**Organic Practices for Climate Mitigation, Adaptation, and Carbon Sequestration***Research-based Practical Guidance for Organic and Transitioning Farmers*

eOrganic Soil Health and Organic Farming Webinar Series

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*Presentation notes, additional information, and references to research literature on which webinar slides are based.*

Slide 1 – *title slide*.

Slide 2 – *Climate change in the news*

Mean global warming to date is about 1.0 C (1.8 F). With rising concern that the internationally accepted goal of limiting warming to 2.0°C would not be sufficient to prevent severe impacts on food production, human society, and natural ecosystems (e.g., 99% loss of coral reefs), the IPCC published a special report in October 2018 analyzing both the benefits of lowering the limit to 1.5°C and the feasibility of achieving it through global mitigation efforts.

In November, 2018, the US Global Change Research Program (USGCRP) published its *Fourth National Climate Assessment*. The report documents major climate change risks to public health, rural and urban communities, agriculture, and society as a whole, and projects major economic losses by mid-century. The authors also cite growing mitigation and adaptation efforts at local, regional and national levels, and emphasize that much more is needed to meet the challenge. The USGCRP steering committee includes representatives from US Departments of State, Defense, Interior, Agriculture, Energy Commerce, Transportation, Health and Human Services, and several other federal agencies.

Full report: USGCRP, 2018: *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II: Report-in-Brief* [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 186 pp. Available online at <http://nca2018.globalchange.gov>.

The Green New Deal, House Resolution 109, introduced in both chambers of Congress on February 7, 2019 by Representative Alexandria Ocasio-Cortez (D-NY) and Senator Ed Markey (D-MA) outlined an aggressive, community-based, nation wide effort to transition the US to a carbon-neutral energy, economic, and food system. While the plan outlined steps that farmers and rural communities can take to sequester carbon and prepare for climate changes already taking place, it did not fully explore the potential for sustainable organic agriculture to help solve the climate crisis.

The same week that the Green New Deal was announced, House Speaker Nancy Pelosi reconvened a Select Committee on the Climate Crisis, and the House Energy and Commerce Subcommittee on Environment and Climate Change and the full Natural Resources Committee met simultaneously to discuss the need to act on climate change and the costs of inaction.

Together, these political developments indicate a new opportunity to elevate in the public eye the potential of soil carbon sequestration and sustainable agriculture to contribute to solutions to the climate crisis.

Slide 3 – *Climate change in agriculture*

Impacts summarized from the Agriculture section on pp 88-89 of the Fourth National Climate Assessment, published in November, 2018.

In the state of California::

*“The impacts of climate change are already being felt in agriculture. In California we have experienced loss of winter chill – crucial hours needed for our orchards and vineyards to maintain winter dormancy. The most recent drought of 2011-17 in California resulted in more than a half-million of acres of farmland fallowed in some years. And changes in precipitation affect grass growth for livestock. These all affect our $50-billion industry.”*

Statement by CA Agriculture Secretary Karen Ross in a March 12, 2019 op-ed, *Opinion: California agriculture is ready to scale up climate solutions.* <https://plantingseedsblog.cdfa.ca.gov/wordpress/?p=17386>.

Slide 4 – *Climate change in organic farming*

A total of 1,403 respondents representing all four USDA regions (Northeast, North Central, South, and West) participated in OFRF’s 2015 survey to identify top research priorities. In addition, 21 listening sessions were held in conjunction with conferences across the US.

Soil health was most often cited as a high research priority (74% of respondents). While climate change was well down on the list at 34%, an additional 42% rated it as a moderate priority, and some farmers in the survey reported severe impacts. Many cited challenges dealing with increasingly erratic temperature and precipitation patterns. After a series of excessively wet years and one severe drought year, one respondent noted that “climate change is about to put me out of business.” Another respondent raised the concern that “irrigation is not truly sustainable” and that improved water capture and conservation is critical for arid region agriculture. \ Climate concerns were greatest in the Southern region, where 42% ranked them as a high priority.

Respondents cited water deficit / excess extremes related to climate change more often than heat or cold, although impacts of shifting temperature patterns on chilling requirements for bud break and on risks from spring frosts also emerged as serious concerns for fruit growers.

While most respondents focused on the need to adapt to the changes, including by changing crops or cultivars grown, a few were interested in the capacity of organic production systems to enhance soil carbon sequestration, and the possibility of capturing economic benefits therefrom through carbon markets and state level soil health / climate initiatives such as that in California.

Slide 5 – *Subtitle slide:**Can Organic Practices Help Farmers and Ranchers Prepare   
for Climate Disruption? Soil Health and resilience to weather extremes.*

Slide 6 – *Organic farming and resilience*

The Rodale Farming Systems trials compare three systems: an organic rotation for livestock operations, including annual feed grain and perennial forage crops, fertilized by legume cover crops and manure; an organic cash grain rotation with legume cover crops, and a conventional corn-soy rotation with synthetic fertilizer. In years of normal rainfall, the three systems gave similar corn and soybean yields; the organic advantage emerged during drought years, when improved soil moisture holding capacity and overall soil health sustained crop vigor and yields while conventionally grown crops suffered. Many other farmers, ranchers, and researchers have observed similar yield trends upon conversion to organic systems.

Between 1981 and 1995, soil organic matter (SOM) levels in the organic rotations increased from 3.45% to about 4%, while the conventionally managed soil showed a slight loss, to 3.2%. Combined with the reduced greenhouse gas (GHG) footprint, this finding led Rodale researchers and others to ask whether organic practices can help mitigate GHG emissions and climate change, as well as improving resilience to weather extremes.

Slide 7 – *Soil health and climate resilience*

Building healthy, living soils is the foundation of the organic farming method, and is achieved through cover cropping, crop rotation, organic amendments, careful tillage, and avoidance of synthetic fertilizers and crop protection chemicals that could hurt soil life. Soils in good health have an active and diverse soil biota (soil food web), which enhances crop health. In exchange for a percentage of the plant’s photosynthetic product, root-symbiotic mycorrhizal fungi and other endophytic (in root tissue) and rhizosphere (root zone) microbes partner with plant roots to facilitate nutrient and moisture uptake, protect the plant from diseases, and enhance plant resilience to drought and other stresses. Other soil organisms live on plant litter, manure, and other organic residues, converting them into soil organic matter (SOM), which enhances moisture and nutrient holding capacity.

