-part-webinar-series-on-greenhouse-gas-emissions-and-soil-quality-in-long-term-integrated-and-tra.

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 project 2008-01247. CRIS Abstracts.*

Collins, D. P. and A. Bary. 2017. *Optimizing nitrogen management on organic and biologically intensive farms.* Proceedings of the Special Symposium on Organic Agriculture Soil Health Research at the Tri-Societies Annual Meeting, Tampa, FL, October 22-25, 2017. http://articles.extension.org/pages/74555/live-broadcast:-organic-soil-health-research-special-session-at-the-tri-societies-conference.

Coulter, J. A., T. A. Delbridge, R. P. King, D. L. Allan, and C. C. Sheaffer. 2012. *Productivity, Economics, and Soil Quality in the Minnesota Variable-Input Cropping Systems Trial*. Crop Management - Symposium Proceedings: USDA Organic Farming Systems Research Conference. Crop Management 12(1): https://dl.sciencesocieties.org/publications/cm/tocs/12/1.

Daigh, A. L. and J. Dejong-Hughes. 2017. *Fluffy soil syndrome: when tilled soil does not settle.* J. Soil & Water Conserv 72(1); 10A-14A.

Delate, K. 2013. *Developing Carbon-positive Organic Systems through Reduced Tillage and Cover Crop Intensive Crop Rotation Schemes.* Final report for ORG project 2008-01284. CRIS Abstracts.*

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 project 2010-03956. CRIS Abstracts*

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

Delgado, J. A., P. M. Groffman, M. A. Nearing, T. Goddard, D. Reicosky, R. Lal, N. R. Kitchen, C. W. Rice, D. Towery, and P. Salon. 2011. *Conservation practices to mitigate and adapt to climate change.* J. Soil Water Conserv. 66: 118A-129A.

DeLonge, M. S., R. Ryals, and W. L. Silver. 2013. *A lifecycle model to evaluate carbon sequestration potential and greenhouse gas dynamics of managed grasslands.* Ecosystems 16: 962-979.

Dimitri, C., L. Kemp, J. Sooby, and E. Sullivan. 2012. *Organic Farming for Health and Prosperity.* Organic Farming Research Foundation (www.ofrf.org), 76 pp.

Dou, F., M. Hons, J. Pl Wight, and H. A. Torbert. 2016. *Improving soil quality, C sequestration, and mitigating greenhouse gas emissions in organic rice production.* Proposal and final report for ORG project 2012-02983. CRIS Abstracts.*

Douds, D. 2015. *On-farm Production and Utilization of AM Fungus Inoculum.* http://articles.extension.org/pages/18627/on-farm-production-and-utilization-of-am-fungus-inoculum.

Duncan, J. 2017. *Cover crop options for hot and humid areas*. ATTRA bulletin, National Center for Appropriate Technology, www.attra.ncat.org, 20 pp.

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.

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

Fauci, M. F., and R. P. Dick. 1994. *Soil Microbial Dynamics: Short- and Long-Term Effects of Inorganic and Organic Nitrogen*. Soil Sci. Soc. Am. J. 58 (3): 801-806.

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.

Finney, D. M., J. S. Buyer, and J. P. Kaye. 2017. *Living cover crops have immediate impacts on soil microbial community structure and function*. J. soil & Water Conserv 72(4): 361-373.

Fortuna, A., D. Collins, and C. Cogger. 2014. *Management to Reduce N_2O Emissions in Organic Vegetable Production Systems*. Webinars at: http://articles.extension.org/pages/70280/two-part-webinar-series-on-greenhouse-gas-emissions-and-soil-quality-in-long-term-integrated-and-tra.

Franzluebbers, A. J., and J. A. Stuedemann. 2015. *Does grazing of cover crops impact biologically active soil carbon and nitrogen fractions under inversion or no tillage management?* J. Soil & Water Conserv. 70(6): 365-373.

Galik, C. S., B. C. Murray, and M. C. Parish. 2017. *Near-Term Pathways for Achieving Forest and Agricultural Greenhouse Gas Mitigation in the U.S*. Climate 2017, 5, 69; doi:10.3390/cli5030069 www.mdpi.com/journal/climate.

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 top soil 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.

Gottshall, C. B., M. Cooper, and Ss M. Emery. 2017. *Activity, diversity and function of arbuscular mycorrhizae vary with changes in agricultural management intensity.* Agriculture, Ecosystems and Environment 245: 142-149.

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?* Agron. J. 98(6): 1377-1383.

