NATIONAL SUSTAINABLE AGRICULTURE COALITION

AGRICULTURE AND CLIMATE CHANGE:

Policy Imperatives and Opportunities to Help Producers Meet the Challenge

NOVEMBER 2019

ABOUT THE NATIONAL SUSTAINABLE AGRICULTURE COALITION

NSAC is an alliance of grassroots organizations that advocates for federal policy reform to advance the sustainability of agriculture, food systems, natural resources, and rural communities.

For a full list of NSAC members, see **https://sustainableagriculture.net/about-us/members** for a full list of NSAC members.

ACKNOWLEDGMENTS

Special thanks to the following NSAC Members who contributed to the research, analysis, and editing of this report:

Jeff Schahczenski, National Center for Appropriate Technology

Mark Schonbeck, Organic Farming Research Foundation

Jim Worstell, Delta Land and Community

Members of NSAC's Climate Change Subcommittee

Copy editing support from **Molly Carey,** NSAC Grassroots Fellow, and **Cristel Zoebisch,** NSAC Policy Fellow

ADDITIONAL PROJECT SUPPORT

This project was supported by contributions made possible by the following organizations:

California Climate & Agriculture Network

Institute for Agriculture and Trade Policy

National Center for Appropriate Technology

National Sustainable Agriculture Coalition

Organic Farming Research Foundation

SUGGESTED CITATION

National Sustainable Agriculture Coalition. 2019. Agriculture and Climate Change: Policy Imperatives and Opportunities to Help Producers Meet the Challenge. Washington D.C.

National Sustainable Agriculture Coalition

110 Maryland Avenue
Washington, D.C.

https://sustainableagriculture.net

FOREWORD ON THE SCOPE OF THIS POLICY PAPER

This position paper reviews the science related to climate change mitigation and adaptation on farms in the U.S., in order to provide a sound rationale for current and future policy development and advocacy related to climate change and agriculture. We then summarize our review in 14 key research-based findings, from which flow eight priority areas for federal policy reform that incorporate 29 specific policy recommendations.

At the start, we would emphasize three important points about the scope of the paper.

- First, the policy recommendations in this paper are based on existing federal farm bill authorities and potential changes to those authorities and funding levels in subsequent farm bills. We recognize that many other federal policies and federal agencies beyond the U.S. Department of Agriculture (USDA) play important roles in addressing topics relevant to climate and agriculture, but we chose to focus here on the farm bill and USDA.

  Importantly too, this farm bill focus does not mean we will not have substantial recommendations for an agricultural component of comprehensive climate change legislation. It is our strong hope that a comprehensive climate bill will clear Congress and become law in our near collective future, and we fully intend, at a later date, to offer our vision for what the agricultural component of such a measure should look like.

- Second, this paper focuses on adaptation to climate change, and mitigation and reduction of greenhouse gases (GHG) on farms in the U.S. It is, however, important to note that there are also significant GHG emissions from off-farm processes connected with the broader agricultural system, such as production and transport of inputs including pesticides and fertilizers, food and fiber processing, and transportation, storage, and distribution of products. A growing body of research indicates that sustainable, regional and local food processing and distribution systems are more resilient to the impacts of climate change and can result in substantially more GHGs sequestered than emitted, while empowering culturally diverse communities to choose food production systems that promote local economies and adapt to changing environments.

  We support the development of regional and local food systems which play an important role in increasing farm viability and resilience, conserving energy, improving the nation's health, fostering ecosystem functions, and reducing GHG emissions in our nation's farming and food system. These broader food system aspects, however, are beyond the scope of this particular position paper.

- Third, this paper does not address indigenous or traditional knowledge and experience in living within the bounds of nature and all that native peoples have learned about survival under difficult and changing environmental, social, emotional and political conditions. This includes the transfer of knowledge from generation to generation, and always considering the rights of future generations when using current resources. Examples include tribal wisdom such as never harvesting more than half of a natural planting of wild herbs; and 400 years of communally operated acequia (irrigation) systems of the U.S. Southwest designed to provide both economic and vital ecosystem services such as preservation of wildlife habitat and protection of water and soil resources. Nor does this paper address the injustices of the siting of fossil fuel infrastructure and polluting industries that disproportionately impact people of color and low-income communities. NSAC is addressing issues of justice, equity, structural racism and white supremacy both internally and in our work in the policy arena though not directly through this paper.

OVERVIEW

For more than 30 years, the National Sustainable Agriculture Coalition (NSAC) has advocated federal agricultural policies that foster the long-term economic, social, and environmental sustainability of agriculture, rural communities and natural resources[1]. Our long-term goal is the establishment of agricultural and food systems across the U.S. that can endure and meet the needs of present and future generations. NSAC works for policies that promote small and mid-sized family farms, new farming and ranching opportunities, racial justice and equity, farmworker justice, and agricultural systems which ensure ecosystem sustainability through building soil health, promoting diverse production systems, protecting water and enhancing habitat for pollinators and other beneficial wildlife.

NSAC played a key role in defining "sustainable agriculture" in the 1990 Farm Bill:

The term sustainable agriculture means an integrated system of plant and animal production practices with a site-specific application that will, over the long term:

- satisfy human food and fiber needs;
- enhance environmental quality and the natural resource base upon which the agricultural economy depends;
- make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls;
- sustain the economic viability of farm operations; and
- enhance the quality of life for farmers and society as a whole.

Public Law 101-624, Title XVI, Subtitle A, Section 160e (7 U.S.C. § 3103 (19)

To meet the long-standing goals of sustainable agriculture, NSAC promotes systems which are resilient to climate change. Agricultural systems cannot be sustainable unless they are resilient to disruptions (of which climate change is the most formidable). Systems managed according to the agroecological principles discussed in this paper (including organic, regenerative, biological, biodynamic, conservation agriculture, permaculture, agroforestry, holistic management, etc.) will result in systems resilient to climate change. NSAC has previously adopted principles and policy positions related to climate change in 2009 and 2014. All NSAC policy positions are available at: **www.sustainableagriculture.net.**

[1] The National Sustainable Agriculture Coalition was launched in January 2009 and adopted existing policy papers of its predecessor organizations - the Sustainable Agriculture Coalition and the National Campaign for Sustainable Agriculture.

In the last two decades, an overwhelming consensus has emerged among scientists that the world has entered an era of rapid global climate change, much of which is attributable to greenhouse gas (GHG) emissions from human activity. Rapid global climate change is impacting agriculture in a variety of ways, including greater weather extremes such as severe droughts and floods, increased heat waves, pest pressures and impacts on crop yields. The exact nature and degree of these changes for any given region will be difficult to predict, although climate scientists are improving on their capacity to do so.

To cope with climate change that is expected to be both rapid and unpredictable, and for farmers to remain economically viable in the face of these challenges, agricultural systems must be resilient and able to adapt to a changing climate. Resilient agriculture systems are those that are more likely to maintain and even improve economic, ecological and social benefits in the face of dramatic changes such as climate change and price swings. The dominant agricultural systems of the U.S. lack resilience to such disturbances due to their low levels of diversity (monocropping), reliance on inputs from nonrenewable resources, exposure of key resources to degradation (e.g., bare fields, water pollution), and depleted soils. In the face of increasing uncertainty, major changes in our food production systems are needed.

At the same time that farmers and ranchers must adapt to climate challenges, current agricultural activities are also a source of greenhouse gases that aggravate climate disruption. The amount of GHGs emitted from an agricultural operation depends on its system of management. Agroecological systems can help reduce agricultural GHG emissions through soil health practices that sequester carbon (C) (including management intensive grazing), nutrient management that minimizes use of soluble nitrogen (N), conservation and planting of trees and shrubs, aerobic composting of animal and plant wastes, and energy conservation, including reduced use of petroleum-derived fertilizers, pesticides and fuel.

Agricultural land can serve as a sink for GHG emissions, especially through C sequestration in soil and woody biomass. However, agricultural land can serve as an effective long-term GHG sink only if agricultural systems are adopted which provide relatively stable GHG reduction or sequestration. In addition to sequestering C, climate-friendly systems must mitigate potent GHG emissions of nitrous oxide and methane. Policy that supports such a stable sink requires tools that can accurately measure GHG reduction or sequestration. Fertilizer use and efficiency, N sequestration and overall GHG emissions of livestock production systems (particularly confined animal feeding operations (CAFOs)) must be assessed and addressed.

Moreover, agricultural C sequestration and GHG mitigation cannot be the only solutions for dealing with overall GHG emissions. Industry, vehicles and other human activities must also greatly reduce emissions. U.S. climate change policy should require all sectors to adopt new technology and long-term permanent solutions to reduce GHG emissions.

NSAC's position is that the ecologically sound sustainable agricultural systems detailed in this paper offer the most resilience for agricultural production in the face of the extreme precipitation, prolonged droughts and increasingly uncertain regional climate regimes expected with global climate change. Such resilience is critical for farmer profitability in the face of a volatile market and increasingly volatile weather conditions. Moreover, adoption of these systems can significantly enhance C storage in soil and plant biomass and decrease net GHG emissions from agricultural production activities. The potential of these sustainable and organic agriculture systems to help mitigate climate change complements their benefits in improving the overall environmental performance of agriculture and protecting the health of rural communities. These systems provide the best that agriculture can offer to the wide array of potential frameworks for climate change policy. *(See the Appendix for descriptions of the sustainable and organic agriculture systems and practices discussed in this paper.)*

NSAC calls upon federal policy makers to prioritize support for federal farm bill policies and programs that enable farmers and ranchers to adopt sustainable and organic agricultural production systems to address the challenges posed by a rapidly changing and disruptive global climate and increasing extreme weather events. We recommend specific actions in this paper that USDA, and in a few limited cases other federal agencies, can take to assist farmers, ranchers and rural communities in coping with and mitigating the potentially devastating environmental consequences of rapid climate change.

The actions we propose will not only help avoid disaster, but will also help farmers and ranchers thrive along with the biological communities and ecosystem functions that working agricultural lands foster. Federal policies must involve cooperation and support from all levels of government, community partnerships, the private sector, universities, and civil society to foster a coherent, effective and results-oriented approach to address climate change. Federal action should also promote sustainable resource use, energy conservation, and GHG reduction, in addition to establishing food security, habitat for beneficial wildlife, and meeting rural community development needs.

It is *imperative* and urgent that the Federal Government assist diverse communities and regions around the country to develop agricultural systems that:

- build soil organic matter, soil health, and agricultural resilience;
- sequester C in soil and above-ground biomass;
- reduce greenhouse gases;
- use resources sustainably; and
- maximize energy conservation.

Federal policy should provide incentives, provide technical support, and implement regulations for adoption of sustainable, organic and resilient agricultural systems and practices that both mitigate climate change impacts and help farmers, ranchers, and rural communities cope with rapid climate change.

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EXECUTIVE SUMMARY

The goals of the NSAC Policy Position Paper are to present the latest science on climate change in agriculture, and to identify priorities for federal policy and USDA programming to help farmers and ranchers meet the growing challenges of climate disruption, and contribute to climate change mitigation through carbon (C) sequestration and reduction of greenhouse gas (GHG) emissions from their operations.

The Fourth National Climate Assessment (NCA4) published in 2018 documents multiple adverse effects of climate change on U.S. agriculture, including:

- Intensified droughts, floods, and storms
- Stresses on crops, livestock, and farm personnel from higher summer temperatures
- Disruption of seasonal development, flowering and fruiting in horticultural crops
- Shifting pest, weed, and disease life cycles and geographic ranges
- Disproportionate impacts on economically disadvantaged rural communities

Record-breaking Midwest flooding in 2019, intense land-falling hurricanes in 2017 and 2018, and historic droughts in California in 2014 to 2017 highlight the urgent need to help producers build the resilience of their operations to ongoing and future impacts of climate change ("climate adaptation").

Agriculture affects climate in two ways: direct GHG emissions, and net loss of C from soil and biomass. Direct agricultural GHG emissions account for 8.4 percent of the U.S. total. Major contributors include nitrous oxide (N_2O) from fertilized soil (49 percent), enteric methane (CH_4) from livestock (32 percent), and GHG from manure storage facilities (14 percent). Currently, loss of soil organic carbon (SOC) as carbon dioxide (CO_2) as a result of soil erosion and in-situ soil degradation contribute another 10 to 12 percent of annual human-caused GHG (global estimate). However, improved agricultural practices for soil health and resource conservation can potentially sequester sufficient SOC and biomass C to make U.S. agriculture climate neutral. USDA policy and programs must emphasize soil health and support producers to become part of the climate solution through C sequestration and reduced GHG emissions ("climate mitigation").

The most practical and cost-effective way to remove excess CO_2 from the atmosphere is through living plants and soils. Farmers and landowners can sequester tons of C per acre in soil and perennial biomass through best management practices for soil health, crop and livestock production, and agroforestry.

Research has demonstrated that agroecological farming and ranching systems, including organic, sustainable, conservation agriculture, and permaculture, can sequester and reduce direct agricultural GHG emissions. For example:

- Sustainable organic or conservation agriculture systems can build ~500 lb. C/ac-year in cropland soils.
- Management intensive rotational grazing (MIG) can reduce direct GHG emissions from livestock production and sequester at least one ton of C/ac-year.

- Agroforestry and silvopasture can accrue more than one ton soil + biomass C/ac-year.
- Best soil health management on the world's agricultural lands plus reforestation of idle and depleted lands could reduce atmospheric CO_2 in the year 2100 by 156 ppm.
- Best soil health management and crop breeding for nutrient efficiency show potential to improve N cycling and reduce N_2O emissions.
- Diversion of manure, yard waste, and food waste from lagoons and landfills into compost production reduces GHG emissions and provides a soil-building amendment.

Our farms and ranches can improve energy use efficiency and become major producers of renewable energy for use within the agriculture sector and beyond. Solar and wind show great promise as low-carbon energy sources, while biofuel production from agricultural biomass requires careful lifecycle assessment and consideration of social impacts.

Based on these and other research findings, NSAC has developed the following policy priorities related to climate change and agriculture:

- Support producers to make U.S. agriculture climate-neutral.
- Remove barriers and strengthen support for sustainable and organic production systems.
- Support climate-friendly nutrient management to reduce N_2O emissions.
- Support composting of manure and other organic "wastes."
- Protect C sequestration potential of sensitive and marginal lands.
- Support climate-friendly livestock production systems, end subsidies for CAFOs.
- Support on-farm energy conservation and low-carbon renewable energy production.
- Fund public plant and animal breeding for climate-resilient agriculture.

Recommended USDA programmatic support for these priorities include:

- Increased emphasis on climate mitigation and adaptation throughout Natural Resource Conservation Service (NRCS) working lands and easement programs, and the Conservation Reserve Program (CRP).
- Increased research into climate impact assessment, public cultivar development, and agroecological systems that minimize net GHG and maximize soil health and resilience.
- Whole farm emphasis across USDA programming, including Whole Farm Revenue Protection (WFRP) insurance.

NSAC urges an immediate transition to a resilient agri-food production system based on sustainable and organic practices detailed in this paper. The current challenges faced by farmers, ranchers and rural communities will intensify unless we implement integrated strategies to deal with our changing climate and build resilience to other disturbances.

I. IMPACTS OF CLIMATE CHANGE ON U.S. AGRICULTURE

Though the influence of atmospheric gases on climate has been known since the 1800s, a significant effort to assess the potential impacts of climate change on agriculture began only in the 1970s when climate anomalies led to crop failures and sharp increases in grain prices (Arhenius, 1896; Stewart and Glantz, 1985). In 1978, USDA joined with the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Department of Defense (DOD) to release the first analysis of agriculture and climate change (National Defense University, 1978). In the 1980s, studies focused mostly on the direct effects of climate change on crop production (Newman, 1980; Rosenzweig, 1985). One early conclusion was that a warmer climate could significantly decrease wheat and corn production in the U.S. while increasing production in Canada, Northern Europe and the Soviet Union (Smit et al., 1988; Adams et al., 1990).

In 1990, the first report of the International Panel on Climate Change (IPCC) was released with an innovative emphasis on climate variability induced by increased emission of greenhouse gases (IPCC, 1990). By the early 1990s, extensive research on impacts of climate change on livestock and rangelands was available (Hahn et al., 1990; Baker et al., 1993). The First U.S. National Climate Assessment (NCA) was published in 2000 (USGCRP, 2000). In the early 2000s, evidence emerged that the advent of agriculture created the first human-caused increase in GHGs (Ruddiman, 2003).

IPCC has now released five Assessment Reports with the fifth report issued in 2014 (IPCC, 2014a; IPCC, 2014b). In addition, the IPCC has prepared several special reports relevant to agriculture, including a thorough review of agriculture and global climate change released in 2019 (IPCC, 2019).

In November 2018, the U.S. Global Change Research Program (USGCRP) released the most comprehensive assessment of research to date on potential climate change impacts on agriculture in the U.S. The report, known as NCA4, was jointly issued by USDA and the other 12 federal agencies which conduct research on global climate change. NCA4 provides detailed consideration of potential impacts of climate change on major crops, pastureland, rangeland, and livestock operations (Gowda et al., 2018).

NCA4 concludes that climate change has and will impact agricultural productivity in the U.S. through increased mean temperatures, alterations in rainfall patterns, more frequent occurrences of climate extremes (including temperature and precipitation), increased atmospheric CO_2 concentrations and altered patterns of pest pressure. This increasing climate volatility will make it more challenging for farmers to stay in operation as they face climate-related challenges and natural disasters in addition to an already challenging farm economy. Adaptation to climate change includes altering what is produced, modifying the inputs used for production, adopting new technologies, and adjusting management strategies. All these adaptations will benefit from incentives and support for farmers.

Among the general conclusions of NCA4 are the following:

TEMPERATURE AND PRECIPITATION CHANGES

- Every region of the U.S. warmed during the last century, but significant regional variation occurred. Alaska, the Western States, and the Great Plains all warmed by more than 1.5°F while the South's average temperature increased minimally with some parts of the South cooling slightly and the Corn Belt cooling slightly in summer.
- Annual temperature over the contiguous U.S. has increased by 1.2ºF (0.7°C) over the last few decades and by 1.8°F (1°C) relative to the beginning of the last century. Additional increases in annual average temperature of about 2.5°F (1.4°C) are expected over the next few decades regardless of future emissions.

- Elevated temperatures play a critical role in increasing the rate of drought onset, overall drought intensity, and drought impact through altered water availability and demand. Increased evaporation rates caused by high temperatures, in association with drought, will exacerbate plant stress, reduce yields, and deplete surface and groundwater resources. The consequences of climate change on the incidence of drought also impact the frequency and intensity of wildfires.

- Soil C, important for enhancing plant productivity through a variety of mechanisms, is depleted during drought due to low biomass productivity, which in turn decreases the resilience of agroecosystems. In 2012, the U.S. experienced a severe and extensive drought, with more than two-thirds of its counties declared as disaster areas. This drought greatly affected livestock, wheat, corn, and soybean production in the Great Plains and Midwest regions and accounted for $14.5 billion in loss payments by the federal crop insurance program. From 2013 to 2016, all of California faced serious drought conditions that depleted both reservoir and groundwater supplies. This lengthy drought, attributed in part to the influence of climate change, resulted in the overdrawing of groundwater, primarily for irrigation, leading to large declines in aquifer levels. The West and Southwest are likely to become drier, while the eastern United States is likely to experience increased rainfall. Heat waves are very likely to be hotter, longer, and more frequent.

- Annual precipitation since the beginning of the last century has increased across most of the northern and eastern U.S. and decreased across much of the southern and western U.S. Over the coming century, significant increases are projected in winter and spring over the Northern Great Plains, the Upper Midwest, and the Northeast. Surface soil moisture over most of the United States is likely to decrease, accompanied by large declines in snowpack in the western U.S. and shifts to more winter precipitation falling as rain rather than snow.

- However, changes in average precipitation will be punctuated by precipitation extremes such as record levels of snowfall in the western U.S. in early 2019. Observed increases in the frequency and intensity of heavy precipitation events in most parts of the United States are projected to continue.

- Increased precipitation extremes elevate the risk of surface runoff, soil erosion, and the loss of soil C. The impact on agriculture will depend on whether farms have established protective measures to reduce soil erosion and water quality degradation such as implementation of grassed waterways, cover crops, conservation tillage, riparian buffers, and waterway protection strips.

CROP IMPACTS

- Average yields of many commodity crops (e.g., corn, soybeans, wheat, rice, sorghum, cotton, oats) decline beyond a certain maximum temperature threshold and thus long-term temperature increases may reduce future yields under both irrigated and dryland production.

- In contrast, even with warmer temperatures, future yields for certain crops such as wheat, hay, and barley are projected to increase in some regions due to anticipated increases in precipitation and C fertilization. Positive impacts of increasing temperatures have been reported for some high-latitude regions such as Alaska. However, yields from major U.S. commodity crops are expected to decline because of higher temperatures, especially when these higher temperatures occur during critical periods of reproductive development.

- Horticultural crops (due to the need for vernalization or chill hours and susceptibility of flowers to temperature fluctuations) are likely to be more sensitive to climate change than grains and oilseeds. For example, climate science finds that acreage suitable for key crops, such as walnuts and some stone fruits, in California's Central Valley may be cut in half by 2050 because of a loss in winter chill hours.

- Climate change is likely to lead to the northward migration of weeds. Weeds respond positively to CO_2 and commonly used herbicides lose their ability to kill weeds in a higher CO_2 environment.

- With increased CO_2 and increased temperatures, there may be an initial expansion of grain and oilseed production in some regions. With continued rising temperatures, this initial expansion may be short-lived, particularly if precipitation patterns become more variable.
- Anticipated increases in crop pests and diseases along with an associated increase in use of petroleum-derived pesticides will likely pose serious hazards to farm workers, rural communities, and aquatic and terrestrial ecosystems.

LIVESTOCK IMPACTS

- Projected increases in daily maximum temperatures and heat waves will lead to further heat stress for livestock. Temperatures beyond the optimal range negatively impact the physiological functions of animals and result in increased intake of water and reduced feed intake. Heat stress also decreases reproductive efficiency. High temperatures associated with drought conditions adversely affect pasture and range conditions and reduce forage crop and grain production, thereby reducing feed availability for livestock.
- More variable winter temperatures also cause stress to livestock and, if associated with high-moisture blizzard conditions or freezing rain and icy conditions, can result in significant livestock deaths.
- Dairy cows are particularly sensitive to heat stress, as it negatively affects their appetite, rumen fermentation (a process that converts ingested feed into energy sources for the animal), and milk yield. Frequent higher temperatures also reduce milk quality (reduced fat, lactose, and protein percentages).
- The dairy industry expects to see production declines related to heat stress of 0.60 percent to 1.35 percent for the average dairy over the next 12 years, with larger declines occurring in the Southern Great Plains and the Southeast due to increasing relative stress.
- Similar heat stress losses impact beef cow-calf, stocker, and feedlot production systems; higher temperatures result in reduced appetites and grazing/feeding activity, which subsequently reduce production efficiencies. Extreme temperature events also increase mortality.
- With the expected earlier springs and warmer winters, disease pressure from livestock pests, parasites and pathogens on cropland, pastureland and rangeland may increase and livestock producers may need to deal with increased parasites and pathogens as climate change results in increased survivability and expansion of the pests' range.
- Forage production may be expanded as growing seasons lengthen, but this benefit will depend on water availability.
- Shifts in plant species in rangelands, particularly an increase in perennial herbaceous species, will create greater spring water demands.

NCA4 also cites research showing the disproportionate impacts of climate change on rural communities that are already less resilient due to multiple socioeconomic disadvantages, such as an increased risk of exposure to extreme heat and poor air quality, lack of access to basic necessities, and fewer job opportunities.

Beyond these already profound impacts, unforeseen climate change feedback events will likely further affect agriculture (Baveye, 2007). As temperature rises, precipitation amounts change, and severe weather events happen more frequently. These changes could cause both negative and positive feedback outcomes in agricultural systems in ways that are difficult to predict. Although some regions of the U.S. may experience extended growing seasons due to rising temperatures, the possible positive outcomes of climate change in the U.S. do not erase the potentially devastating agricultural outcomes described above.

These climate change effects coincide with two additional disruptions that will require significant changes to the current reliance of U.S. agriculture on high levels of external inputs: movement away from GHG-producing fossil fuel energy and the depletion of significant freshwater reserves because of increasing demand by the agricultural sector and other users. U.S. agriculture has largely been designed to work with nonrenewable fossil fuels, abundant freshwater reserves, and a period of relative stability in the climate, all of which are now in question (Battisti and Naylor, 2009). The next generation of farmers and ranchers will need to switch to smarter agricultural systems that rely less on high-energy inputs and conserve water and other natural resources.

Dealing with these disruptions of U.S. agriculture will require the resilience of farms and other agricultural systems including cooperatives, marketing and processing systems, and input supply systems. Upper Midwest corn farmers have adopted earlier planting dates and longer season varieties to increase yields in the face of moderate increases in temperature, while corn yields have suffered in more Southern regions (Butler et al., 2018). Such appropriate innovation and other qualities necessary for resilience will determine the impact of climate change on each system (Worstell and Green, 2017). Policies which encourage flexibility, innovation, and diversity will enable farms and other subsystems to increase their resilience and weather the storm. Resilience of agricultural systems is also highly correlated with lower poverty and higher health outcomes, indicating that resilient agricultural systems have many co-benefits beyond climate adaptation and mitigation (Green et al., 2018).

The following sections summarize research into the impact of agriculture on the climate, explore the climate mitigation and adaptation potential of sustainable and organic agricultural systems, and detail policies which, if implemented, will enable the U.S. agricultural system to thrive and mitigate the most daunting challenge it has ever faced.

II. IMPACTS OF U.S. AGRICULTURE ON CLIMATE CHANGE

Agricultural production is not just affected by climate change — agricultural production systems also have the potential to mitigate or exacerbate climate change trends. This section looks at agriculture both as a significant emitter of GHGs and as a potential sink for GHGs.