Healthy, living soils also develop an open, porous, structure that readily absorbs moisture during rainfall or irrigation, drains sufficiently to regain good aeration soon after the water input, yet retains a large reservoir of capillary water available for plant uptake (WHC). Abundant organic matter and biological activity play major roles in maintaining good structure and WHC, as well as conferring a dark, rich color to the topsoil or A horizon. The most fertile and drought-resilient soils also have a deep, open profile (no subsurface hardpan) allowing unrestricted root growth and affording crops access to deep moisture reserves during dry spells. Including deep rooted cover crops and/or perennial sod in the rotation helps maintain an open profile from surface to bedrock or water table.

Slide 8 – *Guidance for building resilient soils*

The USDA National Organic Standards provide clear guidance for building healthy, resilient soils. While some “industrial scale” organic farms have focused mainly on replacing synthetic inputs with materials permitted by the National Organic Program (NOP), a full implementation of the Standards will go much further toward preparing organic operations for the ongoing and impending effects of climate disruption.

Research has abundantly validated the four NRCS principles of soil health, and has shown that their implementation enhances the resilience of farming systems. Based on his success in restoring a 5,000 acre ranch in North Dakota, rancher Gabe Brown has added a fifth principle: *integrate livestock into the farming system*.

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

Slide 9 – *The living plant is the farmer’s #1 tool for*

Why are cover crops, sod crops, and crop rotations emphasized in the NOP standards and NRCS working lands conservation programs? Healthy, living soils develop through an ongoing partnership between plant roots and beneficial soil micro and macro-organisms. Photosynthesis creates the raw materials for plant growth, crop yield, and soil life. Plant cover protects the soil surface from overheating and drying by direct sun, and the erosive effects of intense rainfall and winds. Living roots work with the soil life to build and maintain SOM, soil structure, pore space, and moisture- and nutrient-holding capacity. All of these processes contribute to soil and cropping system resilience to extreme and erratic weather related to climate changes.

Slide 10 – *Subtitle slide – How does agriculture affect climate change*

Slide 11 – *Greenhouse gases in agriculture*

In this webinar, agricultural greenhouse gas (GHG) emissions and potentials for mitigation and sequestration are discussed in terms of elemental carbon (C) equivalents. Total global GHG emissions are roughly 15 billion tons annually in CO2-C equivalents. One pound of fertilizer N lost as nitrous oxide negates 133 lb soil organic carbon (SOC) sequestration, and one pound of organic carbon lost from rice paddies or manure lagoons as methane negates 7.6 lb SOC sequestration. SOC ~0.5 X SOM.

Slide 12 – *Direct agricultural GHG emissions*

Analyses of “direct” agricultural GHG emissions by US Environmental Protection Agency and International Panel on Climate Change do not include the fossil fuel consumption for farm operations nor embodied energy in fertilizers and other inputs – these are subsumed under other emissions categories (machinery, transportation, industrial process). They also do not include changes in soil organic carbon (SOC) or destruction / restoration of forest, prairie, and other native vegetation (categorized under “forestry, other land use, and land use changes”).

The EPA estimate does include CO2 released after field applications of lime and and urea; the IPCC global estimate does not include any CO2 emissions from agricultural operations.

The differences between US and global analyses reflect greater use of synthetic fertilizer N in the US (hence half of direct US emissions consist of soil N2O), more extensive use of liquid manure storage facilities in the US, and greater fossil fuel use in the US (hence direct agricultural emissions comprise a smaller % of total human-caused GHG emissions). Increasing use of liquid manure storage (a major source of CH4) since 1990 has been the main driver in a 17% increase in total US direct agricultural GHG emissions.

Rice CH4 comprises a much larger slice of the *global* agricultural GHG pie because it is a major staple grain throughout Asia but not in the US. Emissions from residue burning are also larger outside the US.

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

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*.

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.

Slide 13 – *Adding in the CO2*

Discussions of GHG mitigation in US agriculture often focus on fossil fuel consumption in field operations and the “embodied energy” in synthetic nitrogen fertilizer and other conventional inputs – the CO2 emissions from fossil fuel consumed in their manufacture. Despite higher use of synthetic N in the US, these agricultural CO2 emissions only amount to 17% of total direct agricultural GHG, compared to 26% for CH4 (primarily enteric and manure), and 57% N2O (primarily soil, and some manure).

However, when net losses in soil organic carbon (SOC) are taken into account, the global GHG footprint of agriculture doubles to approximately one-quarter of total human-caused GHG emissions. About half of the SOC loss is related to wind and water erosion, which disproportionately remove soil organic matter, exposing it to oxidation or (when eroded sediment is submerged in water bodies) converted to CH4. The other half results from in-situ soil degradation from tillage, bare fallow, excessive nutrient applications, etc.

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

Lal, R. 2003. Soil erosion and the global carbon budget. Environment Int’l 29:437-450.

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

Slide 14 – *Soil and the global carbon cycle*

Five key take-homes from this simplified representation of the global carbon cycle, based on Weil and Brady, 2017 (cited above):

1 – The world’s soils hold twice as much organic carbon as the sum of global vegetation biomass and atmospheric CO2-carbon. With many agricultural soils depleted in SOC to 50% or less of their native levels, a great potential exists to offset a significant percentage of CO2 emissions through improved agricultural practices, such as organic farming.

2 – In addition, soils hold nearly 1,000 billion tons of *inorganic* (carbonate) carbon, mainly in prairie, semiarid, and desert regions, where soil pH is commonly alkaline.

3 – *Plant photosynthesis is the world’s primary sustainable means of CO2 sequestration*. The 3 billion tons C/year absorbed by the oceans is threatening marine ecology through acidification, and urgent action is needed to absorb excess atmospheric CO2 through living vegetation and deposit it in the soil profile as stable SOC.

4 – The ~3% annual imbalance between conversion of plant C into soil organic C and the loss of soil organic C to the atmosphere as CO2 contributes about 15% of annual net carbon emissions, most of the rest coming from fossil fuel use.

