Increasing Soil Health and Sequestering Carbon in Agricultural Soils

A Natural Climate Solution

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Table of Contents

2.3 Convert cropland to herbaceous or woody cover (cont.)

Part 5. Conclusions and Recommendations

Executive Summary

Farm publications are full of articles about soil health, and with good reason. Recent advances and field trials show rewards for farmers who rebuild the health of their soils, along with numerous environmental co-benefits. Because extensive degradation of our nation's soils jeopardizes agricultural productivity and food security, immediate action to rebuild soil health is a national imperative.

In addition, America's farmers and ranchers are already experiencing the impacts of climate change as altered seasonal patterns of temperature and precipitation complicate planting and harvesting and increase financial risk. Healthy soil reduces that risk.

Curbing climate change will be facilitated by actions that remove carbon dioxide from the atmosphere and store it safely. One strategy that is economical and available now is to use the power of plants to remove carbon from the atmosphere and sequester it in agricultural soils and woody plants.

This reports outlines a set of evidence-based agricultural management practices that increase soil carbon sequestration. Widespread adoption of these practices will help increase agricultural productivity, improve water quality, add habitat for wildlife and benefit farmers economically. By using these practices to improve soil health, agriculture not only becomes more resilient, it also becomes part of the climate solution.

Soil Health and Climate Change

The Earth's soil can store over twice the amount of carbon found in the atmosphere. Yet in just 150 years, agricultural soils worldwide have lost a large fraction of this sequestered carbon as a result of agricultural practices that leave soil unprotected from erosion and the microbial decomposition of protected organic material.

Global losses of soil carbon following land conversion to agriculture comprise about 20% of all historical carbon emissions caused by humans. Fortunately, with better agricultural practices we can regain some of that carbon as we rebuild the soil.

Soil is more than just 'dirt.' It comprises an entire ecosystem of microscopic organisms, plants, and animals. In the soil, untold multitudes of bacteria and fungi perform crucial ecosystem functions. These microbes provide plants with water and key nutrients and even protect them from pests and disease. They are critical to both soil health and carbon sequestration.

Soil Health Principles and Practices

The U.S. Department of Agriculture has identified four soil health principles that work because they either protect the habitat of soil organisms from disturbance or erosion or they feed those organisms, increasing their abundance and diversity. The management practices that sequester carbon in soil each exemplify one or more of these four principles:

- Minimize disturbance of the soil, both physical and chemical.
- Keep the soil covered with living plants or crop residue.
- Maximize biodiversity both above and belowground.
- Maximize continuous living roots to provide a year-round food source for soil microbes.

This report details 24 USDA-approved practices that each use one or more of these principles to increase soil health and store carbon in the soil, and provides the expected greenhouse gas impacts of each practice.

Some of these practices are used on cropland, such as reducing or eliminating tillage, planting cover crops, using diverse crop rotations, nutrient management, and mulching.

Other practices involve the addition of areas of perennial vegetation, usually at the edges of fields or on marginal cropland. These practices filter the water that runs off agricultural fields, improve soil health, and sequester carbon: grass filter strips, buffer strips, grass waterways, converting cropland to pasture, shrub and tree planting, hedgerows, riparian forest buffers and multistory cropping. Agroforestry practices such silvopasture and alley cropping are also discussed, as are practices used on grazing lands such as range planting, silvopasture, and prescribed rotational grazing.

Economic and Environmental Benefits

For farmers and ranchers, building soil health with these conservation practices improves nutrient cycling and protects plants from disease. These practices reduce water and temperature stress on crops by boosting water infiltration and water-holding capacity, increase crop and livestock productivity and reduce the need for costly inputs. Increasing soil health also stabilizes yields over time, which helps buffer farmers against the variation in weather that is becoming more common under climate change.

The economic value of healthy soil to farmers has been estimated to be between $40 and $140 per acre, depending on the situation.

Evidence from farmer surveys reveals that using the practices we discuss routinely saves farmers money on costly inputs like fertilizer, fungicides, pesticides, fuel, equipment maintenance and labor.

The environmental benefits of these carbon-sequestering practices extend well beyond the farm, and are of value to all Americans. They include boosting soil health, reducing erosion, improving the quality of surface and coastal waters, increasing biodiversity and sustaining wildlife.

Increasing Adoption Rates of the Recommended Practices

Despite the economic and environmental benefits of the carbon-sequestering management practices discussed in this report, adoption rates remain low. We have made large investments in research on soil health and carbon sequestration over the past few decades. However, unless we can encourage widespread adoption of the recommended practices, the benefits of that research and important opportunites to improve soil health and act on climate change will be lost.

The potential for even small economic losses during the transition to a new management can be a clear deterrent to adoption when margins are slim. In that setting, federal and state incentives for the use of soil health practices are crucial. In addition, various social and psychological barriers often prevent farmers from wanting to adopt new practices. To be successful in the face of these barriers, outreach programs must not only offer the best scientific information available, but must also consider the social and psychological issues that may surround decisions about management strategies in different farming communities.

This report discusses effective outreach strategies that can be used to discover and remediate these barriers to change.

Key Recommendations

The time is right to promote soil health and carbon sequestration in agriculture as a cost-effective natural climate solution. The recommendations detailed in the last section of this report include:

1. Make soil health a central focus of USDA programs.

2. Boost efforts to increase soil health and carbon sequestration at all governmental levels.

3. Build soil health education and outreach programs that will increase adoption of the recommended practices.

4. Expand the capacity to deliver accurate and up to date technical assistance on soil health and carbon sequestration practices.

5. Expand existing incentive programs and develop and fund new ones to ease the transition to carbon-sequestering management practices.

6. Increase equity and inclusion in USDA programs; make outreach results more accessible.

7. Establish a National Soil Monitoring Network for organizing the detailed soil testing required for tracking impacts of management on soil health and soil carbon sequestration.

8. Fund regular soil testing by farmers at a field level to monitor changes in soil health.

9. Increase the availability of USDA data for research purposes.

10. Increase funding for key research in soil health and carbon sequestration.

By increasing the adoption of carbon-sequestering farming practices nationwide, agriculture can become a significant part of the American climate solution.

Introduction

America's farmers and ranchers are on the front lines of our changing climate. Changes in seasonal patterns of temperature and precipitation[1,3] increase financial risk and require adjustments to traditional management strategies . Significant weather-related disasters are increasing[2] as scientific evidence accumulates that climate change is playing a major role.[3,4] Drought, fire, floods, and violent storms now routinely affect farms in every part of the country, causing billions of dollars in agricultural losses.[1-3]

Overlaid on these devastating impacts of climate change, the extensive degradation of our nation's soils jeopardizes agricultural productivity and food security, making immediate action to rebuild soil health a national imperative.

This report provides evidence-based recommendations for agricultural management practices that can address both of these problems. Widespread adoption of the recommended practices will not only help curb climate change but will also rebuild soil health, increase agricultural productivity, help the environment, and benefit farmers economically.

Rebuilding the carbon stocks in agricultural soils is recognized as an important "natural climate solution"[5] that complements direct efforts to reduce greenhouse gas (GHG) emissions. Because healthy soil helps farmers to manage water in both flood and drought conditions, improving soil health is also recognized as a key strategy to increase climate resilience in agriculture.[6]

The accelerating severity of climate impacts touches every sector of the economy, damages human health and welfare, and reduces the stability of ecosystems, making the reduction of atmospheric levels of carbon dioxide and other greenhouse gases increasingly urgent.[7] **Management practices that sequester carbon in the soil can make agriculture part of the climate solution.**

The four main parts of this report put these issues into context, present the many co-benefits of the practices, explore how to increase their adoption and lay out a slate of recommended agricultural practices for carbon sequestration.

Part 1: Soil health and climate change: related problems and solutions. The links between agricultural soil degradation and climate change are considered and soil carbon sequestration in soil as a natural climate solution is discussed. Part 1 also includes a basic primer on soil health and the biological mechanisms of carbon sequestration in soils.

Part 2: Evidence-based practices for carbon sequestration in agricultural soil. A set of science-based agricultural management practices for sequestering carbon is provided. Some of these practices also reduce GHG emissions from fuel and other inputs such as fertilizer and agricultural chemicals. Each recommended practice and its potential contribution to GHG reduction is briefly outlined, with additional details provided for major practices or those considered to be somewhat controversial.

Part 3: Environmental and economic co-benefits of carbon sequestration in agriculture. The recommended agricultural practices have significant co-benefits that add to their value. Most carbon-sequestering practices also improve water quality in streams, rivers and coastal areas, control stormwater, curb erosion, and/or allow the reduced use of synthetic nitrogen fertilizer, pesticides or herbicides. Many of the practices also increase the diversity and vitality of the soil microbial community and some benefit pollinators or increase other types of biodiversity. The economic co-benefits of the recommended practices can also be appreciable, further increasing their value.

Part 4: Increasing adoption of the recommended practices. To fully realize the potential of these carbon-sequestering agricultural practices, they must be widely used. This requires understanding how farmers view both the barriers to making management changes and the benefits of those changes. By applying some fundamental principles of behavior change from the social sciences, we can gain this understanding and design compelling and effective outreach programs.

Part 5: Recommendations. Key ideas from the report are condensed into a set of 10 recommended actions designed to Increase the nation's potential for carbon sequestration in agricultural soils. The recommendations span suggestions for new programs at the state, local and tribal levels, ideas for improved education of agricultural advisors of all types, outreach strategies to address barriers to practice adoption, and a list of key research needs.

We hope that this report will contribute to the growing understanding of soil health as both a natural climate solution and the key to climate resilience in agriculture.

Part 1.

Soil Health and Climate Change: Related Problems and Solutions

Photo: Ron Nichols

1.1 Soil degradation and the climate problem

Global soils are in a crisis situation. The Earth's soil can store over twice the amount of carbon found in the atmosphere.[8] In just 150 years, however, global soils converted to agriculture have lost a large fraction of their stored carbon as a result of agricultural practices that leave soil unprotected from degradation and erosion.[9,10,11] Much of the carbon lost from agricultural soils has been relocated by wind or water erosion, and tons of sediment from prime agricultural land now clogs waterways and is deposited in coastal deltas. Global losses of soil carbon following land conversion to agriculture comprise approximately 20% of all historical carbon emissions caused by humans.[12]

The rich agricultural soils of the United States took tens of thousands of years to develop below native grasslands, prairies and forests. Conversion of native forests and grasslands from sustainable management by Native American tribes to the agricultural methods of European settlers caused massive soil erosion and robbed native soils of their natural fertility. In particular, the routine use of tillage led to large losses of soil organic carbon from erosion and microbial decomposition.[8-11]

Depending on the soil type and local conditions of temperature and humidity, from 42-65% of the carbon in native soil is lost to tillage in the first 50 years after land conversion to agriculture,[8,11,13] with the largest declines occurring in the first 5-10 years.[11-13]

This loss of soil organic carbon after land conversion is clearly shown in an analysis of soil carbon in paired soil samples from native and agricultural sites (forests, grassland and savanna vs nearby cropland or grazing sites).[10] If samples from native and agricultural soils had equal soil organic carbon (SOC), the data points in **Figure 1** would fall symmetrically around the diagonal line. Instead, the data points are consistently below the diagonal, indicating that most soil samples from agricultural lands contain less carbon than do samples taken from nearby undisturbed native sites.

Although the practices used in conventional agriculture have produced high yields for many years, these yields are not sustainable and have come at a cost. Global agricultural soils are now so degraded that the ongoing production of sufficient healthy and nutritious food is in question, particularly in view of the additional stress on food systems from human population growth during the 21st century.[14] Recognizing this problem, the Food and Agricultural Organization of the United Nations designated 2015 as the Year of the Soil to highlight the critical need for global programs to improve soil health. In the United States, although sophisticated plant breeding and highly advanced agricultural technology have produced consistent yield increases, that success has only masked the underlying soil degradation.

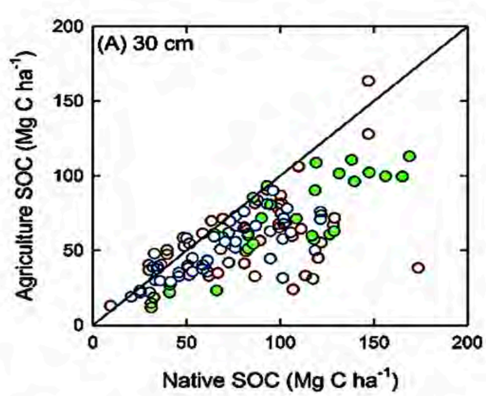

Figure 1. *Soil organic carbon (SOC) for paired native vs. agricultural comparisons. The clustering of points below the diagonal line shows that there is less soil carbon in most cropping or grazing lands than in nearby undisturbed forest (red symbols), grassland (green symbols) or savanna (blue symbols). The same general pattern was seen at 100 cm. Source: Ref. 10, Supplementary Information. Used with permission.*

Healthy soil not only nurtures plants but also buffers the impacts of more frequent and severe flooding and drought under climate change, making increasing soil health a crucial agricultural priority.[6] However, rebuilding degraded soil is a complex process that takes time and depends both on regional climate and local soil types.[15,16,17] Crucially, efforts to rebuild the soil also depend on communicating the benefits of healthy soil effectively enough to motivate farmers to change management strategies that may have been used for decades, even generations.[18,19]

The nature of the climate problem. At the same time that land conversion from forests and grasslands to agriculture was increasing in the United States in the 1800s, the Industrial Revolution was revealing the tremendous benefits of burning fossil fuels for energy. Burning coal began an unprecedented increase in CO_2 emissions from human activities (green line in **Figure 2).** Adding emissions from petroleum products (blue line in Figure 2) led to an acceleration of total CO_2 emissions around 1950 (black line in Figure 2). The growing use of natural gas after that time (red line on Figure 2) continued the upward emissions trend.

Human activities have also caused exponential increases in emissions of two other potent greenhouse gases, methane (CH_4) and nitrous oxide (N_2O). Higher methane emissions began with an increase in animal agriculture and waste as human population size increased[20] and has accelerated with the use of natural gas as a fuel. The initial rise in nitrous oxide emissions began with land conversion to agriculture in the late 1800s then accelerated with the increasing use of synthetic nitrogen fertilizer in the 1940s.

In 2013, the atmospheric concentration of CO_2 exceeded 400 parts per million (ppm) after remaining below 300 ppm for 800,000 years, a period encompassing all of human history (**Figure 3**). By 2020, the atmospheric CO_2 concentration was nearly 415 ppm, and it is still rising exponentially. The current level of atmospheric CO_2 is so much greater than the highest values seen in the previous 800,000 years that it cannot be part of that natural cycle. There must be other driving forces.

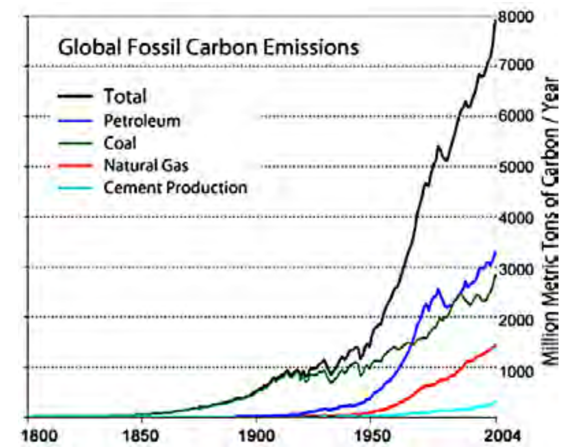

Figure 2. *Carbon emissions over time caused by burning coal, petroleum or natural gas and cement production. The black line is the sum of the emissions from all sources, illustrating the exponential increase in atmospheric CO_2 attributable to human activities; this does not include the additional CO_2 released after land conversion to agriculture. Source: Mak Thorpe, CC BY-SA 3.0 via Wikimedia Commons. Data from https://cdiac.ess-dive.lbl.gov/trends/emis/glo.html#*

The increasing concentrations of CO_2, methane and nitrous oxide in the atmosphere from human activities are those other drivers. The close correspondence between the exponential increase in total atmospheric CO_2 (Figures 2, 3) and the increasing combustion of coal, oil and gas in the 20th century (Figure 2) is the indelible human fingerprint on climate change.

Why atmospheric concentrations of CO_2 and other greenhouse gases matter. Every day the Sun's rays warm the Earth. For the atmosphere to remain at a roughly constant temperature, this heat gain must be balanced by heat loss through the radiation of infrared (heat) waves from Earth back to space. Certain atmospheric gases have special properties that interfere with the heat waves as they move through the atmosphere, slowing heat loss. When the concentrations of these atmospheric gases increase, the rate of heat loss slows and the atmosphere warms. Although the mechanism differs, this outcome is similar to the accumulation of heat that occurs in a sunny greenhouse when the glass interferes with the escape of heat waves.