Gruver, J., R. R. Weil, C. White, and Y. Lawley. 2016 *Radishes A New Cover Crop for Organic Farming Systems.* http://articles.extension.org/pages/64400/radishes-a-new-cover-crop-for-organic-farming-systems.

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 U.S. agroecosystems.* Agriculture, Ecosystems and Environment 245: 124-134.

Harden, J. .W., G. Hugelius, A. Ahlström, J. C. Blankinship, B. Bond-Lamberty, C. R. Lawrence, J. Loisel, A. Malhotra, R. B. Jackson, S. Ogle, C. Phillips, R. Ryals, K. Todd-Brown, R. Vargas, S. E. Vergara, M. F. Cotrufo, M. Keiluweit, K. A. Heckman, S. E. Crow, W. L. Silver, M. DeLonge, and L. E. Nave. 2018. *Networking our science to characterize the state, vulnerabilities, and management opportunities of soil organic matter.* Global Change Biology (2018) 24: e705-e718.

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 project 2010-01954. CRIS Abstracts.*

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 project 2012-02978. CRIS Abstracts.*

Hu, T., P. Sorensen, E. M. Wahlstrom, N. Chirinda, B. Sharif, X. Li, and J. E. Olesen. 2018. *Root biomass in cereals, catch crops and weeds can be reliably estimated without considering aboveground biomass.* Agriculture, Ecosystems, and Environment 251: 141-148.

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* https://www.ipcc.ch/report/ar5/wg3/. *Chapter 11 Agriculture, Forestry, and Other Land Use (AFOLU),* and *Annex II Metrics and Methodology.*

Intergovernmental Technical Panel on Soils (ITPS). 2015. *Status of the World's Soil Resources: Technical Summary.* United Nations Food and Agriculture Organization.

Jackson, L. 2013. *Researcher and Farmer Innovation to Increase Nutrient Cycling on Organic Farms.* Proposal and final report for OREI project 2009-01415. CRIS Abstracts.*

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.

Jackson, L., V. R. Haden, A. D. Hollander, H. Lee, M. Lubell, V. K. Mehta, T. O'Geen, M. Niles, J. Perlman, D. Purkey, W. Salas, D. Sumner, M. Tomuta, M. Demsey, and S. M. Wheeler. 2012. *Adaptation Strategies for Agricultural Sustainability in Yolo County, California: a White Paper from the California Energy Commission's California Climate Change Center.* University of California, Davis. 205 pp. http://www.energy.ca.gov/2012publications/CEC-500-2012-032/CEC-500-2012-032.pdf.

Jones, C. 2010. *Soil carbon: can it save agriculture's bacon?* http://www.amazingcarbon.com/PDF/JONES-SoilCarbon&AgricultureREVISED(18May10).pdf.

Kane, D. 2015. *Carbon sequestration potential on agricultural lands: a review of current science and available practices.* Breakthrough Strategies and Solutions and National Sustainable Agriculture Coalition. http://sustainableagriculture.net.publications. 35 pp.

Kell, D.B. 2011. *Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration*. Ann. Bot. 108(3): 407–418.

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.

King, A. E., and K. S. Hofmockel. 2017. *Diversified cropping systems support greater microbial cycling and retention of carbon and nitrogen*. Agriculture, Ecosystems and Environment 240: 66-76.

Kirschbaum, M.U.F. 1995. *The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage*. Soil Biology and Biochemistry. 27(6): 753–760.

Kittredge, J. 2014-15. *Grazing success through observation and planning at Bishopp Family Farm.* The Natural Farmer, winter 2014-15, pp B23-B26.

Kittredge, J. 2015 *Introduction to biochar in agriculture.* The Natural Farmer, fall 2015, pp B1-B3.

Kittredge, J. 2016-17. *The truth about ruminants and methane.* The Natural Farmer, winter 2016-17, p. 18.

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 & Water Conserv. 70(6): 141A.

Lal, R. 2016. *Beyond COP21: Potential challenges of the "4 per thousand" initiative.* J. Soil & Water Conserv. 71(1): 20A-25A.

Larsen E, J. Grossman, J. Edgell, G. Hoyt G, D. Osmond D, and S. Hu. 2014. *Soil biological properties, soil losses and corn yield in long-term organic and conventional farming systems.* Soil Tillage Res. 139:37-45.

Lee, K.S., Y. C. Choe, and S. H. Park. 2015. *Measuring the environmental effects of organic farming: a meta-analysis of structural variables in empirical research.* J. Environ. Manag. 162, 263–274.