5 – This simplified C cycle diagram does not account for the conversion of biomass C into CO2 through deforestation, fires, etc.

Slide 15 – *The carbon cost of clearing land*

Conversion of native vegetation – forest, prairie, savanna, etc – into crop production causes a rapid loss of SOC (converted to CO2); within a half century, the SOC levels out at a new “steady state” that may be as little as half of the native SOC levels. Losses can be more extreme in tropical regions (75% within 25 years) and in semiarid regions. For example, when Gabe Brown first established his ranch in North Dakota, its SOM had dropped from the native level of 8% (= 4% SOC, or 40 tons/ac in the top 8 inches) to just 2%, a loss of 30 tons C per acre.

Historically, some 30% of total human-caused GHG emissions from 1750 through 2011 have resulted from deforestation, land clearing and other land use changes such as the conversions illustrated in the slide. With slowing deforestation and increasing efforts to restore perennial vegetation, these losses have diminished to about 8-12% of total annual GHG emissions. However, total biosphere C losses (SOC, vegetation, and wetlands) as CO2 since the dawn of agriculture have been estimated at over 500 billion tons, equivalent to 34 years’ worth of total global GHG emissions at current rates.

IPCC, 2014, and Weil and Brady, 2017, cited above.

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

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.

Slide 16 – *Subtitle slide: Can agriculture become part of the climate solution?*

Slide 17 – *Can “carbon farming” offset GHG by converting CO2 into soil organic C?*

Because direct agricultural GHG emissions consist largely of CH4 and N2O, and carbon sequestered this year in soil or biomass *can* be lost through future tillage or unsustainable land use decisions, some scientists urge the agricultural community to focus mitigation efforts on reducing these two powerful GHG, rather than on SOC sequestration *per se*. Others believe that soil C sequestration has tremendous potential, especially when integrated organic or regenerative systems are implemented over large acreages.

In December 2015, the Paris Climate Summit (Conference of Parties, COP21) 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 not only reverse soil carbon losses but also offset all direct agricultural GHG emissions.

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

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

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.

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>.

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.

Slide 18 – *The living plant is humanity’s most practical means to sequester carbon*

The living plant is the carbon pipeline we all need to help mitigate climate change. It was prehistoric living plants that deposited the SOM that gradually became coal, petroleum, and gas several hundred million years ago, and today’s plants offer the most direct and practical means to begin returning all that excess CO2 into the earth.

Slide 19 – *SOC/Crop production tradeoff?*

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

Slide 20 – *Best organic practices build SOC and soil fertility*

Six long term systems trials across the US (Delate et al., 2015) have shown that integrated organic soil management – diverse rotation, cover crops, organic amendments, and lower-impact tillage practices - can simultaneously enhance both mineralization (estimated by microbial respiration = “potentially mineralizable carbon or PMC, or by measurements of N mineralization) and SOM stabilization processes (estimated by permanganate oxidizable carbon or POX-C).

In a meta-analysis of 56 studies comparing organic and conventional systems, Lori et al (2017) found that organically managed soils averaged 19% higher total SOC (statistically highly significant), and 74% higher in dehydrogenase activity, an index of soil microbial metabolic activity.

In a review of 13 studies, Hurisso et al. (2016) found that tillage, raw manure applications, and cover crops (with legume component, tilled in) promote SOC mineralization over stabilization, while finished compost and no-till promote SOC stabilization (sequestration). However, the two processes (measured as PMC and POX-C, respectively) are positively correlated with each other and with crop yields. In other words, organic systems can simultaneously build fertility (ability to release crop-available nutrients) and SOC sequestration. The authors state:

“*Soil organic matter levels are the balance of C inputs to soil (through crop residues and amendments) and losses via mineralization (i.e., CO2 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 poultry litter, applying finished compost enhanced soil microbial respiration 30% and total SOC 43% in organic vegetable production (Bhowmik et al., 2017).

Additional studies (cited in Schonbeck, Jerkins, and Snyder, 2018) indicate that organic systems that integrate multiple practices and a mix of inputs (cover crop + amendments) with a “balanced” ratio of carbon and nitrogen (C:N) support the greatest SOC sequestration as well as long term fertility. While a legume green manure plowdown or poultry litter favors fast-release nutrients over SOC accrual, soluble N fertilizers (not allowed under NOP) often lead to a net destruction of SOC (Khan et al., 2007), especially when accompanied by intensive tillage.

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.

Delate et al., 2015, cited above.

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.

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.

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.

Schonbeck, M, D. Jerkins, and L. Snyder. 2018. *Soil Health and Organic Farming: Organic Practices for Climate Mitigation, Adaptation, and Carbon Sequestration.* Organic Farming Research Foundation, <http://ofrf.orf>. 78 pp.

Slide 21 – *Soil carbon sequestration 101: NRCS Four Principles of Soil Health*

The NRCS principles of soil health provide a roadmap for cropland soil management. Research has abundantly validated these four principles as guidelines for building SOM, sequestering carbon, and developing healthy, resilient soils for long term system sustainability and risk reduction.

For example, living cover for orchard floor and vineyard / berry crop alleys can double SOC compared to tilled or herbicide-maintained bare fallow.

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

Slide 22 – *What will it take?*

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

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-systemswebinar>.

Teague et al., 2016, cited above.

Slide 23 – *C sequestration by different conservation practices*

Continuous no-till by itself can accumulate 510 lb SOC per acre annually, but most of it is physically protected in near-surface aggregates, and is subject to rapid re-oxidation even after a single tillage pass. In practice nearly all “continuous no till” farmers will till every few years as needed to manage perennial weeds or subsurface hardpan.

A cover crop that is terminated by tillage may add only a little SOC since the disturbance stimulates microbial respiration and mineralization of much of the cover crop biomass. Combining the cover crop with no-till termination can enhance both the quantity and stability of sequestered SOC. Even in an organic systems that uses rotational no till (tilling perhaps once a year after cash crops to manage weeds and plant the next cover), deeper roots from the cover crop will build lasting SOC, especially if shallow non-inversion tillage is used.

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.

Chambers et al., 2016, cited above (cover crop, based on NRCS practice code 340).