Figure 3. *Over the past 800,000 years, the CO_2 concentration in the atmosphere has gone through regular cycles, as measured in ancient air extracted from Antarctic ice cores. The processes producing these cycles cause the periodic ice ages. However, the rapid increase in CO_2 levels in the past 150 years cannot be part of this natural cycle because the current CO_2 concentration is so much greater than the previous maximum of 300 ppm. Source: NOAA climate.gov.*

This is why the process leading to atmospheric warming is called the "Greenhouse Effect" and the gases that slow atmospheric heat loss are called "greenhouse gases" (GHGs). Anyone who has returned to a car after a few hours in a sunny parking lot has first-hand experience of the warming power of the greenhouse effect.

The main GHGs in the atmosphere are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and water vapor. Their heat-trapping impacts through the greenhouse effect are nothing new. The Earth's atmosphere has always contained a low concentration of GHGs. In fact, billions of years ago these gases facilitated the evolution of life on Earth by retaining some of the heat generated by the Sun overnight, preventing temperatures from plunging after sunset. Now, however, current GHG concentrations records exceed prehistoric levels by so much that excessive atmospheric warming is producing a dangerous cascade of changes in the climate.[1,3]

Long term temperature records clearly document increases in the global average air temperature, which already exceeds preindustrial levels by over1° C (**Figure 4**). Without the advent of some new driving force, yearly temperatures would have simply varied around the more-or-less constant average seen in the late 1800s. Instead, the data show clear and consistent warming, particularly after about 1970. As of 2020, all 20 of the 20 hottest years since 1884 have occurred since the year 2000 (visible on Figure 4).

Although this rapid increase in the global average air temperature is remarkable, it represents just a fraction of the extra heat retained in the atmosphere from the buildup of greenhouse gases. Over 93% of this extra atmospheric heat has been absorbed by the ocean,[21] mediating a wide range of impacts. More sea water is now evaporating from the warming ocean, increasing humidity and making more water available for rainstorms. The warming air and

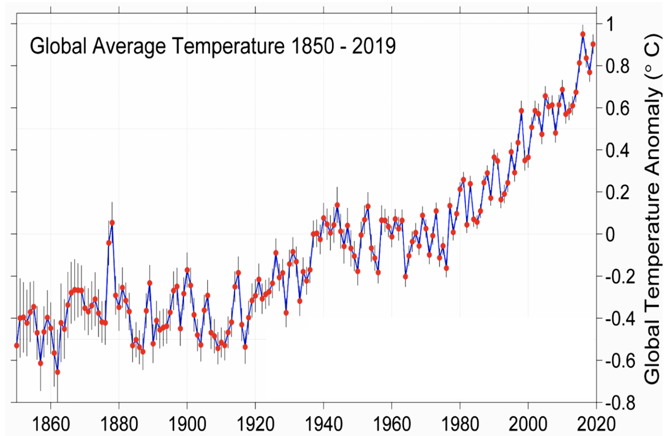

Figure 4. *Annual global average temperature since 1850 (red dots). The scale is the difference in temperature relative to the average between 1951-1980. Despite year-to-year variation due to weather cycles, the steady warming trend since about 1970 is clear. The years 2015-2019 are the hottest since 1850, and all are more than 1°C over the preindustrial levels of the mid-1880s. Source: Berkeley Earth.*

ocean also affect the strength and pattern of global winds and ocean currents.[21]

The overall impacts of climate change on human populations and all of biodiversity are now undeniable.[1-3] **Each year, the need to reduce the emissions of GHGs and lower their concentrations in the atmosphere becomes more urgent**.[7]

The longer that meaningful GHG reductions are delayed, the faster and more painful the required rate of emission reductions will be. If emissions continue on the current exponential trajectory (red lines in Figure 5), global temperatures may rise as much as 4° C from preindustrial levels by 2100 (**Figure 5**, right).[1,3] To hold global temperature increase to 2°C, which most scientists regard as the

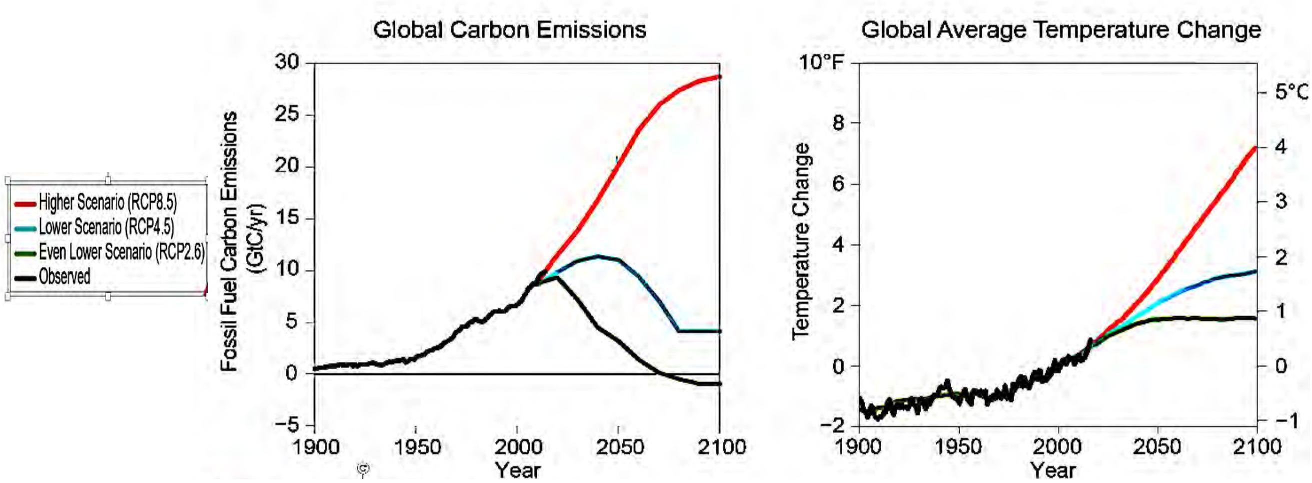

Figure 5. ***Left:*** *Annual global carbon emissions projected to 2100 under different scenarios.* ***Right:*** *Projected global temperature increase for each emissions scenario. For both, observations up to 2018 shown in black. The "Higher Scenario" (red line) shows projected emissions if no climate action is taken ("business-as-usual"), resulting in a projected temperature increase of 4°C by 2100. In contrast, the lowest emissions scenario (green line on left panel) will result in only about a 1°C rise in global mean temperature but requires immediate and stringent emissions reduction. The shaded areas represent the range of temperatures within which the temperature reached for a given scenario is expected with 95% certainty. Source: Ref. 3.*

upper limit to avoid serious impacts, emissions must peak by 2050 (the "Lower Scenario", turquoise lines in Figure 5). Keeping the temperature increase to 1.5ºC or below, as many have urged,[7] requires immediate and significant emissions decreases (the "Even Lower Scenario", green lines in Figure 5).

Economic benefits of acting now to limit future climate change. The impacts of climate change on our economy as well as on our society are becoming severe. For example, the number of climate-related disasters costing over $1 billion is rapidly increasing, along with the price tag. Since 1980, the six years with the most billion-dollar disasters have all been since 2005, and the 263 billion-dollar disasters from 1980-2019 cost > $1.85 trillion.[2] Not only do these disasters result in the loss of life and property, they exact an enormous social toll from physical and psychological suffering that can affect survivors for decades.[22] **Without significant climate action, the incidence of costly disasters and the human suffering they produce will continue to increase.[1]**

Unchecked climate change threatens the US economy. In 2018, the annual price tag for climate impacts in the US by 2090 was estimated at $285-508 billion.[3] Even modestly limiting emissions by following the RCP 4.5 scenario ("Lower Scenario", Figure 5) rather than remaining on the RCP 8.5 trajectory could reduce damages by 22-68% (shaded sections on **Figure 6**).[3] Other models of the economic risks of climate change suggest that limiting global temperature increase to 1.5ºC rather than 2ºC by stringently limiting emissions now could save global economies US $20 trillion (in 2010 dollars).[23]

In 2017, the recognition that climate change poses a significant financial risk to the global economy inspired eight central banks to form the Network for Greening the Financial System (NFGS), which grew to a global membership of 34 central banks by 2019. In a recent report, NFGS documented the climate risks to the financial system and made a number of recommendations for how the global financial system can become more resilient to climate change.[24] In 2020, the US Federal Reserve joined the NFGS and added a discussion of climate risk to its annual Financial Stability Report for the first time.[25]

Economists now increasingly express the view that it is cheaper to move toward a low-carbon economy than it is to continue with business as usual and suffer the social consequences and enormous cost of climate disasters.[26] One report even stresses that the overall economic risk of climate change is likely to be underestimated because the economic impact of some aspects of climate change are difficult to measure.[27]

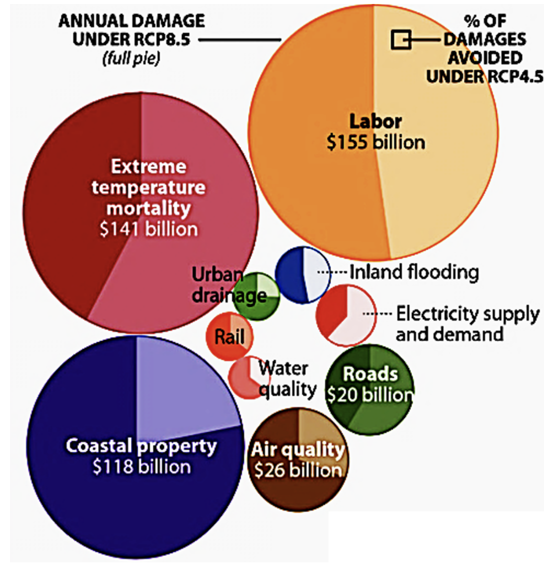

Figure 6. *Estimated annual climate-related costs to different sectors by 2090 under business as usual (RCP 8.5). The size of each circle is proportionate to the expected cost. The decrease in damages under a lower emissions scenario (RCP 4.5) is shown in the lighter colored wedges as a percentage of the expected 2090 damage if we continue on the current emissions trajectory (RCP 8.5). Source: Ref.3 and Inside Climate News.*

Climate inaction is often justified by saying that transitioning to a low-carbon economy is too expensive. The deep concerns of economists now refute that argument.

Escalating climate impacts raise the social cost of carbon, making climate action more valuable. Valid cost/benefit analyses of solutions to climate change rests on the monetary value of avoided emissions, that is, the total cost of societal damage caused by one metric ton of CO_2. This is commonly known as the "social cost of carbon" (SCC). Using the SCC in economic decisions makes cost-benefit analyses of climate action more realistic by including the full spectrum of costs from climate-related damages to health, property, employment opportunities, and other aspects of society.

Negative climate impacts on agriculture are highly likely to increase the SCC, because crops will be adversely affected by rising temperatures, both directly and by increasing moisture stress when high temperatures dry the soil.[1,6] A recent meta-analysis of 56 studies suggests that a global temperature increase of 4ºC could lead to a 30-40% yield reduction in corn and wheat and nearly a 100% yield penalty in soybeans.[28] Such climate-related reductions in yield greatly increase the possibility of global food insecurity as the human population grows to 9 or 10 billion at the end of this century. The expected agricultural losses from unabated climate change are estimated to raise the social cost of carbon by 129%,[28] further motivating policies that accelerate GHG reduction and carbon sequestration.

Curbing climate change requires "negative emissions".

The current global plan to reduce climate change, the 2015 Paris Agreement, was coordinated by the United Nations Framework Convention on Climate Change (UNFCCC). The goal of this plan is to hold global temperature increase to less than 2ºC. Evaluating how that goal can be met involves a complex and detailed modelling effort, the Integrated Assessment Models (IAMs).[29,30,31] By comparing hundreds of different action scenarios, these models guide global policy decisions on climate change. According to current models, we must reach "net zero emissions" before 2090 in order to have a 66% chance of keeping global temperature rise below 2ºC,[30] or by 2050 to limit temperature increase to 1.5ºC.[1]

Because some emissions are currently assumed to be too expensive or disruptive to reduce (i.e., from airline travel, land conversion, and agricultural practices including domesticated animal production),[30] "net zero" is the point at which the ongoing anthropogenic emissions are balanced by actions that remove carbon dioxide from the atmosphere, that is, "negative emissions".[30] In order to reach net zero before 2090, the Integrated Assessment Models reveal that substantial negative emissions must begin by 2030 (**Figure 7**).[30] To reach net zero by 2050, emissions must be slashed immediately.[1]

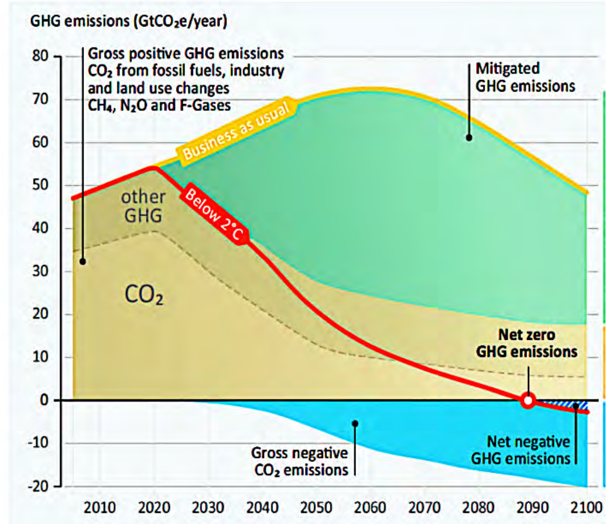

Figure 7. *In order to curb climate change, mitigation efforts to reduce human-caused GHG emissions (the green area) must be complemented by strategies that remove carbon already in the atmosphere causing "negative emissions", which are shown as the blue wedge. Because it is currently assumed that not all GHG emissions can be mitigated, negative emissions must begin before 2030 and increase through to the end of the century and beyond. Source: Ref. 30.*

Negative emissions through natural climate solutions: promises and limitations.

Most of the current methods for producing negative emissions are land-based (**Figure 8).** These involve the removal of atmospheric carbon dioxide by plants through photosynthesis and either the sequestration of the naturally captured carbon in trees or soil or the underground storage of CO_2 that is captured after biomass combustion. In addition, methods to increase the absorption of atmospheric CO_2 onto naturally occurring rock are also under development.[32,33] These land-based strategies are sometimes called "natural climate solutions".[5] In contrast, technologies that capture carbon dioxide directly from the air remain at early stages and are unlikely to be affordable and widely available for at least a decade.[30]

The process of land-based carbon sequestration starts when plants absorb carbon dioxide (CO_2) from the air, water (H_2O) from the soil and energy from the sun. The chemical reactions of photosynthesis then reconfigure those carbon (C), hydrogen (H), and oxygen (O) atoms into sugar molecules ($C_6H_{12}O_6$). Only a small fraction of the

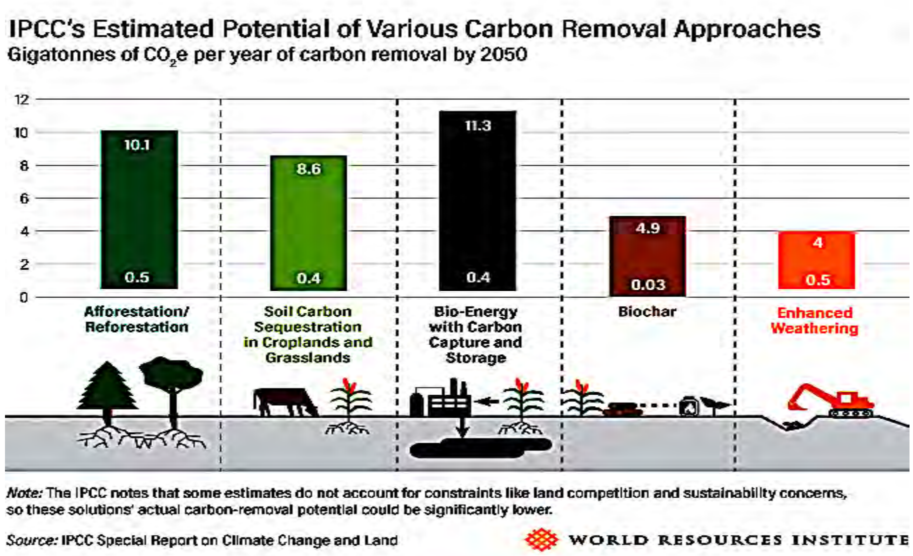

Figure 8. *Five land-based strategies for carbon removal from the atmosphere, with the likely range of global GHG reduction, as outlined by the IPCC.*[23]
Source: https://www.wri.org/blog/2019/08/how-effective-land-removing-carbon-pollution-ipcc-weighs

carbon in this sugar will be sequestered in the soil. Most is used for plant growth, reproduction and maintenance or is passed through roots to soil microbes. The microbes use this sugar for their growth and reproduction, releasing some of the carbon back into the air as CO_2 from their respiration. The small fraction of photosynthetic carbon that is eventually sequestered is either physically or chemically protected from microbial consumption through processes described in more detail in **Section 1.2**.