A. U.S. agriculture as a contributor to climate change

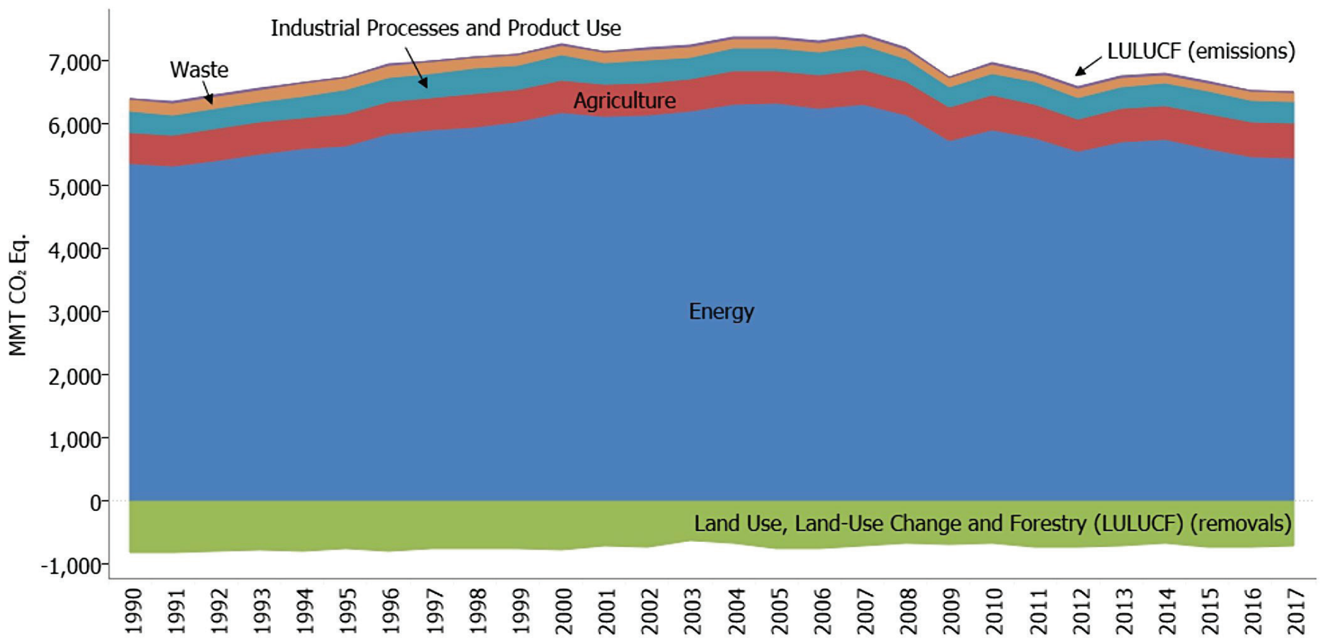

Figure 1. U.S. Greenhouse Gas Emissions and Sinks (MMT CO_2 24 Eq.)
Source: EPA (2019)

Figure 1 *is taken from the agriculture chapter of EPA's latest Inventory of U.S. Greenhouse Gas Emissions and Sinks. This inventory provides the most recent sector-by-sector estimates of GHG emissions in the U.S. The agriculture portion of Figure 1 does not include CO_2 emissions from cropland treated with lime or urea fertilization or GHGs from fuel combustion for on-farm vehicles and equipment (counted in the Energy section of the inventory), or energy for the manufacture of fertilizers and other inputs (counted in the Industrial Processes section of the inventory). Agricultural production is a significant contributor to total direct U.S. GHG emissions, though relatively minor compared to the energy sector.*

The major GHGs emitted by agricultural production sources include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). U.S. agricultural production is a relatively minor producer of CO_2 (CO_2 from agriculture comes primarily from on-farm energy use), but it is a major source of CH_4 and N_2O emissions. As a GHG, CH_4 has a greater global warming potential than CO_2 but a shorter atmospheric life. Over a 100-year period, CH_4 is 28 times as potent as CO_2 (IPCC, 2014b, p.87). N_2O has a relatively low warming effect but a very long atmospheric life and over a 100-year period has a global warming potential that is about 310 times that of CO_2. Both CH_4 and N_2O, while released in smaller overall volumes than CO_2, have significantly higher global warming potential than CO_2. The term CO_2eq (carbon dioxide equivalents) provides a measure that combines the 100-year global warming potential of these different GHGs from a source into one measurement.

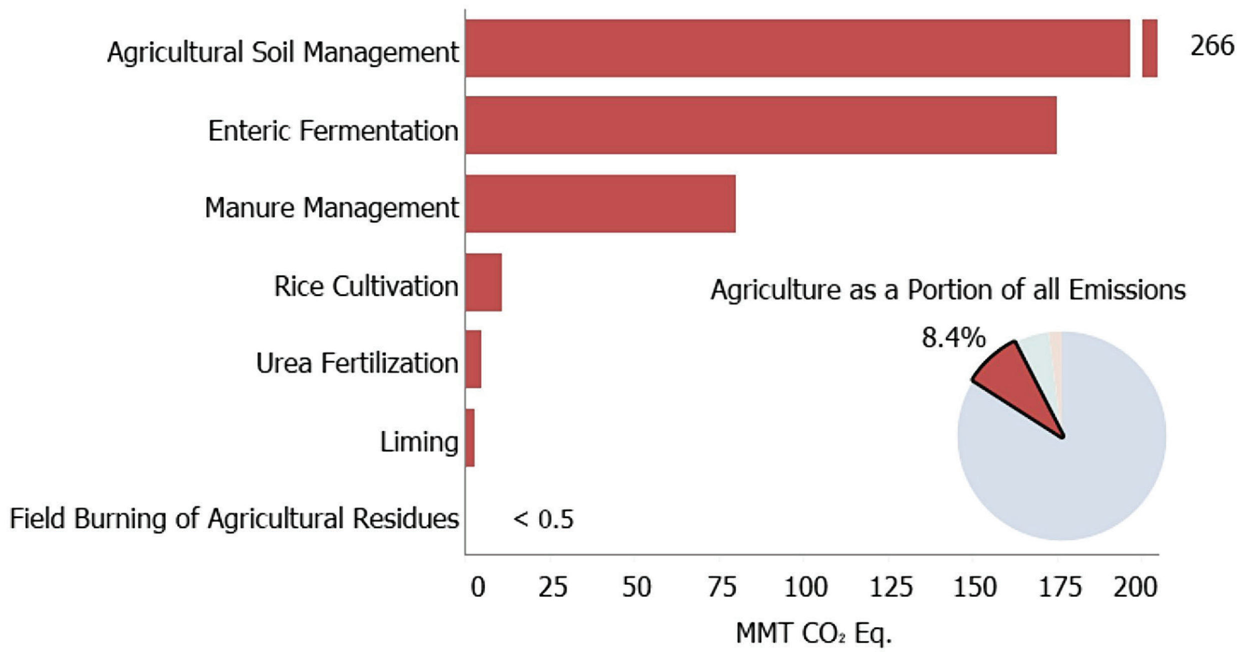

Figure 2. 2017 Greenhouse Gas Emissions from U.S. Agricultural Sector (MMT CO_2 Eq.)

Source: EPA (2019)

Figure 2 *shows the sources of direct GHG emissions within the U.S. agricultural sector, not including CO_2 from fossil fuel use in field operations and manufacture of inputs, or losses of soil organic C.*

N_2O emissions by agricultural soil management were the largest source of U.S. N_2O emissions, accounting for 73.9 percent. This happens through activities such as fertilizer application and other agricultural practices that increase N availability in the soil. Methane emissions from enteric fermentation and manure management represent 26.4 percent and 9.3 percent of total CH_4 emissions from anthropogenic activities, respectively. Of all domestic animal types, beef and dairy cattle were by far the largest emitters of CH_4. Rice cultivation was also a significant source of CH_4. Manure management and field burning of agricultural residues were also small sources of N_2O emissions. Urea fertilization and liming each accounted for 0.1 percent of total CO_2 emissions from anthropogenic activities. (EPA, 2019, Sect. 5-1)

Agricultural Soil Management covers a broad array of practices including fertilization with synthetic fertilizer and animal manures; manure deposition by grazing animals; soil cultivation; production of N fixing crops and forages; irrigation; and other practices. The category covers GHG emissions from both cropland and grasslands. This number does not include silvopastoral efforts and forestlands which are discussed later.

Enteric Fermentation is primarily methane produced by the digestive processes of ruminant animals which are emitted from the animals as gas.

Manure Management emissions are methane and nitrous oxide released from manure during storage and handling.

Rice cultivation, which in the U.S. is done under anaerobic conditions in flooded fields, results in methane emissions.

Field burning of agricultural residues results mostly in CO_2 emissions, which are not counted because it is assumed that CO_2 will be reabsorbed by plants in the next growing season. Field burning, however, also results in release of CH_4, N_2O and other minor GHGs.

Note that the GHG emission data for agricultural activities do not include indirect GHG emissions from the production and distribution of off-farm inputs, especially manufactured fertilizers and pesticides. GHG emissions from these inputs add to the overall C footprint of agriculture.

B. U.S. Agriculture and mitigation of climate change: The potential for significant carbon sequestration in agricultural soils and woody biomass.

Soils are one of five principal global C pools, which also include the oceans, fossil fuel deposits, biotic (plant-based C), and the atmosphere. Soils constitute the largest terrestrial organic C pool (ca. 1500 Pg C[2] to 1 m depth; 2400 Pg C to 2 m depth) which is three times the amount of CO_2 currently in the atmosphere (~830 Pg C) and 240 times current annual fossil fuel emissions (~10 Pg). Thus, increasing net soil C storage by even a few percent is a significant C sink potential. Soil C sequestration is one of a few strategies that could be applied on a large scale and at relatively low cost (Paustian et al., 2016).

U.S. soil organic C has been depleted as land has been converted from forests, native prairie and other grasslands, and wetlands to more chemical-intensive agricultural uses. Long-term extractive farming practices, such as deep tillage without rebuilding of soil C, have further depleted levels of C in agricultural soils. U.S. agricultural soils have lost an estimated 30 to 50 percent of the C contained prior to cultivation. The result is that agricultural soils have the capacity to take up C from root exudates, litter, harvest residues, and animal manures used in agricultural production. The total potential of C sequestration in soils in agriculture, grazing, and forestry ecosystems at 3.7 to 9.3 Pg C per year, with an average of 6.5 Pg C per year for a total of 333.2 Pg C after 60 years, the point at which terrestrial ecosystems would reach their capacity to hold C. U.S. soils alone have a total potential year sequestration of 288 Tg C per year (.288 Pg C/year) (Chambers et al., 2016). Significant long-term soil C sequestration could be achieved by a mix of recommended agricultural systems and management practices and the conversion of degraded soils and drastically disturbed lands to restorative uses. An increase in overall soil C also has positive effects on soil quality and could result in increased productivity, agricultural resilience, and yield stability, especially on carbon-depleted soils (Lal et al., 2003).

Rattan Lal (2019) provided the diagram on p. 10 which compares the loss of C into the atmosphere because of land use changes from 1960 to 2017, in part related to agriculture (the pink area in figure 3). However, Lal also suggests that with proper management of soils and land there is great potential to offset previous losses (blue area in figure 3).

[2] 1 Pg (petagram) is 10 to the 15th power grams or one billion metric tons. One Tg or teragram is one million metric tons or 1/1000 Pg.

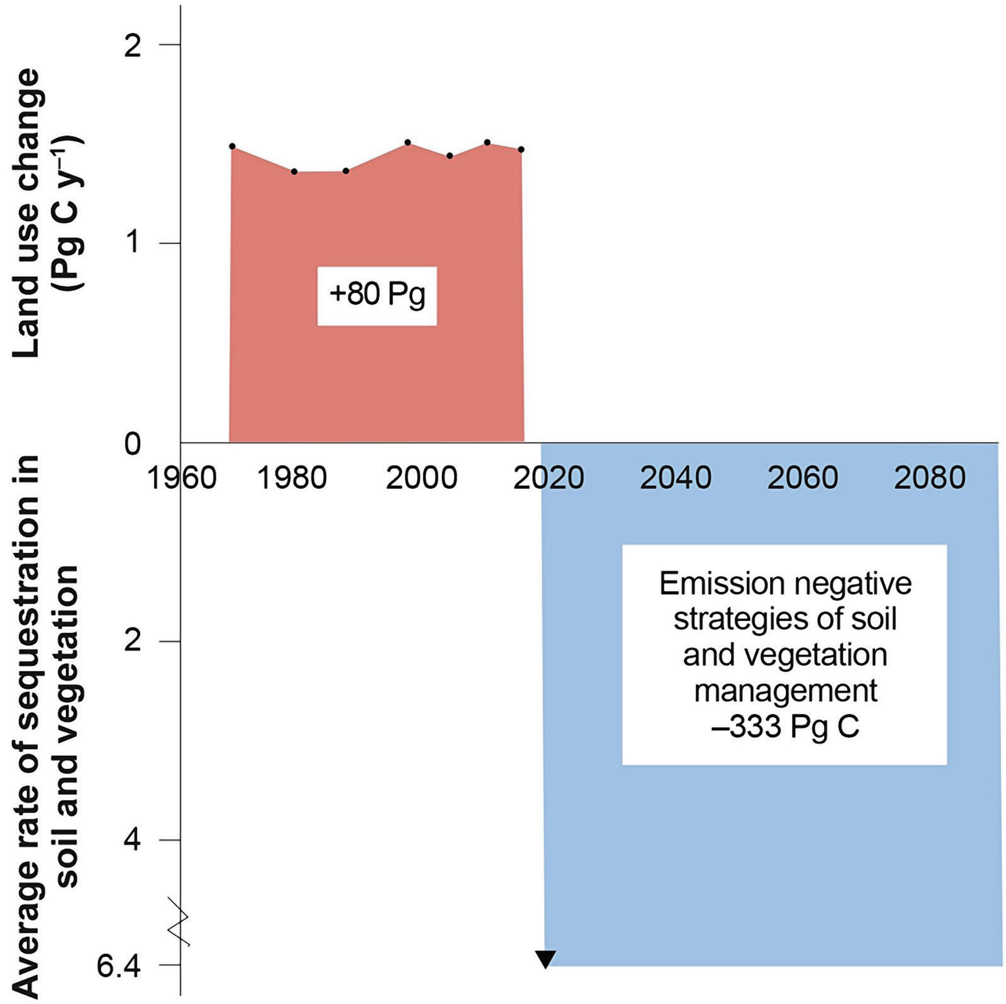

Figure 3. Carbon Sequestration in the Terrestrial Biosphere, Soil, and Vegetation

Source: Lal (2019, p 29A)

NRCS estimates that U.S. farmers can sequester up to 2.5 metric tons of CO_2 equivalents (Eq) per acre annually by adopting specific NRCS recommended practices. The chart on p. 11 shows soil and woody C sequestration/emissions reduction potential by management practice as estimated by NRCS COMET-Planner tool in Swan et al., (2019) and as reported by Biardeau et al., (2016).

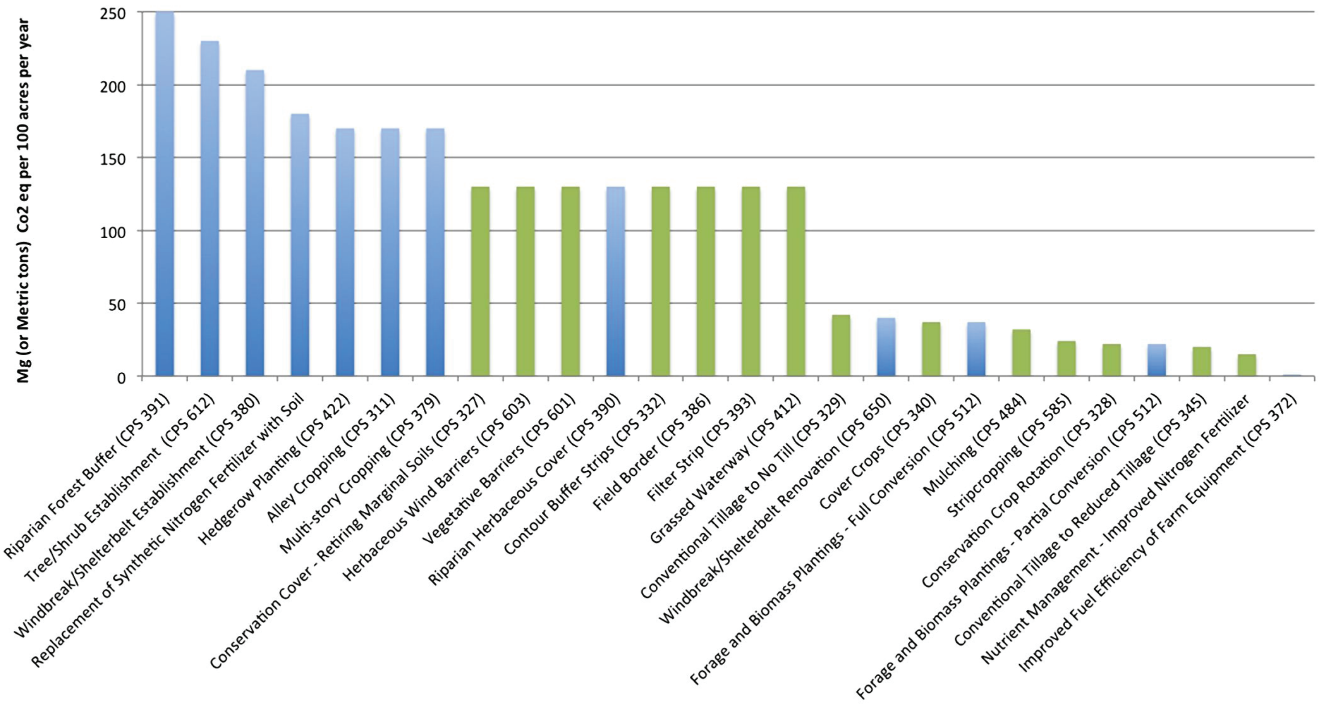

Figure 4. Soil Carbon Sequestration/Emissions Reduction Potential by Management Practice

Source: NRCS COMET-Planner (as excerpted from Biardeau et al., (2016).)

Practices highlighted in green are considered by NRCS as "Soil Health Building Blocks." These practices, and others that boost soil health, do more than store C; they also help farms adapt to more extreme weather conditions through increased water holding capacity, less erosion, and other benefits. A variety of additional practices (in blue) also have significant potential to capture C and reduce emissions according to Comet-Planner.

Recent research indicates that cropping systems can have profound effects on local climate. In parts of the Midwest, a decrease in summer high temperatures and an increase in average rainfall has been attributed to expansion of corn acreage (Alter et al., 2017).

C. Crop Insurance, Structural Issues and Impacts on Climate Change

> *"One of the most pressing concerns about the industrialization of agriculture and food is the consolidation and concentration of markets for agricultural inputs, agricultural commodities, food processing and groceries. In essence, a small minority of actors globally exercise great control over food system decisions. This means that because of an increased consolidation of these markets globally — from the U.S. to China to Brazil, from South Africa to the United Kingdom — the vast majority of farmers, consumers and communities are left out of key decisions about how we farm and what we eat. Transnational agri-food firms are motivated by profits and power in the marketplace, leaving other social, economic and ecological goals behind. This creates an agroecological crisis in the face of climate uncertainty but one that is rooted in social and economic organization."* (Hendrickson, M, et.al., 2017, p.1)

The nature of our national and global agricultural political economy is not conducive to making easy headway on the complex issues of climate disruption. The system is designed for overproduction of major commodities so that the prices of these commodities stay relatively low and the only way for these commodity producers to remain economically viable is to produce more. Producing more of a commodity to make up for low prices often requires using agricultural practices such as monocropping and intensive fertilizer and pesticide inputs that increase GHG emissions. Low prices also reduce a farmer's ability to invest in conservation practices. Seed for cover crops, lack of markets for third crops, additional machinery, and other costs can deter a farmer who is struggling to remain economically viable from adopting climate-friendly practices.

Consolidation in seed, fertilizer, pesticide, and farm machinery industries also narrows what choices farmers can make about how they farm. In an example from Hendrickson, Howard, and Constance (2017), "a farmer may want to enhance soil quality by practicing multi-year rotations with three to five different crops but is prevented because they can't find regional markets for sunflowers or wheat rather than just soybeans and corn. Farmers may also want to practice diversified crop and livestock farming but cannot find available markets for smaller numbers of livestock." With less competition in the marketplace, farmers are constrained to certain seed varieties, animal genetics, and management practices to meet the requirements of what the industry is selling and buying (Hendrickson, Howard, and Constance, 2017).

In addition to structural market forces, federal policy often supports production at all costs. The U.S. federally subsidized crop insurance program illustrates these issues quite well.

First, crop insurance policies are sold through a joint federal and private company program. One way to think of this arrangement is to think of the federal crop insurance program as a large national nonprofit insurance company, where the rules and details are set by the Federal Government and the "implementation" is done by private for-profit companies/agents who act as "contractors" to the Federal Government.

Both the rewards and losses accrued in the operation of the program are borne to some degree by all participating and mostly by the taxpayer. The goal of the general program is on average over time to pay out (indemnities) no more than taken in the sale of the insurance policies (premiums), hence, the notion of a nonprofit. Private insurance companies on the other hand need to take in more premiums than they pay out in indemnities, in at least the medium to longer-run in order to have a surplus revenue with which to invest and make a profit. The profit these companies receive are relatively assured and significant and do not result in very much financial risk.

About 62 percent of the average crop insurance policy premium cost is paid by taxpayers. There is no means testing for farmers and ranchers who use this program so the wealthiest and poorest producer has equal access to its benefits. A single type of policy, known as Whole Farm Revenue Protection (WFRP), represents the greatest proportion of crop and livestock insurance coverage. In turn most WFRP policies cover the major commodity crops such as corn, soybean, wheat, and cotton. WFRP policies represented 69 percent of the total liability coverage of the program in 2018 (RMA, 2019). WFRP coverage is very good coverage with the ability to cover up to 85 percent of the expected revenue value of the crop insured. Not only is the possible coverage high with high subsidization (64 percent in 2018), farmers get the advantage of estimating losses on the basis of either a projected price for the crop at the beginning of the crop year or the "harvest" price actually realized at the end of the season. Thus, if the projected price of corn is $4.00 per bushel and the harvest price is $4.50 a bushel, the farmer's losses are valued at the higher of the two prices. Federal crop insurance makes it almost "riskless" to grow these commodity crops. This type of policy makes it likely that commodity crops will be over-produced.

Current U.S. subsidies for single-crop insurance facilitate a vast overproduction of a few commodities. Systems without robust feedback mechanisms to counteract overproduction inevitably monopolize scarce resources and produce harmful by-products (such as GHGs), reducing resilience. In the U.S., farmer decisions increasingly depend on federal policy — not biology, agronomy, or economics. As the weather becomes increasingly variable, many farmers survive by maximizing crop insurance payouts. In 2019's wettest spring on record in the Midwest, many farmers first consulted their insurance agent and then lobbied to increase payments for not planting (Flavelle, 2019).

Overproduction and the demand for grain in developing countries, especially in times of famine, had led to massive purchases of excess U.S. grain for donation and sale to foreign governments and international non-governmental organizations (NGOs). This effort to "feed the world" can undermine local food production and exacerbate GHG problems. The Feed the Future Initiative (**https://www.feedthefuture.gov/**) begun in 2010 attempts to help food-insecure countries by developing sustainable food production and markets within those countries instead of creating reliance on cheap imported grain. Increasing sustainable production in food-insecure countries will decrease the need for overproduction in the U.S. and thus decrease GHG impact of that overproduction.

Whole Farm Revenue Protection — Climate-Friendly Crop Insurance

Since 2015, Whole Farm Revenue Protection (WFRP) policies have provided protection of up to 85 percent of the average historic whole farm revenue of the farm for any type of crop or livestock produced. The policy is the first crop insurance policy available nationwide in every county in the United States. WFRP provides a significant discount to premium costs depending on the number of products farmed (livestock and crops). For instance, if a farmer produces seven or more products, they can get a 41 percent discount on the base premium rate for the policy. Thus, WFRP is designed to support and incentivize diversity in crop and livestock production. This is key to why WFRP is climate-friendly and why the policy does not result in the same overproduction outcome of single-crop based policies. However, some small and mid-sized specialty crop farms have found the present record-keeping requirements for WFRP too onerous (Henderson, 2019). Adjustment of WFRP implementation will be required for it to reach its full potential.

Considering a future of climatic disruption, WFRP provides a unique potential solution to our current non-climate friendly system of subsidized crop insurance. With likely increasing weather and climate change in the future, having more systems of production with greater crop and livestock diversity should lead to greater resilience while lowering the public cost of crop insurance. The future of climate disruption will mean that farmer and rancher's livelihood will be at greater risk and that whole farm revenue protection will be seen more as a necessary investment rather than simply as an annual expense.

