**Meeting Weather Challenges in the Western U.S.***Organic Practices to Mitigate and Prepare for Climate Change*

eOrganic Soil Health and Organic Farming Webinar Series

May 29, 2019

Developed and presented by Organic Farming Research Foundation, with funding from the Western Region SARE program

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

Slides 1 and 2 – *Title and subtitle slides*

Slide 3 – *Organic farmer research priorities in the Western Region*

A total of 555 respondents from the Western region participated in OFRF’s 2015 nationwide survey of organic farmers to identify top research priorities. In addition, six listening sessions took place in the West (four in CA, two in OR).

Soil health emerged as the most frequently cited research priority; irrigation and drought management ranked fourth after soil fertility and weed management.

The survey took place toward the end of an historic 4-year drought in California, which has resulted in restrictions on availability of irrigation water for agriculture, with significant impacts on vegetable growers. Many western region producers wanted more research on how to improve water use efficiency in crops and pasture, reduce reliance on scarce irrigation water, improve soil moisture retention with compost application and other practices, deal with increasing soil salinity related to drought, and manage drought for pasture soil and grass health.

Several respondents asked how producers can document soil organic carbon (SOC) sequestration through soil health practices, and how they can be remunerated for this ecosystem service.

Slide 4 – *Extremes of drought and flood*

Respondents in the NORA farmer survey and listening sessions most often cited moisture extremes as the greatest impact of climate change on their farming operations. Several noted wild swings between severe and prolonged drought and excessive rainfall. After several years of historic drought in California, NRCS scientist Zahinger Kabir took this photo (lower) near Davis, CA of a walnut orchard in standing water after a heavy winter rainfall.

Slide 5 – *Irrigation in the era of climate change*

Full citation for first quote: Amelie Gaudin, Scott Park, Margaret Lloyd, Anna Azimi, Rebekah Velasco, and Leah Renwick. 2018. *Developing integrated irrigation management strategies to improve water and nutrient use efficiency of organic processing tomato in California*. Final report to Organic Farming Research Foundation.

Full quote from farmer in the NORA 2016 survey, page 25:

*“Irrigation is not truly sustainable, and especially with challenges due to climate change we need better practices that improve our water capture, retention, and cycling (rather than relying upon irrigation that too often utilizes below ground water faster than those reserves can be replenished). It is clear that much of the farming (even certified organic) being practiced in arid parts of the U.S. and abroad is not sustainable. We need to retain sustainable agriculture in more temperate areas (subject to development and land use conversion pressure) before that land is lost forever to farming. Research is needed to validate and further the alternative practices that are working.”*

Slide 6 – *Other climate-related concerns*

Another often-cited climate concern in the Western region is increasing difficulty with unpredictable chill hours disrupting production in walnut pistachio, and other tree nut and fruit crops. Several producers wanted research-based assistance in identifying new crops or cultivars that would make their farming enterprises more resilient to current and expected climate shifts.

Slide 7 – *Subtitle: how does agriculture affect climate?*

Slide 8 – *Greenhouse gases in agriculture*

In this webinar, agricultural greenhouse gas (GHG) emissions and potentials for mitigation and sequestration are discussed in terms of carbon equivalents.

One pound of fertilizer N lost as nitrous oxide (N2O) negates 133 lb SOC sequestration, and one pound of organic carbon lost from rice paddies or manure lagoons as methane (CH4) negates 7.6 lb SOC sequestration.

Total global GHG emissions are roughly 15 billion tons annually in CO2-C equivalents.

Slide 9 – *Direct agricultural GHG emissions in the US in 2017*

Estimates of “direct” agricultural GHG emissions by US Environmental Protection Agency do not include the fossil fuel consumption during farm operations nor “embodied energy” in fertilizers and other inputs. These are subsumed under the emissions categories of machinery, transportation, and industrial processes. “Direct” agricultural GHG emissions also do not include changes in soil organic carbon (SOC) or destruction / restoration of forest, prairie, other native vegetation, or conversion of pasture to cropland or vice versa. These are categorized under “land use, land use change, and forestry”.

The EPA estimate does include CO2 released after field applications of lime and urea, which comprises about 1.5% of the total US direct agricultural emissions.

In 2016, researchers at Washington State University presented a webinar on agricultural GHG in which the “direct” emissions included the CO2 from on-farm fossil fuel use (field operations and other farm vehicles and machinery), and the “embodied energy” related to manufacture of fertilizers, pesticides, and other inputs. They estimated that these CO2 sources account for about one-sixth of total direct agricultural GHG (in CO2 equivalents).

The pie chart is based on EPA data for 2017 plus the 17% “slice” for farm machinery and inputs.

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-andagriculture:-where-does-organic-farming-fit-webinar>.

Environmental Protection Agency (EPA). 2019. Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017. Full Report. <https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2017>. Chapter 5 Agriculture, and Chapter 6 Land Use, Land Use Change, and Forestry.

Slide 10 – *Soil and the global carbon cycle*

This simplified representation of the global carbon cycle illustrates several key points.

The annual imbalance between vegetation organic C delivery to the soil and SOC conversion to atmospheric CO2 looks small relative to the pool sizes and annual flows. However, 2 gigatons of C amounts to some 13% of the estimated total global human GHG emissions of 15 gigatons, and is roughly equal to the total annual direct agricultural GHG. Half of this net annual SOC loss has been attributed to soil erosion, which selectively removes the SOC-rich fractions of topsoil; much of this organic C is oxidized to CO2 or, for water-eroded sediments that remain submerged, converted to CH4 with its larger global warming potential.