It is important to note that carbon in the stalks, leaves and roots of crops or other non-woody plants rarely becomes part of the sequestered fraction. Those plant parts will generally be eaten or will rapidly decompose. In contrast, in woody plants like trees and shrubs, some carbon is stored in the wood of the living plant. When the tree or shrub dies, however, the wood decomposes and the carbon it contained returns to the atmosphere as CO_2 unless the wood is used in building or in some other durable product.
The relative global potential of five land-based negative emissions strategies was recently addressed in comprehensive reports from both the National Academy of Sciences[30] and the IPCC[31] (Figure 8).

The natural climate solutions are:

• ***Forestry-based: Afforestation*** (establishment of forest by planting and/or deliberate seeding on land that was not previously classified as forest), ***Reforestation*** (re-establishment of forest through planting or deliberate seeding on land already classified as forest), and ***Changes in forest management*** (adoption and maintenance of management methods that increase carbon storage).

• ***Soil carbon sequestration in croplands and grasslands***. These methods are the topic of this report and are described fully in **Part 2**.

• ***Bio-Energy with Capture and Storage (BECCS).*** In this method, energy is produced from waste biomass or purposely grown woody or herbaceous feedstocks. This biomass is either combusted to produce electricity or fermented to produce liquid fuel such as ethanol. Carbon dioxide resulting from combustion will be liquified and stored underground or used to enhance removal of crude oil. This method is assumed to be deployed on a very large scale in most Integrated Assessment Models,[30,31,35-37] even though strategies for storing liquid CO_2 below ground have not been tested at scale.[30]

• ***Biochar.*** Biochar is a high carbon byproduct of biomass combustion in BECCS or is produced using pyrolysis, then buried or crushed and applied to cropland as a long-term way to store carbon.[34]

• ***Enhanced rock weathering.*** During a process called weathering, silicate rocks such as basalts slowly dissolve in contact with soil, reacting with CO_2 to form carbonate that either remains in the soil or enters the groundwater. "Enhanced" weathering involves increasing the surface area of such rock by crushing and then applying it to cropland for large-scale CO_2 absorption.[32,33]

Each of these methods can contribute significantly to reducing atmospheric carbon. Each also has limitations, different costs and is at a different stage of readiness for large scale deployment. These benefits, limitations and costs are active topics of discussion.[30-34,35,36,37,38]

One common thread in this discussion is concern about the major dependence on future negative emissions from BECCS in current Integrated Assessment Models.[34,36,37] Another is that biochar and enhanced rock weathering are not ready for use now, althought may emerge as excellent strategies after sufficient study and demonstration trials.[30,32,33] Also, land-based negative emissions strategies are likely to interact in complex ways, and care must be taken to avoid unforeseen consequences that will interfere with sustainability goals.[30,37] Finally, there is wide agreement that it would be very helpful to ensure that going forward, all of the land-based negative emissions strategies are included in the Integrated Assessment Models.[34,37]

Carbon sequestration in agricultural soils is cost effective and available now. In sum, the current evidence suggests that afforestation, forest management, and soil carbon sequestration in agriculture are effective and well understood climate solutions that can be deployed immediately at a reasonable cost.[30,31,37] An excellent side-by-side comparison of the benefits, limitations and costs of the five land-based strategies[37] reveals that soil carbon sequestration positively affects both soil quality and food security while having the fewest negative side-effects.

As discussed below in **Part 3**, the agricultural practices that sequester carbon in the soil have multiple environmental co-benefits that increase their value. Increased adoption of the recommended practices will rebuild our soil, help clean and manage surface waters, and provide resilience to climate change,[6] ensuring that our nation's farms can continue to produce healthful food for future generations.

Despite overall enthusiasm about carbon sequestration in forests and agriculture, many involved in this discussion stress that negative emission strategies should not be viewed as a way to avoid immediate and significant reductions of all possible GHG emissions.[36,37] It is risky to justify weaker emission reductions in the present by assuming that sufficient negative emissions will be achieved by 2050 because the planned strategies may not all deliver the promised reductions. To ensure that our arrival at net zero before 2090 (or 2050) will be a reality and not just a hope, every available climate action must be taken without delay.

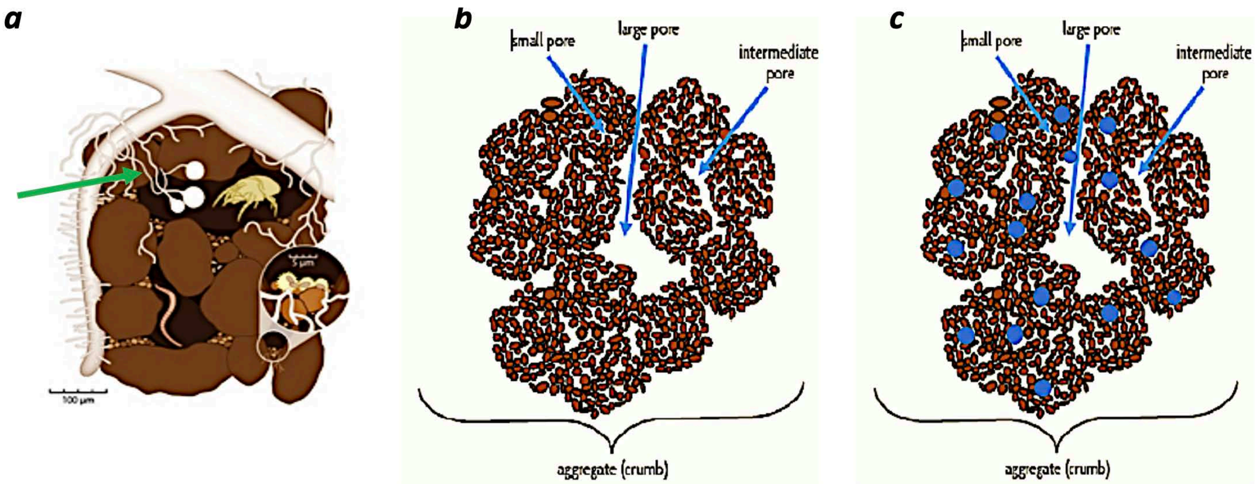

Figure 9. ***a.*** *Soil particles are held together by roots and fungal hyphae (white filamentous strands marked by green arrow). Several of the hyphae terminate in oval spores, the dormant form of mycorrhizal fungi. Multicellular organisms move around in the air and water spaces within and between soil aggregates, and tiny bits of humus (organic matter) are in the smallest spaces are protected from microbial decomposition.* ***b, c.*** *Structure of a soil aggregate showing pores of different sizes that allow infiltration and drainage (blue arrows) and water storage (blue dots). Sources:* ***a.*** *Fortuna, A. 2012. Soil Biota. Nature Education Knowledge 3(10)-1.* ***b*** and ***c*** *modified from Ref. 39.*

1.2 The biological mechanisms of soil health and carbon sequestration in the soil

The physical structure of healthy soil is made by and for soil organisms. Healthy soil is characterized by a specific aggregate structure that is built by soil organisms (**Figure 9**). This aggregate structure provides habitat for the soil food web and is the physical basis for the ecosystem functions of soil. A soil aggregate is a group of soil particles bound by roots, living fungal hyphae (the branching filaments that form the "body" of multicellular fungi), and sugary-sticky substances called glycoproteins exuded from plant roots and fungal hyphae.[39,40,41]

The natural glue that holds soil aggregates together is long-lasting and impervious to water, making soil aggregates water-stable and resistant to erosion.[39,42] An intricate system of pores within these aggregates is stabilized by this glue (Figure 9b, c). This stable system of pores in healthy soil provides the channels through the soil that are essential for water infiltration (**Figure 10).** They also maintain the water and air spaces that are essential for plant growth and provide essential habitat for underground soil organisms.

Tillage breaks down the aggregate structure of soil and its system of pores, essentially reducing soil to a collection of loose particles. These particles can be easily dispersed by raindrops to form a crust on the soil surface that reduces infiltration and causes water to pool or run off (Figure 10). Pooling on level soil can lead to compaction when heavy equipment is brought onto a field that is slow to dry, while runoff increases erosion and the loss of soil organic material. In this way, tillage produces a downward spiral of degradation through ongoing cycles of runoff, erosion and compaction.

In degraded soil, the loss of the protected spaces for water and air within soil aggregates also lowers the quality and availability of habitat for underground soil organisms, reducing the diversity and vigor of the soil food web and jeopardizing ecosystem function.

Healthy soil provides vital ecosystem services.

Healthy soil is not just the basis of productive agriculture, it affects every living creature by providing crucial ecosystem services. One hallmark of healthy soil is relatively high organic matter. This material includes plant residues, animal wastes and other remains of previously living things that fall onto the soil and decompose. Soil organic matter is crucial to soil health because it is the foundation for the soil food web[43,44] and the ecosystem services it provides.

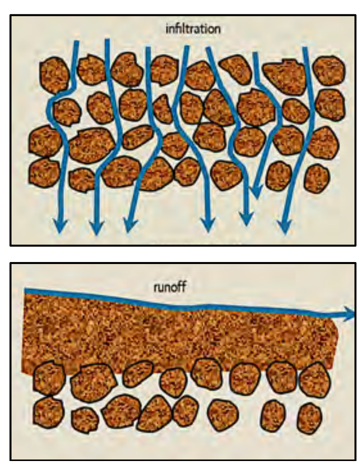

Figure 10. *Top: The aggregate structure of soil and its system of pores allows water to freely infiltrate. Bottom: After soil aggregates are broken by tillage, the remaining unorganized fine particles are dispersed by rainwater to form a crust that reduces infiltration, causing runoff and erosion. Source: Ref. 40.*

Two key ecosystem services provided by healthy soil and its organisms:

• **Water cycling and purification.** Soil aggregates and their pores are stable in water because the sticky glycoprotein exudates are water resistant and persist even after death of the roots or the fungal hyphae from which they came. This intricate pore structure controls water flow through the soil. Water infiltrates and flows through the large and intermediate-sized pores in and between aggregates (Figure 9b, blue arrows, Figure 10, top) while the smallest pores hold water for plants to use in drought periods (Figure 9c, blue dots). As water moves through the soil, it is filtered and purified by a combination of physical and biological forces (more detail below in **Part 3**). In degraded soil where the aggregate structure and its system of pores is collapsed, stormwater runs off and erosion carries valuable topsoil, organic material, excess fertilizer and agricultural chemicals into streams and groundwater.

• **Nutrient cycling.** The decomposition of organic matter in soil releases carbon, nitrogen, phosphorus, sulphur, and other nutrients that were tied up in previously living organisms. This allows these crucial nutrients to be "cycled", that is, taken up by plants and microbes and used again. The decomposition process starts with multicellular organisms on the soil surface like isopods and earthworms that shred plant and animal residue into progressively smaller pieces. These bits of partially decomposed material power the rest of the soil food web, including hundreds, maybe thousands of species of plant growth-promoting bacteria and fungi. Without a healthy and diverse soil food web, decomposition slows and the key nutrients needed for new plant growth are not effectively released.

Soil microbes are essential for soil health and carbon sequestration. Though it is not obvious to the naked eye, healthy soil is very much alive. Every teaspoon of soil holds several billion bacteria and fungi in addition to organisms like nematodes and small arthropods that move within the air and water spaces in soil aggregates (Figure 9*a*). In the soil, many species of bacteria and fungi engage in intimate symbiotic relationships with plants. As described below, these microbes provide plants with water and key nutrients and even protect plants from pests and pathogens.

Soil microbes also play a fundamental role in carbon sequestration. Some plant residue contributes to highly decomposed bits of organic material that are protected in the smallest spaces of soil aggregates (Figure 9a). However, most of the carbon that is eventually sequestered in soil comes from dead root cells or plant exudates that have been consumed and processed by microbes rather than directly from plant residue.[45]

The symbiotic relationships of plants and soil microbes are ancient and so essential that the evolution of land plants may not have occurred without the parallel evolution of at least one of the major

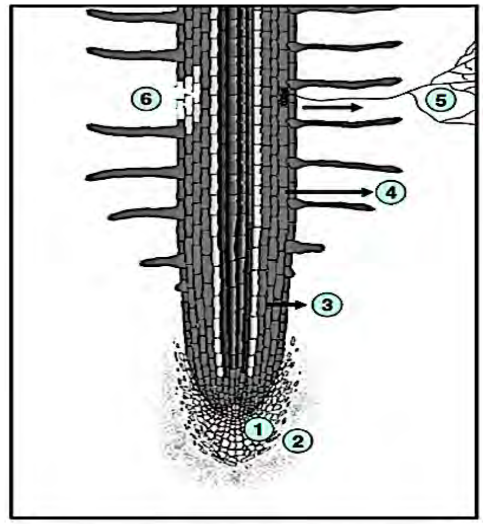

Figure 11. *Schematic diagram of a root showing the sources of carbon entering the soil. 1, 6: cells at the root tip or along the root are shed or die, 2: mucilage at the tip contains carbon, 3: sugars are released in root exudates, 4: CO_2 is released from root respiration, and 5: sugars absorbed in the root are transported by mycorrhizal fungi. Source: Ref. 48. Used with permission.*

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groups of soil microbes, mycorrhizal fungi. This diverse group of fungi evolved at about the same time as land plants (about 450 million years ago) and as obligate plant symbionts, they require living plant roots.[46] Associations of mycorrhizae with some of the earliest land plants suggest that these fungi were instrumental in plant colonization of land by making it easier to obtain sufficient water and nutrients in the harsh terrestrial environment.[46]

As evidence that microbial interactions are of crucial importance to plants, up to 40% of the sugar that plants make during photosynthesis is transferred through roots to mycorrhizae, other symbiotic fungi, and many species of plant growth promoting bacteria (PGPB).[47] Microbes living within root cells receive plant sugars directly, while free-living soil microbes receive sugar and other carbon sources from dead root cells (**Figure 11**, pathways 1, 6) or exudates (Figure 11, pathways 2,3).[48] Sugars from photosynthesis are also exported through mycorrhizal hyphae (Figure 11, pathway 5), and can leach out into the soil to provide PGPB with another source of plant sugars.[49]

This transfer of sugar to microbes represents a huge expenditure of a plant's energy and resources. What do plants get for this investment? As described briefly below, the soil bacteria and fungi that feed on these sugars provide plants with not only water and nutrients,[50] but also with protection from disease, root predators like nematodes,[51] and various abiotic stressors such as heat, drought, or salt.[52,52535455565758 58]

Two major groups of soil microbes interact with plants:

Bacteria

• **Nitrogen-fixing bacteria (Figure 12).** Some bacteria are able to "fix" nitrogen, that is, take elemental nitrogen (N_2) from the air and convert it to a form of nitrogen that can be used by plants (ammonium, NH_4). Obligately symbiotic bacteria form large nodules on the roots of legumes and are the best known of the nitrogen-fixing bacteria in soil (Figure 12). However, many other groups of soil bacteria can fix nitrogen. Some are free-living, while others colonize roots without forming the characteristic nodules seen in Figure 12.[59]

The interaction between nitrogen-fixing bacteria that form nodules and their host plant is intricate, involving mutual chemical signaling before the bacteria are allowed to invade the roots.[60] High nitrogen availability at the seedling stage can repress this chemical communication and reduce nitrogen fixation in the nodules that eventually form.[60]

• **Plant growth-promoting bacteria (PGPB).** There are hundreds of species of bacteria in soil that associate with plants in different ways. Some invade the roots through damaged cuticular tissue while others form microcolonies or biofilms on the root surface[47] (**Figure 13**). Other free-living bacteria simply congregate near roots, where they feed on root exudates that include sugars and other compounds The ability of free-living bacteria to associate with roots without the intricate chemical communication involved in root colonization may allow them to associate with a larger array of plants than the more specific nodule-forming bacterial species.