Lal, 2015, cited above (no till + cover crop).

Photo of roll crop / no till planting operation from Reduced Tillage in Organic Systems Field Day Program Handbook, page 6. <https://rvpadmin.cce.cornell.edu/uploads/doc_699.pdf>

Slide 24 – *C sequestration in diversified rotation*

Adding a cereal grain interseeded with a perennial legume such as alfalfa or red clover to the traditional corn-soy rotation substantially increases biomass production per year, and duration and depth of living root, resulting in enhanced SOC sequestration.

Even when crop intensity (average annual plant biomass production, percentage of the year in living cover) is unchanged, adding one or two new crops to a low diversity rotation has been found to enhance active and total SOC, soil biodiversity, and net C sequestration.

In dryland cereal grain production in the northern Great Plains and other low-rainfall regions, the traditional two year wheat/fallow system depletes SOC even under no-till, whereas rotating the wheat with legumes and other crops (variety, planting and harvest/termination date selected with care to ensure adequate soil moisture for the grain) gradually builds SOC.

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.

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.

West and Post, 2002, cited earlier.

Slide 25 – *C sequestered by improved grazing management*

Management-intensive rotational grazing (MIG) systems, variously called “mob grazing,” “adaptive multipaddock” (AMP), “holistic management,” or “regenerative” grazing systems have been adapted to regions as diverse as upstate New York, the Gulf Coast, and the northern and southern Great Plains, with initial C sequestration rates of one to three tons per acre annually for the first five to ten years after implementation.

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

Brown, 2018, cited above.

Chambers et al, 2016, cited above (NRCS conservation practice 528 Prescribed Grazing).

Teague et al, 2016, cited above (AMP grazing).

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.

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.

Slide 26 – *C sequestered by perennial plantings*

Just as clearing native forest or prairie converts tons of SOC per acre into CO2, converting highly erodible, depleted, or marginal cropland; and riparian or other ecologically sensitive areas back into forest, prairie, or permanent pasture can sequester a ton of carbon or more annually in SOC + perennial plant biomass. Installing windbreaks, hedgerows, silvopasture, alley cropping, and other functional agroforestry plantings accomplishes multiple conservation objectives, of which C sequestration is one. A review of various agroforestry plantings around the world confirmed high C sequestration rates, with the highest occurring in the humid tropical regions, but with temperate and semiarid region plantings showing a potential to accrue 1 ton or more per acre annually.

A recent estimate of the potential for improved management of agricultural soils (cropland and grazing lands) to absorb CO2 between now and the end of the 21st Century came to 38 – 120 billion tons C removed. However, adding reforestation of severely degraded lands and abandoned lands; shelterbelts, riparian woodland, and other conservation forest plantings; community reforestation projects; urban permaculture and green belt plantings, and wetland restoration raises this potential to 209 – 458 billion tons sequestered, which, (for the median value of 333 billion tons) would reduce end of century atmospheric CO2 by some 156 ppm (Lal et al., 2018).

Chambers et al, 2016, cited above (NRCS herbaceous perennial conservation buffer practices)

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.

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

Slide 27 – *Agroforestry: rural and urban*

Multiple studies have shown that silvopasture (integrating trees and pasture) can sequester 3,900 lb SOC/ac-yr (mean of 9 studies) and installing intensive permacultural home gardens in previously underutilized land can accrue 3100 lb SOC per acre/ac-yr (mean of 19 studies).

Feliciano et al., 2018, cited above.

Slide 28 – *How plant roots build stable SOC*

Although soil biomass and biological activity, including plant roots and their symbionts and exudates, are concentrated near the soil surface, at least half of the soil’s organic carbon occurs deeper than 12 inches (Lal, 2015, cited above). The reason for this is that deeper roots, earthworms, and other burrowing organisms can deposit organic carbon throughout the soil profile, and the lower microbial populations and restricted oxygen levels in subsurface levels result in a longer turnover time, so that deep SOC can gradually accrue – provided that the cropping system includes deep rooted crops and soil conditions allow roots and earthworms to explore the subsurface soil horizons.

Different conservation practices sequester C in different parts of the soil profile; for example no-till, organic mulching, and residues of cover or cash crops left on the soil surface accrue SOC in a physically protected form within near-surface aggregates. This SOC plays vital roles in maintaining tilth, moisture infiltration, fertility, and crop nutrition, yet it is vulnerable to re-oxidation following even a single tillage pass. In practice, continuous no-till is not feasible for organic production of annual crops. Even in conventional production with herbicides, most “continuous no-till” systems require a tillage pass every few years to manage herbicide-resistant or perennial weeds, and/or break hardpan.

In contrast, plant roots and their exudates deposit organic carbon throughout the soil profile to the crop’s rooting depth. As microbes transform root carbon, some of their residues becomes highly stabilized SOC adsorbed to mineral clay and silt particles (less subject to oxidation after tillage). A significant portion of this SOC accrues below tillage depth, especially with deeper-rooted crops. Thus, the C sequestered by cover crops may be more stable than that gained through no-till, and no-till termination of high biomass cover crops builds more SOC than either practice alone.

Perennial plantings – sod phase in rotations, conservation buffer plantings, orchard with living orchard floor cover, and agroforestry practices – provide the most stable SOC by combining year-round deep, extensive root systems with no or minimal disturbance. Adding livestock to perennial sod, with best rotational grazing practices for the region and soil type, further accelerates SOC accrual. The cycle of brief, intense grazing and long recovery period causes a massive sloughing of root biomass throughout the top 5 feet or more of the soil profile followed by full regeneration of the root system before the next grazing shock.

Recent research indicates that much of the stable SOC present in most soils is derived from plant roots, and at least one author has recommended crop selection and management for deep, extensive root systems as a means to enhance C sequestration in the soil, especially at depths below the plow layer where tillage will not expose it to oxidation.

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.

Kell, D.B. 2012. *Large-scale sequestration of atmospheric carbon via plant roots in natural and* *agricultural ecosystems: Why and how*. Philos. Trans. R. Soc. B Biol. Sci. 367(1595): 1589–1597.

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.

Weil and Brady, 2017, cited above.