The soil holds twice as much organic carbon as the *sum* of global vegetation biomass and atmospheric gaseous 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.

In addition to SOC, the world’s soils hold nearly 1,000 billion tons of inorganic (carbonate) carbon (SIC), mainly in prairie, semiarid, and desert regions. Further research is needed on the impact of agricultural and land use practices on SIC.

*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.

The diagram does not account for the conversion of biomass C into CO2 through deforestation, fires, etc., nor for the potential to reverse that to a net sequestration through reforestation, conservation buffer planting, and restoration of degraded or abandoned lands into perennial native vegetation.

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

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

Slide 11 – *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 about 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.

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*.

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.

Weil and Brady, 2017, cited above.

Slide 12 - *Sustainable Farming can Build SOC*

Sustainable agricultural systems such as organic farming can reverse the loss of SOC, in a process known as carbon sequestration.

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 some 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 long term farming systems trial at Beltsville, total SOC (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 corn-soy rotation, 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 approximately offset all *direct* agricultural GHG emissions.

Research findings suggest that finished compost and living plant roots can play complementary roles in SOC sequestration. Compost adds stable SOM and may help stabilize the OM deposited in situ by plant roots and aboveground residues. Cover crops, organic amendments (compost or manure), and reduced tillage each contribute to SOC, and 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, 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.

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

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

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 13 – *Quote from California Agricultural Secretary Karen Ross*

Slide 14 – *Methane*

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 organic C as CO2.

If forage protein content and overall quality are inadequate, 100% grassfed cattle can emit more enteric CH4 than cattle receiving grain. Planting a legume-grass mixed pasture and implementing management-intensive rotational grazing (MIG) can maintain high forage quality and reduce enteric CH4 to levels similar to that of grain-supplemented livestock.

Manure lagoons and other liquid manure storage facilities associated with confinement livestock operations are the second largest source of agricultural CH4 emissions, accounting for about 10% of the total direct agricultural GHG footprint of US agriculture. In addition, these manure storage facilities can emit some nitrous oxide (N2O), and pose severe threats to water quality in nearby communities in the event of extreme rainfall events causing lagoons to overflow. Two solutions are to transition livestock production to pasture based systems (eliminating lagoons, though not enteric CH4), and installing airtight covers over liquid manure storage facilities to capture the CH4 as fuel or at least flare it for release as less-harmful CO2. However, increasing use of manure lagoons without this mitigation strategy has been the main driving factor in an upward trend in total US agricultural GHG emissions since 1990.

In Texas, organic rice paddies lost about 110 lb C/ac-yr as CH4, equivalent to a loss of 840 lb C as CO2. Methane emissions increased when rice was planted shortly after a high-biomass cover crop. Paddy rice production accounts for only about 2% of US direct agricultural GHG, but some 10% of the world’s agricultural GHG because of much larger acreages of rice grown in Asia.

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.\*

EPA, 2019, cited above.

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>.

Photo of rice paddy taken from open source, ["IMG\_3891"](https://www.flickr.com/photos/21503112@N07/2830215808) by [mtarlock](https://www.flickr.com/photos/21503112@N07) licensed under [CC BY-SA 2.0](https://creativecommons.org/licenses/by-sa/2.0/?ref=ccsearch&atype=rich)

Slide 15 – *Denitrification and soil N2O emissions*

Nitrous oxide is formed as a byproduct of microbial transformations of soluble inorganic N in the soil, primarily during reduction of nitrate-N (denitrification), and to a lesser degree during oxidation of ammonium-N to nitrate-N (nitrification). Soil conditions that promote N2O emissions include high levels of moisture, soluble N, readily-decomposable organic C, and microbial activity; and impeded gas exchange resulting in low but not zero oxygen levels (hypoxic). N2O emissions are greatest when about 80% of topsoil pore space volume is water-filled, and become minimal when soil moisture drops below field capacity (~60% water-filled pore space) or when nitrate-N levels drop below 6 ppm. Under fully saturated and anaerobic conditions such as flooded rice paddy, denitrifying microbes produce harmless elemental N2 gas, but other microbes release CH4).

For the purposes of estimating N2O release from fertilized cropland, the International Panel on Climate change (IPCC) uses an “emissions factor” of 1% of applied fertilizer N converted into N20 in the soil profile (direct emissions), and 0.75% of soluble N leached into groundwater subsequently converted to N2O (indirect emissions). Thus, if a conventional corn crop receives 200 lb N/ac and half of it eventually leaches to groundwater, IPCC estimates that a total of 2.75 lb N/ac will be emitted as N2O, which would negate 366 lb SOC sequestration.

In conventional agriculture, N2O emissions predictably occur when periods of high moisture (high rainfall, snowmelt, or spring thaw) follow fertilizer N applications in excess of crop needs. Best nutrient management protocols (the “4 Rs of right form, placement, timing and amount) can cut emissions by half.

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 16 – *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 fertilizers. 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, because the finer pore space in fine-textured soils increases water retention and slows gaseous diffusion.

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 ample moisture, soluble N, and 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 termination.

Studies at Washington State University indicated that N2O emissions following incorporation of a hairy vetch green manure into moist soil equaled emissions from urea, and greatly exceeded emissions from finished compost. Grass-legume mixtures will generally emit less N2O at plowdown than an all-legume green manure.