PGPB protect plants from their enemies in some spectacular ways by producing antibacterial or antifungal compounds or competing with pathogens for space or nutrients.[61] Some PGPB cause the induction of systemic resistance mechanisms in plants, resulting in the production of toxins or repellants that reduce soil-dwelling pathogens and even protect plants from insect damage on leaves.[61,62] The soil bacterium *Bacillus subtilis* (Figure 13) can even reduce plant drought stress by exuding a polymeric substance that causes soil that it inhabits to hold more water.[63]

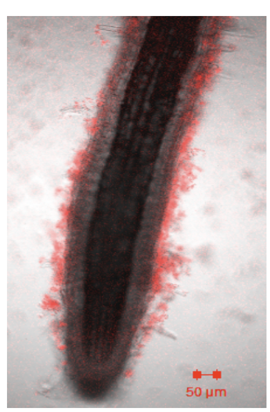

Figure 13. *Cells of the bacterium Bacillus subtilis (stained to appear red) form a biofilm on the exterior of a plant root, where they absorb root exudates and protect the plant from pathogens. Credit: Yaara Oppenheimer-Shaanan.*

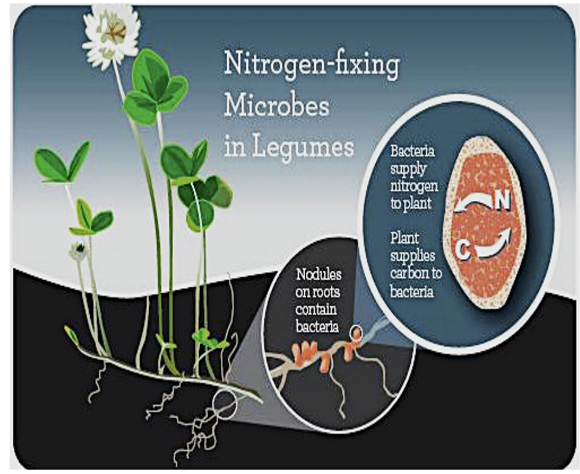

Figure 12. *Nitrogen-fixing bacteria stimulate legume plants to produce nodules where the bacteria reside. Inside the nodules, the plants share carbon (sugar) with the bacteria, and receive nitrogen fixed by the bacteria. Credit: Julie McMahon*

Fungi

• **Arbuscular mycorrhizal fungi (AMF).** These multicellular symbiotic fungi (**Figure 14**) are associated with as many as 85% of herbaceous land plants. An entirely different fungal group, ecto-mycorrhizal fungi, is symbiotic with woody plants, and these will not be discussed here. Arbuscular mycorrhizae invade root cells and their hyphae extend out of the roots far beyond the borders of the root zone, where they obtain water and nutrients that are then transferred back to the roots.[64, 65] Hyphae are fine filaments that comprise the "body" of multicellular fungi (Figure 14, black arrow). Mycorrhizal fungi allow plants to exploit a volume of soil for water and nutrients that is hundreds of times larger than could be exploited by the roots alone, facilitating plant growth and leading to increased water storage in soils near the plants (**Figure 15**). Though mycorrhizae can take up nitrogen on their own, the quantity of nitrogen that they transfer to plants is greatly increased by their interactions with soil

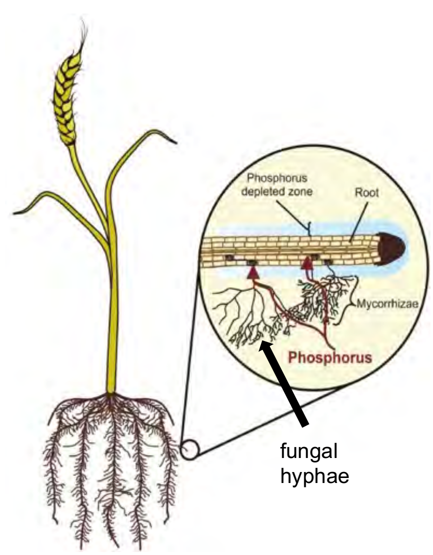

Figure 14. *Inset shows arbuscular mycorrhizal fungus growing into a plant root. Mycorrhizal hyphae branch within root cells where they absorb sugar and give the plant water and nutrients obtained from hyphae that grow far from the plant. Source: Ref. 65.*

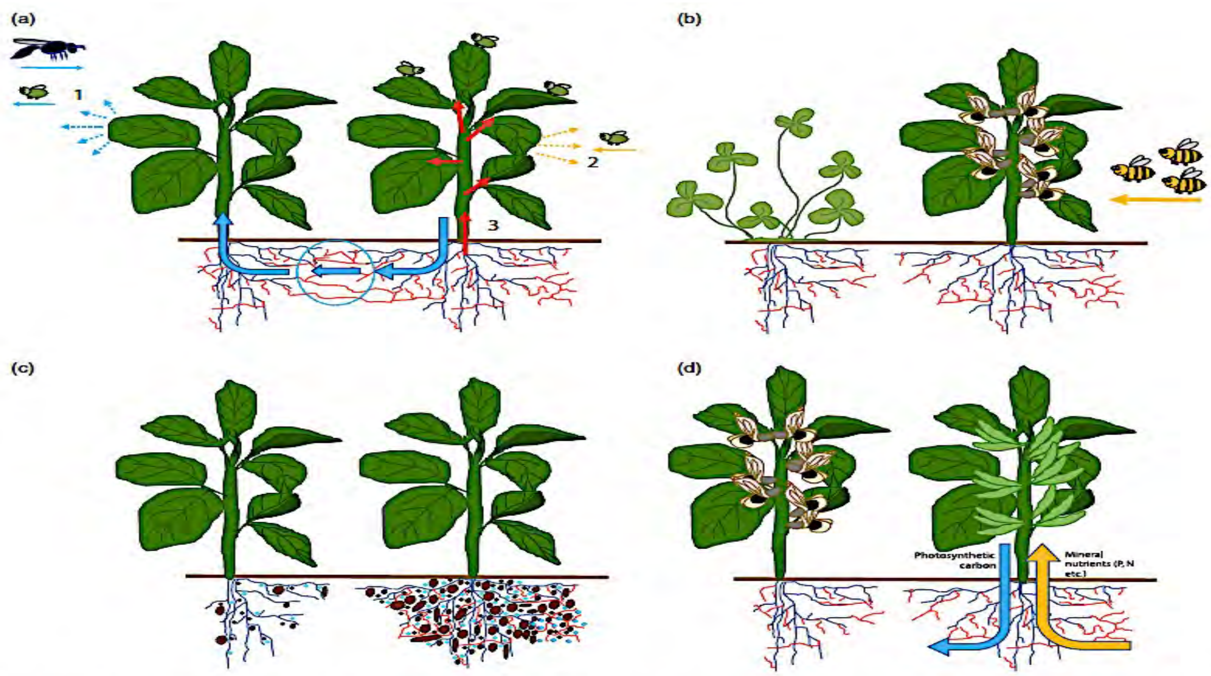

Figure 15. *Mycorrhizal fungi affect plant physiology in multiple ways: a) Hyphae (red filaments) can connect multiple plants; when one plant is attacked by herbivores (green bugs), a chemical signal is sent through the plant(red arrows) to produce repellents (yellow arrows), and the plant signals a neighboring plant through shared mycorrhizae (large blue arrows) to induce chemicals that attract natural enemies (small blue arrows attract black wasp to the second plant), b) Mycorrhizae can boost pollinator visitation by increasing flower number, size or nectar, c) Soil near a plant colonized by mycorrhizae can show increased water retention, soil aggregation & carbon sequestration, d) Mycorrhizae can increase mineral uptake by plants (yellow arrow) and increase the output of carbon that can be sequestered (blue arrow). Source: Ref. 67.*

bacteria.[66] Mycorrhizae also scavenge phosphorous from soil and bring it to plants.[65,66]

Plants transfer a large fraction of the sugar made during photosynthesis to mycorrhizal hyphae that have invaded root cells (Figures 14, 15). Some of this sugar is used for fungal growth, and some leaks from hyphae into the soil. Mycorrhizae can also transfer sugars to other plants, even plants of different species (Figure 15),[67] potentially impacting the species composition of plant communities.

Mycorrhizal fungi also play a key role in the formation of stable soil aggregates by exuding sticky materials (glycoproteins) from their hyphae. These substances are long-lasting and resistant to water, stabilizing soil aggregates even after the fungus itself has died.[68]

Mycorrhizal fungi also protect plants from pathogenic fungi and insect pests by stimulating plant defenses (Figure 15a). Plants with mycorrhizae produce more flowers to attract pollinators (Figure 15b), and increase water availability and carbon sequestration (Figure *15*c, d).

Endophytic fungi. Endophytic fungi are single-celled fungi that live entirely inside plant cells (**Figure 16**). Endophytes in leaves and roots protect many grasses and other plants from insect damage, root nematodes, and mammalian herbivores.[69,70] Various endophytic fungi also play important roles in protecting plants from stress. For example, the endophyte *Pirisporaformis indica* not only promotes vegetative and root growth, it protects plants against a wide variety of pathogens, as well as salt, heat, and drought stress (**Figure 17**).[71] *P. indica* was discovered in the Indian desert and has a very wide host range,[72,727374] suggesting that it could boost the climate resiliency of plants if strategies for using it safely and effectively as a soil amendment could be developed.

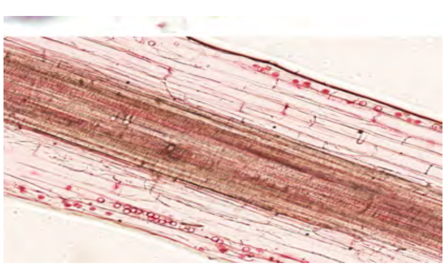

Figure 16. *Single celled endophytic fungi live within root cells. Modified from Ref. 71.*

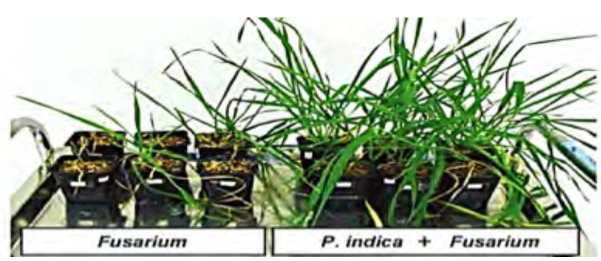

Figure 17. *The endophytic fungus Pirisporoformis indica protects plants from the plant pathogen Fusarium. Source: Ref. 71.*

Microbial communities in agricultural and native soils differ. In one comparison of the diversity of mycorrhizal fungi in forests and cropland, 154 fungal strains were found in soil samples from forests while only 100 strains were found in nearby cultivated sites.[75]Remarkably, only two of the three taxonomic groups of mycorrhizae identified in the samples were found in both forest and cultivated sites, and within each of those groups, only a single strain was found in cultivated sites. Most of the mycorrhizal strains in the cultivated sites (98/100) were not found in any of the forested sites, suggesting a nearly complete turnover in the kinds of mycorrhizal fungi in the soil after forest conversion to agriculture. Evidence that tillage reduces mycorrhizal diversity[76] suggests that frequent disturbance in agricultural soils may be one cause of these differences.

This difference in diversity between fungi in native and agricultural settings is supported by another study comparing bacterial species found in cultivated and native prairie soils.[77] Again, the microbial species and strains in samples from sites converted from prairie to agriculture were significantly different and less diverse than those in samples from native prairie.

There also appear to be functional differences between microbial populations in healthy and degraded soils. For example, bacterial enzyme profiles from soil in fields with a 10-year history of tobacco monoculture ("degraded soil") had higher levels of enzymes characteristic of bacterial stress and pathogenicity than did enzyme profiles from fields planted with tobacco after a varied crop history ("healthy soil").[78]

The changes that appear to typify microbial communities in degraded agricultural soils can potentially be reversed. In fields where soil disturbance was reduced by the adoption of no-till, both microbial biomass and the levels of key enzymes indicative of healthy soil increased.[79] Another study of land converted from agriculture back to grassland or forest revealed that the linkages between different microbial species strengthened with time after the cessation of agriculture, resulting in both improved ecosystem function and an increase in carbon sequestration.[80]

Can soil health be improved by inoculation with mixtures of microbes? The broad host range and ability of some microbes to protect a diversity of plants from multiple stressors suggests that applying commercially available formulations of these microbes could boost the functionality of degraded soil. Such "biostimulants" are appealing because they promise the rapid rehabilitation of degraded soil, requiring little more effort than would an application of fertilizer. Biostimulants also promise an easy method of plant protection when compared to the many years required to breed a disease or drought resistant crop variety.[55] However, it is important to note that simply boosting the microbial populations in degraded soil with an amendment will not maintain soil health if damaging agricultural practices continue to be used.

It is easy to find extravagant claims about commercial microbial products in trade magazines or on company websites, yet solid scientific evidence for their effectiveness is scant. Often these ads show dramatic pictures contrasting one or two plots or fields on which the products were or were not used. Consumers can be easily swayed by this marketing despite an absence of rigorous experimentation and statistical testing.

Introducing soil microbes from commercial mixtures may be problematic. In native soils, microbial communities become adapted to the local environment and the range of host plants that occur there.[81] If microbial populations in agricultural settings also become locally adapted to crops typically grown in a given region or to local environmental conditions, the application of standardized commercial preparations of soil microbes could be disruptive. The microbial species or strains within a commercial preparation might outcompete naturally occurring beneficial microbes that are well adapted to the local environment.[81] Even worse, if commercially available microbial mixes are dominated by a few species or strains that are easy to grow under a wide variety of conditions, they might become invasive and displace locally occurring microbial strains over a wide region.

One potentially safe method for boosting soil microbes is to produce them by inoculating a standardized base of potting mix and compost with soil sampled on-site, then spread the resulting enhanced soil back on the fields. This is a technique that has been well studied for mycorrhizae at the Rodale Institute.[82]

In sum, microbial interactions are complex. Adding soil microbes from commercial preparations to the soil without understanding how they will affect different crops and interact with the resident microbial community may unleash a variety of damaging unintended consequences. More research is needed to clarify the utility and safety of commercial preparations of soil microbes before they can be widely recommended.

Impacts of synthetic nitrogen fertilizer, herbicides, pesticides, fungicides and compost on soil microbes. This is a complex and important topic but a full review is beyond the scope of this report. Only a brief outline and a few key results can be considered here:

- ***Fertilizer.*** Adding synthetic nitrogen fertilizer is sometimes thought to benefit microbial communities by increasing plant growth, since larger plants produce more root exudate and add more organic matter to soil. However, these positive impacts may generally be outweighed by negative impacts of the fertilizer itself.

One review showed that applications of synthetic nitrogen, phosphorous, and sulphur were associated with 50-90% reductions in microbial carbon, 60-90% less microbial respiration, and a 60-90% decrease in the plant root area colonized by mycorrhizal fungi.[83]

- ***Herbicides.*** The effects of herbicides on the microbial community appear to vary among compounds. For example, in one pair of studies, the herbicide Atrazine altered the species composition of the microbial community without affecting ecosystem function,[84] while glyphosate reduced both spore viability and the colonization ability of mycorrhizal fungi.[85]

- ***Pesticides.*** Insecticides and fungicides appear to have a larger impact on soil microbes than do herbicides, with copper fungicide and soil fumigants being particularly damaging.[86] However, the impact of fumigants on microbial communities may be temporary, since there is some evidence that mycorrhizae can rapidly recolonize treated areas.[86] Insecticidal and fungicidal seed treatments can affect both soil microbes and endophytic fungi, although it is currently unclear whether these treatments reduce or alter microbial functions under actual field conditions.[87]

- ***Biopesticides.*** One area that has barely been considered is the impact of naturally sourced "biopesticides" on soil microbes. Many of these compounds are approved for use in organic agriculture and they are generally considered innocuous. However, because these compounds are used precisely because they kill weeds, insects and/or plant pathogens, some impact on non-target soil microbes seems reasonable. Unfortunately, peer-reviewed research on the topic is scant. One recent study showed that azadirachtin (derived from neem seed and approved for organic production) and chlorpyrifos (now banned in some places due to neurotoxic impacts) had equally negative impacts on soil bacteria.[88] In the absence of specific information, it therefore should not be assumed that a compound approved for organic use and derived from natural sources will be harmless to the soil food web.