Slide 29 – SOC saturation

Improved soil management practices do not continue to sequester C indefinitely, but level off once a new, higher, steady state is attained. Several studies on sustainable farming and ranching practices have documented SOC saturation curves:

1 - In Portugal, conversion of depleted cropland to permanent pasture allowed SOM (~SOC X 2) to rebound from 0.87% to 3.0%, with most of the gain occurring in the first six years, leveling off at 10 years.

2 - In South Carolina, conversion of tilled cropland to MIG rotational grazing resulted in a rapid increase in SOC, starting after a two year lag, and continuing for four more years at ~7,000 lb C/ac-year (three farms, average) then leveling off. Other studies in the southern Great Plains showed that converting from continuous grazing to MIG grazing accrued 2,500 – 3,000 lb C/ac-year initially, with sequestration rates tapering off after about 10 years.

3 - A review of multiple studies by West and Post (2002) showed that continuous no-till accrues about 500 lb SOC/ac annually for 10 – 15 years, then levels off. As noted earlier, this surface-accrued SOC is subject to degradation by a single tillage operation.

4 - In the Rodale long term farming systems trial, SOM increased from 3.5% in 1981 to 4.0% in 1995, inched up to 4.2% in 2000, then leveled off.

5 – The West and Post review showed that adding one or more crops to diversify a simple rotation (e.g. corn-soy) resulted in a more gradual increase of 180 lb SOC annually, which continued for up to 40 years.

The take home message is that we cannot expect organic or conservation agriculture alone to save us from the consequences of anthropogenic GHG emissions – we will need to phase off fossil fuels and develop a carbon neutral energy system and society. However, it remains worthwhile – indeed vital – to realize and maximize the potential for agricultural C sequestration, both to facilitate our transition to net zero emissions, and to strengthen agricultural resilience to withstand the climate disruptions already underway and no longer preventable.

Lal (2016) has estimated that implementation of current best soil management practices on cropland (sustainable organic or conservation agriculture) and grassland (MIG) can restore most agricultural soils to about 85% of their original native SOC levels (cropland currently averages 55%) before saturation occurs, and that future innovation could allow agricultural systems to approach 100% of native SOC levels. Lal (2018) further estimated that applying soil health BMPs (including MIG) to all of the world’s cropland and grazing land could initially sequester 1.2 to 2.6 billion tons C annually (8 – 17% of annual anthropogenic GHG), and a total of 39 – 120 billion tons before SOC saturation (2.6 to 8 years’ worth of anthropogenic GHG).

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

Lal, 2016, cited above.

Lal et al., 2018, cited above.

Machmuller et al, 2015, cited above.

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

Wang et al., 2015, cited above.

West and Post, 2002, cited earlier.

Slide 30 – *We know enough to act now*

We don’t know for sure how much SOC can be sequestered and for how long, or the best SOC management practices for every climate, soil, production system, and situation. However, we know enough about the potential for best soil health practices to build resilience and to contribute to climate mitigation to act NOW.

Statement by CA Agriculture Secretary Karen Ross in a March 12, 2019 op-ed, *Opinion: California agriculture is ready to scale up climate solutions.* <https://plantingseedsblog.cdfa.ca.gov/wordpress/?p=17386>.

Statements by Johannes Lehmann of Cornell University and others quoted in: *CO2 soil sequestration plan aims to relieve atmospheric warming,* by Blaine Friedlander, Jan 23, 2019 at:

<https://cals.cornell.edu/news/co2-soil-sequestration-plan-aims-relieve-atmospheric-warming/>

Slide 31 – Subtitle Slide – *Can organic practices help mitigate climate change?*

Slide 32 – *Differing professional opinions on this question*

Meta-analysis is a rigorous statistical procedure for assessing trends or comparisons over multiple studies. Several meta-analyses of organic versus conventional comparisons in terms of soil carbon sequestration and greenhouse gas mitigation have been conducted in recent years.

Soil samples taken across the US from 659 organic fields and 728 conventional fields showed, on average, 13% higher total SOC and 53% higher stable SOC in the organic fields.

A meta-analysis of 56 organic/conventional comparison studies conducted in temperate to tropical, humid to semiarid climates on six continents found an average of 19% higher total SOC and 41% higher microbial biomass in the organic systems.

20 studies from five continents showed mean annual SOC accrual rates of 490 lb/ac-year in organic systems versus just 80 lb/ac in conventional system. About 60% (240 lb) of the gain could be attributed to enhanced *in situ* sequestration; the balance to importation of compost and other organic amendments from off-farm sources.

Organic soils emitted significantly less N2O per acre than conventional, but not on a per unit output basis.

Going “organic by substitution” (NOP allowed fertilizers and pest controls in lieu of synthetic) is not by itself sufficient to enhance SOC or reduce net GHG emissions. One study found no evidence that increasing adoption of organic practices had reduced the nation’s agricultural GHG footprint, and the author pointed out that larger scale organic operations often take this limited approach and thus fail to yield the ecosystem service of C sequestration that can be achieved through integrated, sustainable organic systems.

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.

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.

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

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.

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.

Slide 32 – *Integrated organic systems build SOC*

In the US, results of six long-term farming systems trials show that organic crop rotations that include legume cover or sod crops, organic nutrient sources (compost or manure), and routine tillage accrue significantly more SOC than conventional corn-soybean rotations with tillage. The perennial legume or legume-grass sod phase in the organic systems increases the depth, biomass, and duration / continuity of living roots, and thus play a major role in SOC accrual in these systems. For example, researchers at University of Minnesota have found that a two year organic corn-soy rotation tends to degrade soil health (and invite weed problems), while a four year corn-soy-cereal-alfalfa rotation improves soil condition.

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

Note that these SOC sequestration rates, if achieved on all cropland and grazing lands, would be sufficient to offset direct agricultural GHG emissions (which would require 325 lb C/ac-yr), and approach though not quite achieve the 4 per thousand objective (660 lb C/ac-yr).

Research findings suggest that finished compost and living plant roots may play complementary roles in SOC sequestration. Finished compost adds stable SOM and may help stabilize the OM deposited in situ by plant roots and added as aboveground crop residues). Cover crops, organic amendments (compost or manure), and reduced tillage each contribute to SOC, and work together in additive or synergistic manner to enhance SOC, soil health, and fertility. Thus, integrated systems consisting of multiple practices generally sequester more C and build more soil fertility than single practices such as compost application or cover cropping alone.