D. Overall Conclusions from Current GHG Emission Data and Research in Agriculture

Overall, the 2019 EPA GHG emissions inventory leads to the following conclusions:

1. Agricultural soil management (which leads to emission of N_2O) is the single greatest contributor to direct GHG emissions from agricultural production. If you combine enteric emissions with manure related emissions, livestock is the largest single contributor to agricultural GHG emissions.
2. Emissions from soil management, enteric fermentation from livestock digestive processes particularly cattle and other ruminants, and manure management are the top three sources of agricultural GHG emissions.
3. The conversion of land to cropland from grassland and forestland results in net GHG emissions. A large amount of CO_2 was lost from soils in the past because of conversion of vast acreages of native grasslands and forests to agricultural uses, and losses on a smaller scale continue each year.
4. The U.S. agricultural production sector is a moderate source of total U.S. GHG emissions, with an estimated total from agricultural production activities of 8.4 percent in 2017.
5. Most direct GHG emissions from U.S. agricultural production activities consist of CH_4 and N_2O, two potent greenhouse gases.
6. The U.S. agricultural production sector is currently a net emitter of GHG emissions. That is, agricultural production annually creates more GHG emissions than it captures. In addition to direct agricultural GHG emissions, soil health issues continue to cause net CO_2 emissions that are not included in the EPA analysis. There is, however, the potential for the agricultural production sector to sequester significantly higher levels of soil C through management and land use changes, and even to become climate-neutral.
7. Despite some improvement since 1990, in certain areas overall, the U.S. agricultural production sector has increased its GHG emissions and climate impact. The main driver of this increase is the increasing use of liquid manure storage (i.e., lagoons), which emit far more GHG (primarily CH_4) than dry-stacked or composted manure.
8. Crop insurance that motivates greater crop and livestock diversity, such as Whole Farm Revenue Protection (WFRP), is likely to lead to reduction of GHG emissions particularly from the current mono or bi-cultural systems of production. The myth that current high levels of federal subsidies for the production of a few commodity crops are necessary to feed the world is disingenuous. There is currently plenty of production to feed the world; distributional issues and other causes of food insecurity are the more significant issues.

III. THE ROLE OF SUSTAINABLE AND ORGANIC PRODUCTION SYSTEMS IN MITIGATING THE IMPACTS OF CLIMATE CHANGE

This chapter reviews research findings on agroecosystem mitigation of climate change. Fourteen summary statements of the research findings are provided on p. 38, near the beginning of the policy recommendations chapter.

Focus on systems of practices. Agricultural management practices have substantial impacts on SOC and overall soil health as well as direct agricultural GHG emissions. Thus, farmers and ranchers can play important roles in decreasing the net GHG "footprint" and in building agricultural resilience to the impacts of climate change. While individual practices such as cover cropping or no-till can accrue measurable amounts of SOC, integrated systems of practices based on sound agro-ecological principles have the greatest potential to mitigate agricultural GHG emissions, sequester and stabilize SOC, and attain the full measure of a productive and resilient agriculture (Lal et al., 1998). Integrated production systems include: sustainable, organic, biodynamic, regenerative, and conservation agriculture; holistic management, permaculture, agro-forestry, and others. While these systems differ in significant ways, all show potential to offer part of the solution to climate disruption (see Sidebar). Throughout this discussion, the terms *ecological agriculture* and *agro-ecological systems* will apply collectively to all these approaches to a truly sustainable and climate-friendly agriculture.

A BRIEF COMPARISON OF TWO AGROECOLOGICAL SYSTEMS

Organic agriculture seeks to eliminate chemical soil disturbance by excluding the use of synthetic fertilizers, herbicides, and other crop protection chemicals, as codified in the USDA National Organic Standards. The Standards do allow tillage but require the farmer to adopt tillage and cultivation practices that "maintain or improve" soil condition. New tools and techniques allow organic producers to reduce tillage frequency and intensity, thereby reducing adverse effects on soil health and SOC sequestration (Schonbeck et al., 2017).

Conservation agriculture seeks to eliminate physical soil disturbance by adopting continuous no-till and allows some use of synthetic agro-chemicals when needed. Skilled practitioners of conservation agriculture have cut fertilizer inputs by 50 to 100 percent, and reduced herbicide and other crop protection chemical applications to as few as one per year or less (Montgomery, 2017).

Farming systems research and farmer experience have shown that both approaches can make substantial contributions to SOC sequestration and GHG mitigation, as well as agricultural resilience (Schonbeck et al., 2018).

NRCS has developed a set of four principles of soil health management, which provide sound, science-based guidelines for SOC sequestration, GHG mitigation, and adaptation to the stresses of climate change:

- Keep the soil covered
- Maintain living roots as much of the year as practical
- Diversify the cropping system to build soil biodiversity
- Minimize soil disturbance:
    - Physical – tillage, traffic
    - Chemical – concentrated fertilizers, crop protection chemicals, pollutants
    - Biological – overgrazing, invasive exotics

Two additional principles for soil health, climate mitigation and adaptation include:

- Integrate crop and livestock production (Brown, 2018)
- Return organic residues to the soil ("law of return") (Howard, 1947)[3]

The agroecological systems described in more detail in the Appendix of this policy paper integrate soil, perennial and annual crops, livestock, and water management techniques; and thus can increase production and resilience (ability of systems to withstand disturbance), while enhancing soil C sequestration and reducing GHG emissions. Complex, integrated farming systems do not lend themselves easily to isolating cause and effect relationships among factors, yet research has validated the efficacy of a "whole farm approach" in mitigating the impacts of rapid climate change (Lal et al., 1998; Schonbeck et al., 2018).

Farmers' decisions regarding production system and management practices are based on multiple factors such as habit, custom, profit maximization, market conditions, and ecological context. Past public policy has often not assisted farmers in making decisions which improve their resilience and mitigate climate change. Federal research funding and federal program development must take all these factors into account and support each farmer to identify the best climate mitigation and adaptation strategy for their site and situation.

The 2018 Farm Bill gives authority to various USDA agencies to advance systems that reduce and mitigate GHGs and climate change. This assistance includes programs and funding which can be used to provide farmers and ranchers with information, technical resources, and funding to make ecologically sound choices that address climate change. Below we show how USDA can use that authority to help farmers sequester C and reduce greenhouse gas emissions. Learning from implementing our suggestions will provide a foundation for a 2023 Farm Bill that enables significantly more progress toward limiting climate disruption.

USDA has joined with EPA, the Department of Energy, the U.S. Geological Survey and other federal agencies in producing NCA4, which cites the critical need for producers and rural communities to intensify efforts to mitigate, prepare for, and adapt to climate change (Gowda et al., 2018). The call to action of all these agencies can only be realized if their words are followed with vigorous and persistent action to move U.S. agriculture towards the production systems discussed in this section.

[3] The first five principles of soil health are widely accepted. The sixth principle was promulgated earlier than the others, but in recent years, it has been given short shrift. In the context of climate change, it bears reemphasis.

A. The Starting Point: Sequestering Carbon through Soil Health Improvement Practices

Agricultural production plays a major role in the global C cycle through its impacts on the C balance among soil, biomass, and atmosphere (Figure 5). Native grassland and forest soils hold 20 to 50 tons or more SOC per acre in the top 39 inches of the soil profile (Weil and Brady, 2017). Converting native vegetation to tilled annual cropland can oxidize 30 to 50 percent of the SOC into atmospheric CO_2 over a period of 50 years, and up to 75 percent in 25 years when tropical forest is cleared (Lal, 2016; Olson et al., 2016, 2017; Weil and Brady, 2017). Between 1750 and 2011, more than 500 million tons of plant biomass C and SOC have been converted to CO_2 through deforestation and other land use changes, which account for 30 percent of total anthropogenic GHGs during those 261 years (Lal, 2016). While these losses have slowed in recent decades, net annual global losses of SOC are still estimated at ~2 million tons of C (Weil and Brady, 2017; Figure 5). Half of this loss results from soil erosion, which selectively removes SOC-rich fractions, followed by SOC oxidation or (when sediments are submerged) conversion to CH_4 (Lal, 2003; Olson et al., 2016, 2017).

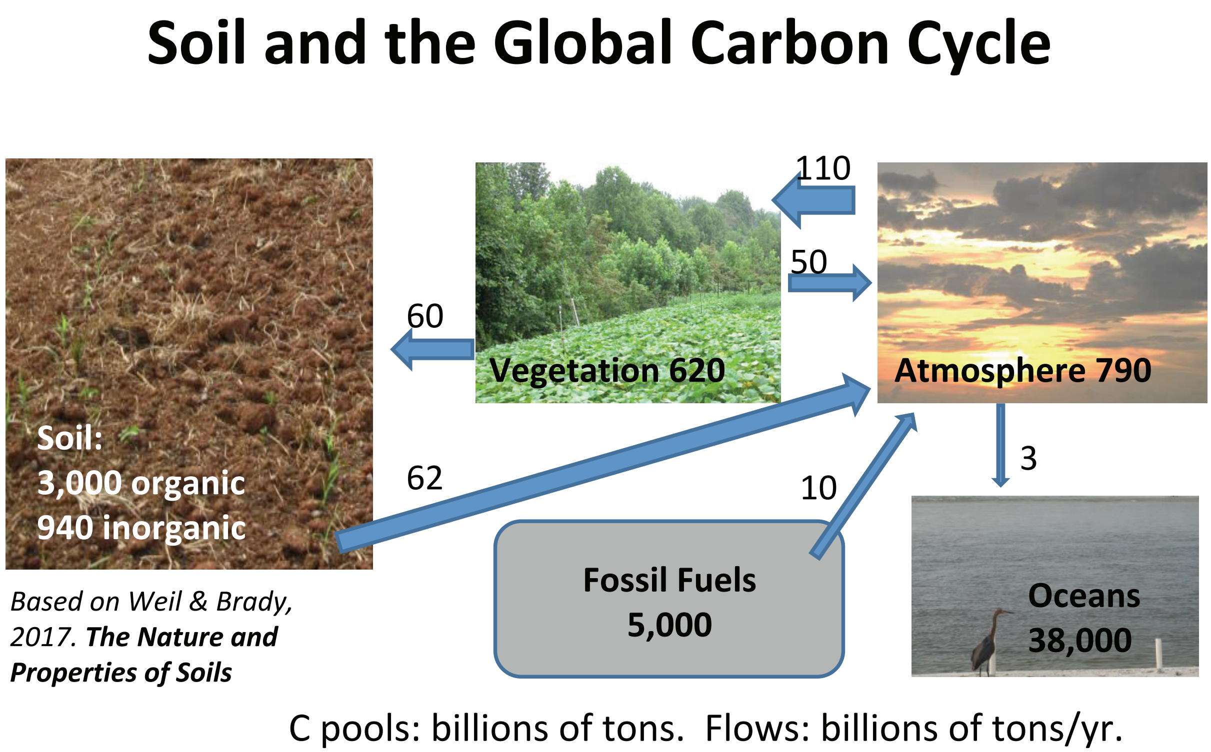

Figure 5. Soil and the Global Carbon Cycle

Figure 5. *The world's soils are currently losing about 2 billion tons more C annually than they gain through plant roots and residue return. Improved soil health management practices can reverse this, resulting in a net annual sequestration of 1 to 2 billion tons annually. Figure credit: Organic Farming Research Foundation (**https://ofrf.org**) webinar, Organic Practices for Climate Mitigation, Adaptation, and Carbon Sequestration: Research-based Practical Guidance for Organic and Transitioning Farmers, presented March 20, 2019, presented and archived by eOrganic, **https://eorganic.org/node/4942.***

Globally, soils store at least twice as much C as currently occurs in the world's vegetation plus atmosphere, making soil one of the planet's largest C sinks (Figure 5). Total SOC to 2 meter (78.8 inch) depth has been estimated at 2400 Pg, which is three times the amount of CO_2 currently in the atmosphere (~830 Pg C) and 240 times current annual fossil fuel emissions (~10 Pg). Thus, increasing net soil C storage by even a few percent represents a significant C sink potential. Soil C sequestration is one of a few strategies that could be applied on a large scale and at low cost (Paustian et al., 2016).

Comparative studies have shown that agro-ecological production systems can help mitigate soil C losses, decrease soil erosion, reduce energy use and air and water contamination, as well as lower the costs of production (e.g., Toensmeier, 2016). These systems include the use of cover crops and resource conserving crops rotations and the integration of livestock production into the cropping system (Boody et al., 2009). With agricultural soils currently averaging 55 percent of their native SOC levels, and a technically realistic potential to restore SOC to 85 percent through best agro-ecological management practices, a substantial opportunity exists for farmers and ranchers to contribute significantly to climate mitigation through the same suite of practices that will help their soils, crops, and livestock to adapt to the impacts of climate change (Lal, 2016).

Over the past several decades NRCS and other soil conservation professionals have promoted continuous no-till for building SOC and soil health, and have considered the soil disturbance from one tillage operation more destructive to SOC and soil life than the herbicides and other agro-chemicals on which continuous no-till systems depend for successful crop production. A review of multiple studies has shown that continuous no-till for corn, soybean, and other field crops can accrue about 510 lb. SOC/ac-yr compared to the same crop rotations with conventional tillage (West and Post, 2002). However, much of this SOC accrues in aggregates near the soil surface, where it is vulnerable to rapid oxidation after even a single tillage pass; most no-till farmers till once every several years to deal with perennial weeds and/or soil compaction (Grandy et al., 2006; Kane, 2015). Crucially, most stabilized soil organic matter appears to derive from microbial processing of root exudates and other organic residues and are not of direct plant origin (Paustian et al., 2016; Kallenbach et al., 2016; Schmidt et al., 2011). Thus, the detrimental effect of chemicals used in no-till systems on soil microbes undermines formation of stable soil organic matter (Druille et al., 2013; Nicolas et al., 2016).

Studies focused on the top 6 to 12 inches of the soil profile may overestimate the amount of SOC sequestered through no-till, as total SOC measured from surface to depths of 2 or 3 feet may show less difference between tilled and no-till systems (Baker et al., 2007). For example, field trials in clay-loam soil of the cool, humid region of eastern Canada found greater SOC near the surface in no-till, while the moldboard-plow treatment had greater subsurface SOC near the bottom of the plow layer, with similar total soil profile SOC for the two management systems (Poirier et al., 2009). Shallower crop root development in no-till systems may accentuate the near-surface distribution of SOC. However, responses of root development and SOC sequestration to tillage practices may differ in other regions, climates, and soil types, and the authors caution that simple changes in tillage practices should not be assumed to increase soil organic C without incorporation of other practices into the system, for example the addition of cover crops, fertilization with animal manures, or other practices to build soil quality (Baker et al., 2007).

Ultimately, all SOC derives from photosynthetic processes that converts atmospheric CO_2 into plant biomass organic C. Thus, increasing the mean annual plant biomass production in the cropping system would be expected to increase SOC accrual. Corn and other field crops respond to synthetic nitrogen-phosphorus-potassium (NPK) fertilizer with higher yields of both grain and residue, which has led to the hypothesis that providing soluble N enhances SOC sequestration (Ramirez et al., 2012). Yet, a review of the Morrow Plots at University of Illinois and 25 other long-term farming systems trials around the world revealed no enhancement in SOC with additional fertilizer (Khan et al., 2007). In the Morrow Plots, the higher NPK rate (applied 1967 to present) doubled crop yields and residue return compared to the unfertilized treatment, yet sharply reduced SOC, especially at depths of 12 to 18 inches. High levels of soluble N and P are known to inhibit the activity of arbuscular mycorrhizal fungi (AMF), which play a significant role in SOC stabilization in cropland and grassland soils (Rillig, 2004). In organic systems that rely on compost or manure as primary sources of organic matter and plant-available N, soil P can accrue to levels that inhibit AMF activity (Van Geel et al., 2017). Thus, cropping practices may limit SOC accrual through the chemical disturbance of fertility inputs as well as through the physical disturbance of tillage.

Ecological agricultural systems that integrate all four of the NRCS soil health principles — soil coverage, living root, biodiversity, and minimal disturbance — show greater potential to sequester SOC in cropland soils than a narrow focus on eliminating tillage. For example, in a meta-analysis of organic systems trials in fragile, low-SOC soils in the Mediterranean region, total C inputs (crops + organic amendments) was the main driver in SOC accrual, while conservation tillage made a significant, but smaller contribution (Aguilera et al., 2013). In the U.S., several long-term farming systems trials have shown significant SOC gains (400 to 1,000 lb/ac-yr) in organic grain rotations that include cover crops versus conventional corn-soy rotations without cover cropping (Baas et al., 2015; Coulter et al., 2012; Wander et al., 1994). In the long term farming systems trial at Beltsville, MD the organic grain rotation with cover crops, light applications of poultry litter, and annual tillage accrued about 5,000 lb/ac more SOC (surface to 39 inches) over a 13-year period than the continuous-no-till corn-soy rotation with conventional inputs and no cover crops (Cavigelli et al., 2013).

In the Rodale long term farming systems trials, an organic rotation that includes alfalfa accrued 3 tons SOC/ac in the first 15 years, compared to the conventional corn-soy rotation, despite similar average annual plant biomass inputs for the two systems. The organic system featured greater crop diversity, greater continuity of living root (averaging 70 percent vs 42 percent of the calendar year), and deeper, higher-biomass root systems (alfalfa), each of which may have contributed to SOC accrual (Wander et al., 1994). In New Hampshire, an organic rotation of corn-rye (cover)-soybean-wheat/clover accrued higher total SOC than a conventional corn-soybean-wheat rotation, even though the former system entailed more tillage and slightly lower average annual plant biomass (Grandy and Kallenbach, 2015). The more diverse organic system enhanced microbial growth efficiency (55 percent of organic residue C consumed by microbes converted to microbial biomass) over the conventional system (45 percent microbial growth efficiency). Perennial sod crops typically have much higher root biomass (3,000 to 8,000 lb/ac) than annual grains (800 to 1,400 lb//ac); thus, inclusion of perennial legumes in the organic rotations likely played a key role in their ability to build SOC (Carpenter-Boggs et al., 2016). Indeed, a simple corn-soy rotation without winter covers has been shown to degrade soil health in Minnesota, even under organic management (Moncada and Sheaffer, 2010)

In non-organic systems, adding one or more new crops to an existing low-diversity rotation can improve SOC sequestration, in part by building functional diversity of soil microbial communities (McDaniel et al., 2014; Tiemann et al., 2015). While the SOC accrual from diversification alone (180 lb/ac-yr) is more gradual than from no-till (510 lb/ac-yr), the former continues for up to 40 years, while SOC under no-till levels off after 15 years (West and Post, 2002). Adding legumes, perennial sod, and other crops with deep, extensive root systems to the rotation further enhances SOC (Blanco-Canqui and Francis, 2016; Kane, 2015; McDaniel et al., 2014). Conservation agriculture cropping systems that integrate cover crops, diversified crop rotations, organic amendments, no-till, and limited use of synthetic fertilizers and herbicides show significant C sequestration potential, estimated at 600 to 1,000 lb SOC/ac-year in (Lal, 2016), and have substantially improved soils from cold-temperate semi-arid regions like the northern Great Plains to tropical regions in Africa (Montgomery, 2017).

Organic Farming, Carbon Sequestration, and Greenhouse Gas Mitigation

Strictly regulated under the National Organic Program (NOP) launched by the Organic Foods Production Act of 1990, organic production is a system that is managed to " … respond to site-specific conditions by integrating cultural, biological, and mechanical practices that foster cycling of resources, promote ecological balance, and conserve biodiversity" (USDA NOP, 2019). Organic systems exclude the use of prohibited synthetic fertilizers and crop protection chemicals, and rely on crop rotations, cover crops, legume green manures, sod crops, composted manure, and other organic amendments to provide for crop nutrition and pest control. Six long-term term farming systems trials across the U.S. have shown greater SOC sequestration in established organic cropping systems than in conventional cropping systems (Delate et al., 2015a). In the Beltsville, MD trial, the organic rotation accrued 2.5 tons/ac more SOC over a 13-year period than continuous no-till with conventional inputs (Comis, 2007, Cavigelli et al., 2013; Delate et al., 2015a). The conventional systems were characterized by low diversity rotations with limited or no use of cover crops; thus, implementation of NOP requirements for crop rotation and cropping system diversity contribute to the observed increases in SOC.

In a meta-analysis of 20 organic/conventional comparison trials from around the world, organic systems accrued an average of 400 lb C/ac-year more than conventional systems, of which about 60 percent was sequestered in situ and 40 percent was imported in the form of compost, manure, and other organic amendments (Gattinger et al., 2012). Another meta-analysis of 59 studies found total SOC averaging 19 percent higher in organic than conventional systems (Lori et al., 2017). In the U.S., a nationwide sampling of 659 organic fields and 728 conventional fields across the U.S. showed 13 percent higher total Soil Organic Matter (SOM) and 53 percent higher stable SOM in the organic soils (Ghabbour et al., 2017).

Most recently a meta-analysis examined 528 studies which each compared at least one organic farm to at least one conventional farm (Sanders and Hess, 2019). On average, organically managed soils had a 10 percent higher organic C content and a higher annual C sequestration rate of 256 kg C /ha. Nitrous oxide emissions averaged 24 percent lower for organic farming, which results in a cumulative climate protection performance of 1,082 kg CO equivalents per hectare per year. Aggregate stability in soil was on average 15 percent higher (median) in organic farming; infiltration differed by 137 percent. Higher infiltration reduces soil erosion and soil loss, which means that organic farming reduces these occurrences by -22 percent and -26 percent, respectively (Sanders and Hess, 2019).

These modest but significant differentials indicate that organic is a viable strategy for improving agricultural C sequestration. However, organic systems may yield somewhat less than conventional, especially for commodity grains, in which the "yield gap" in one study was about 19 percent and can be traced to the lack of plant breeding and agronomic research for sustainable organic systems, compared to the huge scientific investments in high-input conventional systems (Ponisio et al., 2014). The same analysis showed a significant (8 to 10 percent) yield improvement in diversified rotations versus one or two-crop systems. Additional refinements of the organic approach (such as practical means to minimize tillage yet maintain adequate weed control), as well as plant breeding and cultivar development for performance in organic and ecological farming systems are needed to enhance the C sequestration potential of these systems.

Research also indicates that organic production systems are more resilient than conventional systems under both flood and drought conditions (Rodale, 2015). Improved soil health and accrual of both active and stable SOC play major roles in better moisture uptake, drainage, and retention, which will help organic systems meet the challenges of climate disruption. Greater crop diversity and associated soil biodiversity also seems to enhance the capacity of organic systems to adapt to climate change (Chavas et al., 2009; Niggli et al., 2009; Borron, 2006).

Prolonged bare fallow, whether maintained by tillage or no-till with herbicides, destroys SOC. For example, orchards with living orchard floor cover maintain twice the SOC as bare soil orchard floor management (Lorenz and Lal, 2016). In semiarid regions such as the Northern Great Plains, annual cropping systems that alternate wheat with a legume cover crop, or a cash crop (pulse, oilseed, or even cereal grain) can maintain or build SOC while the traditional two-year wheat-fallow system depletes SOC, even under continuous no-till (Engel et al., 2017; Halvorson et al., 2002; West and Post, 2002).

While no-till and minimum tillage enhance *near-surface* SOC, living plant roots build SOC *throughout the soil profile* via rhizodeposition (root exudates + fine root sloughing) followed by microbial conversion of root C into stable SOC adsorbed to soil minerals. Root C is converted more efficiently into SOC (30 to 40 percent) than aboveground plant biomass C (15 to 20 percent), and SOC deposited deeper in the soil profile turns over more slowly and is less subject to tillage disturbance (Weil and Brady, 2017; Kane, 2015). Deep rooted crops such as tillage radish, forage turnip, chicory, sunn hemp, pearl millet, and sorghum form substantial root biomass at depths of 4 to 8 feet (Rosolem et al., 2017; Thorup-Kristensen and Rasmussen, 2016). In China, SOC accruals were tightly correlated with estimated *belowground* biomass, which ranged from 2,320 lb/ac-year for continuous wheat and 2,770 to 3,390 lb/ac-year for diversified annual crop rotations, to 4,910 to 6,250 lb/ac-year for rotations that included deep rooted perennial legumes two years out of four (Fu et al., 2017). At the end of 30 years, the perennial-annual rotations had accrued about 5,000 lb/ac more SOC in the top 12 inches than the annual rotations. Based on these and other findings, Kell (2011, 2012) has recommended managing cropping systems for deep, extensive root development, and breeding new crop cultivars with enhanced root biomass and depth as strategies for SOC sequestration and climate mitigation.

Agricultural C sequestration cannot be expected to offset anthropogenic GHG emissions indefinitely because of the phenomenon of soil C saturation. Implementation of improved soil health management practices on cropland soils typically leads to steady increases in total SOC over a period of 10 to 40 years, after which it reaches a new steady state or plateau. For example, in the Rodale trials, soil organic matter in the organic systems increased from 3.5 percent to 4.2 percent (~ SOC increase from 1.75 to 2.1 percent) over the first 20 years of the trial, then remained steady for the next 15 years (Rodale, 2015). A review of multiple studies indicated that continuous no-till might accrue 510 lb SOC/ac-yr for 10 to 15 years then level off, while diversified crop rotation might accrue 180 lb SOC/ac-yr for 40 years (West and Post, 2002). Each of these examples represents a total accrual of roughly 3 to 4 tons SOC per acre. Conversion of cropland to pasture, or of poorly managed grazing lands to best rotational grazing management builds SOC more rapidly (1 ton/ac-yr or more), but again level off at a new steady state within 10 years, with net total gains of 10 to 15 tons SOC/ac (Jones, 2010; Machmuller et al., 2015; Wang et al., 2015). Assuming SOC reaches a plateau after 25 to 50 years of best practices (Lal et al., 2018) estimated the technical potential for global SOC sequestration at about 52 billion tons (range 21 to 83 billion tons); the median value might reduce atmospheric CO_2 levels in 2100 by 22 ppm.

One important unknown in soil C sequestration is soil inorganic carbon (SIC), primarily in the form of carbonates in surface or subsurface horizons of alkaline soils in arid, semiarid, and prairie regions (Weil and Brady, 2017). SIC comprises nearly one quarter of the planet's total soil C (Figure 2) and can be destabilized by inputs or practices that lower soil pH. In a review of comparative farming systems trials, organic practices resulted in major losses of SIC (9 to 14 tons/ac) in three studies, and little change in SIC in four other studies (Lorenz and Lal, 2016). Additional research is needed to better understand and manage SIC for total net soil C sequestration and climate-friendly management of agricultural lands in low-rainfall regions.