- ***Compost.*** Compost and compost tea are often touted as effective ways to add beneficial soil microbes to degraded soil.[89] However, it is crucial to clarify that although compost includes many bacteria and fungi, compost-associated microbial species are not the same kinds of plant growth-promoting microbes discussed above. Mycorrhizae and most plant-growth-promoting bacteria in the soil are plant symbionts that need living roots to survive (**Figure 18**). They are unlikely to grow in compost pile where there are no living plants and it may become very hot. The microbes typically found in compost are saprophytes that are specialized to feed on dead plant matter. Although adding compost can cause temporary changes in the composition of the community of microbial decomposers in soil, the microbes originally in the soil eventually outcompete the species introduced with the compost.[90]

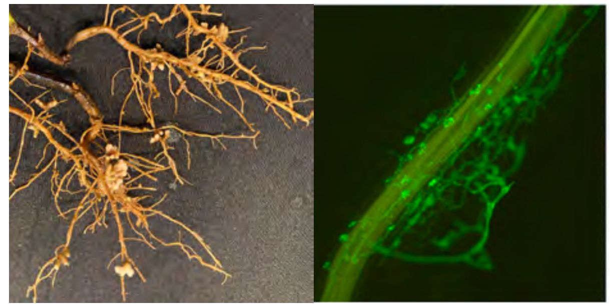

Figure 18. *Examples of key soil microbes that cannot live in compost.* ***Left:*** *Nodules containing nitrogen-fixing bacteria on the roots of a pea plant. Credit: Sara Via.* ***Right:*** *Hyphae and spores of mycorrhizal fungus twine around an alfalfa root. Credit: Zhang, et al., 2010. doi:10.1105/tpc.110.074955.*

This is not to say that compost is not a beneficial soil additive. After compost addition, microbial populations can double, the invasion of roots by mycorrhizae is accelerated,[90] and carbon sequestration can increase. However, these beneficial effects are more likely to be caused by the rich matrix of organic matter in compost than by any new microbes that might be introduced along with it.[90] Adding compost should therefore not be regarded as a source of key soil microbes, but instead as a source of very high quality organic matter that feeds the soil food web.

Nutrient cycling and carbon sequestration depend on a healthy soil food web. Multicellular organisms start the decomposition process. These include earthworms and small arthropods like amphipods, isopods, centipedes and millipedes. They inhabit the soil surface and shallow soil layers and shred or chew plant litter and other dead organic matter (collectively called "detritus"). As the pieces of detritus get smaller and smaller, their origin becomes less recognizable and they become the amorphous organic matter known as humus. As this occurs, the bits of organic material get small enough to be digested by extracellular enzymes exuded from saprophytic fungi and bacteria. Those microbes then absorb the small molecules liberated by this extracellular digestion (sugars and some proteins) and convert them to microbial biomass. As the detritus is decomposed and digested by microbes, key nutrients are released and become available for plant uptake. This is the process of "nutrient cycling", and it can't operate at peak efficiency in degraded soil.

A thriving community of soil bacteria and fungi is also the basis of carbon sequestration in soil. Most of the carbon stored in soil has a microbial signature, suggesting that stored carbon has been processed in various ways by soil microbes.[45,91] Much of the carbon that is eventually sequestered in soil is made up of metabolites excreted by living microbes and bits of microbial debris, such as cell walls (**Figure 19**). Studies have revealed that carbon sequestration is directly proportional both to the abundance of mycorrhizal hyphae in soil[92] and also to their local diversity.[93]

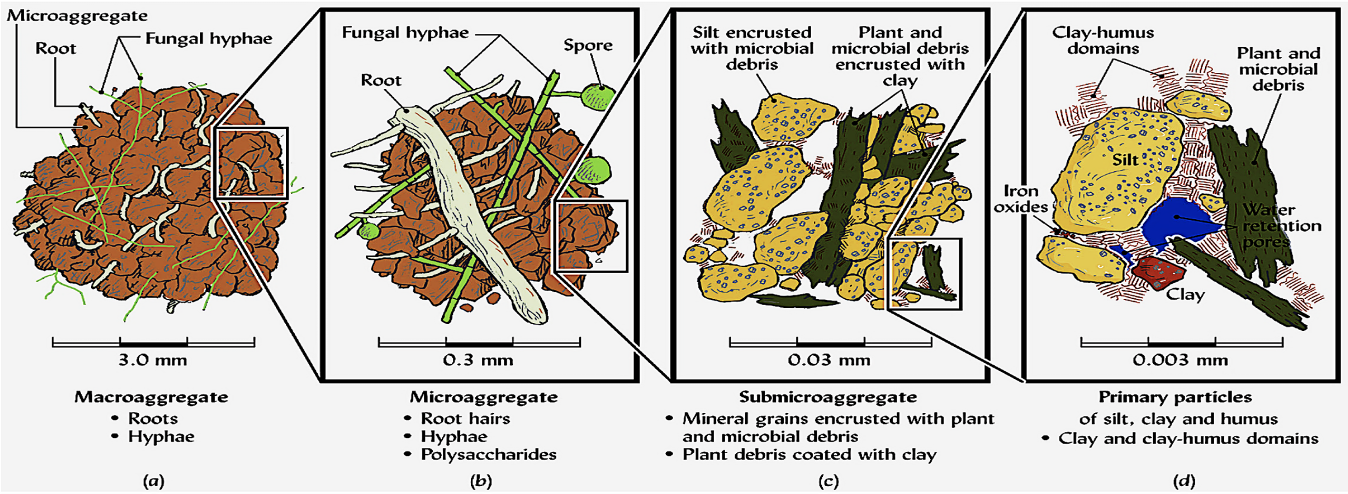

Figure 19. *The structure of soil aggregates. See text for explanation of each panel. Most stored carbon is likely to be microbial debris that is adsorbed onto silt, clay and metal oxides. Other carbon, in the form of humus (organic material that is so decomposed that its source is unclear), is stored in tiny spaces within micro-aggregates as flocculent associations with clay. See text for additional details. Source: Ref. 39.*

Available evidence suggests that agronomic practices that build soil health and boost microbial populations can be expected to increase carbon sequestration.

Mechanisms of carbon sequestration in soil.

Increasingly magnified views of a soil aggregate reveal the intricate structure of healthy soil and the sites of carbon storage (Figure 19). Soil macroaggregates (Figure 19a) are groups of soil particles held together by roots, fungal hyphae, and their sticky exudates. Macroaggregates are the basic building blocks of healthy soil, forming the large and medium pores that allow the infiltration of water. Small pores within macroaggregates fill with water, forming an aquatic environment that protects humus from decomposition by microbes that cannot survive there.[94]

Tillage breaks apart macroaggregates, destroying the pore structure and exposing organic matter within the small pores to wind and water erosion, as well as to microbial decomposition.[95,96] This decomposition releases the previously protected carbon as CO_2 through microbial respiration. The smaller soil subunits called "microaggregates" (Fig. 19b) left behind are less likely to be disturbed by tillage.[95]

The bulk of stored carbon is found in these microaggregates[95,97] where microbial debris is adsorbed onto silt and can be encrusted with clay (Figure 19c). At the very smallest level (Figure 19d), colloidal associations of humus and clay are trapped in tiny spaces between primary soil particles, and bits of microbial debris are adsorbed onto clay and metal oxides.

The above-ground biomass of woody plants provides another site for carbon storage, adding to carbon sequestration in the soil. For this reason, the GHG reductions/acre for management strategies that include woody plants tend to be higher than those involving only herbaceous (non-woody) plants (see **Part 2** for more information).

1.3 The USDA soil health principles: why they are effective

The soil health principles feed, diversify and protect soil microbes.

The Natural Resources Conservation Service (NRCS), a branch of the U.S. Department of Agriculture (USDA) has developed four essential soil health principles to guide farmers toward management strategies that improve soil health.[98] These key soil health principles work because they either protect the habitat of soil organisms from disturbance or erosion or they feed those organisms, increasing their abundance and diversity (**Figure 20**).

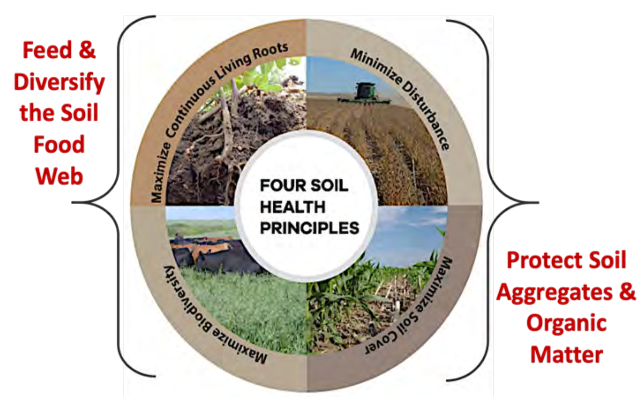

Figure 20. *The four NRCS soil health principles work because they either feed and diversify life in the soil or they protect soil aggregates and help retain organic matter. Modified from a graphic from NRCS.*

The USDA principles for improving soil health:

- ***Minimize disturbance of the soil.*** Soil disturbance may be either physical or chemical. Tillage, the primary source of physical disturbance, breaks up soil aggregates and damages essential habitat for soil organisms. ***Tillage*** also exposes organic matter that had been stored within soil aggregates to microbial decomposition, leading to the release of CO_2 into the atmosphere. Loss of the aggregate structure of soil collapses the pores that allow infiltration, increasing flooding and runoff. The resulting erosion causes additional loss of organic matter. ***Erosion*** and the tillage that causes it, are the greatest causes of degradation in agricultural soils. After erosion, the remaining soil becomes dominated by fine particles that easily form crusts. ***Compaction*** from the use of heavy equipment on tilled soil, particularly when wet, is another source of damaging physical disturbance. By compressing the air spaces in the soil and collapsing the aggregate structure, compaction reduces infiltration and increases the risk of flooding and additional erosion. ***Chemical disturbance*** of healthy soil occurs from agricultural inputs of fertilizer, organic amendments like compost or manure, and the use of herbicides, pesticides, and fungicides. These inputs alter nutrient availability and change the abundance or species composition of the microbial community in various ways.[83-88]

- ***Keep the soil covered at all times, either with a living crop or with crop residue.*** Bare soil is highly erodible by wind or water. The presence of crop foliage and/or plant residue reduces the strength of winds on the surface and blunts the force of raindrops. The presence of living roots year-round further reduces erosion by holding the soil in place. In routinely tilled soils that are left fallow, tons of soil per acre are routinely lost after major thunderstorms.[99] Erosion robs agricultural soil of organic matter and reduces microbial abundance and diversity. It also changes soil texture, leaving a layer of fine particles that form a crust on the surface, increasing runoff and, after drying, preventing seedlings from penetrating the soil surface.

- ***Maximize soil biodiversity.*** Increasing plant diversity on a given piece of land translates into greater microbial diversity, increases in microbial biomass and greater long-term carbon storage.[100] Biodiversity in the soil provides functional stability to the soil ecosystem because species redundancy within the soil food web ensures that critical community and ecosystem functions will be retained across a variety of conditions that may negatively affect individual species.[101] The benefits of increasing plant diversity have a strong evidence base. For example, analyses of the effects of crop rotation show that multi-species crop rotations increased microbial biomass and diversity, soil carbon, and soil nitrogen relative to monocultures or rotations with only two species.[102,103]

- ***Continuously maintain living roots in the soil.*** Plant growth-promoting soil microbes require living plant roots and their exudates, which supply them with carbon. When living roots are not present, microbial biomass decreases and some species may be lost from the system or retreat into dormancy. Dormant forms such as spores cannot persist indefinitely in the soil because they lose vigor and the ability to begin regrowth over time. Thus, leaving soils without living roots from late September to May could result in a diminished microbial population in the soil when seeds germinate the following year.

Improving soil health increases agricultural resilience to climate change. Changing patterns of temperature and precipitation[1,6] put a premium on the ability of healthy soil to drain water from heavy rains while holding water in periods of drought. More rain is falling as downpours, often exceeding the infiltration ability of the soil and causing flooding. Patterns of precipitation across seasons are also changing.[1,3] In the Northern tier of the US, precipitation in winter and spring is increasing while rain in summer is mostly decreasing or remaining constant. Most of the Southwest is growing dryer almost year-round, while the Southeast is tending toward wetter winters and falls with less change in spring and summer. With summers growing hotter,[1,3] the soil will dry out more rapidly making crops more likely to experience water stress, even in regions where rainfall has remained constant.

Because healthy soil benefits farmers in all environments, soil health is widely considered to be a top "no regrets" strategy for increasing agricultural resilience to climate change.[6]

Part 2.

Recommended Practices For Carbon Sequestration in Agriculture

2.1 The scientific basis of carbon sequestration in agriculture

Policy recommendations must have solid scientific support. In recent years, agricultural carbon sequestration has become a topic of great interest in the popular press. Unfortunately, media targeting a general audience do not always present clear and verifiable scientific evidence that particular practices actually sequester carbon as advertised. In order to formulate credible policies encouraging carbon sequestration in agriculture, recommendations must have strong scientific support. The goal of Part 2 is to provide a list of agricultural practices for carbon sequestration and discuss the support for their effectiveness.

The list of effective carbon-sequestering management practices (**Table 1**, next page) was developed using information from recent scientific reports followed by a targeted review of the scientific literature (methods and sources described in **Appendix 1).** The practices are aligned with numbered USDA-NRCS conservation practice standards (CPS*xxx*),[104] which are clearly specified in the NRCS field manual and are already familiar to many farmers and grazers.

Using COMET-Planner to determine the GHG benefits of the recommended agricultural practices. The climate impact of each recommended practice was obtained using COMET-Planner.[105] This is a state-of-the-art tool that evaluates the GHG impacts of the recommended NRCS management practices to a spatial resolution of multi-county groups using a combination of data on local conditions and process-based modelling (see **Appendix 2** for details). For each practice, COMET-Planner computes an "Emission Reduction Coefficient" (ERC).

Each ERC includes changes in both carbon emissions or sequestration and nitrous oxide emissions in units of metric tons of carbon dioxide equivalents per acre per year (tCO_2e/acre-yr), with a positive ERC indicating an emissions reduction.

The GHG impact of each recommended practice is defined as a change from the GHG emissions and carbon sequestration expected from the typical "business-as-usual" practice (the "baseline"). For example, the baseline practice for no-till is conventional intense tillage, while the baseline for cover crop use is leaving a field fallow.

For five states, state-level average GHG reductions for each recommended practice (Table 1) were calculated by Dr. Jennifer Moore at the American Farmland Trust and colleagues using the Carbon Reduction Potential Evaluation Tool (CaRPE).[105b] This tool combines the ERCs from COMET-Planner with acreage data from the 2017 Census of Agriculture, and is primarily used to forecast possible GHG reductions under different future scenarios. Here, we obtained statewide average ERC for each practice by weighting the county-level ERCs from COMET-Planner by the number of irrigated and non-irrigated acres in each county in 2017. For Maryland, the component ERCs for soil carbon, biomass carbon (e.g., carbon stored in wood) and nitrous oxide are shown in addition to the total, while totals only are shown for New York, Illinois, Colorado and Oregon.

The nominal differences among states in ERCs for particular practices might reflect interesting variation in soil types, climate, weather, land use changes or other details, but such an analysis requires additional details. Here, it is more informative to compare the GHG impacts of different practices. For example, in all five states, cropland practices tend to produce a modest per-acre GHG reduction of about 0.3–0.5 tCO_2e/acre-yr. However, because these practices can potentially be used on millions of acres, their widespread adoption could have a large climate impact. In comparison, practices that convert marginal or strategically located cropland to woody vegetation have a large GHG impact per acre but can be potentially applied on far fewer acres.