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

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>.

Delate, K., C. Cambardella, and C. Chase. 2015. *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 US.* Sustainable Agricultural Research 4(3): 5-14.

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.

Hurisso et al, 2016, cited above.

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

Rodale Institute, 2014, cited above.

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

Tavantzis, S. M., R. P. Larkin, A. V. Alyokhin, M. S. Erich, and J. M. Jemison. 2012. *A Systems Approach to Optimize Organic Crop Production: Enhancing Soil Functionality and Plant Health to Suppress Plant Diseases and Pests.* Final report for ORG project 2007-01405. CRIS Abstracts.

Slide 34 – *Compost pros and cons*

While the composting process emits some N2O and (if improperly aerated) CH4, these emissions are far lower in CO2-Ceq than the heavy CH4 emissions when livestock manure is stored in liquid form in lagoons, or when autumn leaves, food waste, and other municipal organic residues are buried and compacted in landfills. A carefully managed compost pile can also reduce N2O and total GHG impact compared to unmanaged, dry-stacked manure. Importing off-farm organic materials from these sources to build SOM is far more sustainable than letting these materials to go to waste and generate CH4.

Conversely, gathering manure or crop residues that could otherwise feed the soil biota of the source field or pasture, or (worse) plant biomass from native ecosystems, in order to make compost, biochar, or other organic amendments is at best a zero sum for the climate, and may be destructive to soil and ecosystem health of the source acreages.

The other serious consideration is that relying on compost or manure to meet all of the nitrogen (N) and potassium (K) needs of a crop rotation will inevitably build up excess levels of P in the soil, which can inhibit the activity of highly beneficial mycorrhizal fungi. Not only do these fungi greatly enhance crop nutrient and water uptake (which can also mitigate N2O emissions), but they also produce a sugar-protein compound (glomalin) that stabilizes SOC and thus plays a substantial role in C sequestration.

Heavy annual compost applications can eventually saturate the soil with soluble N (through mineralization from very high levels of active SOM), which may leach, and can also inhibit the activity of mycorrhizal fungi and other root symbionts.

The benefits of compost, notably its capacity to stabilize SOC, can often accrue from light annual applications (in conjunction with cover crops, etc) or a *single* heavier application that does not cause P excesses. For example, one 22 ton/ac application of cattle manure-bedding compost doubled SOC and dryland wheat yields in a Utah trial – for *15 years!* In California, a one-time compost application to depleted range not only improved forage quality but also resulted in a SOC accrual considerably greater than the organic C in the compost itself.

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-andproductivity-in-organic-dryland-wheat>.

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

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.

Slide 35 – *Summary: building SOC*

The NRCS Four Principles of Soil Health and the NOP Soil Fertility and Crop Rotation Practice Standards provide an excellent framework for sequestering carbon as well as building soil health and resilience. Application of these principles can and should be adapted to your region, climate, soil type, and production system.

Compost complements the SOC-building effects of in-situ contributions of living plants in the rotation; it can be a valuable tool for SOC sequestration when used at rates that do not build excess soil P. Obtain a soil test and compost analysis, and calibrate compost rates accordingly. If soil test P is already optimum (“high”) or above, apply no more P than expected crop removals (~10 lb elemental P/ac for vegetable harvests, ~20-30 lb/ac for grains and forages) – this will still be enough compost to complement and enhance the SOC contributions of crop roots.

Remember that the largest per-acre total C sequestration rates can be achieved through:

* Management-intensive rotational grazing practices adapted for your region.
* Conversion of depleted, marginal, steep, or otherwise erodible cropland to perennial plantings from orchard or vineyard to native prairie or forest species.
* Hedgerow, windbreak/shelterbelt, riparian forest buffer, and other woody buffer/border plantings

Slide 36 – *Summary: preventing SOC losses*

Slide 37 – *What about nitrous oxide?*

Slide 38 – *Denitrification and soil N2O emissions*

Example of application of the IPCC models for agricultural N2O emissions: if a conventional crop receives 200 lb N/ac and half of it eventually leaches to groundwater, a total of 2.75 lb N (2 lb direct, 0.75 lb indirect) will be emitted as N2O, which would negate 366 lb SOC sequestration.

Nitrous oxide is formed during microbial transformations of soluble inorganic N in the soil, primarily reduction of nitrate-N (denitrification). Conditions that promote N2O emissions include high soil N levels, limited but not zero oxygen (under fully anaerobic conditions, denitrification produces harmless elemental N2 gas, but CH4 emission rates soar), and sufficient decomposable organic C to support microbial activity.

In conventional agriculture, N2O emissions predictably occur when periods of high moisture (high rainfall, snowmelt, or spring thaw) follow fertilizer N applications, and increase exponentially as N application exceeeds crop needs. Best nutrient management protocols can cut emissions by half.

N2O emissions generally cease when soil moisture drops below “field capacity” or when nitrate-N drops below 6 ppm.

IPCC, 2014, cited above.

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.

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.

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.

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

Slide 39 – *N2O in organic systems*

On average, organic production systems reduce N2O emissions because most organic N sources do not elevate soil soluble N as much as conventional N. However, more complex N dynamics and higher levels of organic matter and microbial activity in organic systems can result in brief spikes in N2O emissions that can be difficult to predict, detect, or control. Research has shown that N2O emissions increase about 24% for each 1% increase in total SOC, and that emissions from clay-loam can be two or three times those from sandy loam.

While several comparison trials have shown lower emissions from organic than conventional cropping systems, one trial in Michigan documented five-fold greater N2O in the organic system, related to intense bursts of N2O when heavy rain followed poultry litter + cover crop plowdown, creating a “perfect storm” of high moisture, high soluble N, and high levels of readily- decomposable organic C. Increased N2O emissions commonly follow termination (by tillage) of the perennial legume sod phase of organic rotations, especially when moist to wet soil conditions follow the plowdown. A grass-legume mixture will likely emit less N2O after plowing

In California, organic broccoli production reached an economic optimum at 220 lb N/ac from organic sources; however this treatment also resulted in losses of 11 – 27 lb N/ac as N2O, a GHG impact equivalent to loss of 1,400 to 3,400 lb SOC/ac!