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 Contentions Nature of Soil Organic Matter.* Nature 528:60-68.

Lengnick, L. 2016. *New Times, New Tools: Cultivating Climate Resilience on Your Organic Farm.* http://articles.extension.org/pages/73466/new-times-new-tools:-cultivating-climate-resilience-on-your-organic-farm.

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.

Linn, D., and J. Doran. 1984. *Effect of Water-Filled Pore-Space on Carbon-Dioxide and Nitrous-Oxide Production in Tilled and Nontilled Soils.* Soil Sci. Soc. Am. J. 48(6): 1267–1272.

Lorenz, K., and R. Lal. 2016. *Environmental Impact of Organic Agriculture. Advances in Agronomy* 139: 99-152.

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.

Lugato, E., A. Leip, and A. Jones. 2018. *Mitigation potential of soil carbon management overestimated by neglecting N2O emissions*. Nature Climate Change 8: 219-223. www.nature.com/natureclimatechange.

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.

Maas, E. D. v. L., R. Lal, K. Coleman, A. Montenegro, and W. A. Dick. 2017. *Modeling soil organic carbon in corn (Zea mays L.)-based systems in Ohio under climate change*. J. Soil & Water Conserv. 72(3): 191-204.

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.

Manale, A., S. Hyberg, N. Key, S. Mooney, T. L. Napier, and M. Ribaudo. 2016. *Climate change and U.S. agriculture: opportunities for conservation to reduce and mitigate emissions and to support adaptation to rapid change*. J. Soil & Water Conserv. 71(1): 69-81.

Marshall, M.W., P. Williams, A. Mirzakhani Nafchi, J. M. Maja, J. Payero, J. Mueller, and A. Khalilian. 2016. *Influence of Tillage and Deep Rooted Cool Season Cover Crops on Soil Properties, Pests, and Yield Responses in Cotton*. Open Journal of Soil Science , 6, 149-158. http://dx.doi.org/10.4236/ojss.2016.610015.

McDaniel MD, L. K., Tiemann, and S. Grandy. 2014. *Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis*. Ecol Appl. 24(3):560-70.

McGee, J.A., 2015. *Does certified organic farming reduce greenhouse gas emissions from agricultural production?* Agric. Hum. Values 32, 255–263.

McLauchlan K. 2006. *The nature and longevity of agricultural impacts on soil carbon and nutrients: A review*. Ecosystems 9(8):1364-82.

Mia, S., F.A. Dijkstra, B. Singh. 2017. *Long-Term Aging of Biochar: A Molecular Understanding With Agricultural and Environmental Implications*. Advances in Agronomy 141: 1-51.

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.

Moebius-Clune, B.N., D. J. Moebius-Clune, B.K. Gugino, O.J. Idowu, R.R. Schindelbeck, A.J. Ristow, H.M. van Es, J.E. Thies, H. A. Shayler, M. B. McBride, D.W. Wolfe, and G.S. Abawi. 2016. *Comprehensive Assessment of Soil Health: the Cornell Framework*. Edition 3.1. Cornell University, Geneva, NY. 123 pp. Available at http://soilhealth.cals.cornell.edu/training-manual/.

North, K. 2015. *Biochar: a Critical View Through the Ecosystemic Lens*. The Natural Farmer. Fall 2015. *Special Supplement on Biochar in Agriculture,* pp B-23-B27. http://thenaturalfarmer.org/issue/fall-2015/.

Ohlson, K. 2014. *The Soil will Save Us: how scientists, farmers, and foodies are healing the soil to save the planet.* Rodale Press, http://rodalebooks.com, 242 pp.

Olson K. R., M. Al-Kasai, R. Lal, and L. Cihacek. 2016. *Impact of soil erosion on soil organic carbon stocks*. J. Soil & Water Conserv. 71(3): 61A-67A.

Olson, K. R., M. Al-Kaisi, R. Lal, and L. W. Morton. 2017. *Soil ecosystem services and intensified cropping systems*. J. Soil & Water Conserv. 72(3): 64A-69A.

Oo, A. Z., S. Sudo, K. Inubushi, M. Mano, A. Yamamoto, K. Ono, T. Osawa, S. Hayashida, P. K. Patra, Y. Terao, P. Elayakumar, K. Vanitha, C. Umamageswari, P. Jothimani, and V. Ravi. 2018. *Methane and nitrous oxide emissions from conventional and modified rice cultivation systems in South India*. Agriculture, Ecosystems, and Environment 252: 148-158.