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.

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.\*

Carpenter-Boggs et al., 2016, cited above.

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 et al., 2017 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 17 – *Subtitle slide – Organic farming practices to meet climate challenges*

Slide 18 – *Pop quiz: best biotechnology for mitigating and adapting to climate change*

Slide 19 – Living plants build healthy, resilient soils and sequester C

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.

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.

Actually the most accurate answer to the pop quiz question in the preceding slide is: “*Living plants in partnership with the soil lif*e.”

Slide 20 – *How roots build SOC throughout the soil profile*

Plant roots play an important and hitherto under-appreciated role in long term carbon sequestration. Emerging evidence suggests that the majority of stable SOC originates from plant roots and their exudates (Rasse et al., 2005). Crop breeding and management for enhanced root depth and biomass have been recommended as strategies for carbon sequestration and climate mitigation (Kell, 2011, 2012).

Studies at Washington State University have shown that perennial forage crops have much higher root biomass (3,000 – 8,000 lb/ac) than annual grains (800 – 1,400 lb/ac), which may explain why rotations that include a perennial sod phase often build and maintain higher SOC than all-annual crop rotations.

A study in Denmark showed that organically grown cereal grains may develop higher root biomass (~1,900 lb/ac) than conventionally grown grains (~1200 lb/ac).

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 world’s SOC occurs deeper than 12 inches (Lal, 2015, cited above). The reason for this is that 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. In addition, the disturbance of tillage rarely reaches below 12 inches.

Different conservation practices sequester C in different parts of the soil profile; for example no-till, organic mulching, and plant residues 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). Thus, the C sequestered by cover crops may be more stable than that gained through no-till, and no-till termination of 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.

Carpenter-Boggs et al., 2016, cited above.

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.

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.

Slide 21 – *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, temperature extremes, and other stresses. Other soil organisms live on plant litter, manure, and other organic residues, converting them into soil organic matter (SOM), which sequesters carbon and 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. Abundant organic matter and biological activity play major roles in maintaining good structure and water holding capacity. 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 22 – *Climate benefits of organic practices*

Organic and sustainable farming practices simultaneously enhance resilience to weather extremes and directly mitigate GHG emissions. For example “sustainable crop intensification” – practices such as tight crop rotation, cover crops, intercrops, relay crops, and perennial sod phase in the rotation that maximize biomass production and living root biomass, depth, and duration – build SOC, reduce N2O emissions (by utilizing soluble N), and sustain soil and crop health, stress tolerance, and yield stability.

Crop diversification supports a more diverse and balanced soil biota as well as reducing economic risks of crop loss from weather extremes or other causes. Diversified rotations also accrue more SOC than simpler rotations with similar annual plant biomass production.

Careful nutrient management, especially nitrogen (N) is vital for limiting N2O emissions. Avoiding surplus soluble N, P, other nutrients, and salts in the soil also enhances the capacity of crop roots to host a vibrant, diverse, and beneficial rhizosphere microbiota including mycorrhizal fungi, all of which promote efficient nutrient cycling. Mycorrhizal fungi are most active at low to moderate soil N and P levels; enhance crop drought tolerance and help stabilize SOC.

Management intensive rotational grazing (MIG) effectively builds SOC, reduces CH4 emissions by minimizing the need for manure storage, and at the same time improves forage and livestock health, and overall resilience of the grazing system to drought and other stresses.

Making and using compost can contribute to soil and crop health and – when organic residues are diverted from landfills or manure lagoons – substantially reduce CH4 emissions.

Slide 23 – *Combine practices to sequester C*

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 to manage perennial weeds or break hardpan. A cover crop that is terminated by tillage may add only a little SOC since the disturbance stimulates microbial respiration. Combining the cover crop with no-till termination can enhance SOC quantity and stability. In organic rotational no till (tilling after cash crops to manage weeds and plant the next cover, crop roots can 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, 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, 2015, cited above.

Photo of cover crop roll-crimping and no till planting in one operation is from *Reduced Tillage in Organic Systems Field Day Program Handbook*, page 6. [*https://rvpadmin.cce.cornell.edu/uploads/doc\_699.pdf*](https://rvpadmin.cce.cornell.edu/uploads/doc_699.pdf)

Slide 24 – *Diversify the 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.

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.

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.

Slide 25 – *Make and use compost wisely*

While the composting process emits some N2O and (if improperly aerated) CH4, these emissions are far less than the heavy CH4 emissions when manure is stored in lagoons or when autumn leaves, food waste, and other municipal organic residues are landfilled. 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, taking plant biomass from native ecosystems, grazing lands or croplands 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 health in the source acreages.

Relying on compost or manure to meet all of the nitrogen (N) needs of a crop rotation usually builds soil P to excessive levels that can inhibit mycorrhizal fungi and compromise their nutrient cycling and SOC stabilization benefits. Heavy annual applications of higher-analysis compost can also saturate the soil with soluble N, which may leach and/or compromise biological nutrient cycling. However, the benefits of compost, notably its capacity to stabilize SOC from crop residues, can often accrue from light applications that do not pose these risks.