Table 1

Greenhouse Gas Reductions From Agriculture: Recommended Practices for Carbon Sequestration								
		GHG Reduction (Tonnes CO2e/acre-yr)						
		Maryland			Other States			
NRCS Conservation Practice	Description of practice	Soil CO_2	N_2O	MD Total	NY Total	IL Total	CO Total	OR Total
Cropland Management								
Residue and Tillage Management - No-Till (CPS 329)	Intensive Till to No Till or Strip Till	0.47	0.04	0.51	0.43	0.73	0.30	0.23
	Reduced Till to No Till or Strip Till	0.37	0.03	0.40	0.33	0.58	0.24	0.18
Residue and Tillage Management - Reduced Till (	Intensive Till to Reduced Till	0.16	0.01	0.17	0.15	0.22	0.10	0.07
Conservation Crop Rotation (CPS 328)	Decrease Fallow Frequency or Add Perennial Crops to Rotations	0.21	0.01	0.22	0.22	0.22	0.26	0.24
Cover Crops (CPS 340)	Add Legume Seasonal Cover Crop (50% Fertilizer N Reduction)	0.79	-0.21	0.59	0.22	0.64	0.11	0.07
	Add Non-Legume Seasonal Cover Crop (25% Fertilizer N Reduction)	0.29	0.01	0.30	0.12	0.49	0.11	0.04
Mulching (CPS 484)	Add Mulch to Croplands	0.32	0.00	0.32	0.32	0.32	0.21	0.27
Nutrient Management (CPS 590)	Reduce Synthetic N Fertilizer by adding Dairy Manure	0.20	-0.07	0.13	0.11	0.21	0.05	0.09
	Reduce Synthetic N Fertilizer by adding Chicken Manure	0.15	-0.08	0.07	0.05	0.07	0.01	0.05
	Reduce Synthetic N Fertilizer by adding Compost (CN ratio 25:1)	0.36	-0.05	0.32	0.34	0.62	0.17	0.22
Stripcropping	Add perennial cover to rotation of strips of annual crops	0.11	0.13	0.24	0.24	0.24	0.16	0.20
Land use changes- add herbaceous plants								
Forage and biomass planting (CPS 512)	Convert cropland to grass, forage or biomass feedstock, harvested	NA	NA	0.60	1.25	0.88	0.31	0.60
Conservation Cover (CPS 327) / Riparian Herbaceous Cover (CPS 390) / Contour Buffer Strips (CPS 332) / Field Border (CPS 386) / Filter Strip (CPS 393) / Grassed Waterway (CPS 412) / Vegetative Barrier (CPS 601/342)	Convert Cropland to Permanent Unfertilized Grass or Grass & Legume Cover	NA	NA	0.39	0.97	0.97	0.41	0.39
Land use changes- add woody plants								
Tree/Shrub Establishment (CPS 612)	Conversion of Annual Cropland to a Farm Woodlot	NA	NA	8.86	12.10	9.19	24.97	8.86
Riparian Forest Buffer (CPS 391)	with Woody Plants	NA	NA	5.56	6.60	7.12	8.36	5.56
Alley Cropping (CPS 311) or Multi-story Cropping (CPS 379)	Replace 20% of Annual Cropland with Woody Plants	NA	NA	1.77	2.42	1.84	4.99	1.77
Hedgerow Planting (CPS 422)	Replace Strip of Cropland with 1 Row of Woody Plants	NA	NA	4.89	13.10	NA	10.16	4.89
Windbreak/Shelterbelt establishment		NA	NA	8.06	9.20	21.60	10.80	8.06
Grazing								
Silvopasture (CPS 381)	Tree/Shrub Planting on Grazed Grasslands- 10% stocked							
Prescribed/Rotational Grazing (CPS 528)	Replace Extensive Grazing Management (60% or more Forage Removal) with Intensive Grazing Management (40% Forage Removal)	0.03	0.02	0.04	0.01	0.03	0.01	0.01
Range Management	Seeding Adapted Perennial or Self-Sustaining Forages to Improve Grassland	0.50	0.00	0.50	0.43	0.50	0.34	0.43
NA = Not Available	Values computed using CaRPE by Dr. Jennifer Moore, USDA-ARS (see text for details)							

The ERCs estimated by COMET-Planner and shown in Table 1 are not meant to apply to any specific site. Instead, the weighted averages for each state in Table 1 reflect the corresponding ranges of values within and between the component multi-county regions in each state, and should be used for educational and planning purposes only. For details about GHG emissions for a specific site, users must enter historical land use and management data for that location directly into COMET-Farm. For more detail see Appendix 2 and the 2019 COMET-Planner report.[105]

2.2 Cropland management practices

The recommended carbon-sequestering practices used on cropland each implement one or more of the NRCS Soil Health Principles. They reduce disturbance (no-till, reduced-till and nitrogen management), keep the soil covered (no-till, cover crops, mulching), maintain living roots (cover crops, conservation crop rotation, stripcropping) and/or increase plant diversity (cover crop mixtures, conservation crop rotation, stripcropping).

Tillage: No-till (CPS 329) or Reduced-till (CPS 345). In conventional tillage, the soil with its residue from the previous crop is first inverted with a plow or disk. Then the soil is pulverized and packed to make a seedbed (**Figure 21**). This process can involve 4-5 passes across the field with various pieces of heavy equipment and leaves less than 15% of the residue from the previous crop on the surface.[104] Conventionally tilled soil has a uniform and loose consistency above a compacted layer called the "plow pan" that is about 8-12" deep, just below the reach of a plow or disk (**Figure 22,** right).

Although tillage may appear to loosen the soil and reduce compaction, it actually makes soil compaction more likely by breaking up the aggregate structure of the soil and disrupting the stable system of pores (see Figures 9 and 19, **Part 1**). Tilled soil is essentially just loose unconnected particles that are highly susceptible to wind and water erosion (Figure 21, right). With no vegetation on the surface to protect the soil, these loose particles quickly disperse in wind and form a crust with the first rain. Without the pores of the aggregate structure, water infiltration is reduced and runoff and erosion increase.[40,106,107]

Methods of reduced-till. Mulch-till, ridge-till, and strip-till are hybrid strategies in which tillage is limited to narrow strips where the seeds are planted. In reduced tillage, most of the soil is undisturbed and 15-30% of the crop residue remains on the surface between the crop rows.[104] Strip-till is increasingly used in both grain and vegetable systems. In this practice, narrow strips (6-18" wide) are

Figure 21. ***Left:*** *In conventional tillage, initial plowing or disking mixes in crop residue and vegetation but leaves soil in medium to large chunks.* ***Right:*** *Additional tillage then pulverizes and packs the soil to form a fine seedbed. From Ref. 40.*

shallowly tilled and planting occurs in the tilled strips, while the rest of the field is untilled.

Strip-till requires fewer passes across the field than conventional tillage, saving fuel. Since fertilizer and herbicide are applied only in the strips, costs and GHG emissions are further reduced. Strip-tilling also helps to control weeds because weed seeds are not brought to the surface by tillage in the soil between crop rows. Maintaining the dried mulch layer from a terminated cover crop or using a living mulch like grass or clover between the strips further suppresses weed germination and growth.[108]

Strip-till combines some of the best features of conventional tillage and no-till. The tilled strips can be prepared to form a good seedbed for small-seeded crops and they warm up earlier in spring than untilled soil. But like no-till, strip-till retains crop residue between rows and improves water infiltration by leaving most of the field untilled. Despite these advantages, most commercial vegetable fields and fields on organic farms are still conventionally tilled for seedbed preparation and weed control. Encouraging the use of strip-till in vegetable and organic production would improve soil health, reduce erosion and improve water quality while sequestering carbon.

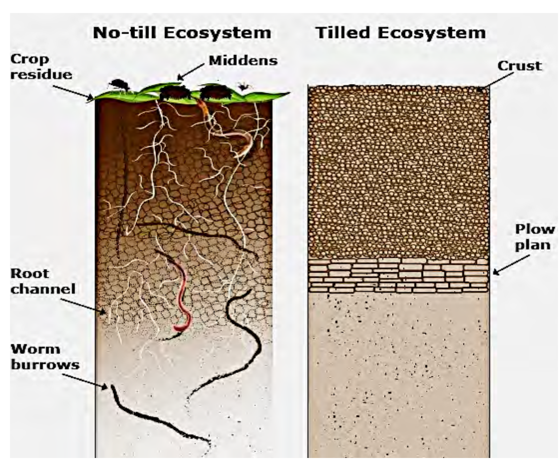

Figure 22. ***Left:*** *Continuous no-till allows the natural soil structure to be rebuilt over time. Roots and earthworm burrows create channels that extend into the subsoil. This overall structure is porous, allowing water to infiltrate, but is also highly stable and resistant to compaction.* ***Right:*** *Tilled soil has little soil structure, with a uniform layer of compacted soil just below the depth of the tillage equipment, called the plow pan. From Ref. 106.*

Impacts of tillage on soil microbes. Tillage reduces the abundance of soil microbes and shifts the microbial community from one dominated by fungi toward one in which bacteria dominate.[109,110] By physically disrupting the network of mycorrhizal hyphae in the upper soil layer, tillage reduces the highly beneficial effects of mycorrhizae on plant growth, plant health and the stability of soil aggregates.

Reducing tillage improves soil health. In no-till, more than 30% of the residue of the previous crop is retained on the surface.[104] No-till improves soil health by maintaining the aggregate structure of the soil, protecting the soil food web and increasing water infiltration.[106,107] In continuous no-till, the physical and biological structure of the soil can rebuild itself (Figure 22, left). Untilled soil is covered with crop residue, other plant litter and the remains of earthworm activity. Roots and worm burrows add organic matter and form channels that extend deep into the soil, boosting infiltration of water to more than twice that measured in conventionally tilled fields.[106] Without tillage, the soil remains firm but porous and can support the weight of farm equipment without collapsing like tilled soil.[106]

Impacts of tillage on GHG emissions and carbon sequestration. When tillage breaks up soil aggregates, some of the carbon-containing organic matter that was protected in tiny spaces within aggregates is exposed to decomposition and the carbon is released back to the atmosphere as CO_2 from microbial respiration.[8,9,13,39,111] In addition, tillage dramatically increases erosion of carbon-rich topsoil by both wind and water. All told, carbon is lost at an exponential rate when native soils are tilled, with over half gone within 20 years.[112] By retaining the aggregate structure of the soil, no-till both reduces erosion loss and prevents the loss of carbon protected within aggregates. However, this GHG benefit is slightly reduced in humid environments where the release of nitrous oxide (N_2O) can increase in untilled soils.[13]

Tillage not only speeds the loss of carbon already in the soil, it also reduces the potential for new carbon sequestration by breaking apart soil macroaggregates. The microaggregates that remain hold much of the stored carbon, and can reassemble into macroaggregates over time. However, if fields are regularly tilled, existing macroaggregates are destroyed and there is not enough time for new microaggregates to form or reassemble into macroaggregates, reducing the potential for carbon sequestration.[95]

After the cessation of tillage, carbon stocks are rebuilt quickly, at about the same rate that they were originally lost.[111,113] Once tillage is reduced, the aggregate structure is rebuilt and the network of beneficial interactions between soil microbes grows over time, progressively increasing the efficiency of carbon uptake and storage in agricultural soils.[80,92]

Calculating the GHG impact of no-till and reduced till. The ERCs for tillage from COMET-Planner (Table 1) are based on converting conventional full-width tillage to either no-till (CPS 329) or to any type of reduced tillage (CPS 345)[104] including strip till, ridge till, chisel plowing, field cultivating, tandem disking, vertical tillage or any other reduced tillage scheme that doesn't meet the NRCS Soil Tillage Intensity Rating (STIR) for no-till (CPS 329).[104] The estimated GHG impacts of reducing tillage in COMET-Planner reflect increases in soil carbon from reduced disturbance and changes in nitrous oxide emissions from the altered soil environment but do not include effects of alterations in fertilizer application that may be implemented along with tillage reductions.[105]

Adoption of no-till and reduced tillage is increasing. The 2017 US Census of Agriculture includes data on tillage methods for 282 million acres of the total 320 million acres of harvested cropland in the US. In 2017, conventional tillage was used on 28% of the reported acres (**Figure 23a**), a 10% decline from 2012 levels. Reduced tillage was used on 35% of acres, a 7% increase from 2012 (Figure 23b), while no-till was used on 37% of cropland acres (Figure 23c), a 2% increase.[114]

Although the 5-year nationwide increase in no-till was small, several Northeast states increased no-till up to 15% while increases of 8–11% were seen in some Northwest states,[114] reflecting the overall variation among states in adoption of reduced-till and no-till (Figure 23). States in the Mid-Atlantic and Southeast have the highest rates of no-till and a mix of reduced-till and no-till is seen in the Midwest.

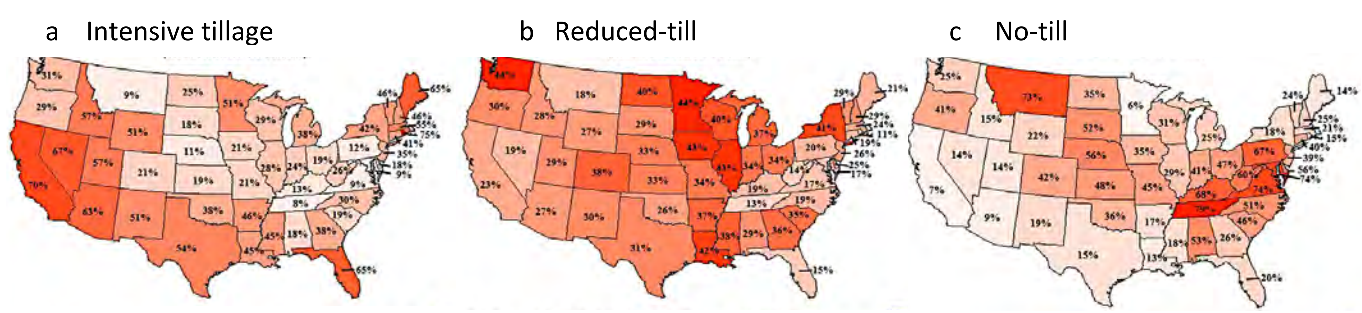

Figure 23. *The fraction of acres in each tillage system by state, using data from the 2017 Census of Agriculture. Only the 88% of all cropland acres for which tillage method was reported is included. From Ref. 114.*

However, the majority of producers in Florida, Maine and states in the Southwest and Mountain areas continue to use intensive tillage (Figure 23c).

The use of no-till varies widely among commodities. Most farmers who grow row crops use herbicide tolerant varieties of corn, soybeans and cotton in which weeds can be controlled with herbicide throughout the season. This greatly facilitates no-till. However, as weed resistance to glyphosate increases, the development of effective strategies for integrated weed management in no-till using cover crops and crop rotation becomes more urgent. For example, cover crops that are mechanically terminated with equipment like a roller-crimper could help to control resistant weeds while reducing both chemical disturbance to the soil and herbicide pollution of surface waters.

In fruits, vegetables, and organic production, herbicide tolerant plants are not used. This leaves weed control largely dependent on tillage and routine cultivation. This may partially explain why intensive tillage remains relatively common in states with large fruit and vegetable industries such as Florida, California and other states in the Southwest. In contrast, in Midwestern states where the production of herbicide-resistant row crops predominates, no-till is more common (Figure 23).

Developing effective integrated weed management strategies that would allow reduced tillage in fruit, vegetables and organic production is an urgent research priority. Reducing tillage in fruit, vegetable and organic production would increase soil health and water quality while curbing erosion and sequestering carbon. The increased water-holding ability of no-till soils would be an extra benefit in states like California that increasingly face prolonged climate-related heat waves and droughts and the associated chronic water shortages.[1,3,4]

Does no-till really sequester more carbon than conventional tillage? No-till is a key strategy for erosion control and the improvement of soil health,[40,111] yet the extent to which it increases carbon sequestration has been questioned. There is general agreement that the reduction of disturbance in no-till allows more carbon to accumulate in the top 15-20 cm of the soil profile than in conventionally tilled fields.[39,40,112] However, several reports of more carbon at depths of 20-40 cm under inversion tillage than under no-till[115,116,117,118,119] have led to the suggestion that no-till may not be an effective carbon-sequestering practice.

Evaluating the validity of the results leading to this claim is complicated by variability in the sampling methods used, the difficulty of estimating small changes in soil carbon with limited replication[120] and the large inherent variability among soil samples, particularly from deep soil layers.[121,122] Using a meta-analysis of 25 studies, a clear picture emerged of the difference in carbon storage

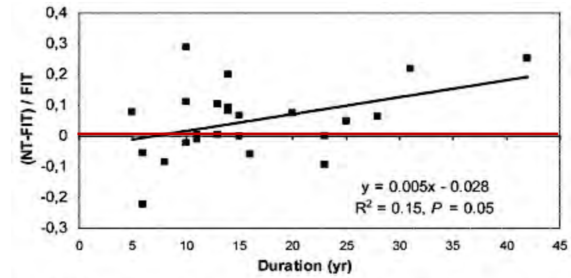

Figure 24. *Compilation of results from 25 studies comparing carbon stored under full inversion tillage (FIT) and no-till (NT). The y-axis shows the proportional difference in carbon storage between the two, with the red line indicating no difference. A y-axis value of 0.1 indicates 10% more carbon stored in NT, and a value of -0.1 means that 10% more carbon was stored in FIT. Most data points show more carbon storage in no-till, and the best fit line indicates that this trend increases with the duration of the time since tillage. From Ref. 123.*

between full-inversion tillage and no-till (FIT and NT, respectively, **Figure 24**). Results illustrate a significant relationship between the relative amount of carbon stored in no-till fields and the duration of the study,[123] as well as a tendency toward greater carbon storage in no-till than under inversion tillage. Most of the data points fall above the red line in Figure 24, which marks the point of equal carbon storage in the two tillage systems (i.e., NT = FIT). Data points above the red line come from studies in which more carbon was stored under no-till (i.e., NT > FIT), while points below the line are from studies where greater carbon storage was seen under inversion tillage (i.e., FIT > NT).

Despite considerable variability in the data, the carbon storage in most the 25 studies fall above the red line, indicating more overall carbon storage in no-till. Together with the significant increase in the benefit of no-till over time, this evidence supports the use of no-till as a strategy for carbon sequestration.