Osmond, D. L., J. M. Grossman, G. Jennings, G. D. Hoyt, M. Reyes, and D. Line. 2014. *Water Quality Evaluation of Long Term Organic and Conventional Vegetable Production under Conservation and Conventional Tillage*. Final report on ORG project 2009-05488. CRIS Abstracts.*

Panicker, G. K. 2017. October 9 response to September 28 blog post by National Sustainable Agriculture Coalition, *Conservation Groups Deliver Farm Bill Recommendations*, available at http://sustainableagriculture.net/blog/conservation-consensus/.

Pardon, P., B. Reubens, D. Reheul, J. Mertens, P. De Frenne, T. Coussement, P. Janssens, and K. Verheyen. 2017. *Trees increase soil organic carbon and nutrient availability in temperate agroforestry systems*. Agriculture, Ecosystems and Environment 246: 98-111.

Parkin, T. B., and R. T. Venterea. 2010. *USDA-ARS GRACEnet Project Protocols. Chapter 3. Chamber-Based Trace Gas Flux Measurements*. 39 pp. https://www.ars.usda.gov/ARSUserFiles/np212/Chapter%203.%20GRACEnet%20Trace%20Gas%20Sampling%20Protocols.pdf.

Parkin, T. B., T. C. Kaspar, D. B. Jaynes and T. B. Moorman. 2016. *Rye Cover Crop Effects on Direct and Indirect Nitrous Oxide Emissions*. Soil Sci. Soc. Am. J. 80 (6): 1551-1559.

Petit, C. 2012. *Soil's hidden secrets*. Science News 181 (2): 16. https://www.sciencenews.org/.

Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., Kremen, C., 2014. *Diversification practices reduce organic to conventional yield gap*. Proc. R. Soc. B 282, 20141396.

Powlson, D. S., C. M. Stirling, C. Thierfelder, R. P. White and M. L. Jat. 2016. *Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems?* 2016. Agriculture, Ecosystems and Environment 220: 164–174.

Powlson, D.S., A.P. Whitmore, and K.W.T. Goulding. 2011. *Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false*. Eur. J. Soil Sci. 62(1): 42–55.

Rasse, D. P., C. Rumpel, and M-F. Dignac. 2005. *Is soil carbon mostly root carbon? Mechanisms for a specific stabilization*. Plant and Soil 269: 341-356.

Reeve, J., and E. Creech. 2015. *Compost Carryover Effects on Soil Quality and Productivity in Organic Dryland Wheat*. http://articles.extension.org/pages/73247/compost-carryover-effects-on-soil-quality-and-productivity-in-organic-dryland-wheat.

Reinbott, T. 2015 .*Identification of factors affecting carbon sequestration and nitrous oxide emissions in three organic cropping systems*. Final report on ORG project 2011-04958. CRIS Abstracts.*

Richard, T. and G. Camargo. 2011. *Greenhouse Gas Emissions Associated with Dairy Farming Systems*. http://articles.extension.org/pages/32626/greenhouse-gas-emissions-associated-with-dairy-farming-systems-webinar.

Rillig, M.C. 2004. *Arbuscular mycorrhizae, glomalin, and soil aggregation*. Can. J. Soil Sci. 84(4): 355–363.

Rodale Institute. 2014. *Regenerative organic agriculture and climate change: a down-to-earth solution to global warming*. 16 pp. https://rodaleinstitute.org/assets/RegenOrgAgricultureAndClimateChange_20140418.pdf.

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

Roper, W. R., D. L. Osmond, J. L. Heitman, M. G. Wagger, and S. C. Reberg-Horton. 2017. *Soil Health Indicators Do Not Differentiate among Agronomic Management Systems in North Carolina Soils*. Soil Sci. Soc, Am. J 81 (4): 828-843.

Rose, M. T., T. R. Cavagnaro, C. A. Scanlan, T. J. Rose, T. Vancov, S. Kimber, I. R. Kennedy, R. S. Kookana, and L. Van Zweiten. 2016. *Impact of Herbicides on Soil Biology and Function* Advances in Agronomy Vol 136: 133-220.

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.

Rowntree, J. E., R. Ryals, M. S. DeLonge, W. R. Teague, M. B. Chiavegato, P. Byck, and T. Wang. 2016. Potential mitigation of Midwest grass-finished beef production emissions with soil carbon sequestration in the United States of America. Future Food J. Food Agric. Soc. 4:31–38.

Ryals, R., and W.L. Silver. 2013. *Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands*. Ecol. Appl. 23(1): 46–59.