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

Slide 26 – *Managing the N2O beast*

Nitrous oxide is a wild card and a challenge to manage in any farming system. The abundant active soil organic carbon and high biological activity of healthy, organically managed soils contributes fertility and resilience – yet can also lead to a burst of N2O if a green manure plowdown or organic fertilizer application is followed by untimely heavy rain. More research is needed to help all farmers – organic and otherwise – to monitor N2O risks and limit this part of their GHG footprint. Findings to date provide some preliminary guidelines.

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

Mycorrhizal fungi support tight N cycling and may directly inhibit N2O formation.

In Colorado, organic lettuce receiving in-row drip (fish- or cyanobacteria-based fertilizer) required only 25 lb N/ac for optimum economic yield, a rate and emitted almost no N2O.

While cover crops have slight and inconsistent impacts on direct N2O emissions (from the field itself), they reduce indirect emissions by recovering nitrate-N from the subsoil. Deep-rooted crops can scavenge most of the nitrate-N throughout the top 5 -7 feet of the soil profile. Of these, pearl millet, sorghum-sudangrass, and some other crops release natural nitrification inhibitors that further mitigate both 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 27 – *System of rice intensification*

Rice is traditionally grown in flooded paddies to control weeds less flood-tolerant than the crop itself. 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, non-flooded soil conditions sharply reduce CH4 emissions, increase N2O somewhat, and reduce net GHG per ton yield by 60%. Enhanced root function and nutrient efficiency allow lower N fertilizer rates, which can mitigate N2O.

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

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, first published in this issue of The Natural Farmer.

Slide 28 – *Restore soil with livestock*

Pasture-based livestock systems can minimize or eliminate the need for manure storage facilities with all their GHG emissions and threats to water quality.

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, the northern and southern Great Plains, and rangeland in the Western region with initial C sequestration rates of one to three tons per acre annually for the first five to ten years after implementation. Silvopasture systems that integrate tree crops with grazing can further enhance total C storage.

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.

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.

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.

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 29 – MIG versus continuous grazing

Pastured livestock can emit more enteric CH4 than those receiving grain, since a 100% grass diet is often higher in fiber and lower in protein than diets that include grains, soybeans, and other 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. However, when the scientists re-calculated *total* GHG footprints based on estimated C sequestration of 890 lb C/ac-yr, the 100% grassfed organic milk GHG footprint decreased to only 80% that of conventional confinement dairy milk. In addition, MIG improves forage quality, which can reduce per-animal enteric CH4 by 30% compared to lower forage quality under continuous grazing.

Pastures can 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 can largely prevent this problem.

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

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

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 and Camargo. 2011, cited earlier

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>.

Wang, et al., 2015, cited above.

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

Slide 30 – *Plant perennial crops and conservation buffers*

Just as clearing native forest or prairie converts tons of SOC per acre into CO2, converting highly erodible, depleted, or marginal cropland back to 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, including C sequestration. A meta-analysis showed that agroforestry plantings in temperate and semiarid region can sequester ≥1 ton C per acre annually, and even more in humid tropical regions. Converting disused land into intensive permacultural home and community gardens sequestered 3,100 lb/ac in SOC alone (mean of 19 studies), while silvopasture systems accrued 3,900 lb SOC/ac-year (mean of 9 studies).

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.

Feliciano et al. 2018, cited above.

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 31 – *Subtitle slide – Technical and financial assistance in meeting climate challenges*

Slide 32 – *Estimating GHG footprints and documenting benefits of practices*

In order for farmers to realize economic benefits from ecosystem services of C sequestration and GHG mitigation (e.g., through carbon markets and offsets), improved means for estimating C sequestration and net GHG impacts of farming systems and practices are urgently needed.

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, which can take 5 to 20 years of improved practices to accrue. In addition, standard soil tests that sample surface to 6 inches do not account for sequestration below this depth, which can be substantial.

Permanganate-oxidizable carbon (POX-C) is itself an active fraction of the SOC, yet it is a strong indicator of the SOC stabilization function of the soil life. Soil respiration, also known as potentially mineralizable carbon (PMC) indicates the mineralization function. A four-day incubation protocol based on the Solvita test has given a reliable index of PMC. Both POX-C and PMC show strong correlations with soil fertility and crop yields.

Another useful measurement, for which reliable in-field tests are becoming available, is soil nitrate-N, which can inform growers whether and to what degree soil N is vulnerable to denitrification or leaching. Soil nitrate-N measurements can help farmers fine-tune nutrient management and N application rates for optimum N efficiency N2O mitigation.

The Cornell Comprehensive Assessment of Soil Health offers the POXC and PMC, a protocol for estimating readily mineralizable organic N (likely to be converted to ammonium-N and nitrate-N during the current season), and several other soil health measures. NRCS is in the process of finalizing 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 labs), POX-C, PMC, available organic N, a microbial diversity assay, and a set of four enzyme assays related to C, N, P, and sulfur (S) cycling.

Monitoring and predictive modeling for CH4 and especially N2O are especially challenging, and require further research and development. Ongoing work at Washington State University (OFOOT) and Colorado State University (COMET Farm) aims to develop improved models for organic crop and livestock production.

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-andagriculture:-where-does-organic-farming-fit-webinar>.

Schipanski, M., 2016. *Decision support to quantify GHG mitigation and ecosystem services from organic production systems.* Proposal for ORG project 2016-06180. CRIS Abstracts.\*

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 33 – *NRCS conservation programs*

USDA Natural Resources Conservation Service (NRCS) offers conservation programs that share the cost of implementing many of the practices discussed thus far. These include the working lands programs – Environmental Quality Incentives Program (EQIP), Conservation Stewardship Program (CSP), and Regional Conservation Partnership Program (RCPP); the Conservation Reserve Program, and the Agricultural Conservation Easement Program. For more, visit <https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/>.