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

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.\*

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.

Eagle, cited above.

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.

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>.

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.\*

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.

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.

Slide 40 – *Tightly coupled N cycling in organic tomato in California*

In a study of 13 organic tomato field in central California, three distinct N cycling patterns emerged.

Two fields showed N deficiency, possibly related to poor synchrony between N release from applied amendments (manure) and relatively low soil biological activity and SOC.

Four fields showed tightly coupled N cycling and also had the highest levels of active and total SOM, and high level of microbial and plant root enzymes involved in N mineralization. While crops received some in-row soluble N as fish emulsion or Chilean sodium nitrate, the bulk soil was amended with a yard waste compost with a moderate C:N ratio (15-18:1) and a slow release of N.

The seven N saturated fields generally received more total organic N input, and from lower C:N sources such as guano, poultry litter fertilizer, and all-legume cover crops. Overall biological activity was similar to the tightly coupled fields, but with more enzyme activity associated with SOM breakdown and less activity related to N mineralization.

N deficient and tight N cycling fields both had soil nitrate-N low enough to suggest crop N limitation, but activity levels of plant root enzymes in the tight N cycling fields were similar to the high-N fields, indicating crop capacity to access N from organic sources in the soil.

UC Davis researcher Louise Jackson states in her 2013 report: “Since genetic pathways regulating N uptake are highly conserved across plant species, studies on these N metabolism genes in a model plant such as tomato are highly relevant to other crops.”

Bowles, T. M., A. D. Hollander, K. Steenwerth, and L. E. Jackson. 2015. *Tightly-Coupled Plant-Soil Nitrogen Cycling: Comparison of Organic Farms across an Agricultural Landscape*. PLOS ONE peer-reviewed research article. <http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0131888>. Numerous other articles available at <http://ucanr.edu/sites/Jackson_Lab/>.

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>.

Slide 41 – *Limiting nitrous oxide: a summary*

On healthy soils, field corn and other crops may need half as much N as the soil test lab recommends – and possibly none at all if planted after a cover crop with substantial legume component.

In Colorado, organic lettuce fertilized with in-row drip (fish fertilizer or blue-green algae-based “cyano-fertilizer”) required only 25 lb N/ac for optimum economic return, a rate and form of N that emitted almost no N2O.

While cover crops have slight and inconsistent impacts on *direct* N2O emissions, they reduce *indirect* emissions related to N leaching. Deep-rooted crops can scavenge most of the nitrate-N from the top 5 -7 feet of the soil profile. Of these, pearl millet, sorghum-sudangrass, and some others release natural nitrification inhibitors that further mitigate leaching and N2O emissions.

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.

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.

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.\*

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

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.

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.

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.

Slide 42 – *Subtitle slide – Mitigating methane emissions*

Slide 43 – Methane: the bad news

In fully-anaerobic conditions, certain microbes called *methanogens* convert organic carbon into CH4, which then escapes to the atmosphere. Dairy cattle have been estimated to release 450 – 570 lb enteric CH4 per animal annually, equivalent to a loss of 2560 – 3270 lb C as CO2.

In Texas, organic rice paddies lost about 110 lb C/ac-yr as CH4, equivalent to a loss of 840 lb C as CO2. CH4 emissions increased when rice was planted shortly after a high-biomass cover crop.

Pastured livestock can emit more enteric CH4 than grainfed, since a 100% grass diet is often higher in fiber and lower in protein than diets that include grains and high-protein concentrates.

One study found organic 100% grassfed dairy emitted twice as much CH4 per gallon of milk as conventional confinement dairy because of lower milk production and higher per-animal enteric CH4.

Pastures can also develop “hotspots” of N2O emissions in areas of high stocking density and soil compaction (e.g. a watering area or shady spot in a continuously grazed pasture, where cattle frequently congregate). MIG systems that move cattle to new paddocks every 12-72 hours might minimize this problem.

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.\*

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.

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-systemswebinar>.

Photos from ATTRA bulletins *Nutrient Cycling in Pastures* (Barbara Bellows, 2001), and *Converting cropland to Perennial Grassland* (Preston Sullivan, 2003).

Slide 44 – *Methane: the good news*

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

The SOC sequestration and enteric CH4 mitigating impacts of switching to a continuous grazing system to a MIG rotational grazing system were equally evident in studies in Michigan and Texas, and rendered livestock production net GHG-negative (climate mitigating).

Richard and Camargo, 2011, cited above.

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

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>.

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.

Wang et al, 2015, cited above.

Slide 45 – *Summary: climate-friendly livestock*

Slide 46 – *System of rice intensification*

Rice is traditionally grown in flooded paddies, partly for weed control, as the crop is more flood-tolerant than most weeds. However, the saturated, anaerobic conditions stress crop roots, inhibit their potential microbial symbionts, and hurt yields. Traditionally, rice seedlings are set out in clumps of 3 to 5 in high density plantings to compensate for the stress and low per-plant grain set, but the roots still suffer 75% rot by the end of flowering.

In the System of Rice Intensification, developed in the late 20th Century by Jesuit priest Henri de Laulanié and further researched and developed by Dr. Norman Uphoff of Cornell University and others, young rice seedlings are transplanted singly on 1-ft centers and grown in moist but not constantly flooded soil. Compost is used to provide nutrients, and weeds are hoed as needed. This system greatly improves soil health and allows the crop to grow much larger, deeper root systems, to partner with mycorrhizal fungi and other beneficial soil microbes, to utilize N and other nutrients more efficiently, and to sustain higher yields. Moist but non-flooded soil conditions sharply reduce CH4 emissions while somewhat increasing N2O emissions. Enhanced root function and nutrient efficiency will allow N fertilizer rates to be reduced, which can mitigate N2O.

Thakur et al, 2016, cited above.

Uphoff, Norman. 2013-14. *Development of the System of Rice Intensification in Madagascar*. The Natural Farmer, Winter 2013-14, Special Supplement on Crop Intensification. <http://www.nofa.org/tnf/Winter2013B.pdf>. Photo taken by Dr. Uphoff.