In addition to representing sequestered C, SOC is a key indicator of soil health. Building SOC enhances fertility and moisture holding capacity, improves resistance to compaction, surface crusting, and wind and water erosion, and improves crop stress tolerance. By increasing the organic C content of soils through agroecological practices — especially enabling microbial creation of stable soil organic matter — farmers can make their operations more resilient in the face of climate change as well as reducing the net GHG footprint of the operation.

B. Nutrient Management to Mitigate Nitrous Oxide Emissions from Soil

N_2O emissions from cropland and grazing land soils account for 49 percent of direct agricultural GHG emissions (in CO_2eq) in the U.S. (EPA, 2019). In fact, arable soils emit more N_2O to the atmosphere than all other anthropogenic sources combined (4.2 Tg of a global anthropogenic flux of 8.1 Tg N_2O^-N yr-1 according to Paustian et al., (2016)). Mitigation of soil N_2O through improved nutrient management has emerged as a high priority in efforts to reduce the net GHG footprint of our agricultural and food system (Cogger et al., 2014; Powlson et al., 2011).

Soil N_2O is formed through microbial transformations of soluble N, primarily denitrification (reduction of nitrate, NO_3^-), and some during nitrification (oxidation of ammonium, NH_4^+ to nitrite NO_2^- and then NO_3^-) (Charles et al., 2017; Cogger et al., 2014). Soil N_2O emissions increase sharply when high soil moisture levels (above field capacity, ~80 percent of pore space water filled), restricted oxygen levels, abundant readily decomposable organic C (manure, succulent green manure, active SOC), and high levels of soluble N (NH_4^+ and NO_3^-) occur together (Baas et al., 2015; Jackson 2010; Li et al. 2009). Sharp pulses of N_2O commonly occur when heavy rains follow N fertilizer applications or incorporation of a legume green manure, or during spring snowmelt after fall plowdown of alfalfa (Burger et al., 2005; Han et al., 2017; Westphal et al., 2018). Microbial formation of N_2O also increases with soil temperature, with emissions from Corn Belt soils increasing 18 to 28 percent for each 1°C (1.8°F) increase in mean July temperature (Ball et al., 2007; Eagle et al., 2017). Thus, climate change itself may lead to a positive feedback with soil N_2O.

Conditions that slow gas diffusion through the soil promote N_2O emissions; thus fine-textured (silt loam and clay loam) soils emit on average 2.8 times as much N_2O as sandy loams, and soil compaction also intensifies emissions (Charles et al., 2017; Balaine et al., 2016). N_2O emissions become minimal whenever soil moisture drops below field capacity (50 to 60 percent of pore volume water filled) or soil NO_3^-N levels drop below 6 ppm (Cai et al., 2016; Thomas et al., 2017).

IPCC estimates a N_2O emissions factor (EF) of 1 percent of fertilizer N emitted from the field as N_2O (direct emissions), and an additional 0.75 percent of leached N converted to N_2O after it leaves the field (indirect emissions). In conventional farming systems that rely mainly on synthetic fertilizers for N, N_2O emissions show direct relationships with N application rates and methods, rising sharply as rates exceed crop needs (Eagle et al., 2017; Millar et al., 2010). Reliable, research-based nutrient management protocols based on the "4 Rs" (right amount, timing, placement, and form) for reducing N_2O emissions by 50 percent or more have been developed for conventionally produced field crops (e.g., Osmond and Line, 2017).

Ecological farming systems that utilize organic sources of N and depend more on soil biological activity for plant-available N result in more complex soil N dynamics and more unpredictable N_2O emissions. On average, organic N fertilizers have an EF of 0.57 percent, but this varies from as low as 0 to 0.3 percent for finished compost or crop residues, to 1.2 percent for manure slurry and liquid biogas digestate (Charles et al., 2017). Mixing organic and soluble sources of N double the EF of the former (Ibid.)

Many farming systems trials have documented lower annual N_2O emissions from organically managed soils than from the conventional treatment (Cavigelli, 2010; Reinbott, 2015; Skinner et al., 2014). Yet, N_2O emissions increase about 24 percent for each 1 percent increase in total SOC (Eagle et al., 2017), and high emissions can occur in organic production systems. For example, in a three-year trial in Michigan, an organic grain rotation that received pelleted poultry litter (4.5 percent N) at 2,900 to 4,400 lb/ac-yr emitted five times as much N_2O as the conventionally fertilized rotation (Baas et al., 2015). Brief, intense bursts (~0.6 lb N_2O^-N/ac-day) followed heavy rains in the organic system. In California, organic broccoli required 220 lb N/ac (organic fertilizers + green manure) for economically optimum yields; however, this organic N application was estimated to release 11 to 27 lb N_2O^-N/ac (Li et al., 2009), which negates 1,460 to 3,600 lb/ac SOC sequestration.

Cover crops, sod crops, and conservation tillage, all considered important practices for soil health and SOC accrual in annual crop rotations, have mixed impacts on soil N_2O emissions. A growing cover crop can reduce potential N_2O losses by taking up soluble N, and deep rooted species like pearl millet or tillage radish can effectively scavenge surplus NO_3^-N from surface to 5 feet or more (Rosolem et al., 2017), However, N_2O emissions can increase after the cover crop is terminated, especially when all-legume covers are tilled in higher-rainfall climates (Basche et al., 2014; Han et al., 2017; Li et al., 2009). A recent modelling study based on farming systems in Europe indicated that adding a clover cover crops (terminated by plowdown) to existing crop rotations would boost N_2O emissions sufficiently to offset cover crop C sequestration and accrue large net GHG emissions by the year 2100 (Lugato et al., 2018).

When no-till practices retain surplus moisture (under roll-crimped cover, or because of slower drying in untilled soil), N_2O emissions from synthetic, organic, or cover crop sources can be higher than in the same soil and rotation with tillage. This increase may be sufficient to negate the SOC sequestering effects of no-till (Mkhabela et al., 2008; Yarwood, 2016). In other studies with organic vegetable crops, no-till cover crop termination reduced N_2O emissions compared to tilling the cover and laying plastic mulch (Chen et al., 2015).

The challenging aspect of soil N_2O mitigation is that crops *require* sufficient soluble N, adequate moisture, and beneficial microbes to thrive and yield. Yet soluble N from any source — including active soil organic matter — is subject to conversion to N_2O in moist, biologically active soil. The U.S. EPA estimates that, in cropland, about 38 percent of U.S. total soil N_2O emissions derive from "mineralization and asymbiotic (free-living, non-nodule bacteria) N fixation" — i.e., the very soil microbial activity upon which ecological agriculture depends for crop nutrition (EPA, 2019). Another 38 percent is attributed to synthetic fertilizers, 15.5 percent to crop residues including legume green manures, and 8.4 percent to organic amendments. In grasslands, the share for mineralization and asymbiotic N fixation jumps to 47 percent, residues 30 percent, manure deposited during grazing 20 percent, and all applied fertility inputs just 3 percent (EPA, 2019). Thus, soil health building practices that consistently enhance SOC sequestration exert unpredictable and sometimes adverse effects on soil N_2O emissions.

These findings raise an important question: can *agroecological systems be designed to grow high-yielding crops in healthy soils with low soluble N concentrations?* Recent research indicates that the answer may be yes.

In a study of 13 organic tomato fields in Central California, two fields with low SOC and less than 6 ppm NO_3-N throughout the season gave low, N-limited tomato yields; seven fields with moderate SOC and higher NO_3-N gave high yields and increased risk of N leaching and N_2O emissions; and four fields with high SOC gave equally high crop yields despite season-long NO_3-N levels below 6 ppm (Bowles et al., 2015; Jackson, 2010; Jackson and Bowles, 2013). In the last group of fields, *tightly coupled nitrogen cycling,* facilitated by rhizosphere soil microbes and plant root enzymes involved in N transformations and uptake allowed the crop to obtain sufficient N despite bulk soil soluble N levels remaining below the threshold for N_2O formation.

In Colorado, organic lettuce grown on in-row drip fertigation with fish emulsion or "cyano-fertilizer" (an on-farm fermentation product based on N fixing cyanobacteria), receiving a total of 25 lb N/ac gave good yields with no increase in N_2O emissions over unfertilized control (Toonsiri et al., 2016). Thus, standard recommendations for organic or conventional lettuce (~100 lb N/ac) may not serve either the climate or the farmer's bottom line.

Another indication of the potential to reap high yields without high soluble N comes from corn breeding endeavors at Mandaamin Institute in Wisconsin. Genetic traits that enhance the crop's capacity to utilize N from slow release organic sources and to host significant N-fixing activity in its rhizosphere have been successfully transferred from Mexican and Central American land races into standard non-GMO Corn Belt hybrids. The new cultivars, soon to become available to producers, give competitive yields with superior protein levels and greatly outperform standard hybrids in soils with low soluble N, including tropical soils in Africa (Goldstein, 2015, 2018). Modern corn hybrids that were developed *in* and *for* high-fertility-input conventional systems have apparently lost the capacity to partner with N-cycling and N-fixing microbes; additional selection in healthy soils with low N inputs can reverse this trend (Goldstein, 2016).

N_2O emissions and cost of inorganic fertilizer in conventional corn production in the Midwest can be reduced up to 50 percent by fine-tuning application of N (Millar et al., 2010). N applications in excess of plant uptake greatly aggravate N_2O losses in both conventional and organic systems, whether the crop is corn, wheat, barley, or vegetables (Li et al., 2009; Millar et al., 2018). In grain crops, N_2O loss is reduced by applying N at variable rates across the field depending on patterns of soil fertility; applying N in root zone rather than broadcast on soil surface, timing N application when crops can use it (several weeks after planting), and using slow release coatings to delay dissolution if applying early (Paustian et al., 2016).

Arbuscular mycorrhizal fungi (AMF) are key root symbionts for most grains, legumes, and many vegetable crops, enhancing nutrient and moisture uptake efficiency, suppressing crop disease, and contributing to stable SOC. In addition, AMF can promote tight N cycling and reduce N_2O emissions by facilitating plant root removal of excess soluble N and moisture from the soil profile (Hamel, 2004; Jackson, 2013). However, elevated soil P levels (in the "very high" range on soil tests) inhibit AMF activity in organic production systems that use large amounts of compost or manure (Hu et al., 2016; Van Geel et al., 2017).

Laboratory experiments indicate that mixing biochar into the soil at 1 percent by volume (roughly 10 tons/ac if mixed into the plow layer) may cut N_2O emissions by three quarters, similar in efficacy to nitrification inhibitor and urease inhibitor chemicals (Cai et al., 2016).

Additional research is clearly needed to explore each of these strategies further, and to identify and verify soil health and nutrient management practices that can maintain crop yields and minimize N_2O emissions. Development of new and improved crop cultivars for ecological systems with enhanced capacity to thrive and yield on low soluble N levels through tightly coupled nutrient cycling may also play an important role in N_2O mitigation in agriculture.

C. Keeping the Land in Grass, Planting Field Edges and Marginal Lands to Perennials, Supporting Pest Control and Reducing Surface Reflections

Protecting native grasslands to retain their huge reserve of SOC is essential for climate stabilization, as converting prairie to cropland is known to destroy half its SOC (Weil and Brady, 2017). Restoration of permanent cover on the land through programs such as the farm bill's Conservation Reserve Program and the Wetlands Reserve Program can initially sequester > 1 ton C/ac-yr, yet may not fully restore native SOC levels (Manale et al., 2016). However, converting cropland, especially marginal cropland, to pasture-based systems can accrue at least 800 lb C/ac annually, and much more under management intensive rotational grazing (Manale et al., 2016; Richard and Camargo, 2011). A 2017 synthesis of hundreds of studies indicated that improved grazing management increased C sequestration by an average of 250 lb C/ac-yr, conversion from cropland to grasslands led to an average increase of 780lb C/ac-yr, and sowing legumes 590 lb C/ac-yr also tended to lead to increased soil C. The best-managed grazing systems achieved more than 900 lb C/ac-yr (Conant et al., 2017).

Planting herbaceous perennial conservation buffers (e.g., field borders, filter strips) on annual cropland has been estimated to sequester 375 to 850 lb C/ac-year (Chambers et al., 2016). Agroforestry systems and conversion of depleted cropland, highly erodible land, or other marginal land to woody perennial vegetation can store more than 1 ton C/ac-yr in soil and biomass; silvopasture and permaculture gardening on previously underutilized land appear especially effective, accruing ~3,900 and 3,100 lb/ac-yr respectively in SOC alone (Feliciano et al., 2018). Hedgerows planted on contour sequester C directly and by checking soil erosion (Walter, 2003). On one California organic farm, hedgerows and riparian habitat stored 18 percent of the farmscape's total C), while occupying only 6 percent of the total farm area (Smukler et al., 2010). When these reforestation and perennialization practices are added to soil management for SOC sequestration, the global technical potential for total (soil + biomass) C sequestration by the year 2100 increases to ~ 367 billion tons (range 230 to 504), sufficient to reduce atmospheric CO_2 by 156 ppm (Lal et al., 2018). A goal adopted by many countries is 0.4 percent growth per year in global soil C required to make global agriculture climate neutral (Kon Kam King et al., 2018).

Hedgerows and other flowering native habitats increase the presence of natural enemy insects and birds, making the farm more resilient to pest insects, rodents and pest birds (Asbjornsen et al., 2014; Letourneau et al., 2015; Morandin, et al., 2014; Baumgartner et al., 2019). Insect flight periods are occurring earlier in the season because of climate change. Insects are also completing their life cycles faster, resulting in more generations of pests and enhanced winter survival. These changes will likely cause the increased occurrence and spread of invasive insects (Robinet and Roques, 2010). Climate change is impacting nesting, migrations, and the synchrony between birds, habitat and food sources. Other existing challenges become worsened with global warming: uncertain food reserves, migration barriers, and habitat loss and fragmentation (Johnson et al., 2011). By providing woody perennials that sequester C, such as hedgerows (Falloon et al., 2004), the farm will be able to better support natural enemy insects and birds, making it more likely that they will find the habitat that suits their needs as their distributions shift with the changing climate (National Audubon Society, 2014).

In addition to impacting the global C cycle and atmospheric CO_2 levels, deforestation, reforestation, and other land use changes can also change the radiation balance by altering the Earth's surface albedo, the extent to which the surface reflects light from the sun. Changes in land surface cover can alter the fluxes of heat to the atmosphere and thus the distribution of energy within the climate system and, in so doing, can alter climate at the local, regional, and even global scale (Marland et al., 2003; Pielke, 2005). Clearly, the conversion of all sensitive, marginal, erosion-prone, or depleted cropland to native perennial vegetation or perennial production systems can play a substantial role in agricultural climate mitigation efforts.

D. Livestock management, grazing, and crop-livestock integration

Environmental and climate concerns with modern agriculture commonly focus on livestock production (Steinfeld et al., 2006). According to the United Nations Food and Agriculture Organization (FAO), over the past 50 years, global meat production has almost quadrupled from 84 million tons in 1965 to 335 million tons in 2018 (FAO, 2018). USDA predicts growth in U.S. meat production will continue with poultry production rising at an annual growth rate of 1.8 percent while beef and pork production growing at 1 percent and 1.3 percent respectively (USDA, 2019).

The primary direct GHG impact of all livestock production is enteric CH_4 generated in the digestive tract of ruminants by methanogens, anaerobic microbes in the domain *Archaea* that convert organic carbon into CH_4, which the animals then expel into the atmosphere. Livestock emit CH_4 regardless of whether they live on pasture or in confinement. On average, about 4 to 12 percent of gross energy intake for livestock is converted to CH_4, resulting in annual emissions from cattle of about 450 to 570 lb CH_4 per animal-year (equivalent in climate impact to losing 4,500 to 5,800 lb SOC as CO_2) (Richard and Camargo, 2011).

Current data on livestock related GHG emissions indicate that enteric fermentation emissions, primarily from beef and dairy cattle, have risen 6.9 percent since 1990. Emissions related to manure management rose 66 percent since 1990. The majority of this increase is due to swine and dairy cow manure, where emissions increased 29 and 134 percent respectively. The EPA points out that the shift toward larger dairy cattle and swine CAFOs since 1990 has translated into an increase in use of liquid manure management systems, which have higher potential CH_4 emissions than dry systems. CAFOs generally rely on large-scale row crop grain production systems, which generate additional GHG emissions as noted throughout this paper.

In Manitoba, Canada grass-based systems, access to high-quality pasture reduced CH_4 emissions from steers by 50 percent compared to steers grazing lower-quality mature grass (Ominski et al., 2001). Management-intensive rotational grazing (MIG) systems maintain high quality forage and have reduced per-animal enteric CH_4 by 30 percent compared to continuous grazing systems in Texas and Michigan (Stanley et al., 2018; Wang et al., 2015). MIG systems also reduce pasture runoff, improve manure distribution (less N leaching, fewer GHG hotspots), and enhance forage vigor, productivity, and drought resilience (Beetz and Reinhardt, 2010; Figure 3). Well-managed MIG systems considerably enhance forage biomass and especially root biomass and rhizodeposition, resulting in SOC sequestration rates exceeding one ton per acre annually in multiple studies and often yielding a net negative GHG footprint even at "average" per-animal enteric CH_4 levels (Machmuller et al., 2015; Teague et al., 2016).

Figure 6. *Livestock access to healthy, living soil with forages that in turn support healthy livestock. This system can also sequester over a ton of SOC per acre annually for 10 years*. Photo: NSAC.

In ruminants that receive grain-based feed, changes in grain to forage ratio, grinding and pelleting of feed, reducing protein content, addition of fats, and the use of enzymes can modulate enteric CH_4 emissions. Proper feed storage and handling practices can also reduce system GHG emissions by reducing spoilage and loss. In Australian research, feeding dairy cows a diet high in natural omega-3 sources, such as alfalfa, flax, hemp, and grasses, rebalanced the cow's rumen and reduced enteric CH_4 by 15 to 20 percent (Sudmeyer, 2018). A limited number of in vitro trials have shown that adding seaweed to the diet can reduce methane emissions from ruminants (Duarte et al., 2017). One in vivo study found that diet that included 3 percent seaweed resulted in more than 80 percent reduction in CH_4 emissions from sheep (Xixi et al., 2016). Further research is needed to explore how much enteric CH_4 can be cost-effectively reduced by ruminant diet changes.

Waste management also affects livestock GHG emissions. In manure lagoons, other liquid/slurry storage systems, and large stockpile systems, anaerobic decomposition converts much of the carbon in the manure to CH_4. Under aerobic conditions, such as in drybed or compost systems, N_2O is produced. Research in Canada indicates that total GHG emissions from dairy manure are smaller for compost than for manure slurry (1.9 X compost) or manure stockpiles (1.5 X compost). GHG emissions from beef manure are much lower overall but were four to six times higher from slurry than from compost, while stockpiled manure GHG were 1.3 X compost (Pattey et al., 2005).

Valid comparisons of GHG emissions from different livestock production systems require a comprehensive life cycle analysis (LCA) (Garnett, 2009). In addition to enteric and manure-storage GHG, this analysis must consider:

- SOC balance in pasture versus cropland for feed grains
- Embodied energy (CO_2 emissions) in fertilizers and pesticides for growing grain
- Soil N_2O from fertilized fields versus pasture
- Energy use for heating, cooling, and ventilation required to protect CAFO livestock from temperature extremes and lethal levels of ammonia (NH_3) and hydrogen sulfide (H_2S)
- GHG impacts of over-application of manure to acreages near CAFOs

In many livestock-producing regions of the U.S., the amount of waste produced exceeds the capacity of the surrounding land base to utilize N in the waste for plant production (Steinfeld et al., 2006; Thorne, 2007). Heavy manure applications can result in substantial direct (on-site) and indirect (offsite, from leached or volatilized N) emissions of N_2O (EPA, 2019). In addition, manure applications to snow-covered or frozen ground can lead to CH_4 emissions when the waste is temporarily submerged during thaw. Comparative analyses of net GHG footprint of livestock systems often assume waste application rates consistent with NRCS nutrient management criteria, which the farmers utilizing the waste often exceed; as a result, GHG emissions from larger confinement operations are often underestimated.

In contrast, grass-based livestock production with best MIG practices adapted to region, climate, and condition of pasture and range:

- Distribute manure evenly on the land
- Avoid overloading nutrients through appropriate stocking rates and sufficient recovery periods
- Encourage populations of dung beetles and other beneficial soil organisms that enhance nutrient cycling (Weil and Brady, 2017)
- Use little or no synthetic N or other agrichemical inputs
- Eliminate or minimize the need for manure storage facilities
- Maximize SOC sequestration
- Provide opportunities to integrate crop and livestock production for enhanced nutrient cycling and uptake efficiency

For example, North Dakota rancher Gabe Brown restored 5,000 acres of depleted dryland through MIG practices adapted to the cold, dry (16 inches/year) climate, and integration of livestock grazing with cropland managed according to the four NRCS principles of soil health to produce grains and forages for the region's long winter. Over a 20-year period, topsoil SOC levels were restored from 1 percent to 3.5 percent, approaching the region's native SOC levels of 4 percent (Brown, 2018). Applying this SOC increment just to the top 8 inches of the soil profile works out to sequestration of 125,000 tons of C on this ranch alone.

Introducing trees into management intensive grazing systems (silvopasture) may enable even higher levels of carbon sequestration without decreasing total livestock productivity. Increased water infiltration and nitrogen use efficiency, mineral fertilization from deep rooted trees, and summer shade for animals are among the reasons silvopastoral systems can outperform treeless pastures. Though long-term data from the U.S. is lacking, the practice has been used in tropical/subtropical regions of northeastern Australia and in areas of Western Australia with a temperate climate. Growing *Leucaena leucocephala* in rows in C4 grassland in subtropical regions increased SOC by 17 to 30 percent over 40 years (sequestration rate of 250 lb C/ac-yr) (Conrad et al., 2018). Shorter term studies from other regions support the potential of silvopastoral systems for sustainably increasing SOC in Nicaragua (Hoosbeek et al., 2018) and Alberta (Baah-Achearnfour et al., 2014).

Climate change could make livestock production more challenging in some regions due to increased heat stress, lower quality feed, water shortages and migration of disease and insects to new areas (Gowda et al., 2018" – Reidmiller). Sustainable production systems that reduce the overall stress on livestock, such as grass-based rotational grazing systems that maintain high quality forage, could help livestock deal with stresses brought on through climate change. Animals that can engage in natural behaviors outside as opposed to being crowded together indoors tend to be healthier and need fewer antibiotics, which reduces the rate of antibiotic resistance in food-borne bacteria (Clancy, 2006a, 2006b). In addition to reducing the GHG footprint of the operation, well-managed MIG systems build soil fertility and protect soil, air, and water quality. All these benefits working together will increase the resilience of livestock production systems in the face of rapid global climate change.

E. Composting, Organic Residue Recycling, Biochar, and Other Organic Amendments

Two central principles of ecological agriculture since the beginning of the organic movement have been to return manure and other organic residues to the land, and to compost them first to stabilize nutrients and enhance their benefits to soil life, tilth, and fertility (Howard, 1947). Returning on-farm generated manure, plant residues, and processing byproducts (e.g., cotton gin waste, apple pomace, dairy or soy whey) to the land conserves organic carbon and recycles nutrients, thereby reducing fertilizer needs. Composting nitrogenous materials with high carbon materials and managing windrows to optimize temperature, moisture, and aeration can reduce GHG emissions and stabilize nutrients, and the finished product can provide slow-release N to crops for several years (Lynch et al., 2006). Crop-livestock integrated systems provide on-farm manure for making compost, facilitate within-farm nutrient cycling, enhance SOC sequestration through perennial forage crops in the rotation, and therefore have been recommended to maximize net GHG mitigation in organic systems (Gattinger et al., 2012).

In addition to stabilized N, finished compost delivers stable organic C estimated in one study at 222 lb per ton of compost (Carpenter-Boggs et al., 2016), making contributions to SOC that can persist for centuries (McLaughlan, 2006). The percent of applied organic C retained as stable SOC is generally greatest for finished compost, followed by solid manure and uncomposted plant residues, while liquid manure (slurry) or liquid biogas digestate build little or no SOC (Cogger et al., 2013; Hurisso et al., 2016; Sadeghpour et al., 2016; Wuest and Reardon, 2016).

In Washington State, organic vegetable rotations were amended with compost (dairy manure, bedding, and yard waste) at ~7 tons/ac annually or with poultry litter at 2.2 ton/ac annually (same total N content). After 11 years, the compost amended soil had 43 percent more total SOC and 60 percent more permanganate-oxidizable organic C (indicator of SOC stabilization) than soil receiving poultry litter (Bhowmik et al., 2017). Many studies have shown that organic inputs with very low carbon-to-nitrogen (C:N) ratios (e.g., poultry litter, 7:1) or very high C:N (e.g., grain residues > 35:1) build less stable SOC than those with moderate ratios (composted manure and bedding, or legume-grass cover crops, ~20:1) (Baas et al., 2015; Cates et al., 2015; Cogger et al., 2013; Grandy and Kallenbach, 2015; Reeve and Creech, 2015).

Compost and living plant roots appear to play different and complementary roles in building stable SOC. A meta-analysis of 13 studies including 76 individual sites showed that compost applications promote SOC stabilization while cover crops, especially succulent (low C:N) green manures may promote SOC mineralization (breakdown) (Hurisso et al., 2016). Several studies indicate that cover crops plus compost can build more SOC than either alone (Delate et al., 2015b; Hooks et al., 2015; Hurisso et al., 2016).