While none of these program pays for C sequestration or GHG reduction *per se*, they offer financial and technical assistance for practices such as cover cropping, management intensive rotational grazing, and perennial conservation buffer plantings that can help farmers prepare for and help mitigate climate change, but are difficult or infeasible for producers to adopt without cost share. CSP will offer comprehensive conservation planning beginning in 2020.

Language in the 2018 Farm Bill mandates an increased emphasis throughout the NRCS programs – and USDA research programs as well – on soil health and investment in improved soil health management. Although the bill stops short of using the words “climate change,” it prioritizes helping farmers to adapt to and mitigate against “increasing weather volatility through CSP and EQIP.

NRCS launched a nationwide Soil Health Initiative in 2011, which now includes an extensive web site at: <https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/soils/health/>, and an archive of excellent webinars on soil building, climate mitigation and adaptation in agriculture, adaptive nutrient management, crop-livestock integration, and other relevant topics, at <http://www.conservationwebinars.net/previous-webinars>.

One of the first outputs of the Soil Health initiative is the NRC Four Principles of Soil Health (summarized in slide), which provide a science-based roadmap for managing agricultural soils for climate mitigation and adaptation as well as long term fertility.

Slide 34 – *California Healthy Soils Program*

The California Healthy Soils Initiative was initiated by Governor Jerry Brown in 2015 and funded by Senate Bill 859 in September 2016. The bill requires the CA Dept. of Food and Agriculture to offer “incentives, including loans, grants, research, and technical assistance, or educational materials and outreach, to farmers whose management practices contribute to healthy soils and result in net long-term on-farm greenhouse gas benefits.” The bill also mandates a number of “dairy methane management practices, including anaerobic digesters and non-digester strategies” that include solid manure management and composting, and pasturing livestock to distribute manure and reduce / eliminate need for storage facilities.

In a March 12, 2019 opinion editorial, California Agriculture Secretary Karen Ross stated:

*“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. ”*

Karen Ross, Secretary, CA Dept. Food and Agriculture , March 12, 2019 *Opinion: California agriculture is ready to scale up climate solutions.* <https://plantingseedsblog.cdfa.ca.gov/wordpress/?p=17386>.

Slide 35 – *Other state soil health programs*

This information, and other examples from other states are given in:

Isaak Walton League of America. 2019. *State and Local Soil Health Strategies: Building Soil Health Policy from the Ground Up*

<https://www.iwla.org/docs/default-source/conservation-docs/agriculture-documents/state-soil-health-policies.pdf?sfvrsn=2>

A couple of examples from outside the region illustrate the range of services that can be provided at the state level. The State of Maryland has offered cover cropping cost share at up to $75 per acre for the past several years, resulting in cover crop plantings on over 50% of the state’s cropland. In 2017, Maryland implemented a new Health Soils Program to promote additional soil health practices based on emerging science on soil biology and carbon sequestration. Iowa has offered cost share for cover cropping ($15 – 25 per acre) and a $5/ac discount on crop insurance for acres on which cover cropping was implemented.

Slide 36 – *Subtitle slide – Meeting climate challenges in the Western region*

Slide 37 – *Saving water through soil health and deficit irrigation*

In an OFRF-funded on-farm study, Dr. Amelie Gaudin and colleagues at University of California at Davis and farmer collaborator Scott Park of Park Farm Organics, conducted experiments to determine whether the farmer’s integrated soil health building practices - diverse rotation, cover crops, compost, conservation tillage, and controlled traffic – would enhance irrigation water use efficiency in organic tomato. Increasingly severe droughts, high cost of irrigation water, and concerns about N leaching (lost nutrients, groundwater pollution) have made water use efficiency a top priority for California farmers. Trials were conducted at UC Davis and on Scott Park’s farm in the Sacramento Valley, a region impacted by California’s drought and irrigation water restrictions in recent years.

Slide 38 – *2016 trial: deficit irrigation at Part Farm Organics*

In the 2016 experiment at Park Farm Organics, irrigation was cut off at 45 days prior to harvest (compared to 30 days in the control), saving about 6 acre-inches of precious irrigation water and reducing the potential for nitrogen leaching. Moisture reserves in the healthy, organically managed soil were sufficient to sustain 62 ton/ac tomato yields in the deficit irrigation treatment (essentially same as controls), which translates into a 19% improvement in irrigation water efficiency. Early cutoff also enhanced soil microbial activity at harvest time (measured surface to 12 inches), which helped immobilize some of the leftover nitrate-N (measured surface to 4 inches). This might reduce risks of N2O emissions during winter rains, especially with actively growing winter cover crops utilizing moisture and nutrients.

For more information, search database at <https://ofrf.org/research/database> under Amelie Gaudin, or see video at <https://www.youtube.com/watch?v=yapM4_SUu6I>.

Slide 39 – *2017: organic enhances water efficiency*

In the second year of the trial, with replicated treatments at both Scott Park’s farm and a nearby conventional farm, the savings in the Park organic field with deficit irrigation was only 0.17 ac-ft; however both deficit and standard irrigation required much less irrigation water (0.57 and 0.74 ac-ft) at the Park Farm than at the conventional field only one mile away (1.51 and 1.71 ac-ft). Thus, the organic field had much higher irrigation efficiency (tons yield per acre-ft), especially when irrigation was cut off two weeks early with essentially no impact on yield.