Additional clarity on this issue has recently emerged with the finding that geographical location is a key source of variability in the effectiveness of carbon sequestration in no-till.Recent studies reveal that no-till performs particularly well in the temperature and humidity combinations that typify the Eastern US and Midwest states.[15,124,125] Because the conditions favorable for no-till are found on the majority of US cropland acres,[125] this additional evidence increases the support for promoting no-till in US agriculture as a carbon-sequestering practice.

How much carbon is lost after periodic tillage? In fields under continuous no-till, carbon sequestration increases over time as the soil structure is rebuilt.[112] Clearly, the longer a field can be in continuous no-till, the better the conditions for soil health and carbon sequestration. However, occasional tillage can be useful under some circumstances. For example, as the number of herbicide resistant weeds increases, even farmers that routinely use no-till may turn to periodic tillage for weed control. How much of the carbon sequestered during no-till is lost from such periodic tillage?

Although it is clear that continuous tillage causes rapid carbon loss,[112,126] there are few studies of the impacts of occasional tillage or tillage of different intensities on soil carbon stocks that have built up during a period of no-till. Using standard in-field soil tests to detect a short-term carbon loss after periodic tillage is complicated by the same sources of variability in field testing already discussed: lack of standard methods for soil sampling, spatial heterogeneity in soil carbon, the difficulty in estimating small changes in soil carbon, and geographical variation in environmental conditions.

One study that combined data from soil samples in three Midwest locations with mathematical models evaluated impacts of periodic tillage on steady state carbon stocks.[127] After a period of no-till long enough for soil carbon stocks to reach a steady state, models showed that intensive tillage every year led to an expected 27% reduction in steady state soil carbon, while tillage every other year reduced steady state carbon stocks by 18%. Less frequent or less intensive tillage had smaller effects.

For example, intensive tillage once every 10 years, shallow cultivation each year, or vertical ripping every four years each resulted in only an estimated 6-7% reduction of steady-state carbon stocks relative to continuous no-till.[127]

Interpreting the meaning of modelled changes in steady state carbon is difficult, yet other studies have also suggested that shallow cultivation or periodic vertical tillage is far less damaging to carbon stocks than is conventional tillage involving moldboard plowing or deep disking.[13] Far more work is needed, but if these results hold true in additional analyses, controlling tough perennial or herbicide resistant weeds through tillage every 10 years or shallow cultivation each year might not cause major setbacks to carbon sequestration programs. For now, however, it is best to recommend as little tillage as possible.

Given the importance of sequestering carbon in agricultural soils as a natural climate solution, funding additional research to evaluate the impact of periodic or shallow tillage on the loss of stored carbon should be a high priority.

Nitrogen Fertilizer Management (CPS 590).

Synthetic nitrogen fertilizer has been routinely applied to cropland since the 1940s, increasing the emission of nitrous oxide from the soil and causing both groundwater and surface water pollution. When emissions from manufacturing, transportation and application to farmland are pooled, one ton of synthetic nitrogen fertilizer is responsible for the emission of 3.2-4.5 tCO_2e.[128]

Fertilizer-related nitrous oxide (N_2O) emissions from the soil increase linearly with application rate up to the point at which plants cannot take up additional nitrogen, increasing exponentially beyond that point.[129] This exponential increase in direct N_2O emissions from soil after high rates of fertilizer application is a powerful reason to use application strategies that match nitrogen additions to plant size and rates of nutrient uptake. Carefully planning fertilizer rates and application timing is particularly beneficial in moist or irrigated situations where nitrogen fertilizer is rapidly converted to nitrous oxide.[130]

In the soil, nitrogen from synthetic fertilizer is rapidly changed into water-soluble nitrate (NO_3), which is transported from the field in runoff or by leaching through the soil to groundwater below fields. This transport of nitrate is a significant source of water pollution. Nitrogen that leaches into surface waters also causes indirect N_2O emissions, which comprise 35-40% of all nitrous oxide emissions from agriculture.[131]

One positive development in fertilizer management that addresses these problems is the aptly named "4R" program (Right Source, Right Rate, Right Time, Right Place), which helps farmers use synthetic nitrogen more efficiently.[132] This program specifies the best types of fertilizer to use in particular situations (Right Type), recommends split applications of fertilizer to more closely match plant uptake with nitrogen availability (Right Time), suggests precision fertilizer application based on field sensing and cautions farmers not to exceed recommended rates (Right Rate), and encourages application of fertilizer in ways that maximize plant uptake, such as banding or injecting (Right Place). With this comprehensive approach, the 4R program helps farmers gain the most benefit from fertilizer applications while minimizing costs and environmental damage.

Using slow-release fertilizer or nitrification inhibitors can slow the conversion of nitrogen in fertilizer applied at planting to nitrous oxide or nitrate.[133,134] These strategies might be particularly useful to slow or prevent nitrogen transport into groundwater during spring rains, as when extensive flooding in Maryland during May 2018 caused much of the nitrogen applied as starter fertilizer on corn to be lost through leaching and runoff before it could be used by the plants.[135]

Calculating the GHG impact of Nitrogen Fertilizer Management. The COMET-Planner ERCs for managing nitrogen fertilizer (Table 1) are based on a reduction of nitrous oxide emissions from adopting strategies for fertilizer management that include reducing nitrogen fertilizer rates by 15%. These include use of nitrification inhibitors, and a shift from fall to spring nitrogen application. In addition, COMET-Planner provides ERCs for replacing 20% of the synthetic nitrogen fertilizer with various organic amendments over five years that will reduce synthetic nitrogen by 4% per year for five years. The total nitrogen applied remains the same, and is assumed to be at the average regional N fertilization rate by crop, as listed in Appendix 2 of the COMET-Planner report.[105] These amendments add enough organic matter through decomposition to replace 4% of the synthetic nitrogen, increasing

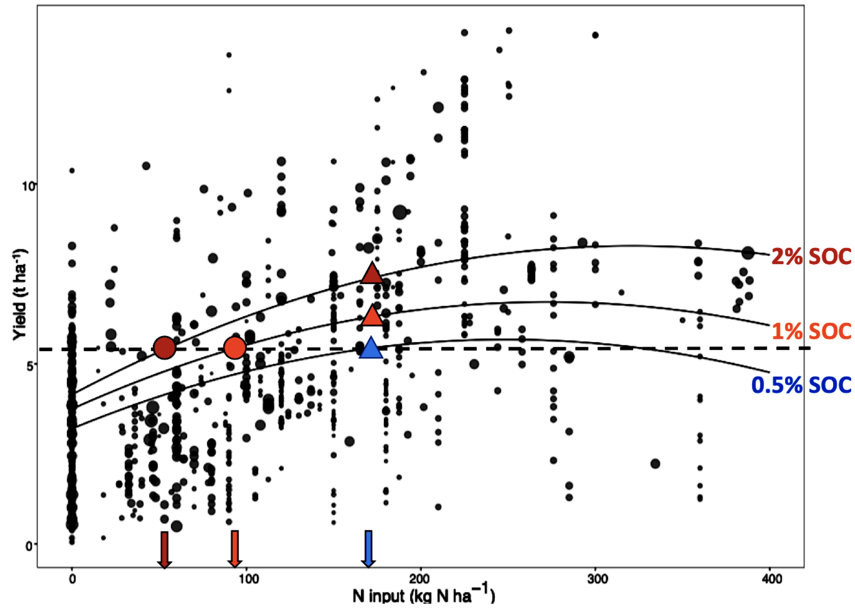

Figure 25. *The relationship between yield, nitrogen input and soil organic carbon (SOC), which makes up about 50% of soil organic matter (SOM). Fitted lines show the average yield at different fertilizer levels for soil with 0.5%, 1% and 2% SOC. Black data points are from original papers used in the meta-analysis, with size of the symbol representing the % SOC at the study site rounded to the nearest integer; colored symbols were added in this report. Corn in the US typically receives about 150 lb N/acre (equivalent to 168 kg N/ha, blue arrow). The colored triangles above this arrow illustrate the yield at this fertilizer rate for soil with different SOC levels. The colored circles suggest how much less N might be needed in soils with 1% or 2% SOC to obtain the same yield as soil with 0.5% SOC when fertilized at the typical rate. Modified from Ref. 136.*

carbon storage with only a small increase in nitrous oxide emissions.

Increasing soil organic matter can allow reduced use of synthetic nitrogen fertilizer. In soil with high soil organic matter (SOM), nitrogen is made available to plants by microbial-related decomposition, reducing the need for synthetic nitrogen fertilizer.[112] A recent meta-analysis of the interacting effects of external nitrogen input and soil organic carbon (SOC) on corn yield (**Figure 25**) provides additional evidence for the benefits of SOM (about half of which is SOC).[136] This study showed that for a given amount of fertilizer, yield was greater in soils with more SOC (see the triangles indicating yield at 200 kgN/ha for soil with different levels of SOC, Figure 25). It also showed that more fertilizer was required in fields with lower SOC (blue triangle) to produce the same yield as in soils with higher SOC (red and orange circles on the dotted constant-yield line, Figure 25).

Finally, this study showed that for all SOC levels, little yield benefit was obtained for application rates of more than 200 kg N/ha (178 lbs N/acre), supporting other studies suggesting that fertilizer levels can often be reduced by 15% with little impact on yield.[128,137,138]

University recommendations serve as a basis for fertilizer application decisions for many farmers. Generally, these do not consider the nitrogen made available through decomposition of soil organic matter, which could reduce the amount of fertilizer needed in fields with high organic matter. This omission appears to stem from the complexity of calculating how much extra nitrogen is available in a given field, which depends on SOM levels, soil type, temperature, moisture and the soil carbon:nitrogen (C:N) ratio.[139,140]

Instead, most University fertilizer recommendations account for existing soil nitrogen by averaging yields for each fertilizer rate across many local fields with different (unmeasured) levels of available soil nitrogen.[139,140] More research into efficient ways to account for the additional nitrogen available in soil with high organic matter should be a high priority, since it would allow many farmers to reduce their applications of synthetic nitrogen.

Some University nutrient recommendations take into account whether farmers are using crop rotation. This is important because residual soil nitrogen from a previous crop can fulfill part of the nitrogen needs of the next crop. For example, in Minnesota, 20-27% less synthetic nitrogen fertilizer is recommended when non-irrigated corn is grown after soybeans, which add nitrogen to the soil, than when corn is grown in continuous culture.[140] In Michigan, recommended rates of nitrogen application for corn are reduced by 20–40 lbs/acre depending on the details of the crops grown with corn in the rotation.[139]

The yield benefit of crop rotation is clearly illustrated by a study in Iowa showing that more than three times as much fertilizer is required to achieve the same yield in continuous corn (CC in **Figure 26**, next page) as in corn rotated with soybeans (SC, compare the stars in Figure 26).[141] This study also showed that yield in corn grown in continuous culture significantly lags the yield of corn grown after soybeans at every nitrogen rate, suggesting that rotating corn with soybeans provides benefits to the corn beyond nitrogen.

Partial replacement of N fertilizer with organic amendments (CPS 590).

Application of manure, biosolids, or compost boosts soil health by adding organic material and nitrogen and reducing the need for synthetic nitrogen fertilizer. In addition, nitrogen is released more slowly from these organic amendments than from synthetic fertilizer, making it less likely to be lost through conversion to nitrous oxide or nitrate before it can be taken up by the crop.

Organic amendments also benefit soil health and increase crop growth in other ways. Extra organic matter helps hold water in the soil, while nutrients other than nitrogen that are released by decomposition also increase plant growth. The larger plants that result sequester more carbon because the greater root biomass and healthier plants produce more root exudates. Larger plants may also leave more residue both above and below ground, increasing the organic matter added to the soil.

Manure and composted food or yard waste are the main types of organic amendments. Diverting these waste products from anaerobic storage such as manure lagoons or landfills not only gives them monetary value, it also has GHG benefits because less methane is produced in aerobic than in anaerobic decomposition of these waste products.[130] For example, composting manure before it is applied reduces joint methane and nitrous oxide emissions by 31-78% compared to the use of raw manure.[142] Not all organic amendments may be safe, however. Many samples of biosolids from municipal waste treatment contain high levels of household toxins and pharmaceutically active compounds,[143] suggesting that spreading municipal biosolids on agricultural soils as fertilizer substitutes should be regarded with caution.

When calculating rates of carbon sequestration for payment or carbon credits, it is important to note that carbon in compost or manure that is brought in from another location is "imported carbon", not carbon that has been sequestered on-site. Because this imported carbon represents a carbon loss from the site of origin, it must be excluded from measures of on-site carbon increases.

Does compost have benefits for carbon sequestration beyond the simple addition of organic matter?

Claims that small applications of compost can dramatically boost carbon sequestration over many years are widely touted, but the data are inconclusive.[144,145,146] For example, in compost applications to California grasslands, increased soil carbon was found in the top 10 cm in just one of two experimental sites.[144,145] Claims from these studies that increased carbon sequestration can continue for 100 years are extrapolations of conditions in the first few years that do not take into account environmental or other changes that are expected to occur over time.[146] Compost diverted from the waste stream can certainly be a valuable addition of organic matter. However, claims that a single

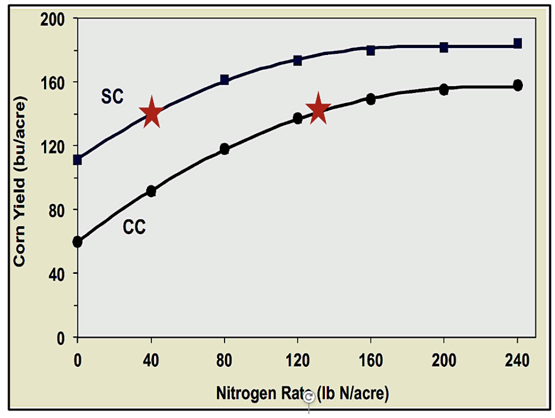

Figure 26. *Yield for corn after soybeans (SC) or continuous corn (CC) at various nitrogen rates at 88 Iowa sites from 2000 – 2013. Stars indicate points at which yields in SC and CC are roughly equal, showing the large amount of extra nitrogen required in continuous corn to achieve the same yield as in corn rotated with soybeans. Modified from Ref. 141.*

addition of compost will lead to dramatic increases in carbon sequestration over decades should be viewed with caution.

As discussed in detail in **Part 1.1,** it is also crucial to note that despite claims to the contrary,[89] any advantages observed from compost applications are unlikely to be due to the addition of microbes found in the compost as is often claimed.

In most states, not enough composted food and yard waste is available from reputable contractors for widespread use in agriculture. If municipal and commercial composting operations were scaled up, more of the food and yard waste now sent to landfills could become valuable source of nitrogen and organic material for agriculture. Such facilities could provide significant economic and environmental benefits by providing new business opportunities and reducing the use of synthetic nitrogen fertilizer.

Conservation crop rotation (CPS 328).

As defined by the USDA-Natural Resources Conservation Service (NRCS), conservation crop rotation involves adding at least one annual or perennial crop to a rotation in order to achieve various conservation objectives, including reducing periods of fallow during which soil is bare.[104] Reducing fallow periods boosts soil microbial populations by adding plant diversity and providing year-round living roots. Avoiding fallow also reduces erosion and improves water quality. Depending on the specific crops added to a rotation, other benefits may also accrue, such as adding nitrogen for the next cash crop, adding forage for livestock, and increasing habitat for wildlife and natural enemies of insect crop pests. Conservation crop rotation can increase carbon sequestration by adding biomass during an otherwise fallow period, particularly when deep-rooted perennials are added to a rotation.[113]

Calculating the GHG impact of conservation crop rotation.

The estimated GHG changes for this practice from

COMET-Planner (Table 1) are based primarily on increased soil carbon sequestration from the extra carbon inputs provided by an additional crop during an otherwise fallow period. When legumes are used as cover crops, or in cover crop mixtures, the nitrogen they fix generally increases nitrous oxide emissions. For dry climates, COMET-Planner averaged the carbon sequestration rates from eliminating summer fallow and the addition of perennial crops to rotations; after averaging, the impact on nitrous oxide was close to zero.[105]

Cover crops (CPS 340). A cover crop is defined as a crop that is planted during part of a rotation when a field might otherwise be left fallow. Cover crops are usually not harvested for sale, although they may be grazed.

Calculating the GHG impact of cover crops. The COMET-Planner ERCs for cover crop use (Table 1) assume the use of either leguminous cover crops that replace 50% of the required nitrogen for the following cash crop or non-leguminous cover crops that replace 25% of the next crop's nitrogen requirement. In either case, soil carbon increases due to additional plant residues, while changes in nitrous oxide are small.