Sadeghpour, A., Q. M. Ketterings, G. S. Godwin, K. J. Czymmek, and F. Vermeylen. 2017. *Agro-Environmental Consequences of Shifting from Nitrogen- to Phosphorus-Based Manure Management of Corn*. Soil Sci. Soc. Am. J. 81(5): 1127-1138.

Schmidt, J. E., C. Peterson, D. Wang, M. Scow, A. C.M.Gaudin. 2018. *Agroecosystem tradeoffs associated with conversion to subsurface drip irrigation in organic systems*. Agricultural Water Management 202: 1-8.

Schonbeck, M., D. Jerkins, and J. Ory. 2016. *Taking stock: analyzing and reporting organic research investments, 2002-2014*. Organic Farming Research Foundation (www.ofrf.org), 222 pp.

Schonbeck, M., D. Jerkins, andJ. Ory. 2017. *Soil Health and Organic Farming: Practical Conservation Tillage*. Organic Farming Research Foundation (www.ofrf.org), 30 pp.

Scialabba, N. E. 2013. *Organic Agriculture's Contribution to Sustainability*. Symposium Proceedings: USDA Organic Farming Systems Research Conference. https://dl.sciencesocieties.org/publications/cm/tocs/12/1.

Six, J., R. Conant, E. Paul, and K. Paustian. 2002. *Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils*. Plant Soil 241(2): 155–176.

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.

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.

Stephensen, G., L. Gwin, C. Schreiner, and S. Brown. 2017. *Breaking new ground: farmer perspectives on organic transition*. Oregon Tilth and Oregon State University's Center for Small Farms & Community Food Systems. 53 pp. https://tilth.org/resources/breakingground/.

Sun H, P. Koal, D. Liu, G. Gerl, R. Schroll, A. Gattinger, R. G. Joergensen, and J. C. Munch. 2016. *Soil microbial community and microbial residues respond positively to minimum tillage under organic farming in Southern Germany.* Appl Soil Ecol. 108:16-24.

Syswerda, S.P., A.T. Corbin, D.L. Mokma, A.N. Kravchenko, and G.P. Robertson. 2011. *Agricultural Management and Soil Carbon Storage in Surface vs. Deep Layers.* Soil Sci. Soc. Am. J. 75(1): 92-101.

Tariq, A., Q. D. Vu, L. S. Jensen, S. de Tourdonnet, B. O. Sander, R. Wassmann, T. Van Mai, and A. de Neergaard. 2017. *Mitigating CH4 and N2O emissions from intensive rice production systems in northern Vietnam: Efficiency of drainage patterns in combination with rice residue incorporation.* Agriculture, Ecosystems, and Environment 249: 101-111.

Teague, R. 2016-17. *Regeneration of soil by multi-paddock grazing.* Transcript of Sept 7, 2016 presentation at Harvard by Jack Kittredge. The Natural Farmer, winter 2016-17: B26-B30.

Teague, W.R., 2018. Forages and pastures symposium: cover crops in livestock production: whole-system approach: Managing grazing to restore soil health and farm livelihoods. Journal of Animal Science 96, 1519–1530.

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.

Thakur, A. K., N. T. Uphoff, and W. A. Stoop. 2016. *Scientific Underpinnings of the System of Rice Intensification (SRI): What Is Known So Far?* Advances in Agronomy 135: 147-179.

Thies, J. E. 2007. *Nitrous oxide losses during soil freeze-thaw events during winter.* http://impact.cals.cornell.edu/project/nitrous-oxide-losses-during-soil-freeze-thaw-events-during-winter.

Thomas, B. W., X. Hao, F. J. Larney, C. Gover, M, H. Chantigny, and A. Charles. 2017. *Non-Legume Cover Crops Can Increase Non-Growing Season Nitrous Oxide Emissions.* Soil Sci. Am. J. 81 (1): 189-199.

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.

Toonsiri, P., S. J. Del Grosso, A. Sukor, and J. G. Davis. 2016. *Greenhouse Gas Emissions from Solid and Liquid Organic Fertilizers Applied to Lettuce* J. Environmental Quality Vol. 45 No. 6, p. 1812-1821.

Topp, E. and E. Pattey. 1997. *Soils as sources and sinks for atmospheric methane*. Can. J. Soil Sci. 167-178.

Tubiello, F. N., M. Salvatore, S. Rossi, A. Ferrara, N. Fitton, and P. Smith. 2013. *The FAOSTAT database of greenhouse gas emissions from agriculture*. Environmental Research Letters 8: 015009 (10pp). doi:10.1088/1748-9326/8/1/015009.