The organically managed soil had a moisture content of 0.165 g / g dry soil, compared to just 0.084 for conventional, which clearly illustrates the increased drought resilience arising from integrated soil health practices.

An upward trend in fruit quality was also noted from the organic field, with a trend toward higher phenol content and a lower % of rotten fruit (5 vs 10% unmarketable).

Slide 40 – *Winter cover crops in California’s rainy season*

“I took these photograph in the same day close to each other in same soil type, after a storm event in a Solano, CA walnut orchard. Only difference is the cover crops. Poor soil structure which is associated with poor soil health causes the water not to infiltrate.” Z. Kabir

Saturated soil conditions will deter beneficial aerobic soil micro-organisms, promote CH4 and N2O emissions, and compromise drought resilience during the hot, dry summer season.

This slide and the following one are used here with permission from Dr. Kabir.

Slide 41 – *Cover crop versus fallow, after winter rain in California*

“I took these photos, other side of the County Road 98 near woodland, CA after a heavy rain fall event (about 2” of RF) with the same soil. As you can see, two fields opposite side of the road. The important difference is cover crop vs fallow. Cover crop field all rain water infiltrated but the fallow field soil is sealed off due to rain fall impact and remaining on the field and running off from the field.” (Z. Kabir)

While the fallow field is fully submerged, methanogenic archaea will convert organic residues into CH4 and plant-available nitrogen into elemental N2. Later, as the soil begins to dry and allow a limited amount of oxygen to reach the microbial community, CH4 emissions will cease but N2O emissions will intensify.

Slide 42 – *N2O challenge in organic broccoli*

Broccoli is such a heavy and inefficient N feeder that it is difficult to grow profitably and in a climate-friendly manner, even with organic practices. While the crop needs large amounts of N to yield well, harvest removes less than half of the N applied. In the Mediterranean climate, most of the year’s rainfall happens during winter months after harvest, which accentuates N leaching and denitrification.

Washington State U conducted on-farm broccoli N fertilizer rate trials at three maritime and two interior semiarid sites, with feather meal (11-0-0) applied at 0-240 lb/ac (2016) or 0-480 lb N/ac (2017). Seven site-years provided yield data; one of these showed yield plateau at 150 lb/ac, the others at >200. Using feather meal (NOP allowed, $6.36/lb N) enhanced marketable yields by 11 – 88 lb per lb N. At $2.50 /lb for organic broccoli, farmers realized a 4 to 34 fold return on investment for the fertilizer.

Field trials at University of California Santa Cruz provided the basis for modeling studies of broccoli yield and soil C and N dynamics in response to 0, 75, 150, and 225 lb N/ac in the form of blood, meat, and feather meals, with or without compost or legume-cereal cover crop prior to the broccoli. The yield curve indicated 215 lb/ac needed for optimum yield, and N losses from this system would approach 180 lb/ac leached, and another 23 lb/ac emitted as N2O, which would require an additional 3,060 lb/ac SOC sequestration to offset.

In other trials with organic rotations of broccoli followed by strawberry, most of the N mineralized from the broccoli residues leached during winter rains (~ 18 inches over a three month period), long before strawberry could utilize it, since the latter’s major growth and N demand took place during May-August.

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>.

(Fertilizer was broadcast in the WA trials; band application in crop grow zone might have enhanced nutrient use efficiency (Doug Collins pers. commun.)

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>.

Muramoto, J., C. Shennan, and J., M. Gaskell. 2015. *Nitrogen management in organic strawberries: challenges and approaches*. (Webinar) [http://articles.extension.org/pages/73279/nitrogen-management-in-organ­ic-strawberries:-challenges-and-approaches](http://articles.extension.org/pages/73279/nitrogen-management-in-organ%1fic-strawberries:-challenges-and-approaches)

Slide 43 – *Winter cover crop recycles N*

While strawberry planted after broccoli in central California could not utilize the leftover N, vigorous, deeper-rooted winter cover crops do so quite effectively.

In an eight-year trial conducted by Dr. Eric Brennan of USDA Agricultural Research Service in the Salinas Valley (Salinas Organic Cropping Systems Experiment) on a Chualar loamy sand (well drained but high bulk density restricts root growth at and below 30-inch depth), a double cropping system of spring lettuce followed by fall broccoli sustained high lettuce yields (1000 boxes/ac, about 30 lb/box) only when a winter cover crop was grown prior to the lettuce. In the system that left the field fallow three winters out of four, lettuce yields declined sharply to a few hundred boxes per acre, and sometimes to a total crop failure. Cover crops of rye alone, mustard, or rye with vetch, fava, and pea were similarly effective, indicating that their main benefit was not N fixation, but recovery of N left over from the broccoli crop. Broccoli was fertilized with about 145 lb N/ac (organic sources), only about 25% of which was removed in harvest. During winter fallow, leaching by heavy winter rains depleted soil N, whereas vigorous winter cover crops recovered N and their residues delivered it to the lettuce. Although N2O was not monitored, it is likely that dentrification was also curbed by the cover crop.