Three concerns have been raised regarding compost use:

- Compost is rich in phosphorus (P) and can build excess soil P if used heavily to meet crop N or soil organic C needs. Excess soil P inhibits the mycorrhizal fungi that play important roles in SOC stabilization, soil aggregate development, and nutrient cycling; P surpluses can also pollute surface waters.
- SOC gains from an application of compost or other organic amendments from off-farm sources do not represent C sequestration, only C import from other acreages.
- The composting process can emit significant amounts of N_2O and/or CH_4, depending on how well the starting mix, aeration, and moisture levels are managed.

Regarding GHG emissions, production of one ton of compost containing 222 lb stable organic C was estimated to generate N_2O and/or CH_4 emissions equivalent to a loss of 110 lb SOC as CO_2 (Carpenter-Boggs et al., 2016). However, when organic materials are diverted from manure lagoons or landfills (e.g., food waste, yard waste, municipal leaves) to make compost for agricultural use, the GHG emissions from the composting process and materials transport are far outweighed by the avoided CH_4 emissions from anaerobic decomposition in lagoons and landfills, and the enhanced plant growth and SOC accrual on treated acreage (DeLonge et al., 2013). Careful management of compost windrows can further reduce GHG emissions (Brown et al., 2008).

What about biochar?

Biochar, or "black carbon," is a soil amendment created by pyrolysis (intense heating with low oxygen supply) of organic residues (e.g., chipped brush, wood waste, crop residues, manure), which can stabilize SOC, especially if the char is aged a few years before application (Blanco-Canqui, 2017; Mia et al., 2017). The biochar method is based on observations that about half of the stable SOC in fertile prairie soils (Mollisols) is derived from "black carbon" formed in periodic prairie fires, and that indigenous human communities in the Amazon Basin built anomalously fertile "terra preta" soils by amending the native, low-SOC Oxisols with a mixture of cooking fire charcoal, manure, and other organic residues (Kittredge, 2015; Schahczenski, 2018; Wilson, 2014).

Concerns with the biochar "fad" include the GHG emissions from pyrolysis and the "harvest" of existing plant biomass as feedstock (similar to concerns with biofuels), and even "land grabs" by biochar enterprises in developing countries (North, 2015). However, biochar based on manure or other organic residues that would otherwise be headed for "waste" disposal, or on carefully managed harvests from perennial plantings can be sustainable. In a recent analysis of "technical potential" for global agricultural C sequestration, about 14.5 percent of the projected 156 ppm reduction in atmospheric CO_2 by the year 2100 was attributed to implementation of biochar technology (Lal et al., 2018).

Regarding organic materials imports from off-farm sources, the removal of manure, hay, crop residues, and other plant biomass from off-farm sites to amend a farm's fields withdraws organic C from the "donor" acreage, with no net gain to the world's SOC pool. "Baling off" residues of annual cash or cover crops can cause erosion and destroy some SOC, while careful grazing of residues does much less damage (Blanco-Canqui et al., 2016a, 2016b). However, composting – and land-applying all organic residues that would otherwise be disposed as "waste" – is an important societal strategy for climate mitigation and adaptation/resilience in the agriculture and food system. For example, EPA estimates that the U.S. landfills some 24 million tons of dry tree leaves every autumn – a material that makes a valuable amendment for micronutrients and beneficial soil fungi (Panicker, 2017).

Regarding excess P from heavy applications of organic nutrient sources, a little compost or manure goes a long way. For example, an organic corn-soy-wheat rotation that included alfalfa or vetch cover crops and received 0.7 to 1.3 tons/ac-year poultry litter accrued about 400 lb SOC/ac more than conventional continuous no-till corn-soy, and the 0.7 ton rate did not build up P (Cavigelli et al., 2013). In Utah, a single heavy application of manure-bedding compost (22 tons dry weight per acre, ~38 percent C, C:N ~20) in 1995 doubled dryland wheat yields for 15 years. In 2008, SOC in the top four inches of soil was 1.3 to 1.5 percent compared to 0.6 to 0.7 percent in an untreated control (Reeve and Creech, 2015). In California, a single application of "composted green waste" (total N 225 lb/ac) to rangeland enhanced forage growth and increased "ecosystem C storage" by 25 to 70 percent three years after application, an increment that significantly exceeded the C content of the compost itself (Ryals and Silver, 2012).

F. Reducing agricultural GHGs through reduced inputs, energy conservation, and increased energy efficiency.

Initially, much attention was focused on reducing agricultural GHG footprints through energy conservation, reduced fossil fuel consumption, and avoided or minimal use of N fertilizers and other synthetic agrochemicals. Each year, U.S. agriculture uses at least 40 to 46 billion pounds of synthetic fertilizer and one billion pounds of synthetic pesticides, herbicides, and other crop protection chemicals, all of which consume fossil fuel in their manufacture, transport, and field application (ERS, 2019; EPA, 2017). Mechanized tillage, planting, and harvest operations also burn fossil fuels. Yet, when these CO_2 emissions are included in an analysis of U.S. direct agricultural GHG, they account for only about one-sixth of the total (Figure 7).

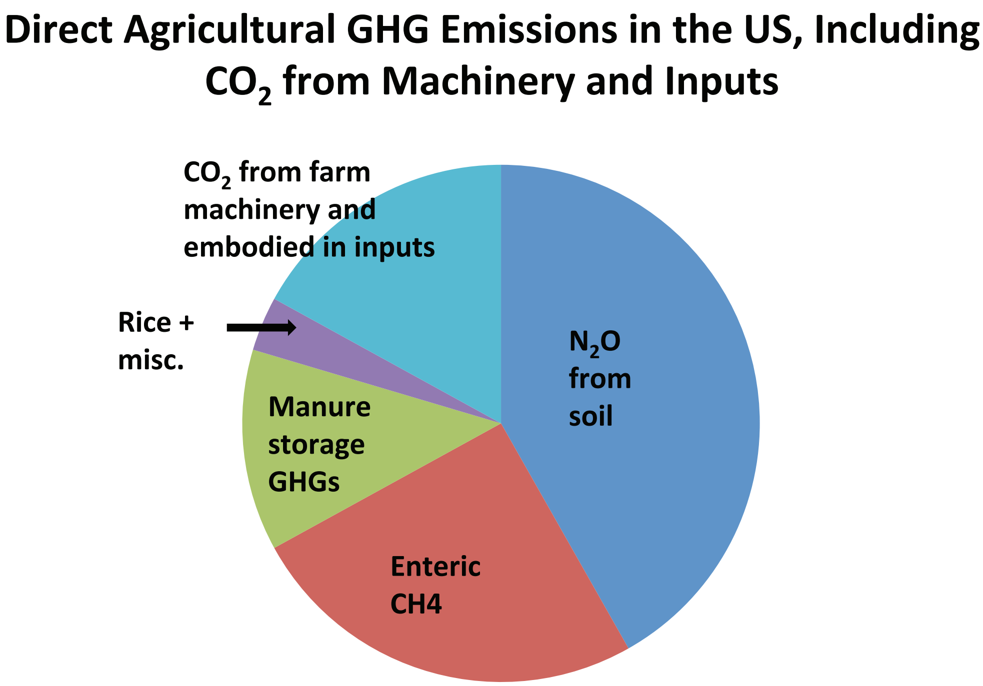

Figure 7. Direct Agricultural GHG Emissions in the U.S.

Figure 7. *When CO_2 emissions from fossil fuel consumption in field operations and manufacture of N fertilizer and other inputs are included, they comprise only 17 percent of the total direct agricultural GHG emissions in the United States (based on Carpenter-Boggs et al., 2016).*

Organic production systems reduce their carbon footprints by eliminating synthetic inputs, although tillage and cultivation for cover crop, residue, and weed management add some direct CO_2 emissions. In the Rodale farming systems trials, organic systems achieved a net 29 percent reduction in energy use by deriving N from legumes and manure in lieu of synthetic fertilizers (Rodale, 2011).

The immediate priority of any sustainable energy policy is to increase conservation and energy efficiency. Reducing unnecessary use of energy is common sense, saves money, and benefits the environment. Likewise, numerous studies have shown that improving the efficiency with which energy is used is the cheapest and quickest energy "source." Agricultural policy should support producers in energy conservation measures and on-farm fuel efficiency, not only for GHG mitigation, but also to reduce direct costs and risks of production, including the increasing spikes and volatility in the costs of synthetic fertilizer (Huang et al., 2009).

G. Water Management

Agricultural water management can significantly influence both carbon and nitrogen cycling in soils, and thereby net a GHG footprint. Soil moisture and aeration levels that favor aerobic microbial activity (~ 50 percent of pore space water filled and 50 percent air filled – near or slightly below field capacity) can promote microbial conversion of residues into stable SOC and avoid their degradation into CH_4. Ecological agriculture generally improves the soil's capacity to absorb and retain rainfall, drain promptly after heavy rain or irrigation to restore aerobic soil conditions and reduce flood impacts, hold plant-available moisture to tide crops over dry spells, and to allow and encourage deep, extensive root development which builds SOC and absorbs excess soluble N (Manela, 2007; Rawls et al., 2003). These attributes of soil health promote crop vigor and resilience to weather stresses and shorten the periods of excessive soil moisture that can lead to spikes in N_2O emissions.

In contrast, practices such as liquid manure spraying can lead to saturation of the land, which in turn can produce CH_4 or N_2O from the waste, depending on the degree of oxygen deficit. Similarly, irrigation can temporarily saturate soils, especially in furrows between plastic-mulched crop beds or grow zones, leading to GHG emissions. Farmers can mitigate this GHG source by increasing the efficiency of pumping, conveyance, and application, and by avoiding irrigation in excess of crop needs. Irrigation efficiency and solar or wind powered pumps also reduce CO_2 emissions.

In flooded fields such as rice paddies, organic matter is degraded into CH_4 and emissions have been estimated at 110 lb C/season, equivalent in climate impact to a loss of 1,120 lb SOC in the form of CO_2 (Dou et al., 2016). Rice paddy CH_4 accounts for only about 2 percent of U.S. direct agricultural GHG emissions, but it accounts for 10 percent worldwide, owing to the much larger acreages of rice grown in Asia, where rice is the leading staple grain in human diets (IPCC, 2014a). Any policies related to rice production, however, must consider that flooded rice fields provide other valuable ecosystem services (e.g., habitat for waterfowl). Flooded rice fields are recognized globally as an important surrogate wetland habitat for millions of waterbirds (Eadie et al., 2008; Elphick, 2000). Rice farmers can reduce CH_4 emissions without reducing the value of rice fields for waterbirds (Sesser et al., 2016). The following three techniques reduce the time the rice fields are flooded and hence reduce GHG emissions. Growers can 1) drill or broadcast seeds into a dry or moist seedbed, instead of seeding into a flooded field; 2) drain standing water earlier during the rice growing season in preparation for harvest; and 3) cyclically wet and dry the rice fields during the growing season instead of continuous flooding (EDF, 2011; California EPA Air Resources Board, 2015). The latter practice requires caution when sensitive species are relying on the rice fields during the breeding season.

Weather extremes, including local drought and flooding, are predicted to become more common with climate change. Environmentally responsible water management combined with soil health practices that build moisture holding capacity and maintain good drainage can enhance agricultural resilience and reduce net GHG footprints. At the watershed level, ecological farming practices can be complemented with water management strategies that capture stormwater, recharge groundwater, improve water quality, store carbon, and protect local habitat (SARE, 2006). Groundwater and surface water need to be managed with a "whole system" approach that protects instream flows, terrestrial habitats and prevents groundwater overdraft. Reusing highly treated wastewater can help meet water needs without depleting current water sources. Additional ecological agriculture strategies for conserving water include converting cropland to managed grassland or riparian forest buffers in riparian areas, constructing and restoring wetlands, measuring and conserving irrigation water, creating conservation easements, choosing water-efficient crops and resource-conserving crop rotations, and limiting the impact of nitrogen and pesticide runoff from farms into local water supplies.

Another way that water management in agriculture can impact the climate is through artificial drainage of naturally wet soils, which usually accelerates the oxidation of these soils' large reserves of SOC, resulting in a net emission of CO_2 even under the best rotation and ecological practices. Peat and muck soils (Histosols), permafrost soils (Gelisols) and any wetland areas are especially subject to massive SOC losses when drained for cultivation (Weil and Brady, 2017). Preservation of wetland, peat bogs, and permafrost soils will play an important role in societal efforts to curb net GHG emissions and slow climate change.

A summary of research findings on agroecosystem mitigation of climate change are presented in the introduction to the Recommendations section, starting on **page 37**.

IV. AGRICULTURE, ENERGY AND CLIMATE CHANGE

Agriculture has a major role in producing and using energy in ways that mitigate climate change. Powering America's farms with low carbon renewable energy rather than fossil fuels can increase the control of farmers and ranchers over their energy sources, reduce costs, and combat climate change. The production and use of agriculture-based biofuels must be accompanied by careful consideration of environmental and social responsibility as well as a rigorous and comprehensive assessment of the GHG emissions from the production of bio-based energy.

A. Low-Carbon Energy: Solar and Wind

Low-carbon alternatives to fossil fuels include wind (to generate electricity or power pumps) and solar (to generate electricity and heat water or buildings). On-farm energy production eliminates the need to run electric lines or pipelines to remote locations. It also allows farmers to decrease their reliance on increasingly expensive fossil fuels, produce energy from low-carbon sources with fewer GHG emissions, develop new value-added revenue sources, reduce on-farm costs, and complement organic and sustainable farming practices. The National Sustainable Agriculture Information Service (ATTRA) provides extensive resources on renewable energy options for farms and ranches (ATTRA, 2006).

Solar energy, including the use of photovoltaic cells to convert sunlight into electricity, can be used on farms and ranches to meet or supplement numerous energy needs (USDOE, 2019). Solar air and space heaters can reduce energy costs for livestock and dairy operations that require careful temperature control. Solar water heating can provide water for pen cleaning. Farmers can also use solar energy directly to heat, as well as light, greenhouses. Solar electric or photovoltaic systems can power general electricity needs including fencing, lighting, water pumping, and crop drying.

Farmers and ranchers who own unoccupied land and live in an area with good wind resources may consider harnessing wind energy to meet their energy needs in a cost-effective and environmentally responsible way. Wind turbines convert the kinetic energy in wind to mechanical energy, which can then be used to generate electricity or pump water for irrigation or livestock. Farmers and ranchers who live in a state with net metering programs may be able to sell excess energy back to their utility providers. Various guidebooks are available to help farmers and ranchers decide whether wind energy is feasible for their operations (U.S. DOE, n.d.; Ontario, n.d.).

While sunlight and wind are themselves carbon-free, the components and facilities that produce them must be manufactured, built, and maintained. At the end of their lives, plants must be retired or replaced, and their components disposed of or recycled. These processes produce GHGs equivalents. Numerous life cycle analyses (LCA) of GHG production per kilowatt hour (kWh) have been conducted. A metastudy of these LCAs indicates that wind energy emits an average of 34.11 grams of CO_2 per kWh over its lifetime, while solar energy systems emit an average of 49.91 grams of CO_2 per kWh (Nugent and Sovacool, 2014). These figures compare to 66 grams per kWh for nuclear energy (Sovacool, 2008) and 1,001 grams per kWh and 429 grams CO_2 per kWh for coal and natural gas, respectively (U.S. DOE, 2016).

Higher capacity wind turbines, both with taller hub heights and larger rotor diameters, generate lower GHG emissions, whereas there is little change on GHG emissions for larger solar installations since solar panels are modular and have the same efficiency at all sizes. The source of equipment is also critical to LCA GHG emissions. For example, "[t]he same manufacturing process in Germany would result in less than half of the total emissions that such a process would entail in China. This was primarily due to China's significantly greater dependence on black coal for electricity production in comparison with Germany's much greater reliance on natural gas and nuclear power" (Nugent and Sovacool, 2015).

Currently, large-scale solar panel installations are sometimes being installed on prime farmland, key wildlife habitat, and other healthy soil-plant ecosystems that presently sequester carbon and perform other vital functions.[4] Thoughtful integration of solar collectors into a diverse farm landscape can maximize benefits and avoid or minimize costs to productivity and other ecosystem services.

B. Energy from Agricultural Biomass

Agricultural biomass is being targeted as a "second generation" agricultural source for bioenergy, following on the heels of corn starch-based ethanol. Much of the biomass being targeted is crop residues. The eminent soil scientist Rattan Lal, however, has raised concerns about this use of crop residues when he observed:

> *"This is a dangerous trend because crop residue is not a waste. It is a precious commodity and essential to preserving soil quality. In addition to controlling erosion and conserving soil water in the root zone, retaining crop residues on the soil is also necessary for recycling nutrients, improving activity and species diversity of soil micro- and macro-fauna, maintaining soil structure and tilth, reducing nonpoint source pollution and decreasing the risks of hypoxia in the coastal regions, increasing use efficiency of fertilizers and other inputs, sustaining biomass/agronomic yield, and improving/maintaining soil organic matter content… In view of its numerous environmental and agronomic benefits, there is a strong justification for adopting the slogan "grains for people, residues for the soil." This equity is essential to maintaining soil quality at a level at which it can provide all ecosystem services and functions essential to sustainable use of soils for generations to come. Use of biofuels could substantially reduce gaseous emissions, provided that appropriate sources of feedstock are identified, especially those which do not degrade soil and environment quality"* (Lal, 2007).

Groundbreaking research by a team of USDA Agricultural Research Service (ARS) scientists led by Wally Wilhelm, a scientist with the Agroecosystems Management Research Unit in Nebraska, indicated that the corn stover needed to replenish soil organic matter was greater than that required to control either water or wind erosion in the ten counties investigated (including nine of the top corn producing states in the U.S.) (Wilhelm et al., 2007). Another early study examined the impacts of corn stover removal over a 4-year period from sites with different soils in Ohio. The study showed that removal above 25 percent of the stover resulted in adverse impacts on soil quality. In addition, this and other studies indicate that removal of the corn stover has the most adverse impacts on sloping or erosion prone soils (Blanco-Canqui and Lal, 2009). A recent review of stover harvest literature suggests that 40 percent removal by mass (i.e., 60 percent remaining in the field) was an upper limit for maintaining SOC and preventing erosion. This five-year study concluded that long-term studies are needed to ensure that corn stover removal at even the 40 percent level is not detrimental to soil health (Obrycki et al., 2018).

This research calls into question the assumptions underlying estimates of biomass available in the U.S. for biomass-based energy production such as Perlack's billion ton annual-supply study (Perlack et al., 2005). Since removal of corn stover impacts soil erosion and soil health, less conventional perennial crops may provide a potentially more sustainable supply of cellulosic feedstock without reducing soil organic matter and undermining the productive capacity of the soil.

[4] See **http://www.nexteraenergyresources.com/locations-map.html**

C. Agricultural Bioenergy Crops

1. GHG Emission Life Cycle Analysis

A primary objective of U.S. public policy that supports the production of biofuels using agricultural resources is to reduce global GHG emissions. The reasoning is that biofuels are derived from plant-based carbon, which is drawn from atmospheric CO_2 during photosynthesis. When biofuel is combusted, the CO_2 released back into the atmosphere was originally fixed by the plant.

There is significant controversy, however, regarding this alleged "carbon neutrality" of bioenergy – particularly when derived from oilseeds (biodiesel), feed corn starch (ethanol) or even from some cellulosic sources. The controversy focuses on which factors should be included in the LCA for bioenergy, with much attention on the issue of indirect land conversion. If large amounts of agricultural land are used for bioenergy production, the pressure increases to convert other land in grasslands or forests to agricultural food production. When land is broken for cultivation, a large amount of soil and plant biomass carbon is released. The released CO_2 could exceed the amount of net GHG emission reductions, relative to fossil fuel production and use, from the system for production of bioenergy feedstock.

GHG increases from land conversion cannot be limited to a local assessment because rapid climate change is a global phenomenon (Searchinger, 2008). The determination of bioenergy GHG emissions requires careful LCA of the biofuel under consideration, including analysis of global land use change implications of establishing the specific biofuel feedstock (Sanderson and Adler, 2008). Lifecycle GHG emission analysis should also include GHG emissions from synthetic fertilizer and pesticides and other inputs used to produce bioenergy feedstocks. One study indicates that soil organic C storage does not offset fertilizer-induced N_2O flux in established biofuel feedstock grasses and no C storage occurs in corn-soybean rotation. The most comprehensive LCA GHG analysis of biofuel sources estimates that total lifecycle GHG emissions (g CO_2eq MJ–1, 100 cm) are 59 to 66 for corn ethanol, 14 for stover ethanol, 18 to 26 for switchgrass ethanol, and –7 to –0.6 for *Miscanthus* ethanol. The GHG emissions associated with poplar- and willow-derived ethanol may be higher than that for switchgrass ethanol due to lower biomass yield (Qin et al., 2016). In short, this research indicates that only ethanol from *Miscanthus* biomass sequesters more carbon in the soil than its manufacture produces. However, high levels of water usage by the non-native *Miscanthus* can result in water shortages downstream (McAlmont et al., 2017).

Agricultural bioenergy production could have some advantages. Establishment and maintenance of a perennial crop such as switchgrass or *Miscanthus* can be far less capital intensive and require less synthetic fertilizer and pesticides than corn. An annual biofuel crop could improve the conservation performance of an annual crop production system. A prime example is camelina, an oil crop that yields about twice the amount of oil as soy and is tolerant of cold and drought. Camelina has been grown for years in Montana and several land-grant colleges around the country have conducted research and field trials on camelina. It can be incorporated into Northern Plains wheat-fallow rotations, can help break up pest cycles and increase wheat productivity, with an overall reduction in pesticide use in the crop rotation system. A camelina-wheat rotation results in much higher biomass production and return of crop residues to soil than the wheat-fallow system (Chen et al., 2015). Mediterranean climates where low rainfall prevents the use of many crops in rotation, camelina appears to reduce weed infestations when used in rotations as either a winter or summer crop (Royo-Esnal and Valencia-Gredilla, 2018).

The LCA GHG performance of these systems can be improved even more if they are established on degraded or abandoned agricultural land, which can result in a significant increase in soil carbon sequestration (Tilman et al., 2006). Perennial grain crop production also shows potential for high levels of carbon sequestration and high levels of LCA GHG performance, though little public research has been supported in the U.S. A perennial rice variety released in China is reportedly planted on thousands of hectares and has yields comparable, if not higher, than local varieties (Huang et al., 2018; Haspel, 2019). Compared to annual varieties, relative LCA GHG performance, especially CH_4 production, is in progress.

2. Other Environmental Considerations

Even if a biofuel feedstock results in a net reduction of GHG emissions relative to the use of fossil fuels, there are other important questions about the effects of its establishment on the environment. In recent biofuel LCAs by EPA, both corn ethanol and soybean biodiesel production were found to result in net GHG emissions increases. Most of these production systems did have lower net GHG emissions than the gasoline and diesel they replaced (EPA, 2009). There are, however, important environmental and social questions about further expansion of corn monocultures or simple corn-soybean rotations. Over the long-term, mixtures of native perennial grasses and other flowering plants could provide more usable energy per acre and are far better environmentally than corn, soybeans, and other row crops. In addition, replacing some corn and soybean production with native perennial grasses could address current overproduction issues and work to decrease the price volatility of commodities.

Analysis of ecological impacts of bioenergy projects should not be limited to the field level but should also include changes to landscape diversity and potential impact on primary and secondary habitat (Firbank, 2008). An example of such analysis is research on the expansion of corn acreage in the upper Midwest fueled by the recent corn ethanol boom. Douglas Landis and colleagues (2008) studying the impacts in upper Midwest corn states found that the lower landscape diversity lowered the supply of natural enemies of the soybean aphid. Farmers who relied on integrated pest management strategies to control the aphid lost an estimated $239 million per year in ecosystem services across a four-state region (Landis et al., 2008). As a result, pesticide use increased as did GHG emissions associated with pesticide production, distribution, and application. These landscape level changes can have profound effects on overall GHG emissions, the surrounding ecosystems, and farmer income.

Another issue is the potential for bioenergy crops to become invasive. Several crops targeted for development as bioenergy sources are novel grasses and trees with invasive characteristics including rapid growth, ability to propagate vegetatively, prolific seed production, few pests and diseases, and ability to tolerate water stress and low fertilization levels. While these vigorous crops can sequester a lot of carbon, they often displace native vegetation by over-exploiting moisture reserves throughout the soil profile, adversely affecting indigenous soil microbiota including mycorrhizal symbionts of native forest or prairie plant species, or both (Wolfe and Klironomos, 2005).

Moreover, genetic engineering of many of these bioenergy candidate species is underway to increase these invasive traits. Genetically modified crops are subject to limited environmental assessment before their introduction, but there are currently no requirements to assess the environmental risks of a wide-scale introduction of bioenergy plants that have not been genetically modified unless the plant is already listed as a noxious weed (Tomasino et al., 2007). Finally, the new techniques of gene-edited agricultural crops have so-far escaped any regulatory review, because of the mistaken view that these techniques are very similar to classical breeding and are more "precise" in developing the specific traits (e.g., drought resistance) without impacting other traits. This assumption has recently been disproven, and the potential for human risks and ecological damage from gene-editing is not properly assessed (Kosicki et al., 2018).

3. Social Considerations

The mix of crops and livestock produced on agricultural land can also have profound effects on the structure of the social landscape, including the scale of farm operations and opportunities for entry into farming and the diversity and quality of employment in rural areas. These are critical issues that should not be ignored in any policy choices about which crops and systems receive public subsidies or other public incentives, including incentives for biofuel production. When scarce farmland is used for bioenergy instead of food production or the many other valuable functions of rural land, the impact on local human and biological communities can be damaging (Popp et al., 2014).