USDA. 2016. USDA Building Blocks for Climate-Smart Agriculture and Forestry: Implementation Plan and Progress Report. 60 pp. https://www.usda.gov/sites/default/files/documents/building-blocks-implementation-plan-progress-report.pdf.

USDA National Organic Program Final Rule, https://www.ams.usda.gov/rules-regulations/organic.

USDA Natural Resources Conservation Service. *Soil health*. https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/, and *Conservation Stewardship Program,* https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/csp/.

USDA Natural Resources Conservation Service. 2011. *Soil quality indicators: Particulate Organic Matter.* April, 2011. 2 pp. Accessed via *Soil health assessment,* https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/assessment/.

USDA Natural Resources Conservation Service, 2014. *National Planning Procedures Handbook (NPPH), Edition 1.* https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=36483.wba.

Van Geel, M., E. Verbruggen, M. De Beenhouwer, G. van Rennes, B. Lievens, and O. Honnay. 2017. *High soil phosphorus levels overrule the potential benefits of organic farming on arbuscular mycorrhizal diversity in northern vineyards*. Agriculture, Ecosystems, and Environment 248: 144-152.

Wander, M. M. 2015. *Nutrient budget basics for organic farming systems.* 6 pp. http://articles.extension.org/pages/18794/nutrient-budget-basics-for-organic-farming-systems.

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.

Wander, M. M., C. Ugarte, E. Zaborski, and E. Phillips. 2014. *Organic systems and climate change.* Proposal and final report for ORG project 2010-03954. CRIS Abstracts.*

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.

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.

Westphal, M., M. Tenuta, and M. H. Entz. 2018. *Nitrous oxide emissions with organic crop production depends on fall soil moisture.* Agriculture, Ecosystems, and the Environment 254:41-49.

Wild Farm Alliance. 2017. Making Biodiversity a Priority: Updating Organic System Plans. 10 pp. Available at www.WildFarmAlliance.org.

Williams, A., A. S. Davis, A. Jilling, A. S. Grandy, R. T. Koide, D. A. Mortensen, R. G. Smith, S. S. Snapp, K. A. Spokas, A. C. Yannarell, and N. R. Jordan. 2017. *Reconciling opposing soil processes in row-crop agroecosystems via soil functional zone management.* Ag Eco Env 236: 99-107.

Wilson, G.W.T., C.W. Rice, M.C. Rillig, A. Springer, and D.C. Hartnett. 2009. *Soil aggregation and carbon sequestration are tightly correlated with the abundance of arbuscular mycorrhizal fungi: results from long-term field experiments.* Ecol. Lett. 12(5): 452–61.

Wilson, K. 2014. *How Biochar Works in Soil.* Biochar Journal, 2014. Excerpted by Jack Kittredge in *The Natural Farmer.* Fall 2015. *Special Supplement on Biochar in Agriculture,* pp B8-B12.. http://thenaturalfarmer.org/issue/fall-2015/.

Wuest, S. B., and C. L. Reardon. 2016. *Surface and root inputs produce different carbon/phosphorus ratios in soil.* Soil Sci. Soc. Am. J. 80: 463-471.

Zhang, Q., G. Liang, W. Zhou, J. Sun, X. Wang and P. He. 2016. *Fatty-Acid Profiles and Enzyme Activities in Soil Particle-Size Fractions under Long-Term Fertilization.* Soil Sci. Soc. Am. J. 80(1): 97-111.

Zhong, L., S. Bowatte, P. C. D. Newton, C. J. Hoogendoorn, and D. Luo. 2018. *An increased ratio of fungi to bacteria indicates greater potential for N2O production in a grazed grassland exposed to elevated CO2.* Agriculture, Ecosystems, and the Environment 254: 111-116.

Zuber S. M., and M. B. Villamil. 2016. *Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities.* Soil Biol Biochem. 97:176-187.

* For project proposal summaries, progress and final reports for USDA funded Organic Research and Extension Initiative (OREI) and Organic Transitions (ORG) projects, enter proposal number under "Grant No" and click "Search" on the CRIS Assisted Search Page at: http://cris.nifa.usda.gov/cgi-bin/starfinder/0?path=crisassist.txt&id=anon&pass=&OK=OK.

Note that many of the final reports on the CRIS database include lists of publications in referred journals that provide research findings in greater detail.

ORGANIC FARMING RESEARCH FOUNDATION

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