Compost by itself enhanced total SOM, but did not conserve soluble N; thus the amendment and the cover crop played complementary roles in soil health and net GHG mitigation.

Similarly, in conventionally grown vegetable trials on the same soil type in Salinas Valley, winter rains leached some 230 lb nitrate-N/ac from a bare fallow soil profile after heavily fertilized vegetables. November-planted cover crops of cereal rye or phacelia attained ~3,200 lb/ac biomass by the termination date (March 20), and reduced N leaching by 65 - 70%, partly through N uptake and partly by reducing downward movement of water by about 38%.

Brennan, E. 2018. Lessons from long-term, cover crop research in the Salad Bowl of the World – 10 minute youtube video, <https://www.youtube.com/watch?v=JurC4pJ7Lb4>

Brennan, E. B., and V. Acosta-Martinez. 2017. Cover cropping frequency is the main driver of soil microbial changes during six years of organic vegetable production. Soil Biology and Biochemistry 109: 188-204.

Wyland, L. J., L. E. Jackson, W. E. Chaney, K. Klonksi, S. T. Koike, and B. Kimple. 1996. *Winter cover crops in a vegetable cropping system: impacts on nitrate leaching, soil water, crop yield, pests and management costs.* Agriculture, Ecosystems and Environment 59: 1-17.

Slide 44 – *Tightly coupled N cycling in 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 soil organic matter, and high levels 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.

Seven fields showed N saturation. These 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 (≤ 6 ppm) to suggest crop N limitation – and also to prevent significant N2O emissions. 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 45 – *Balancing C and N in organic inputs*

A research team at Washington State University compared the crop and soil impacts of two nutrient sources in organic vegetable production in a maritime soil in Washington State: on-farm mixed compost made from dairy manure, bedding and yard waste (higher C:N) at rates of 6 to 8 tons/ac annually, and composted poultry litter (low C:N) at 1.8 – 2.6 tons/ac annually. Crop yields, soil physical, chemical, and biological properties, and potential to emit N2O, were monitored over an 11 year period.

At the end of that time, plots receiving the higher C:N mixed compost had 43% higher total SOM, 30% higher microbial respiration, 60% higher POX-C, higher levels of enzyme activities involved in nutrient cycling, and a more balanced nematode community than plots receiving poultry litter. Higher levels of nitrifying bacteria and bacterial feeding nematodes were seen with poultry litter, which suggest a potentially greater risk of N2O emissions. As noted earlier, poultry litter applications can result in significant N losses in this form, especially when wet conditions follow application.

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.

Bowmik, A., A. Fortuna, L. J. Cihacek, A. I. Bary, and C. G. Cogger. 2015., *Use of Biological Indicators of Soil Health to Estimate Reactive Nitrogen Dynamics in Long Term Organic Vegetable and Pasture Systems.* Soil Science Society of America Meeting, Nov 15-18, 2015, Minneapolis, MN, Poster No. 1205.

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.\*

Slide 46 – *More compost research findings.*

One concern about annual compost applications such as in the Washington State trials is that the SOC may not represent SOC sequestration per se, rather, the transfer of organic materials from one locale to another, with potential depletion of the “donor” acres. However, several studies in the Western region and others suggest that the benefits of compost, notably its capacity to stabilize SOC, can accrue from light annual applications or a *single* heavier application that does not create nutrient excesses.

For example, one 22 ton/ac (dry weight) application of cattle manure-bedding compost (C:N ~20) doubled SOC and dryland organic wheat yields in a Utah trial – for 15 years! In California, a one-time compost (manure + yard waste) 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. Other studies have shown that relatively small amounts of compost can work synergistically with cover crops, rotation, and other soil health practices to build stable SOC.

Life cycle analysis of composting and land application of materials that would otherwise be held in lagoons or disposed in landfills shows substantial net reduction in GHG impacts.

Cavigelli et al., 2013, cited above.

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.

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.

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.\*

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 47 – *Living cover build orchard and vineyard SOC and resilience*

Maintaining bare orchard floor with tillage or herbicides can severely deplete SOC, damage soil health, compromise water retention, and does not save on irrigation water. Irrigated organic orchard in Utah showed unchanged irrigation demands and significantly improved soil health and tree root development with legume (trefoil) alleys and either living mulch (shallow rooted species like alyssum) or straw mulch in tree rows.

In a study of organic cherry production in Oregon, living orchard floor cover maintained the highest active and total SOC as well as enzyme activities related to nutrient cycling and uptake; applied organic mulch or landscape fabric were intermediate, and the conventional treatment in herbicide-maintained bare fallow had the lowest SOC and soil health indicators.

Bonterra Organic Vineyards in Mendocino County, CA worked with Pacific Agroecology to study soil health in nine organic, three biodynamic, and one conventional vineyard, and found 9% and 13% higher total SOC in organic and biodynamic, respectively versus conventional.

In Spain, organic olive orchards with perennial living cover (mowed periodically) have twice the SOC as conventional olive with clean tilled orchard floor. Almond orchards in the same region realized a 26-48% increase in SOC from reduced tillage + green manures versus no cover.

Azarenko, A. N., R. E. Ingham, D. D. Myrold, and C. F. Seavert. 2009. *Ecological Soil Community Management for Enhanced Nutrient Cycling in Organic Sweet Cherry Orchards.* Final report for ORG project 2005-04461. CRIS Abstracts.\*

Bonterra Organic Vineyards, <https://www.bonterra.com/soil-study/>.