A comprehensive study in Minnesota evaluated possible effects on various factors in two Minnesota watersheds that could arise from changes in farming systems, from the increased adoption of minimum tillage to the reestablishment of perennial plants and wetlands (Boody et al., 2005). Projected outcomes included both environmental outcomes, including GHG emissions and carbon sequestration, as well as net farm income outcomes, including opportunities for beginning farmers and increases in social capital and interconnections within the communities in the watersheds. Overall, the study indicates that more diverse farming systems with increased use of perennials and a broader base of crops and sustainable livestock systems could result in increased social benefits to rural communities. This includes more farming opportunities, a more diverse income base and an increase in social networks within the communities. Such multifunctional agricultural systems have been prioritized in the European Union's Common Agricultural Policy (CAP). Multifunctionality in CAP stresses enhancement of the interrelationships between agriculture production, landscape protection and social services (Conto et al., 2013). These social considerations may be especially vulnerable to policies that are intended to stimulate bioenergy production.

NATIONAL SUSTAINABLE AGRICULTURE COALITION POLICY RECOMMENDATIONS

The agroecological farming systems described in this position paper can and must play an important role in addressing climate change. These systems have been proven to help farmers and ranchers reduce greenhouse gas (GHG) emissions and increase storage of carbon in agricultural soils. These systems can also increase the resilience of farming and ranching operations as unpredictable weather aberrations associated with climate change intensify. They are also the best systems for minimizing other conservation and environmental impacts from agricultural production.

This paper has reviewed the latest research showing how these systems can best reduce and mitigate GHGs and the impacts of climate disruption. Following we present specific recommendations based on fourteen conclusions that emerged from this research.

RESEARCH-BASED FINDINGS FOR ADDRESSING CLIMATE CHANGE ADAPTATION AND MITIGATION IN AGRICULTURAL SYSTEMS

1. **Enhancing Soil Health** – Improved soil health practices build soil organic carbon (SOC), and thus contribute to climate mitigation by removing carbon dioxide (CO_2) from the atmosphere, and to climate adaptation by making soils, crops, and agro-ecosystems more resilient to weather extremes through increased water infiltration, drought tolerance, and yields.
2. **Supporting Biodiversity** – Increased diversity of crops and cropping systems can enhance SOC sequestration, as well as the ecological and economic resilience of farms and ranches to climate change. Diverse ecological agricultural systems help conserve and protect water resources, support natural enemy insects and birds, control soil erosion, and provide other conservation benefits in addition to climate mitigation and adaptation.
3. **Whole Farm Systems** – Ecological farming systems (such as well-designed organic production systems that integrate diversified crop rotations, year-round soil coverage, organic residue return, reduced soil disturbance and agroforestry) sequester more carbon than single practices such as cover cropping or no-till.
4. **Soil, Nutrient, and Water Management** – Additional research is urgently needed to identify soil, nutrient, and water management strategies to mitigate nitrous oxide (N_2O) emissions, especially for ecological farming systems that emphasize biologically-based soil management. Soils emit N_2O when sufficient nitrate-nitrogen (more than 6 ppm), decomposable organic carbon (C), and microbial activity coincide with high moisture levels and limited oxygen. Soil N_2O emissions comprise 49 percent of direct agricultural GHG and can arise from synthetic or organic nitrogen (N) sources. One promising lead is tightly coupled nutrient cycling, in which soil biota, crops, and inputs are co-managed so that crops obtain sufficient N from soils low in soluble N.
5. **Biomass Potential** – Breaking sod or clearing forest for crop production destroys much soil and biomass organic C. Converting cropland to permanent pasture can sequester 800 lb SOC/ac-year. Reforestation, agroforestry, and woody perennial buffer plantings accrue more than one ton of soil and biomass C/ac-year.
6. **Changing Pest Pressures** – Conserving and re-establishing woody habitat that sequesters carbon will also support natural enemy insects and birds that will help with pest control as new challenges arise because of changing pest phenologies brought on by climate change.
7. **Benefits of Perennials** – While the best soil health management on the world's cropland could yield a net reduction of 22 ppm in atmospheric CO_2 levels by the year 2100, reforestation and perennialization of disused, depleted, or ecologically sensitive lands increase the potential reduction to 156 ppm.
8. **Reduced Livestock-related GHG Emissions** – Cattle and other ruminant livestock emit enteric methane (CH_4) whether raised on pasture or in confinement. However, management-intensive rotational grazing systems (MIG) shrink the GHG footprint of livestock production by eliminating manure storage facilities, improving forage quality (30 percent reduction in enteric CH_4), and sequestering at least one ton of SOC/ac-year in grazing lands.

9. **Livestock Life Cycle Analysis** – The preponderance of evidence indicates concentrated animal feeding operation-based (CAFO) systems produce vastly more GHGs than well managed grazing systems. However, since some authors have used data on livestock-related GHGs to justify CAFOs, others to advocate for pasture-based systems, and still others to condemn all livestock production and meat consumption, unbiased life cycle analyses (LCA) of comparing MIG and other livestock systems are urgently needed.
10. **Compost and Biochar** – Appropriate use of compost or biochar can enhance SOC sequestration. The composting process emits some GHG but diverting materials from landfills and manure lagoons into well-managed compost operations reduces the GHG impact several-fold.
11. **Crop Residues and Native Vegetation** – Removal of hay, crop residues, or native vegetation biomass to make compost, biochar, other organic amendments, or biofuels can deplete soils on the "donor" acreages and thus fail to yield net C sequestration or climate mitigation. Similarly, biofuel crops require a thorough and impartial LCA to determine their net GHG impacts.
12. **Energy Emissions** – CO_2 emissions from field operations and manufacture of N fertilizer and other agricultural inputs add about 17 percent to direct U.S. agricultural GHG emissions. Farmers can reduce energy-related GHG by using biological sources of N, reducing tillage, and producing on-farm solar or wind power.
13. **Breeding for Resilience** – Developing new public crop cultivars and livestock breeds for increased input efficiency, wide adaptability, performance under organic and sustainable management, and genetic diversity results in more resilient agricultural systems.
14. **Impact of Flooding** – Flooded soils emit CH_4 and N_2O. Best soil health management practices mitigate water-related GHG emissions by promoting prompt drainage, enhancing crop drought resilience, and reducing irrigation needs. In contrast GHG emissions are increased by anaerobic conditions created by excess application of liquid manures, winter fallow in Mediterranean climates with heavy winter rainfall, or in flooded fields such as rice paddies.

POLICY RECOMMENDATIONS BASED ON RESEARCH FINDINGS

No matter what role U.S. agriculture is called on to play in federal climate change legislation or international climate change frameworks, farming systems based on these findings and relevant ongoing research provide the best long-term approach to dealing with climate change, the best future for our nation's farmers, ranchers and rural communities, and the best overall food and farming system for people.

The recommendations below are based primarily on current Farm Bill authorities and existing U.S. Department of Agriculture (USDA) policies and programs. The National Sustainable Agriculture Coalition (NSAC) intends to issue further recommendations at a later date that are more specific to support a robust climate and agriculture section of the comprehensive climate bill we hope Congress will pass during its 2021-2022 session.

The 2018 Farm Bill provides authority to the USDA to implement policies that recognize the benefits of climate-friendly agriculture systems for our nation's farmers, ranchers, rural communities and the environment in dealing with climate change. Many of our research-based policy recommendations below relate to the implementation and administration of existing conservation, research, outreach, risk management, and other programs under the current Farm Bill, while others would require additional farm bill or appropriations funding or other legislative changes.

Future legislation, including both the 2023 Farm Bill and comprehensive federal climate change legislation, might change USDA authorities and resources, and that of other federal agencies, in a way that will impact – hopefully improve – our ability to address climate disruption. As federal climate change authority develops, widespread adoption of science-based climate-friendly production systems must be recognized as fundamental to addressing agricultural and food security concerns related to climate change. Some of our overarching recommendations below aim to inform policy advocacy responses to future legislative and budgetary opportunities as they unfold.

PRIORITY AREA 1:

Support producers to make U.S. agriculture climate-neutral

These recommendations are based on research findings 1, 2, 4 and 13

1.1 Establish a national goal for increasing carbon stored in U.S. soils at rates that surpass the internationally proposed 0.4 percent growth per year in global soil carbon required to make global agriculture climate neutral (Kon Kam King et al., 2018).

USDA has made erosion reduction, healthy soils and improved water quality national priorities. That is reflected throughout USDA conservation, farming research, and rural development programs. Increasing carbon stored in our soils is facilitated by preventing erosion, which facilitates healthy soils and improved water quality. By making carbon sequestration a national priority, USDA should logically focus a significant portion of conservation, energy, research, and rural development program spending on systems and practices that will address these important issues through funding allocation, ranking, support services, financial assistance, and other policies throughout its suite of programs.

The recommendations in subsequent sections will help increase rates of carbon sequestration in U.S. working lands. However, overarching research initiatives are required to support these recommendations and design new systems for stable sequestration of carbon.

1.2 Establish a Monitoring, Evaluation, and Reporting (MER) system to provide USDA with the tools necessary to collect, report on, and utilize data regarding the impact of conservation programs on soil health, carbon sequestration, greenhouse gas (GHG) emission reductions, and other climate change mitigation metrics.

Measurement, evaluation, and reporting requirements on conservation outcomes are needed for all conservation programs and initiatives, including a description of all the many approaches, methods, and metrics the agency is developing or already has in place. This information is necessary in order to define, evaluate, and communicate outcomes specifically related to the potential of USDA conservation programs to help farmers mitigate impacts of climate change.

While USDA currently is able to measure conservation effects on a national, regional, and landscape scale through the Conservation Effects Assessment Program (CEAP), CEAP is not able to assess the effects of individual USDA conservation programs and initiatives. Furthermore, CEAP is not currently authorized in statute, and thus is limited in the framework it can provide for expanding measurement, evaluation, and reporting on USDA conservation programs. In order to build the necessary partnerships, infrastructure, and capacity to measure, evaluate, and report on the effects of conservation programs and initiatives on carbon (C) sequestration and net GHG footprint, USDA will need a targeted source of funding.

More specifically, under the authority of current and future legislation, USDA should:

- Make GHG and climate change mitigation a Resource Concern addressed by Natural Resources Conservation Service (NRCS) programs
- Undertake a comprehensive MER process in relation to C sequestration, GHG reduction, and climate mitigation and adaptation across all USDA conservation programs.
- Implement cooperative agreements and data sharing arrangements with federal, state, and local agencies, universities and colleges, and NGOs to support the implementation of the monitoring, evaluation, and reporting process.

1.3 Restore funding for the Conservation Stewardship Program (CSP) to previous funding levels prior to cuts made in the 2014 and 2018 Farm Bills.

Conservation programs, and especially CSP, can play vital roles in helping producers become part of the climate solution as well as preparing their operations to withstand the impacts of climate. The 2018 Farm Bill directed USDA to highlight soil health and increased payment rates for key soil health/carbon sequestration practices including cover crops, resource-conserving crop rotation, and managed rotational grazing. However, combined the 2014 and 2018 Farm Bills also cut CSP funding nearly in half, greatly restricting both farmer access and environmental improvement, including climate mitigation. Thus, Congress must take steps in the next farm bill to restore full funding to CSP. This restoration of funding is needed because farmer demand for the programs far exceeds the supply of funds, and interest in the conservation programs has been steadily growing. But first and foremost, it is also needed because climate, natural resource, and environmental issues related to agriculture remain daunting.

1.4 Restore the option for automatic contract renewals under CSP provided that previous contract commitments are being kept and continual improvements are being made.

Given the long-term nature of soil health improvement, soil organic carbon (SOC) increases, and the need to make sure stable carbon remains stable with no backtracking, it is important for farmers to able to seamlessly continue sequestering carbon and building healthy soils on a long-term and continuous basis. Contract renewals should not be limited to a single renewal and should not be made to compete with new contracts.

1.5 Retain and expand CSP's focus on soil health and SOC sequestration. Target CSP enhancement activities to minimize overall GHG emissions, including those related to soil nitrogen and water management, livestock production, pest control, agroforestry and the production of farm inputs. Revise enhancement payment schedules to reflect a priority on soil health and SOC sequestration consistent with this CSP focus and the need to accelerate change.

These practices and systems include, but are not limited to, conversion of marginal cropland to grass, resource-conserving crop rotations, continuous cover cropping, management intensive rotational grazing, organic conversion, conservation tillage, and advanced high-level integrated nutrient and pest management.

1.6 Revise all NRCS Conservation Practice Standards (CPS) and conservation enhancements to prioritize soil carbon sequestration.

The six Principles of Soil Health Management detailed above should be used as a guide for maximizing the efficacy of CPS in enhancing carbon sequestration and mitigating and adapting to climate disruption. Criteria for each CPS that can affect carbon sequestration should ensure sequestration improvements, and considerations should provide practical information on maximizing carbon sequestration outcomes, including through combining the Practice with other Conservation Practices.

For example, CPS 328 (Conservation Crop Rotation) and other relevant CPS and enhancements should be revised as follows:

- Ensure that high residue crops, especially perennials, are included as at least one of the crops in any approved rotation.
- Eliminate bare fallow in any approved rotation by including moisture conserving cover crops or residues.
- Ensure that any SOC lost through one crop is replaced by another crop in the rotation.

1.7 Include within annual Requests for Proposals from Agriculture and Food Research Initiative (AFRI), Organic Agriculture Research and Extension Initiative (OREI), Sustainable Agriculture Research and Education (SARE), and other relevant National Institute of Food and Agriculture (NIFA) competitive grant programs the following six research, education, and extension priorities:

1. Research, design, and promote practical, on-farm systems that increase stable carbon sequestration.
2. Improve methods for measuring SOC concentrating on creating assessment systems that are rapid, low-cost, and remote.
3. Research, design, and promote practical, on-farm systems to optimize nutrient cycling and minimize nitrous oxide emissions from agricultural soils.

4. Research, design, and promote intensive rotational grazing, silvopasture, and other advanced approaches to climate mitigation in livestock production.
5. Evaluate total GHG footprint of different livestock and integrated crop livestock production systems.
6. Conduct breeding research and develop new public crop cultivars and livestock breeds for resilience to climate disruption and performance in climate-mitigating farming and ranching systems.

1.8 Increase the capacity of the SARE program to help farmers increase carbon sequestration and meet the challenges of rapid climate change.

SARE is one of USDA's best-positioned programs to contribute practical on-farm research and education for climate change mitigation and adaptation. Over its 31 years of operation, the SARE program has been highly successful in building the knowledge and tools necessary to promote sustainable agriculture, and in getting that knowledge and tools into the hands of farmers and ranchers. In many cases, producers themselves have been involved in developing and conducting research and education, adding a practicality to the outcomes that have yet to be matched in other USDA research programs. In addition, regional councils guiding the program have addressed region-specific questions, which in the face of climate change will be highly valuable, as different regions are expected to face different climate challenges.

We strongly advise a dramatic increase in funding for SARE to explicitly incorporate climate change mitigation and adaptation into SARE-funded research. This funding should be targeted both to long-term systems research and more immediate on-farm research, demonstration and outreach based on SARE-developed systems that save energy, reduce GHG emissions, sequester carbon, and build healthy soils.

We also recommend that USDA, in developing a strategic plan for addressing climate change across Research, Education, and Economics (REE), build upon the programmatic elements of SARE. These elements have made SARE a success at translating research into outreach, education, and adoption of sustainable farming systems by farmers and ranchers.

1.9 Focus climate change research, conservation incentive programs, and federal commodity and crop insurance on whole-farm systems.

Given the range of uncertainty about the specific impacts of climate change on agriculture in any given location, adaptation strategies should not be viewed as a set of single practice prescriptions. Resilience in agricultural systems is a function of the health of the agricultural ecosystem. It is therefore essential that strategies for adaptive response to climate change focus on whole-system approaches, as opposed to piecemeal components. Small changes in an otherwise vulnerable system may provide some benefit but are not sufficiently adaptive. Therefore, we urge:

- An emphasis on "sustainable systems for agricultural production" and not just "sustainable practices" in its research, education, and extension activities concerning climate change.
- Increased emphasis on systems approaches to risk management (such as the Risk Management Agency's (RMA) Whole Farm Revenue Protection crop insurance program).
- Comprehensive, whole-farm conservation planning in NRCS working lands and easement conservation programs.
- Substantial reform of USDA commodity and crop insurance programs with the long-term goal of reorienting our farm safety net system from overproduction, specialization, and environmental harm to a new safety net that puts farmers and climate-smart agriculture first.

1.10 Adopt a new permanent easement component specifically addressed to C sequestration and GHG mitigation within the Conservation Reserve Program (CRP), including the Grassland Option.

This approach will take full advantage of the potential for CRP to support highly effective C-sequestering and climate-mitigating practices such as forest buffers and other permanent vegetative covers.

1.11 Place an emphasis within Value-Added Producer Grants (VAPG) – under the new Local Agriculture Market Program (LAMP) – on awards that help farmers create new markets for third and fourth rotational crops for row crop systems (including perennials) that promote soil health and increase soil organic matter (SOM) and SOC.

Feasibility and working capital grants through the VAPG program to support new markets and mid-tier value chains for new uses for existing crops (e.g., oats, alfalfa) or for new emerging crops (e.g., kernza, pennyroyal) could accelerate farmer-owned approaches to more diversified and climate friendly cropping systems. The results of such a new emphasis could be improved farm income, higher levels of entrepreneurship, and new viable production systems that enhance climate mitigation and adaptation.

PRIORITY AREA 2:

Remove barriers and strengthen support for sustainable and organic production systems

These recommendations are based on research findings 3, 4, 5, 6 and 10

2.1 Reevaluate NRCS models used to measure and assess soil quality.

We urge NRCS to revise or replace the Soil Conditioning Index (SCI) model so that it does not underestimate the benefits of cover crops, sod crops, resource-conserving crop rotation, and tight (no-fallow) diversified crop rotations, especially in cropping systems that include some tillage. For some climates and soils, it can be very difficult or impossible to achieve a positive SOM factor in SCI for annual cropping systems, even with conservation tillage and high biomass cover crops. Meanwhile, recent and ongoing research on SOM dynamics may substantially change our understanding of the impact of cover crops, tillage and other management variables on SOM and soil quality. We urge NRCS to ensure improved prediction technology is in place to accurately estimate the SOM benefits of cover crops, while simultaneously including practice standard guidance that optimizes planting rates and methods for biomass production.

2.2 Throughout all USDA REE supported programs and funding streams, provide additional priority for sustainable and organic research, education, and extension to maximize agriculture's role in mitigating climate change and ensuring that U.S. agriculture can remain resilient in the face of anticipated climate change scenarios (e.g., increasing frequency of extreme weather events, unpredictable weather patterns, increasing temperatures, etc.).

Greater efforts should be made to promote sustainable and organic agriculture as systems of production that can build soil health, improve nutrient cycling, lower fossil fuel energy inputs and thereby lower GHG emissions from agriculture. Solid on-farm research with innovative farmers will improve sustainable and organic systems so that tillage-associated carbon losses, soil nitrous oxide (N_2O) and methane (CH_4) emissions, and fossil fuel use can be lowered even further. Major funding increases or redirection should be made to pursue these lines of inquiry through the Agricultural Research Service (ARS) and through NIFA's competitive and capacity programs (including Hatch, Smith-Lever, McIntire-Stennis, and Evans-Allen). Particular attention should be given to ensure the continuation of existing research and establishment of new research that includes long-term comparative studies of farming and cropping systems and of systems for livestock and poultry production.

2.3. Promote organic agriculture to make agriculture more resilient in the face of climate change while reducing GHG emissions from the agriculture production sector.

More specifically, USDA should:

- Pursue additional opportunities to align NRCS conservation practice standards and the development of an Organic System Plan (OSP).
- Train NRCS staff in organic systems and assist in the development of a cadre of organic technical service providers.
- Ensure that financial and technical assistance for organic systems in general, and for conventional producers in the process of transitioning to organic systems in particular, are available through Environmental Quality Incentives Program (EQIP) and CSP in every state and country in the nation.
- Incorporate specific CSP enhancements for organic cropping and livestock systems and include organic-specific options for more generally available enhancements such as conservation tillage, nutrient management, pest management, and invasive species control.

PRIORITY AREA 3:

Support climate-friendly nutrient management to reduce agricultural N_2O emissions

These recommendations are based on research findings 4 and 14

3.1 Modify the following CPS to improve soil health and water quality:

- Strengthen nutrient management criteria in practices, especially CPS 590 (Nutrient Management) to enhance the capacity of NRCS to protect water quality.

As noted above, recent research has indicated that crops growing in healthy, biologically active soils may need far less nitrogen (N), phosphorus (P), and potassium (K) than is recommended for a "high" soil test report for P and K. Other studies have shown that moderate to high inputs of soluble NPK can adversely affect soil life and can actually decrease SOC and reduce the soil's capacity to provide for crop nutrition through organic matter and nutrient cycling. Even when fertilizer inputs result in greater annual crop residue returns, SOC levels do not increase and sometimes decrease significantly.

- Consider further opportunities to improve CPS to utilize the inherent connection between soil health management and water quality protection.

As noted earlier in this paper, excessive N and P inputs from either synthetic or organic sources can reduce the activity of mycorrhizal fungi and other beneficial soil organisms and diminish the crop's capacity to develop beneficial partnerships with soil organisms. In other words, excess soluble fertilizer inputs not only threaten water quality, but also compromise soil health and make crops more dependent on additional soluble NPK inputs. On the other hand, careful management of soil health and soluble nutrient levels can promote "tightly coupled nutrient cycling" in which crops obtain sufficient N and other nutrients to sustain high yields, while soil nitrate-N is low enough to minimize leaching and denitrification risks.

3.2 Reinstate several high level CSP enhancements for nutrient cycling and stewardship for water quality, soil health, and overall agricultural resilience.

The loss of these enhancements in the 2017 overhaul of CSP represents a major missed opportunity to reduce N_2O emissions from cropland and pastureland soils, and to improve crop, forage, and livestock health and hence their resilience to impacts of climate disruption. Specifically, we urge NRCS to reinstate the following CSP enhancements, each of which can readily be linked to Additional Criteria or Considerations of CPS 590 (Nutrient Management), CPS 317 (Composting Facility), CPS 340 (Cover Crop), or CPS 528 (Prescribed Grazing):

- Use of legume cover crop as a nitrogen source
- Using legumes, animal manure, and compost to supply 90 to 100 percent of nitrogen needs
- Placement of hay feeding areas on low fertility soils
- Rotation of supplement and feeding areas
- Reduce concentration of nutrients imported onto the farm (75 percent of livestock feed on farm; 50 percent of N and 90 percent of P and K from on-farm sources)
- On-farm composting of farm organic waste

We also urge NRCS to consider additional enhancements based on new and emerging research regarding nutrient cycling in agroecological systems, and building on a strengthened CPS 590 (as recommended in 3.1 above).

3.3 Include research into advanced nutrient management and mitigation of agricultural N_2O emissions as a priority in NIFA grant program Requests for Applications.

Research into the following topics can lead to new practical information and tools to help producers reduce N_2O emissions (which account for nearly half of all direct agricultural GHG emisions) and protect water quality while reducing fertilizer costs and building long-term agricultural resilience:

- Managing for tightly coupled N cycling in a range of crops, soils, and regions
- Managing soil biota for enhanced nutrient cycling and N use efficiency
- Plant breeding and selection for improved nutrient use efficiency and enhanced capacity to partner with N_2O fixing, mycorrhizal, and other beneficial microbes

3.4 Increase emphasis on best nutrient management for N_2O mitigation and cost effective crop production in extension/outreach components of NIFA grant programs.

PRIORITY AREA 4:

Increase support for composting as a climate friendly alternative to landfill and manure lagoon disposal of organic "wastes"

These recommendations are based on research finding 10

4.1 Modify the following CPS to improve soil health and water quality. For example:

- Rename CPS 317 (Composting and Composting Facility) and expand the purposes, criteria and considerations to include the composting process itself and the proper use of compost based on sound nutrient management.
- Revise criteria for CPS 317 (Composting and Composting Facility) and CPS 633 (Waste Recycling) to support composting of both on-farm and off-farm sourced organic residues so that they do not become "wastes" discarded in landfills or held in waste lagoons, where they will emit large amounts of CH4. If composted, they become a valuable soil amendment for building soil health and resilience and sequestering SOC."

PRIORITY AREA 5:

Strengthen protection of C sequestration potential of sensitive and marginal lands

These recommendations are based on research findings 5, 6, and 7

5.1 Expand the role of CRP to explicitly support carbon sequestration goals.

CRP and other programs that take land out of row crop production require long-term grass or tree cover. CRP clearly provides one of the largest, if not the largest, soil carbon sinks created by a federal program. CRP and other programs that keep land in permanent cover with predominantly perennial plant systems should be bolstered to ensure that current carbon storage services are maximized. Changes in these programs may include revising the Environmental Benefits Index (EBI) to give substantial weight to carbon sequestration and adding payments to enhance the carbon sequestration capacity of these lands, while maintaining soil erosion measures and measures for wildlife and water quality protection. The use of these lands for biomass/biofuel feedstocks should occur only if implemented in a way that retains and protects them for multiple ecological functions.

Much could be done to enhance the carbon sequestration potential of CRP lands. Ensuring that more of the land is provided permanent protection from annual crop production would definitively enhance CRP as a means to sequester soil carbon. Permanent protection options could be targeted to the most highly erosive land or land with the highest ecological benefits for wildlife and water protection. Legislation should be considered for a permanent easement option on CRP lands to serve as soil carbon banks.

For CRP land that is coming out of CRP contracts, USDA should fully implement the CRP Transition Incentives Program (CRP-TIP) in the 2018 Farm Bill, with a strong emphasis on re-enrolling land in Continuous CRP (CCRP) and CSP and a focus on soil health and organic systems. This program will conduct outreach to connect retiring farmers with beginning farmers, veterans, and farmers of color. The bill also expands eligibility to all CRP contract holders, not just retiring farmers. Additionally, within CRP-TIP, participating farmers are now able to get a two-year head start on certifying land coming out of CRP into organic production.