Slide 47 – *Estimating the farm’s GHG footprint*

Total soil organic matter percentage, given on standard soil tests, is a fairly good indicator of soil carbon sequestration. However, it is difficult to measure precisely and does not rapidly give a detectable response to management changes. A 1-point increase in SOM (e.g., from 2.0 to 3.0%) in the top 6 – 8 inches represents about 5 tons additional SOC sequestration. In addition, this does not account for sequestration below this depth, which can be substantial.

As noted above, POX-C is a good indicator of microbial activity related to SOC stabilization, while a four day respiration (PMC) measurement indicates crop nutrient mineralization, and both parameters reflect soil fertility.

Another useful measurement, for which reliable in-field tests are becoming available, is soil nitrate-N, which can help farmers fine-tune nutrient management and N application rates for optimum efficiency and minimum leaching and N2O risks.

The Cornell Comprehensive Assessment of Soil Health includes POX-C, PMC and an estimate of readily mineralizable organic N

NRCS is developing a Technical Note outlining six recommended soil health measures and lab procedures therefor. These include total SOC by “dry combustion” method (more precise than “loss on ignition” used by most labls), POX-C, the four-day PMC, available organic N, a microbial diversity assay, and enzyme assays related to C, N, P, and sulfur (S) cycling.

Several models are becoming available to help producer evaluate the overall GHG footprint of their farming systems, and identify opportunities for improvement. These models are still undergoing development and refinement, especially for organic systems. For more on these resources for, see *Soil Health and Organic Farming: Organic Practices for Climate Mitigation, Adaptation, and Carbon Sequestration*, <http://ofrf.org>.

Slide 48 – *Research frontiers in climate mitigation and resilience*

Research priorities include exploring the potential climate-mitigation benefits of breeding crop cultivars and managing cropping systems for deep, extensive root systems, enhanced root-microbe partnerships, and tighter N cycling. In recent years, more and more evidence has emerged that crop cultivars and breeding lines show considerable genetic variation in rooting depth and architecture; association with mycorrhizal fungi, N fixing bacteria, and other beneficial rhizosphere (root zone) and endophytic (within root tissue) microbes; and possibly the activity level of root enzymes involved in tightly coupled N cycling. Cultivar selection combined with best soil and crop management practices to provide adequate crop N nutrition at bulk soil nitrate-N levels below the critical 6 ppm threshold for microbial N2O formation, would effectively mitigate the single largest component of direct agricultural GHG emissions.

Research priorities also include a few climate-related concerns that have thus far received limited study. First, climate change itself is likely to impact soil C and N dynamics through rising soil temperatures and more frequent inundation by extreme rainfall events and flooding. As soils warm, SOC oxidation is expected to accelerate, especially in cold-temperate regions. Permafrost thawing in Gelisols (arctic tundra soils) could lead to a 30% increase in annual net global SOC losses. The surface accrual of SOC in no-till systems will not be sufficient to offset these trends, and additional research into deep SOC sequestration (deep rooted vegetation) and other cutting edge strategies for biological / agricultural C sequestration is urgently needed to meet the mounting challenges.

Warming soil may also speed N2O emissions by 18 – 28% for every 1 C (1.8 F) increase. In addition, periods of flooding or excessive rainfall may boost CH4 and/or N2O emissions depending on the degree of oxygen depletion.

Soils of prairie, semiarid, and arid regions hold 20 – 90% of their carbon in inorganic forms, primarily carbonates. Changes in plant community or soil management can lead to substantial losses of soil inorganic carbon (SIC) in the form of CO2. For example, efforts to ameliorate soil alkalinity will convert carbonate to CO2 + H2O as soil pH decreases to 7.0 or less.

In a review of seven studies comparing organic versus conventional systems on such soils, conversion to organic management caused losses of 9 – 14 tons SIC/ac within 3 to 19 years in three studies, but did not have significant impacts on SIC in the other four.

Further research is urgently needed to improve our understanding of SIC dynamics in soils of low-rainfall regions, and to develop organic soil management practices that will not result in accelerated CO2 emissions from this soil carbon pool.

Eagle et al., 2017, cited above.

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.

Kell, 2011, cited above.

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.

Lorenz and Lal, 2016, cited above.

Weil and Brady, 2017, cited above.

Slide 49 – *Making climate mitigation pay: carbon markets*

I left this topic for last for three reasons. First, I am not an economist. Second, this webinar is already too long. Third, it is very difficult to measure precisely the C sequestration (soil + vegetation) and the longevity thereof (turnover time) in agricultural ecosystems. Thus, the precise estimates of GHG mitigation benefits of agricultural systems and production practices that would be required in order for farmers to participate directly in carbon markets are difficult at best to obtain with current understanding and technology. This hurdle is clearly illustrated by the IPCC quote here.

However, producers can benefit indirectly from carbon markets or carbon taxes if revenues collected thereby are used to support agricultural practices known to sequester C, mitigate N2O and CH4, and/or enhance crop and livestock resilience to weather extremes and climate disruptions.

Slide 50 – *California’s healthy soils program and natural and working lands strategy*

In her March 12, 2019 opinion editorial (cited earlier), California Secretary of Food and Agriculture Karen Ross announced:

*“California took bold action by setting a goal for carbon sequestration as part of our climate portfolio and just last month released a Natural and Working Lands Strategy to store carbon in our trees, shrubs, grasses and soils.*

*“California is supporting farmers in sequestering carbon as part of a comprehensive program to foster healthy soils, which are essential to sustainability. At the Global Climate Action Summit in September 2018, California launched a Global Soil Health Challenge in partnership with France, the Netherlands and Baja California. The good news is that California is not alone. Maryland, Hawaii, Oklahoma, Utah, and other states are moving forward in this arena, and we need increased public and private financing to help our rural communities and farmers scale-up as fast as possible. Practices that build healthy soils to sequester carbon also help conserve water, improve yields, protect pollinators, and generate new jobs for rural economies. ”*

Slide 51 – *Making climate mitigation pay: co-benefits of best practices*

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

Slides 52-54 – *Credits / Questions*

\* 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 refereed journals that provide research findings in greater detail*.