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

Reeve., J. 2014. *Organic Stone Fruit Production: Optimizing Water Use, Fertility, Pest Management, Fruit Quality and Economics.* Final report for OREI project 2009-01338, CRIS Abstracts.\*

Vicente-Vicente, J. L., B. Gómez-Muñoz, M.B. Hinojosa-Centeno, P. Smith, R. Garcia-Ruiz. 2017. *Carbon saturation and assessment of soil organic carbon fractions in Mediterranean rainfed olive orchards under plant cover management*. Agriculture, Ecosystems and Environment 245: 135-146

Rowley, M., B. Black, and G. Cardon. 2012. *Alternative Orchard Floor Management Strategies.* Utah State University Cooperative Extension, Horticulture/Fruit/2012-01pr, 4 pp.

Slide 48 – *Sequestering C in dry regions: can deep roots backfire?*

In dryland production, farmers face severe tradeoffs among crop yield, soil moisture, and long term soil health and carbon sequestration. In low-rainfall regions, agricultural N2O and CH4 emissions are reduced, but so is SOC sequestration. When soil moisture is limiting, deep, extensive, active roots can be a mixed blessing. Care is needed to choose cover crops that are both deep rooted and water efficient. For example, experience in Montana indicates that alfalfa, can deplete soil moisture so severely that subsequent grain yields are depressed for several years.

However, simply leaving the cover crop out (alternate year cereal grain and fallow) hurts soil quality and water holding capacity in the long run. The traditional two year wheat/fallow system, intended to save up soil moisture, 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 leave adequate soil moisture for the next grain crop) 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 49 – *Building SOC on limited rainfall*

Doug and Anna Crabtree grow some 7,000 acres of dryland organic specialty grains, pulses, and oilseeds, and have designed a highly effective, diversified crop rotation (15 production crops and 10 cover crops) that has substantially restored soil health over a 10 year period. Increasingly variable rainfall with an extreme drought in 2017 have posed severe challenges - yet even when grain crops fail, this diversified, no-fallow cropping system protects soil from wind erosion and SOM losses. They have also documented steadily increasing SOM, from about 2.1% when they first purchased the land to now approaching 3% in the best fields. <https://www.vilicusfarms.com/>.

By combining crop rotation, cover crops, and no-till, and integrating crop production with MIG livestock, North Dakota rancher and author Gabe Brown has rebuilt 5,000 acres of rangeland and cropland soil from a severely depleted state (2% SOM or ~1% SOC) 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, G. 2018. *Dirt to Soil: One Family’s Journey into Regenerative Agriculture.* Chelsea Green Publishing, White Junction, VT. 223 pp.

Slide 50 – *Subtitle slide – some unanswered questions*

Slide 51 – *Soil inorganic carbon*

Soil inorganic carbon (SIC), primarily carbonates of Ca, Mg, K, and Na, comprises nearly one-quarter of the world’s total soil carbon pool, and can account for 20 to 90% of total soil carbon in prairie, semiarid, and desert soils. Bringing these soils into crop production may require soil amendments and practices that could convert some of this carbonate-C into CO2. For example, amendments to lower excessively alkaline pH would be expected to react with carbonates and release CO2. Organic amendments or even the addition of new and different crops to the ecosystem to build SOC, biological activity, soil health, and fertility for agricultural production could also modify the balance of environmental conditions and possibly affect the stability of carbonates in subsoil horizons such as this one in the photo.

In a review of seven farming systems trials, three studies (in New Mexico, North Dakota, and Spain) found SIC 18 – 67% (9 – 14 tonsC/ac) lower after 3 to 19 years under organic management compared to conventional, while four other studies (North Dakota, Nebraska, Minnesota, and Spain) found little difference in SIC between conventional and organic. With SIC accounting for about 900 billion tons of C sequestered in the world’s soils (~60 years’ worth of human-caused GHG emissions!), further research into sustainable management (i.e. conservation) of the SIC pools in prairie, steppe, and desert soils seems like an urgent priority.

Lorenz and Lal, 2016, cited above.

Weil and Brady, 2017, cited above.

Slide 52 – *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 have documented SOC saturation:

1 - In Portugal, conversion of depleted cropland to permanent pasture allowed SOM 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 10 years.

3 - In the Rodale long term farming systems trial, SOM (~SOC X 2) increased from 3.5% in 1981 to 4.0% in 1995, inched up to 4.2% in 2000, then leveled off.

4 - A review of multiple studies on non-organic cropping systems 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.

5 – The same review showed that adding one or more crops to a simple rotation (e.g. corn-soy) resulted in a gradual increase of 180 lb SOC annually, leveling off after about 40 years.

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 before saturation occurs (cropland currently averages 55%), 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).

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 vital to realize the full potential for agricultural C sequestration, not only to ease our transition to net zero emissions, but most importantly to strengthen agricultural resilience to withstand the climate disruptions already underway. The resilience and ecosystem health gains from restoring agricultural soils to 85 – 100% of their native SOC levels can be permanent – and could prevent mass starvation as the climate itself becomes more challenging.

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 earlier.

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

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.

Wes and Post, 2002. Cited earlier.

Slide 53 – *Will climate change itself make mitigation more difficult?*

Eagle et al., 2017, cited above.

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.

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.

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

Slide 54 – *Research needs and opportunities.*

Slides 55 – 57 – *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.