5.2 Rigorously enforce Sodsaver.

Sodsaver protects existing grasslands, particularly native prairie and other ecologically important grasslands, by requiring that newly cultivated land not receive crop insurance benefits without actual production history. Many of these grasslands are in areas with high erosion levels when perennial cover is removed, or with naturally wet or slow-draining soils in which tile drains accelerate losses of SOC and nitrate-N. They often are more marginal land for cropping purposes and hence have always been in grass and prairie. USDA should conduct outreach and education to inform farmers about the difficulties of meeting conservation compliance requirements for soil erosion in these regions and should increase producer awareness of the land's ineligibility for federal crop insurance during the four-year period needed to establish an actual cropping history.

Likewise, the Environmental Protection Agency (EPA) should administer the Energy Independence and Security Act's (EISA) Renewable Fuel Standard, as intended by the EISA, to not allow ethanol production on previously uncropped land. EPA's lack of enforcement has unfortunately led to conversions of prime grasslands to cropping for ethanol production purposes.

5.3 Strengthen conservation compliance to incorporate soil health.

Require compliance plans and implementation to increase soil carbon levels and measures such as nutrient management planning and integrated pest management measures to reduce the inputs of synthetic nitrogen and pesticides, and to minimize N_2O emissions from fertilized soils. Designate a small percentage of farm bill mandatory spending for compliance technical assistance and enforcement.

Conventional row crop operations subsidized through farm bill commodity programs have been identified as systems with relatively large levels of net GHG emissions. USDA should take immediate steps to ensure effective enforcement of existing conservation compliance measures for controlling soil erosion. In addition, however, legislative measures should be enacted to require the adoption of conservation compliance plans that include additional measures (such as conservation tillage combined with cover cropping) to increase soil carbon levels and measures (such as nutrient management planning and integrated pest management) to reduce the inputs of synthetic nitrogen and pesticides, and to minimize N_2O emissions from fertilized soils.

PRIORITY AREA 6:

Support climate-friendly livestock production systems and end subsidies for concentrated animal feeding operations (CAFOs) with their massive GHG and water pollution impacts.

These recommendations are based on research findings 8 and 9

6.1 Provide full life-cycle assessment (LCA) for all livestock production systems, including factors such as indirect land use changes related to feed production or other inputs and overall energy consumption, in assessing the net GHG emission levels for systems receiving EQIP or CSP funding intended to reduce GHG emissions.

This analysis is particularly important for CAFOs. CAFOs generally rely on large-scale row crop grain production using synthetic fertilizers and pesticides and often store animal waste in lagoons and other systems that generate additional GHG emissions. Without a comprehensive LCA of GHG emissions, public funding could be used to increase net GHG emissions.

With 50 percent of total EQIP funding set aside for livestock production systems under the 2018 Farm Bill, we urge NRCS to give careful review to the suite of livestock practices available through EQIP. The farm bill makes clear that the livestock set-aside includes grazing management practices. In reviewing livestock conservation practice standards, we urge NRCS to ensure that revisions maximize the capacity of these practices to mitigate potentially adverse impacts of livestock production on soil health (e.g., compaction, erosion, nutrient overloads, overgrazing), water quality (nutrients, pathogens, sediments) and climate (e.g., GHG emissions). EQIP was never intended to be an incentive for concentrated livestock production, yet unfortunately that is what it has, in part, become. USDA should take concrete steps to phase out EQIP funding for CAFOs, beginning with immediately stopping funding of new or expanding CAFOs.

6.2 Apply a comprehensive lifetime assessment of GHG emissions to funding priorities and ranking under the Rural Energy for America Program (REAP).

REAP funding should not be used to fund single components of farming systems that emit large amounts of GHGs through high fossil fuel energy use or reliance on inputs which generate high levels of GHGs. REAP should also not fund methane digesters, which do not meaningfully reduce GHG emissions from the livestock sector.

6.3 Make regionally adapted management-intensive rotational grazing (MIG) and other similar pasture-based systems a top national conservation priority, including transition strategies.

As noted above, confinement- and pasture-raised ruminants emit similar amounts of enteric CH_4, but their other environmental impacts differ greatly. Advanced grazing systems, particularly MIG, have been shown to improve soil, forage, and livestock health dramatically, to reduce water pollution, and to sequester large amounts of carbon. Well-managed grazing systems also mitigate manure-related water impacts and GHG emissions.

6.4 Modify NRCS CPS to improve soil health, carbon sequestration, and water quality. For example:

- Add the following consideration to NRCS CPS 550 (Range Planting): MIG systems can dramatically improve soil health, water quality, and carbon sequestration, and should be considered when opportunities exist.

We urge NRCS to include this addition to reflect that fact that MIG systems can dramatically improve soil health, water quality, and carbon sequestration. Additionally, MIG systems tend to prevent selective grazing, as standard criteria mandate species mixes that minimize selective grazing. MIG can help improve forage availability as well as forage quality, while simultaneously achieving important conservation benefits.

- Limit NRCS CPS 359 (Waste Treatment Lagoon): Limit eligibility for this Practice to existing confinement livestock operations only. Do not offer technical assistance or cost share under CPS 359 or other standards for new or expanding CAFOs. Strengthen requirements such that liquid manure be applied at ecologically acceptable rates.

While we recognize that this practice is designed and intended to reduce water resource impacts of CAFO operations, the increasing use of liquid manure storage facilities has been the major driver of increased total U.S. agricultural GHG emissions between 1990 and 2018, as detailed above. We believe that because NRCS has a responsibility to protect natural resources and the environment, it is extremely problematic that the agency has continuously been in the business of supporting and subsidizing CAFO expansion in areas already in high environmental risk.

PRIORITY AREA 7:

Support on-farm energy conservation and low-carbon renewable energy production

These recommendations are based on research findings 11 and 12

7.1 Increase the focus of EQIP, CSP, and REAP on climate change mitigation, energy conservation, and renewable energy production.

USDA should continue and expand the use of both EQIP and CSP, both of which are authorized to promote energy conservation, to assist farmers and ranchers in obtaining energy audits of their operations, improving the energy efficiency of their operations, and establishing renewable energy systems.

More specifically, USDA should:

- Incorporate on-farm energy audits into NRCS comprehensive conservation planning and energy specific conservation activity plans.
- Increase the capacity of NRCS to provide technical assistance on energy conservation and renewable energy on farms.
- Use grants and cooperative agreements to involve state, local and non-profit partners with expertise in energy audits, energy conservation and on-farm solar, wind and other renewable energy production.
- Increase the number of energy conservation practices and systems approved for technical and financial assistance through conservation programs, especially those which provide for relatively low cost, long-term or permanent farming system changes or use low carbon energy sources such as wind and solar power, and provide significant funding for applicants requesting assistance for energy conservation measures, especially beginning and limited resource farmers.
- Add, retool, and strengthen CPS and resource management quality criteria to reflect the new emphasis on energy conservation and production, GHG emission reductions and carbon sequestration, making extensive use of decades of sustainable agriculture research results and the on-farm experience of farmers working with agricultural systems.
- Expand the use of EQIP and CSP to fund energy audits and the establishment of on-farm renewable energy, with emphasis on low carbon energy including wind and solar power. Specific on-farm biofuel and bioenergy crops and applications would be included only once LCAs have confirmed a net energy savings and GHG footprint reduction.
- Focus REAP on low carbon on-farm energy resources, especially small wind and solar technologies.

7.2 Review NRCS CPS 512 (Forage and Biomass Planting) to ensure the inclusion of "Produce feedstock for biofuel or energy production" does not come at the expense of critical conservation benefits.

As NRCS reviews and modifies CPS, we urge careful scrutiny of biofuel harvest as one of the purposes, as this process can easily compromise conservation benefits. Thus, we urge NRCS to ensure conservation objectives are maintained. We also urge NRCS to include this concern when reviewing the "Additional Criteria for Producing Feedstocks for Biofuel or Energy Production" section of this standard.

PRIORITY AREA 8:

Fund public plant and animal breeding for a climate-resilient agriculture

These recommendations are based on research finding 13

8.1 Increase research resources for the development of publicly available seeds and animal breeds adapted to regional climate regimes and to climate-friendly, low-input, ecological farming systems.

The scientific consensus is that climate change will result in rapid and unpredictable changes in the growing regimes for crops and forages and conditions for animal agriculture that may vary on a regional basis. The development of publicly available seeds and breeds suited to a variety of local climate conditions will be critical to farmers and ranchers in coping with climate change. A major factor in the resilience of sustainable and organic agricultural systems will be plant varieties and animal breeds that are selected to perform under specific local climate conditions, forage availability, and pest regimes. As local climate conditions change, the availability of a diversity of plant and animal genetic resources will be needed to address the growing challenges of global climate change, increasing pest and pathogen pressure, food security, and safety and resiliency concerns.

Cultivars that are better adapted to sustainable organic systems, especially integrated, minimum-till, high-biomass-cover crop based organic systems, will facilitate adoption of these climate-friendly practices. Cultivars with deep, extensive root systems and/or enhanced capacity to "partner" with soil microbiota for efficient nutrient cycling can directly contribute to C sequestration and N_2O mitigation. Livestock breeds that are better adapted to performance in pasture-based systems, especially MIG, will facilitate adoption of this highly beneficial system of livestock production.

Therefore, ensuring the access to the greatest diversity of germplasm resources, and the capacity to develop adapted seed and breed varieties is crucial to resiliency of farming and ranching systems.

A major recommitment is required to bolster funding for classical plant and animal breeding, particularly through ARS and the AFRI competitive grants program. Additional specific recommendations to USDA on incorporating a seeds and breeds initiative throughout its research programs is provided in the National Sustainable Agriculture Coalition's position paper on Seeds and Breeds, available at:

http://sustainableagriculture.net/our-work/campaigns/fbcampaign/seed-breeding-and-research/

CONCLUSION

The National Sustainable Agriculture Coalition (NSAC) supports an immediate and environmentally beneficial transition to a resilient agri-food production system based on sustainable and organic agricultural systems and practices. We call upon federal and state governments to prioritize sustainable agriculture systems and policies that enable farmers, ranchers and rural communities to address the challenges posed by a changing climate through a variety of mechanisms. We have identified the highest priority areas for change with detailed recommendations. Top priority mechanisms include land use practices that maximize carbon (C) sequestration in soil and plant biomass, nutrient management to minimize nitrous oxide (N_2O) release, and advanced grazing management to replace concentrated animal feeding operations (CAFOs).

NSAC and its members believe that it is possible and necessary to begin building this resilient agricultural system and employing sustainable practices immediately. Part of this requires removing disincentives for sustainable production through government programs such as single-crop insurance subsidies and addressing structural barriers that incentivize overproduction of commodities and market consolidation. We also believe that implementing sustainable practices can be affordable and cost-effective for producers, especially with government support, since the costs of implementing climate-mitigating and adaptive production systems and practices will be offset by reduced costs related to energy, fertilizers, and other inputs and often result in increased yields. Taking insufficient action will be more costly.

Climate change poses a serious threat to our environment, our rural communities, our farmers and ranchers, and the millions of Americans who rely on them for food and fiber. Shifting to a more resilient, sustainable agricultural system will mitigate climate change while building an agri-food system that is better for our planet and its people. Failing to do so will result in devastating consequences for people, agriculture, and the environment.

APPENDIX:
SUSTAINABLE AGRICULTURE SYSTEMS AND PRACTICES THAT MITIGATE CLIMATE CHANGE

Agroforestry

Agroforestry is a general term for production systems and buffer plantings that utilize trees and other woody perennials for production and/or conservation purposes. Agroforestry practices have been shown to sequester large amounts of carbon in soil and biomass, as well as protecting water, wildlife, and other resources.

Biological nitrogen fixation

The conversion of molecular nitrogen (N_2) to ammonia (NH_3) through biological fixation by bacteria begins the process of making nitrogen available to plants. Once this "fixed" nitrogen is incorporated into the plant biomass, it can become part of the soil reservoir and taken up again by plant roots as nitrate (NO_3^-). Biological nitrogen fixation allows nutrients in soil to be actively cycled in the ecosystem, rather than relying on throughflow of nutrients to nourish plants.

Composting

Composting is the controlled aerobic microbial decomposition of organic materials such as manure, plant residues, or other organic products, combined and managed in windrows, piles, or enclosed facilities by certain microorganisms. These microbes consume oxygen and use nutrients including carbon, nitrogen, phosphorus, and potassium as they feed on the organic matter. The resulting composted manure is a humus-like organic material, fine-textured, low-moisture, and with a non-offensive earthy odor. If high enough temperatures have been reached during the composting process, pathogens and weed seeds have been killed.

Conservation agriculture

Conservation agriculture is an ecological cropping system that integrates diversified, resource-conserving crop rotations that include cover crops and perennial sod (forage) crops as well as annual production crops, with continuous no-till, organic inputs, and limited, judicious use of synthetic fertilizers, herbicides, and other crop protection chemicals only when needed to sustain economically viable production.

Conservation tillage

Conservation tillage refers to strategies and techniques for establishing crops in the previous crop's residues, which are purposely left on the soil surface. The principal benefits of conservation tillage are improved water conservation and the reduction of soil erosion. Additional potential benefits include reduced fuel consumption, planting and harvesting flexibility, reduced labor requirements, and improved soil tilth (NCAT/ATTRA, n.d.).

Crop residue management

Crop residue management refers to any tillage method that leaves crop residue on the surface to reduce erosion. Crop residue left on the surface shields the soil from rain and wind until emerging plants provide a protective canopy. Crop residue also improves soil tilth and adds organic matter to the soil. Less tillage reduces soil compaction and saves farmers time and fuel.

Ecological agriculture

Ecological agriculture is a general term for all farming and ranching systems that integrate multiple best production, conservation, and soil health management practices to help mitigate climate change, enhance resilience, and optimize triple bottom line outcomes: farm economic viability, resource and environmental protection, and social capital for rural communities and society as a whole.

Integrated pest management

Integrated pest management (IPM) is an effective and ecologically-based approach to crop management that uses current, comprehensive information on the life cycles of pests and their interaction with the environment to prevent pest damage by using primarily cultural and biological controls with the least possible hazard to people, property, and the environment.

Nutrient management

Nutrient management is the practice of using nutrients wisely for optimum economic benefit while building soil health and minimizing impact on the environment. Proper application of plant nutrients helps achieve optimum crop yields while improper application can lead to water quality problems.

Organic agriculture

Organic agriculture is a system of agriculture that uses crop rotation, green manure, compost, biological pest control, and mechanical cultivation to maintain soil productivity and manage weeds and pests. Organic agriculture does not use synthetic fertilizers or pesticides, plant growth regulators, livestock feed additives or genetically modified organisms.

Permaculture

Permaculture is a system for creating highly diversified and integrated production landscapes based largely on native perennial food and fiber producing species. Permaculture aims to simulate the natural ecosystem structures and processes in the locale, and to minimize dependence on soil disturbance and off-site sourced inputs. Multistory plantings, high carbon (C) sequestration, and multiple ecosystem services (e.g., beneficial habitat and conservation biological pest control) characterize permaculture systems.

Polyculture and crop rotation

Polyculture is the practice of growing multiple crops in the same space, as crops would grow in a natural ecosystem. Polyculture includes techniques such as crop rotation (growing different crops in the same area in sequential seasons), multi-cropping (growing different crops simultaneously), and intercropping (growing different crops in between rows of a primary crop). Crops grown in this way are less susceptible to disease than monoculture crops, and also increase local biodiversity.

Regenerative agriculture

Regenerative agriculture is any ecological system that seeks to move beyond "sustainable" (maintain current condition of soil, water, land, vegetation, wildlife, etc.) to restore soil health and other ecosystem attributes to a higher level of function through best stewardship practices. Regenerative agriculture may be based on organic (no chemical disturbance) or conservation agriculture (no tillage disturbance) systems.

Resource conserving crop rotation

As defined in the 2008 Farm Bill at Section 1238 G, resource-conserving crop rotation includes at least one resource conserving crop, reduces erosion, improves soil fertility and tilth, interrupts pest cycles, and in applicable areas, reduces depletion of soil moisture, or otherwise reduces the need for irrigation.

Restoration of degraded soils

Soil restoration seeks to reverse and repair the degradation of soil as a resource that takes hundreds of thousands of years to form, and to promote functional plant-soil systems. Returning soils to their original state as soon as possible after disturbance, stopping application of chemicals, using bacteria to break down pollutants, and applying cover crops are all ways to help restore degraded soil. Without soil restoration, soil erosion and loss of soil organic matter and nutrients damage agricultural outputs in addition to the larger ecosystem.

Rotational grazing

Rotational grazing is periodically moving livestock to fresh paddocks to allow pastures to regrow. Feed costs decline and animal health improves when animals harvest their own feed in a well-managed rotational grazing system (NCAT/ATTRA, n.d.). Advanced grazing management systems, including management intensive rotational grazing (MIG), mob grazing, and adaptive multi-paddock grazing, are now eligible for supplemental CSP payment under the 2018 Farm Bill, and are especially effective in sequestering C and reducing some of the greenhouse gases (GHGs) associated with livestock production.

Seeds and Breeds

The concept of "Seeds and Breeds" refers to the maintenance of genetic resources of plant varieties and animal breeds that are necessary for the survival of sustainable and organic agricultural systems for current and future generations. Top breeding priorities include development of public crop cultivars and animal breeds for ecological, climate-friendly farming systems, as well as regional adaptation and resilience to weather extremes.

Silvopasture

Silvopasture integrates trees or other woody perennials into existing pasture or rangeland in order to provide natural shade and shelter for livestock, reduce wind erosion, increase biodiversity, provide additional harvestable products, and enhance C sequestration and soil health. A review of agroforestry systems indicates a very high C sequestration potential for silvopasture (Feliciano et al., 2018).

Water management

Sustainable agriculture strategies for conserving water include converting cropland to managed grassland in riparian areas, constructing and restoring wetlands, measuring and conserving irrigation water, creating conservation easements, choosing water-efficient crops and resource-conserving crop rotations, and limiting the impact of nitrogen and pesticide runoff from farms into local water supplies. Water management strategies for maximizing carbon sequestration include monitoring soil organic carbon and soil inorganic carbon pools and sediments affected by erosion processes, irrigation, drainage, and sub-irrigation.

REFERENCES

Adams, R.M., C. Rosenzweig, R.M. Peart, J.T. Ritchie, B.A. McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote & L.H. Allen. 1990. Global Climate Change and U.S. Agriculture. *Nature,* 345: 219-223.

Aguilera, E., L. Lassaletta, A. Gattinger, and B. S. Gimeno. 2013. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: a meta-analysis. *Agriculture, Ecosystems & Environment,* 168, 25–36.

Alter, R., C. Hunter, J. Winter, and E. Eltahir. 2017. Twentieth Century Regional Climate Change During the Summer in the Central United States Attributed to Agricultural Intensification. *Geophysical Research Letters,* 45(3):1586-1594. https://doi.org/10.1002/2017GL075604

Arrhenius, S. 1896. On the influence of carbonic acid in the air upon the temperature of the ground. *Philosophical Magazine and Journal of Science*, (fifth series) 41, 237–275.

Asbjornsen, H., V. Hernandez-Santana, M. Liebman, J. Bayala, J. Chen, M. Helmers, C.K. Ong, and L.A. Schulte. 2014. Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. *Renewable Agriculture and Food Systems,* 29, no. 2.

ATTRA. 2006. National Sustainable Agriculture Information Service. *Renewable Energy Opportunities on the Farm.* Available at: https://attra.ncat.org/attra-pub/download.php?id=306

Baah-Achearnfour et al. 2014. Trees increase soil carbon and its stability in three agroforestry systems in central Alberta, Canada. *Forest Ecology and Management,* 328:131-139.

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.*

Baker, B.B., J.D. Hanson, Bourdon, R.M. & J.B. Eckert. 1993. The Potential Effects of Climate Change on Ecosystem Processes and Cattle Production on U.S. Rangelands. *Climatic Change,* 23(Oct.): 97-117.

Baker, J.M., T.E. Ochsner, R.T. Venterea & T.J. Griffis. 2007. Tillage and Soil Carbon Sequestration: What Do We Really Know? *Agriculture, Ecosystems and Environment,* 118: 1-5.

Balaine, N., T. J. Clough, M. H. Beare, S. M Thomas, and E. D. Meenken. 2016. Soil Gas Diffusivity Controls N_2O and N2 Emissions and their Ratio. *Soil Science Society of America Journal,* 80 (3): 529-540.

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

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. *Journal of Soil and Water Conservation,* 69(6): 471–482.

Battisti, D. S. & R. L. Naylor. 2009. Historical Warnings of Future Food Insecurity with Unprecedented Seasonal Heat. *Science,* 323: 240-245.

Baumgartner, J., S. Kross, and S. Heath. 2019. Supporting beneficial birds and managing pest birds. Wild Farm Alliance, Watsonville, CA. Available at: https://d3n8a8pro7vhmx.cloudfront.net/wildfarmalliance/pages/337/attachments/original/1548794888/1WFA_Support_and_Manage_Birds-for_web.pdf?1548794888

Baveye, Philippe. 2007. Soils and Runaway Global Warming: Terra incognita. *Journal of Soil and Water Conservation,* 62 (No. 6): 139A-143A.

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

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

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

Blanco-Canqui, H. 2017. Biochar and Soil Physical Properties. *Soil Science Society of America Journal,* 81 (4): 687-711.

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

Blanco-Conqui, H. & R. Lal. 2009. Corn Stover Removal for Expanded Uses Reduces Soil Fertility and Structural Stability. *Soil Science Society of America Journal,* 73: 418-426;.

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

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

Boody, G., B. Vondracek, D.A. Andow, M. Krinke, J. Westra, J. Zimmerman & P. Welle. 2005. Multifunctional Agriculture in the United States. *Bioscience,* 55: 27-38.

Boody, G., P. Gowda, J. Westra, C. van Schaik, P. Welle, B. Vondracek, D. Johnson. 2009. Multifunctional Grass Farming: Science and Policy Considerations. In A. J. Franzluebbers (ed.), *Farming with Grass: Achieving Mixed Agricultural Landscapes in Grassland Environments*. Soil and Water Conservation Society e-book. Available at https://www.swcs.org/resources/publications/farming-with-grass-online

Borron, S. 2006. Building Resilience for an Unpredictable Future: How Organic Agriculture Can Help Farmers Adapt to Climate Change. U.N. Food & Agriculture Organization. http://www.fao.org/3/a-ah617e.pdf

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

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

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

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

Butler, EE, ND Mueller, and PJ Huybers. 2018. Peculiarly pleasant weather for U.S. maize. *Proceedings of the National Academy of Sciences,* 115 (47), 11935-11940.

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

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

Cates, A., M. D. Ruark, and J. Hedtke. 2015. Long term tillage, rotation, and perennialization effects on particulate and aggregate organic matter. Recording from the Organic Agriculture Research Symposium, LaCrosse, WI, February 25-26. http://eorganic.info/node/12972.

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

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

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

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

Chavas, Jean Paul, J.L. Posner, & J.L. Hedtcke. 2009. Organic and Conventional Production Systems in the Wisconsin Integrated Cropping Systems Trial: II. Economic and Risk Analysis 1993-2006. *Agronomy Journal,* 101:288-295.

Chen, G., C. R. Hooks, M. Lekveishvili, K. H. Wang, K. H., N. Pradhan, S. Tubene, S., R. R. Weil, and R. Ogutu. 2015. Cover Crop and Tillage Impact on Soil Quality, Greenhouse Gas Emission, Pests, and Economics of Fields Transitioning to Organic Farming. Final report for project ORG 2011-04944. CRIS Abstracts.*

Clancy, K., 2006a. Greener Pastures: How grass-fed beef and milk contribute to healthy eating. Union of Concerned Scientists. Available at: http://www.ucsusa.org/assets/documents/food_and_agriculture/greener-pastures.pdf.

Clancy, K., 2006b. Greener Eggs and Ham: The Benefits of Pasture-raised Swine, Poultry and Egg-Production. Union of Concerned Scientists. Available at: http://www.ucsusa.org/assets/documents/food_and_agriculture/greener-eggs-and-ham.pdf

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

Cogger, C. G. M. Ostrom, K. Painter, A. Kennedy, A. Fortuna, R. Alldredge, A.; Bary, T. Miller, D. Collins, J. Goldberger, A. Antonelli, and B. Cha. 2013. Designing Production Strategies for Stewardship and Profits on Fresh Market Organic Farms. Final report for OREI project 2008-01247. CRIS Abstracts.*

Comis, D. 2007. No Shortcuts in Checking Soil Health. Agricultural Research Service. July 2007: 4-5. Available at: http://www.ars.usda.gov/is/AR/archive/jul07/soil0707.pdf

Conant, R.T., C.E.P. Cerri, B.B. Osborne, and K. Paustian. 2017. Grassland management impacts on soil carbon stocks: A new synthesis. *Ecological Applications,* 27:662–668. doi:10.1002/eap.1473.

Conrad et al. 2018. Soil organic carbon and nitrogen sequestration and turnover in aggregates under subtropical Leucaena-grass pastures. *Soil Research,* 56: 632-647.

Contò, F.; Fiore, M.; Di Matteo, A. 2013. Building a multifunctionality agricultural house and indicators for social/health farms. *PAGRI,* 3:41–56.

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

Delate, K., C. Cambardella, and C. Chase. 2015a. Effects of cover crops, soil amendments, and reduced tillage on carbon sequestration and soil health in a long term vegetable system. Final report for ORG project 2010-03956. CRIS Abstracts*

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

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.

DiTomaso, J.D., J.N. Barney & Alison M. Fox. 2007. Biofuel Feedstocks: The Risk of Future Invasions (CAST Commentary); see also Raghu, S., R.C. Anderson, C.C. Daehler, A.S. Davis, R.N. Wiedenmann, D. Simberloff & R.N. Mack. 2006. Adding Biofuels to the Invasive Species Fire? *Science,* 313:1742.

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.*

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

Duarte, C.M., J. Wu, X. Xiao, A. Bruhn, and D. Krause-Jensen. 2017. Can seaweed farming play a role in climate change mitigation and adaptation? *Frontiers of Marine Science,* 4: 1-8. https://doi.org/10.3389/fmars.2017.00100

Eagle, A. J., L. P. Oander, K. L. Locklier, J. B. Heffernan, and E. S. Bernhardt. 2017. Fertilizer Management and Environmental Factors Drive N_2O and NO_3 Losses in Corn: A Meta-Analysis. *Soil Science Society of America Journal,* 81 (5): 1191-1202.

Elphick, C.S. 2000. Functional equivalency between rice fields and seminatural wetland habitats. *Conservation Biology,* 14:181–191.

Engel, R. E., P. R. Miller, B. G. McConkey, and R. Wallander. 2017. Soil Organic Carbon Changes to Increasing Cropping Intensity and No-Till in a Semiarid Climate. *Soil Science Society of America Journal,* 81 (2): 404-413.

Environmental Defense Fund (EDF). 2011. Creating and quantifying carbon credits from voluntary practices on rice farms in the Sacramento Valley: accounting for multiple benefits for producers and the environment. Final Report to NRCS From Environmental Defense Fund, Inc., Sacramento, CA.

EDF. 2019. Greenhouse Gas Market Opportunities for Rice. Available at: https://www.edf.org/sites/default/files/11767_Rice-Fact-Sheet-5-16_0.pdf

ERS. 2019. Fertilizer Use and Price. Available at: https://www.ers.usda.gov/data-products/fertilizer-use-and-price/summary-of-findings/

Falloon, P., D. Powlson, and P. Smith. 2004. Managing field margins for biodiversity and carbon sequestration: A Great Britain case study. *Soil Use and Management,* 20:240-247.

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.

Firbank, L.G. 2008. Assessing the Ecological Impacts of Bioenergy Projects. *Bioenergy Research,* 1:12-19.

Flavell, C. 2019. Floods and Trump's Trade War Create an Uncertain Year for Farmers. *New York Times,* May 31, 2019.

Food and Agriculture Organization. 2018 Food Outlook - Biannual Report on Global Food Markets – November 2018. Rome. 104 pp. Available at: http://www.db.zs-intern.de/uploads/1541755718-2018FAOOutlookNov.pdf

Fu, X., J. Wang, U. M. Sainju, and W. Liu. 2017. Soil Carbon Fractions in Response to Long-Term Crop Rotations in the Loess Plateau of China. *Soil Science Society of America Journal,* 81 (3): 503-513.

Garnett, T. 2009. Livestock-related Greenhouse Gas Emissions: Impacts and Options for Policy Makers. *Environmental Science Policy,* 12: 491-503.

Gattinger, A., A. Muller, M. Haeni, C. Skinner, A. Fliessbach, N. Buchmann, P. Mader, M. Stolze, P. Smith, N. E. Scialabba, and U. Niggli. 2012. Enhanced topsoil carbon stocks under organic farming, *PNAS,* 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.

Goldstein, W. 2015. Breeding corn for organic farmers with improved N efficiency/N fixation, and protein quality. Proceedings of the Organic Agriculture Research Symposium, LaCrosse, WI February 25-26. http://eorganic.info/node/12972.

Goldstein, W. 2016. Partnerships Between Maize and Bacteria for Nitrogen Efficiency and Nitrogen Fixation. Bulletin 1. Mandaamin Institute, Elkhorn, WI, 49 pp. http://www.mandaamin.org/about-nitrogen-fixing-corn.

Goldstein, W. 2018. High Methionine, N Efficient Field Corn from the Mandarin Institute/ Nokomis Gold Seed Co. Proceedings of the 9th Organic Seed Growers Conference, Feb 14-17, Corvallis, OR, pp 25-26. https://seedalliance.org/all-publications/.

Gowda, P., J.L. Steiner, C. Olson, M. Boggess, T. Farrigan, and M.A. Grusak, 2018. Agriculture and Rural Communities. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II [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, pp. 391–437. https://nca2018.globalchange.gov/chapter/agriculture-rural.

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

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

Green, J., J. Worstell, C. Canarios, R. Haggard, K. Alford & S. Bush. (2018). Exploring the relationships between local agrifood system resilience, multiple measures of development, and health in the Southern United States. *Community Development Journal,* 48:5. https://doi.org/10.1080/15575330.2018.1527778

Hahn, G.L., P.L. Klinedinst & D.A. Wilhite. 1990. Climate Change Impacts on Livestock Production and Management. (Paper presented at the American Meteorological Society Annual Meeting, Anaheim, CA. February 4-9).

Hamel, C. 2004. Impact of arbuscular mycorrhizal fungi on N and P cycling in the root zone. *Canadian Journal of Soil Science,* 84(4):383-395.

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

Haspel, T. 2019. "Can perennial grains solve the carbon-storage problem?" *The Washington Post,* February 5, 2019.

Henderson, E., 2019. Personal communication. Results of RMA-funded project examining lack of participation in the Whole Farm Revenue Program by small and mid-sized specialty crop growers in California.

Hendrickson, M. et. al. 2017. Power, Food and Agriculture: Implications for Farmers, Consumers and Communities (November 1, 2017). Available at SSRN: http://dx.doi.org/10.2139/ssrn.3066005

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.*

Hoosbeek et al., 2018 Trees enhance coil carbon sequestration and nutrient cycling in a silvopastoral system in south-western Nicaragua. *Agroforestry Systems,* 92:263-273.

Howard, Sir Albert. 1947. The Soil and Health: A Study of Organic Agriculture. *University Press of Kentucky* (2006), 307 pp.

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.*

Huang, W., W. McBride & U. Vasavada. 2009. Recent Volatility in U.S. Fertilizer Prices: Causes and Consequences. *Amber Waves,* 7(1): 28-31.

Huang, et al., 2018. Performance, Economics and Potential Impact of Perennial Rice PR23 Relative to Annual Rice Cultivars at Multiple Locations in Yunnan Province of China. *Sustainability,* 10, 1086; doi:10.3390/su10041086;

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

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

IPCC, 2014b. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, https://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf

IPCC, 2019. Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. U. N. Environmental Programme. Available at: https://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf

Jackson, L. 2010. Soil Microbial Nitrogen Cycling for Organic Farms. http://articles.extension.org/pages/18657/soil-microbial-nitrogen-cycling-for-organic-farms.

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.

Johnson, R. J., J. A. Jedlicka, J. E. Quinn, and J. R. Brandle. 2011. Global Perspectives on birds in agricultural landscapes in W. B. C. a. S. L. Ortíz, ed. Integrating agriculture, conservation and ecotourism: Examples from the field, issues in agroecology – Present status and future prospectus. Springer Science+Business Media.

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

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

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

Kell, D.B. 2011. Breeding crop plants with deep roots: their role in sustainable carbon, nutrient and water sequestration. *Annals of Botany,* 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. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 367(1595): 1589– 1597.

Khan, S., R. Mulvaney, T. Ellsworth & C. Charlie Boast. 2007. The Myth of Nitrogen Fertilization for Soil Carbon Sequestration. *Journal of Environmental Quality,* 2007 36: 1821-1832;

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

Kon Kam King, J., Granjou, C., Fournil, J., & Cecillon, L. 2018. Soil sciences and the French 4 per 1000 Initiative—The promises of underground carbon. *Energy Research & Social Science*, 45, 144–152. https://doi.org/10.1016/j.erss.2018.06.024

Kosicki, M. K. Tomberg and A. Bradley, 2018. Repair of CRISPR-Cas9–induced double-stranded breaks leads to large deletions and complex rearrangements. *Nature Biotechnology*, 36:675-771. DOI: 10.1038/Nbt.4192

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

Lal, Rattan. 2007. There Is No Such Thing as Free Biofuel from Crop Residues. Soil Science Society of America. Past President's Message. Available at: https://www.soils.org/about-society/presidents- message/archive/2.

Lal, R. 2008. Carbon Sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 363: 815-830.

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

Lal, R. 2019. Conceptual basis of Managing Soil Carbon: Inspired by Nature and Driven by Science. *Journal of Soil and Water Conservation,* 74(2): 29A-34A.

Lal, R., J.M. Kimble, R.F. Follett & C.V. Cole. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect.* Ann Arbor Press, Chelsea MI.

Lal R., J.M., R.F. Follett & J.M. Kimble. 2003. Achieving Soil Carbon Sequestration in the U.S.: a challenge to the policymakers. *Soil Science,* 168: 827-845.

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. *Journal of Soil and Water Conservation,* 73(6): 145A-152A.

Landis, D., M.M. Gardiner, W. van der Werf & S.M. Swinton. 2008. Increasing Corn for Biofuel Production Reduces Biocontrol Services in Agricultural Landscapes. *Proceedings of the National Academy of Sciences,* 105: 20552-20557.

Letourneau, D. K., S. G. Bothwell, Allen, R. R. Kula, M. et al. 2015. III. Habitat eradication and cropland intensification may reduce parasitoid diversity and natural pest control services in annual crop fields. *Elementa: Science of the Anthropocene,* 3, no. 1.

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.

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

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

Lugato, E., A. Leip, and A. Jones. 2018. Mitigation potential of soil carbon management overestimated by neglecting N_2O emissions. *Nature Climate Change,* 8, 219-223. www.nature.com/natureclimatechange.

Lynch, D.H., R.P. Voroney, & P.R. Warman. 2006. Use of 13C and 15N natural abundance techniques to characterize carbon and nitrogen dynamics in composting and compost-amended soils. *Soil Biology and Biochemistry* 38, 103-114.

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

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

Manela A.P. 2007. Soil Carbon and the Mitigation of Flood Risks. Chapter 11 in J.M. Kimble et al. (eds.), *Soil Carbon Management: Economic, Environmental and Social Benefits,* (CRC Press Boca Raton).

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

Marland, Gregg et. al. 2003. The Climatic Impacts of Land Surface Change and Carbon Management and the Implications for Climate-change Mitigation Policy. *Climate Policy* 3, 149-157.

McCalmont, J. P., Hastings, A., McNamara, N. P., Richter, G. M., Robson, P., Donnison, I. S., & Clifton-Brown, J. (2015). Environmental costs and benefits of growing Miscanthus for bioenergy in the UK. Global change biology. *Bioenergy,* 9(3), 489–507. doi:10.1111/gcbb.12294,

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

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

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

Millar, N., G.P. Robertson, P.R. Grace, R.J. Gehl, and J.P. Hoben. 2010. Nitrogen fertilizer management for nitrous oxide (N_2O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for US Midwest agriculture. *Mitigation Adaptation Strategies for Global Change* 15(2), 185–204.

Mkhabela, M.S., A. Madani, R. Gordon, D. Burton, D. Cudmore, A. Elmi, and W. Hart. 2008. Gaseous and leaching nitrogen losses from no-tillage and conventional tillage systems following surface application of cattle manure. *Soil Tillage Research,* 98, 187–199.

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

Montgomery, D. R. 2017. *Growing a Revolution: bringing our soil back to life.* W. W. Norton & Company, New York, 316 pp.

Morandin, L. A., R. F. Long, and C. Kremen. 2014. Hedgerows enhance beneficial insects on adjacent tomato fields in an intensive agricultural landscape. *Agriculture, Ecosystems & Environment,* 189: 164-170.

National Audubon Society. 2014. Audubon's Birds and Climate Change Report: A Primer for Practitioners. *National Audubon Society,* New York.

National Defense University. 1978. *Climate Change to the Year 2000: A Survey of Expert Opinion.*

Newman, J.E. 1980. Climate Change Impacts on the Growing Season of the North American Corn Belt. *Biometeorology,* 7, 128-142.

Newman, J.E. 1980. Climate Change Impacts on the Growing Season of the North American Corn Belt. *Biometeorology* 7: 128-142. Rosenzweig, C. 1985. Potential CO_2-Induced Effects on North American Wheat Producing Regions. *Climatic Change* 7, 367-389.

Nicolas V, Oestreicher N, Vélot C. 2016. Multiple effects of a commercial Roundup® formulation on the soil filamentous fungus Aspergillus nidulans at low doses: evidence of an unexpected impact on energetic metabolism. *Environmental Science and Pollution Research* 23, 14393–14404; doi: https://doi.org/10.1007/s11356-016-6596-2.

Niggli, U., A. Fließbach, P. Hepperly & N.Scialabba. 2009. Low Greenhouse Gas Agriculture: Mitigation and Adaptation Potential of Sustainable Farming Systems. U.N. Food & Agriculture Organization.

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

Nugent, D. and B. K. Sovacool, 2014. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy,* 65, 229-244.

Obrycki et al., 2018. Corn stover harvest, tillage and cover crop effects on soil health indicators. *Soil and Water Management and Conservation.* 82, 910-918. https://dl.sciencesocieties.org/publications/sssaj/articles/82/4/910.

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

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

Ominski, K. H., D.A. Boadi, K. M. Wittenberg, D.L. Fulawka & J.A. Basarab. 2001. Estimates of Enteric Methane Emissions from Cattle in Canada Using the IPCC Tier-2 Methodology. *Canadian Journal of Animal Science* 87, 459–467.

Ontario (n.d.) Green Energy Generation. Accessed 4/30/2019 at http://www.omafra.gov.on.ca/english/engineer/energy.html.

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

Parry, M., 1990. *Climate Change and World Agriculture*. London: Earthscan Publications.

Pattey, E., M.R. Trzcinski, & R.L. Desjardins. 2005. Quantifying the reduction of greenhouse gas emissions as a result of composting dairy and beef cattle manure. *Nutrient Cycling in Agroecosystems* 72, 173-187.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature,* 532(7597), 49-57. DOI:10.1038/nature17174.

Perlack, R.D., L.L. Wright, A. Turhollow, R.L. Graham, B. Stokes, & D. Erbach. 2005. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. U.S. Department of Energy; U.S. Department of Agriculture, Report No. ORNL/TM-2005/66.

Pielke, Roger A. 2005. Land Use and Climate Change. *Science,* 310: 1625-1626.

Pittelkow, C. M., Y. Assa, M. Burger, R. G. Mutters, C. A. Greer, L. A. Espino, J. E. Hill, W. R. Horwath, C. van Kessel, and B. A. Linquist. 2014. Nitrogen Management and Methane Emissions in Direct-Seeded Rice Systems. *Agronomy Journal,* 106, 968-980. doi:10.2134/agronj13.0491

Poirier, V., D.A. Angers, P. Rochette, M.H. Chantigny, N. Ziadi, G. Tremblay & J. Fortin, 2009. Interactive Effects of Tillage and Mineral Fertilization on Soil Carbon Profile, *Soil Science Society of America Journal,* 73, 255-261.

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. *Proceedings of the Royal Society,* B 282, 20141396.

Popp, J. ,Z. Lakner, M Harangi-Rakos, and M Fari, 2014. The effect of bioenergy expansion: food, energy, and environment. *Renewable and Sustainable Energy Reviews,* 32, 559-578

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. *European Journal of Soil Science,* 62(1), 42–55.

Qin et al., 2016. Influence of spatially dependent, modeled soil carbon emission factors on life-cycle greenhouse gas emissions of corn and cellulosic ethanol. *Global Change Biology and Bioenergy,* 8,1136-1149. https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12333

Rawls, J.W., Y.A. Pachepsky, J.C. Ritchie, T.M. Sobecki & H. Bloodworth. 2003. Effects of Soil Organic Carbon on Soil Water Retention. *Geoderma,* 116, 61-76.

Reeve, J., and E. Creech. 2015. Compost Carryover Effects on Soil Quality and Productivity in Organic Dryland Heat. 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.*

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.

Rillig, M.C. 2004. Arbuscular mycorrhizae, glomalin, and soil aggregation. *Canadian Journal of Soil Science,* 84(4), 355–363.

Risk Management Agency (RMA). 2019. Summary of Business, https://www3.rma.usda.gov/apps/sob/current_week/insplan2018.pdf

Robinet, C. and A. Roques. 2010. Direct impacts of recent climate warming on insect populations. *Integrative Zoology,* 5, 132-142.

Rodale Institute. 2011a. The farming systems trial: celebrating 30 years. 21 pp. https://rodaleinstitute.org/our-work/farming-systems-trial/farming-systems-trial-30-year-report/.

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

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

Rosenzweig, C. 1985. Potential CO_2-Induced Effects on North American Wheat Producing Regions. *Climatic Change,* 7, 367-389.

Ryals, R., and W.L. Silver. 2012. Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. *Ecological Applications,* 23(1), 46–59.

Royo-Esnal, A., and F. Valencia-Gredilla, 2018. Camelina as a rotation crop for weed control in organic farming in semiarid Mediterranean climate. *Agriculture,* 8, 156.

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

Sanders J and J. Hess (Eds), 2019. Leistungen des ökologischen Landbaus für Umwelt und Gesellschaft . Braunschweig: Johann Heinrich von Thünen-Institut, 364 p, Thünen Report 65. Accessed May 2, 2019 at: https://www.thuenen.de/media/publikationen/thuenen-report/Thuenen_Report_65.pdf

Sanderson, M. & Paul Alder. 2008. Perennial Forages as Second Generation Bioenergy Crops. *International Journal of Molecular Sciences,* 9, 768-788.

SARE (Sustainable Agriculture Research & Education) 2006. Smart Water Use on Your Farm or Ranch. Available at http://www.sare.org/publications/water/water.pdf

Schahczenski, J., 2018. Biochar and Sustainable Agriculture. USDA ATTRA https://attra.ncat.org/attra-pub/download.php?id=322.

Schmidt et al., 2011. Persistence of soil organic matter as an ecosystem process. *Nature,* 478:49-56.

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.

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.org. 78 pp.

Searchinger T, R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, & T. Yu. 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions From Land-Use Change. *Science,* 31: 1238-1240.

Sesser, K.A., Reiter, M.E., Skalos, D.A., Strum, K.M. and Hickey, C.M., 2016. Waterbird response to management practices in rice fields intended to reduce greenhouse gas emissions. *Biological Conservation,* 197, 69–79.

Sesser KA, Iglecia M, Reiter ME, Strum KM, Hickey CM, Kelsey R, et al., 2018. Waterbird response to variable-timing of drawdown in rice fields after winter-flooding. *PLoS ONE,* 13(10), e0204800. https://doi.org/10.1371/journal.pone.0204800

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. *Science of the Total Environment,* 468–469: 553–563.

Smit, B., L. Ludlow, and M. Brklacich. 1988. Implications of a global climatic warming for agriculture: A review and appraisal. *Journal of Environmental Quality*, 17 (4), 519-27. http://ciesin.columbia.edu/docs/004-144/004-144.html.

Smukler, S. M., Sánchez-Moreno, S., Fonte, S.J., Ferris, H., Klonsky, K., O'Geen, A.T., Scow, K.M., Steenwerth, K.L., Jackson, L.E. 2010. Biodiversity and multiple ecosystem functions in an organic farmscape. *Agriculture, Ecosystems & Environment,* 139, 80-97.

Sovacool, B., 2008. Valuing the greenhouse gas emissions from nuclear power: A critical survey. *Energy Policy,* 36, 2950-2963.

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.

Steinfeld H, P. Gerber, T. Wassenaar, V. Castel, M. Rosales & C. de Haan. 2006. Livestock's long shadow: Environmental issues and options. U.N. Food and Agriculture Organization.

Stewart, T. and M. Glantz, 1985. Expert Judgment and climate forecasting: A methodological critique of "Climate Change to the Year 2000". *Climatic Change,* 7, 159-183.

Sudmeyer, R., 2018. Carbon farming: reducing methane emissions from cattle using feed additives. Department of Primary Industries, Government of West Australia. Accessed 4/29/2019 at: https://www.agric.wa.gov.au/climate-change/carbon-farming-reducing-methane-emissions-cattle-using-feed-additives

Suddick, E. C., Scow, K. M., Horwath, W., Jackson, L. E., Smart, D. R., Mitchell, J., & Six, J. 2010. The Potential for California Agricultural Crop Soils to Reduce Greenhouse Gas Emissions. A Holistic Evaluation. *Advances in Agronomy,* 107(C), 123-162. https://doi.org/10.1016/S0065-2113(10)07004-5

Swan et al. 2019. "COMET-Planner: Carbon and greenhouse gas evaluation for NRCS conservation practice planning" http://comet-planner.nrel.colostate.edu/COMET-Planner_Report_Final.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. *Journal of Soil and Water Conservation,* 71(2), 156-164.

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

Thorne, P.S. 2007. Environmental health impacts of concentrated animal feeding operations: anticipating hazards – searching for solutions. *Environmental Health Perspectives,* 115, 296-297.

Thorup-Kristensen, K., and C. R. Rasmussen. 2016. Identifying new deep-rooted plant species suitable as undersown nitrogen catch crops. *Journal of Soil and Water Conservation,* 70(6), 399-409.

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. *Ecology Letters,* 18(8), 761–771.

Tilman D., J. Hill & C. Lehman. 2006. Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass. Science 314: 1598-1600; Fargione, J., J. Hill, D. Tilman, S. Polasky & P. Hawthorne. 2008. Land Clearing and the Biofuel Debt. *Science,* 319, 1235-1237.

Toensmeier, E. 2016. *The Carbon Farming Solution: A Global Toolkit of Perennial Crops and Regenerative Agriculture Practices for Climate Change Mitigation and Food Security.* Chelsea Green Publishing, White River Junction, VT.

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. *Journal of Environmental Quality,* 45, 1812-1821.

U.S. Congress, 2018. Agriculture Improvement Act of 2018, House Resolution 2. Public Law 115–334: (115th Congress).

USDA, 2019. USDA Agricultural Projections to 2027. Office of the Chief Economist, World Agricultural Outlook Board, U.S. Department of Agriculture. Prepared by the Interagency Agricultural Projections Committee. Long-term Projections Report OCE-2018-1, 117 pp. Accessed 4/29/2019 at: https://www.usda.gov/oce/commodity/projections/

USDA NOP (2019) National Organic Program Final Rule, Accessed 4/29/2019 at: https://www.ams.usda.gov/rules-regulations/organic.

USDOE (Department of Energy), n.d. Small Wind Guidebook. Available at https://windexchange.energy.gov/small-wind-guidebook

USDOE (Department of Energy), 2016. Environment Baseline, Volume 1: Greenhouse Gas Emissions from the U.S. Power Sector. Available at: https://www.energy.gov/sites/prod/files/2017/01/f34/Environment%20Baseline%20Vol.%201--Greenhouse%20Gas%20Emissions%20from%20the%20U.S.%20Power%20Sector.pdf

USDOE (Department of Energy), 2019. Solar Energy in Agriculture — Resources. Available at: https://farm-energy.extension.org/solar-energy-in-agriculture-resources/

U.S. EPA. 2009. EPA Lifecycle Analysis of Greenhouse Gas Emissions from Renewable Fuels. Available at: http://www.epa.gov/oms/renewablefuels/420f09024.htm.

U.S. EPA. 2017. Pesticide Industry Sales and Usage. 2008-2012 Market Estimates. Available at: https://www.epa.gov/sites/production/files/2017-01/documents/pesticides-industry-sales-usage-2016_0.pdf

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

USGCRP, 2000. Climate Change Impacts on the United States, Available at: https://www.globalchange.gov/browse/reports/climate-change-impacts-united-states-potential-consequences-climate-variability-and-3

USGS (U.S. Geological Survey), 2008. Carbon Sequestration to Mitigate Climate Change (Fact Sheet 2008- 3097). Available at http://pubs.usgs.gov/fs/2008/3097/pdf/CarbonFS.pdf

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

Walter, C., P. Merot, B. Layer, and G. Dutin. 2003. The effect of hedgerows on soil organic carbon storage in hillslopes. *Soil Use and Management,* 19(3), 201-207.

Wander, M. M., S. J. Traina, B. R. Stinner, and S. E. Peters. 1994. Organic and Conventional Management Effects on Biologically Active Soil Organic Matter Pools. *Soil Science Society of America Journal,* 58, 1130-1139.

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

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

West, T.O., and W.M. Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. *Soil Science Society of America Journal,* 66(6), 1930–1946.

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

Wilhelm, J. M. F. Johnson, D. L. Karlen & D. T. Lightle. 2007. Corn Stover to Sustain Soil Organic Carbon Further Constrains Biomass Supply. *Agronomy Journal,* 99, 165-1667.

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

Wolfe, B. E., and J. N. Klironomos. 2005. Breaking new ground: soil communities and exotic plant invasion. *BioScience,* 55(6), 477-487.

Worstell, J., & J. Green. 2017. Eight Qualities of Resilient Food Systems: Toward a Sustainability/Resilience Index. *Journal of Agriculture, Food Systems, and Community Development,* 7(3), 23-41.

Wuest, S. B., and C. L. Reardon. 2016. Surface and root inputs produce different carbon/ phosphorus ratios in soil. *Soil Science Society of America Journal,* 80, 463-471.

Xixi, L., Norman H. C., Kinley R., Laurence M., Wilmot M., Bender H., de Nys R., Tomkins N. 2016 Asparagopsis taxiformis decreases enteric methane production from sheep. *Animal Production Science,* 58, 681-688. https://doi.org/10.1071/AN15883

Yarwood, S. 2016. Agricultural Greenhouse Warming Potential and Carbon Sequestration in Organic and Long-term Rotational Systems. Proposal and progress report for ORG project 2012-02977. CRIS Abstracts.*

Zhang, Z., N. Zimmermann, A. Stenke, X. Li, E. Hodson, G. Zhu, C. Huang, and B. Poulter. 2017. Wetland methane emissions in future climate change. *Proceedings of the National Academy of Sciences,* 114, 9647-9652; DOI: 10.1073/pnas.1618765114

*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.

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