Cover crops offer a wide variety of agronomic and environmental benefits (Figure 27). Cover crops add organic matter to the soil, enhance the aggregate structure and increase the soil's water-holding ability,[147] all of which help to stabilize yield over time.[148] Cover crop roots also scavenge excess nitrogen remaining from the previous cash crop, bringing it up from below the root zone and back to the surface where it can be used by the next crop.[147]

Using nitrogen-fixing legumes as cover crops or including them in multispecies cover crop mixtures also adds nitrogen to the soil. Planting a cover crop in place of winter or summer fallow keeps live roots in the soil, feeding the soil food web and facilitating nutrient cycling. Cover crops are also a key tool for weed control, a function that is particularly important in organic agriculture.[108,149,150]

Cover crops also benefit farmers economically. By boosting plant productivity and allowing farmers to reduce costly inputs like fertilizer and herbicide, cover crops increase profits.[151,152] Further discussion of the economic and environmental benefits of cover crops can be found in **Part 3** of this report.

Multispecies cover crop mixes have additional benefits. Mixes containing three or more different cover crop species are particularly beneficial for soil health because:

- A more diverse plant community leads to increased microbial diversity in the soil.[153,154] Microbial diversity benefits plants by acting as a type of "insurance." In some years or under some conditions, certain microbe species may perform better than others. Microbial diversity thus increases the chance of having a high-functioning microbial community in any given year, which helps to stabilize yield.

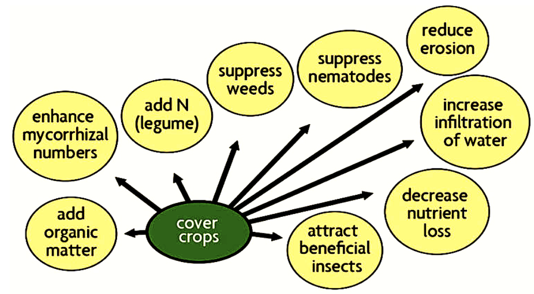

Figure 27. *Multiple benefits of cover crops. Source: Ref. 40.*

- Growing a mixture of plants generally increases total biomass relative to a monoculture, because different species exploit the soil resources in different and often complementary ways.[101]

- Each species in a cover crop mix can help a farmer solve a different problem. For example, a legume can add nitrogen to the soil and adding the deep-rooted tillage radish reduces soil compaction and scavenges nutrients, while the slowly decomposing biomass of a grass can help with weed control in the spring.[151]

- Specific cover crop species and mixes vary in their effect on soil nitrogen, weed control, the amount of organic matter they add, the best timing for planting and termination, their impacts on soil moisture and temperature, and other factors that affect the growth and yield of the cash crops.[144] Strategically deploying mixtures of cover crops that provide multiple benefits is a key part of a long-term soil health program.

Managing cover crops to increase carbon sequestration: Plant early and terminate late. To maximize the residual biomass available for weed control in the next crop and boost carbon sequestration, it is best to plant cover crops as early as possible and to terminate them as late as can be managed.

Fall cover crops are often planted too late for sufficient growth before winter. Waiting to plant the cover until corn or soybeans are harvested can leave little time for plant growth before winter,[144,155] reducing biomass and resulting in lower carbon sequestration. Reduced root growth before winter also compromises the ability of the cover crop to effectively scavenge the nitrogen remaining from the previous crop before it sinks below the root zone.

Early termination sacrifices biomass from spring growth. Cover crops are often terminated several weeks before planting time, and some farmers use cover crops that won't survive the winter. Both of these strategies reduce the magnitude of carbon sequestration and the potential for weed control in the next crop.

Figure 28. ***Left:*** *A cereal rye cover crop is rolled while soybean seeds are no-till drilled into the rolled cover crop.* ***Right:*** *Organic soybeans emerging from cover crop residue three weeks after planting. Credits: Jason Johnson, NRCS.*

For herbicide tolerant row crops, "planting green" right into living cover crops allows for significant spring growth before the covers are terminated with herbicide.

For other crops or to avoid the environmental impacts of herbicides, a "roller-crimper" (a heavy cylinder that flattens the cover crop and kills it by crimping the stems) can be used to terminate the cover crop just before planting into the crimped cover (**Figure 28,** left). In one clever strategy, organic soybeans are planted into a standing cover crop that is terminated a few weeks later with a roller-crimper while the bean seedlings are still flexible enough to bounce back.[151,152] Using one of these techniques to delay cover crop termination in the spring by several weeks can greatly increase cover crop biomass, adding additional organic matter to the soil. The thicker layer of dead biomass from the additional biomass acts as mulch to smother germinating weed seeds (Figure 28, right), potentially reducing both herbicide use and costs.[156, 157]

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When cover crops are planted early and harvested late, they add up to 10 times more biomass than obtained on the more traditional timetable.[157] Motivating growers to plant cover crops early and terminate them late boosts the potential for carbon sequestration, adds more organic matter to the soil and improves weed control in the next cash crop. Using cover crops for weed control is particularly useful in organic production systems.[158]

Special problems that favor the use of cover crops and accelerate the return on investment.

Although achieving meaningful economic returns from cover crop use can take several years,[146] this timetable can be accelerated when a farmer faces one or more of these increasingly frequent problems:

Problem 1: Herbicide-resistant weeds reduce yield or contaminate seed. The use of glyphosate has increased 15-fold since the release of "Roundup-Ready" corn and soybeans in 1996.[159] This flood of herbicide caused intense selective pressure on weed populations, providing an immense advantage to any variants that could tolerate the herbicide and leading to the rapid evolution of glyphosate resistance. Herbicide resistance to glyphosate and every other herbicide is now ubiquitous in weeds. Stubborn weeds like Palmer Amaranth, waterhemp and marestail are now so highly herbicide resistant that they must be controlled as seedlings. Even multiple herbicide applications may not prevent yield loss or seed contamination that reduces the selling price of the crop.[151]

Herbicide resistance in weeds will only get worse with time, and with few new herbicide chemistries available or in development, alternative weed control methods will become increasingly valuable. Already, Palmer Amaranth is close to uncontrollable, and marestail in Illinois is resistant to four different herbicide chemistries.[151]

Planting a high-biomass cover crop like cereal rye before corn or soybeans and either "planting green" into the standing cover or terminating the cover just before planting (Figure 28, left) produces a thick mulch layer that aids in weed control by inhibiting the germination of weed seeds (Figure 28, right). Under most circumstances, using a cover crop to control weeds will allow farmers to reduce herbicide use or apply less expensive herbicides. When resistant weeds are present, the right cover crop can prevent serious financial loss.[151]

Problem 2: Increasing flooding and drought. Climate-related changes in the quantity and timing of rain are causing increasing problems in agriculture, particularly at planting and harvesting.[160]

Figure 29. *Widespread flooding damaged corn plantings across Maryland's Eastern Shore in 2018. Credit: Jim Lewis*

Figure 30. *Flooding in spring 2019 in an Iowa field that was tilled and left fallow without a winter cover crop. Credit: Pacific Standard*

For example, in 2018, record-breaking spring rains in Maryland caused the loss of many acres of early planted corn (**Figure 29**). Cover crops increase water infiltration by improving the aggregate structure of soil and its system of pores, adding organic matter to deeper soil layers, and reducing compaction. After heavy rains, increased infiltration means less flooding, runoff, and erosion. When actively growing, cover crops also transpire some of the floodwater, which helps to dry flooded fields. According to a recent report, cover crops can reduce flooding and its impacts by 20%.[161]

In 2019, devastating floods across the Midwest produced catastrophic losses to agriculture put the problems caused by fall tillage into stark relief (**Figure 30**). Fall tillage is common in the Midwest. By breaking up the network of roots and vegetation that supports the soil and its system of pores, fall tillage reduces water infiltration and leaves fields vulnerable to erosion for the entire winter and spring seasons. In fields left fallow after fall tillage, heavy spring rain tends to either run off and erosion or remain in pools (Figure 30). This standing water can take a long time to dry enough to support the heavy equipment needed for spring planting. After the 2019 floods, 20 million acres of corn, soybeans and other crops could not be planted because fields were too muddy.[162]

This historic flooding event provided a unique opportunity for many farmers to see and compare the fates of fields that had been tilled (as in Figure 30) with nearby fields managed using no-till and cover crops.[163] Many farmer saw that no-till fields had less flooding and could be worked sooner than those that were conventionally tilled. Cover crops helped even more by reducing erosion. Although crop residue left in no-till fields blunts the eroding force of rain, the living roots of cover crops anchor the soil in ways that crop residue cannot.

Of the farmers who reported using cover crops in 2019 in the National Cover Crop Survey, 78% were able get their crops planted despite the floods. Among those who could not plant, 36% said that they noticed less planting failures in fields that had a cover crop than in those that had been conventionally tilled.[164]

Droughts are now also more frequent due to climate change.[1,3,6,160] The organic matter added by cover crops increases the water-holding ability of soils, an important benefit during dry periods. In addition, mulched cover crop residue reduces soil evaporation and keeps the soil cooler, which helps to retain soil moisture and reduce plant stress in the increasingly hot summers under climate change.

Midwest farmers who planted cover crops before and during the major drought in 2012 reported that they needed less irrigation, and their yields were higher by 9.6% in corn and 11.6% in soybeans in that drought year compared with yields in nearby fields with similar management but no cover crops.[151]

Keeping the soil cool and retaining soil moisture by using cover crops is also important for the health of beneficial soil bacteria and mycorrhizal fungi, which make important contributions to water availability in their own right. Mycorrhizae are more vigorous in soil where cover crops have been used, bringing crucial moisture to plants when conditions are dry. Finally, when cover crops reduce compaction and help retain moisture, crop roots can grow deeper, further increasing water uptake (**Figure 31**).

Figure 31. *The deep roots of a cereal rye cover crop stabilize the soil, reduce compaction and retain moisture, allowing the soybeans that follow to root more deeply and gather additional water and nutrients. Source: Ref 147. Illustration by Carlyn Iverson.*

Climate-related increases in flooding and drought are likely to continue and even intensify.[1,160] Increasing infiltration and water retention and boosting soil health through practices like no-till and cover crops is a simple and economical way to minimize climate risks to agriculture.[6]

Problem 3: Soil is compacted. Soil compaction from heavy equipment is accelerated in wet conditions when the need to plant or harvest on time drives farmers to enter fields before the soil has dried sufficiently. This is an increasing problem as heavy downpours become more common under climate change.[1,160] Soil compaction can reduce yield up to 20%[165] By reducing infiltration, it increases the spiral of flooding and erosion, which jeopardizes future production.

Soil compaction is sometimes addressed with a form of vertical tillage called sub-soil ripping, but that is generally only a temporary solution.[151] Using deep-rooted cover crops to break up soil compaction through "biotillage" is a longer-lasting solution that reduces compaction while boosting soil health and sequestering carbon.[166] For example, the roots of tillage radish can grow >5 ft in just a few months, breaking through compacted soil (**Figure 32**). Deep-rooted cover crops can also add organic matter to deeper soil layers and create channels that further increase infiltration. The roots of future cash crops preferentially grow down these channels, gaining access to additional water and nutrients.[39,151]

Cover crop use is low but increasing. Data from the 2017 US Census of Agriculture for cover crop use nationwide shows low rates of cover crop adoption, particularly outside the Mid-Atlantic states (**Figure 33,** left).[167] The picture is somewhat better for cover crop use in the major commodity crops corn, soybeans and cotton (Figure 33, right), but even in those crops the average cover crop use nationwide is only 6.7%.[168] Although current cover crop usage is low, the average yearly increase nationwide between 2012 and 2017 was over 8% in the commodity crops. If this continues, up to 40 million acres could be in cover crops by 2029,[168] sequestering carbon and improving the resilience of American agriculture.

Figure 32. *Deep-rooted cover crops like tillage radish help to alleviate soil compaction and boost soil health by adding organic matter to deep soil layers. Arrow marks the radish taproot. Source: Ref. 146.*

Mulching (CPS 484). This practice involves spreading high carbon plant residues on cropland. This additional biomass can add to the biomass remaining from a cover crop, boosting weed control, adding organic matter, retaining soil moisture and cooling the soil.

Calculating the GHG impact of mulching. The COMET-Planner ERCs for mulching reflect the additional carbon sequestration that can result from adding high carbon (low nitrogen) mulch such as straw or crop residues to cropland.[105] However, if this material comes from off-site, it can't be considered as a local increase in carbon because it represents a carbon loss somewhere else.

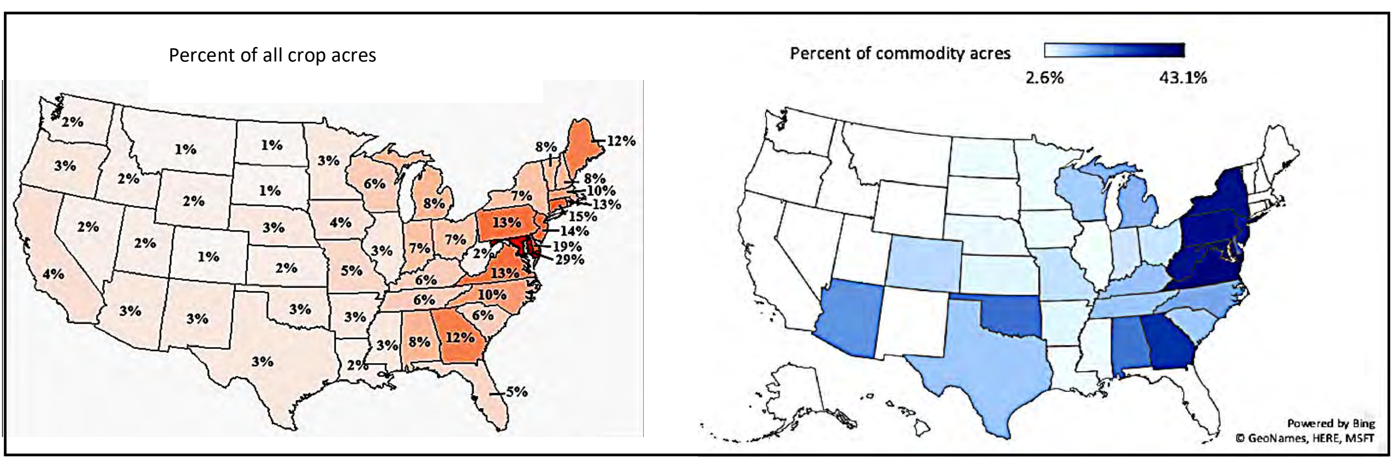


Figure 33. ***Left:*** *Cover crop adoption across the US as a percentage of total cropland acres (calculated from data in the 2017 US Census of Agriculture). Source: Ref. 167.* ***Right:*** *Cover crop adoption as percentage of acres in corn, soybeans and cotton. Source: USDA-SARE and Ref. 167.*

Stripcropping (CPS 585). In this practice, row crops, forages (legume or non-legume), and small grains are arranged in equal-width strips across a field (**Figure 34**). Each year, the rotation proceeds across the strips.

Differences in the annual cycles of the crops mean that mature plants are present on some strips when other strips are bare or just planted. This reduces wind erosion and the damage that blowing soil can cause to seedlings.

Calculating the GHG impact of stripcropping. The COMET-Planner ERCs for this practice reflect the impacts of adding an unfertilized perennial (e.g. grasses, legumes, or hay crop) to a rotation of annual crops. The reduced disturbance and additional plant residues from the perennial forage increases soil carbon stocks while the lack of fertilizer application on the perennials lowers nitrous oxide emissions.[105]

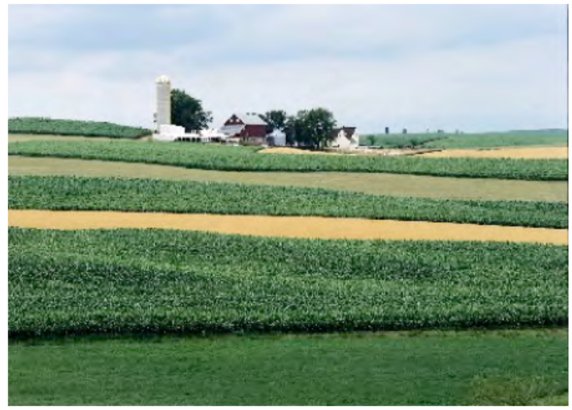


Figure 34. *Stripcropping. Each strip is wide enough for the crops to be worked separately. The strips are often planted on the contour. Credit: NRCS New York.*

2.3 Convert cropland to permanent unfertilized herbaceous or woody cover

Permanent unfertilized plantings of perennial plants have significant conservation benefits. In this category, land previously used for row crops or food production is planted with perennial grasses, legumes or other herbaceous or woody plants, depending on the specific practice and its purpose. These plantings protect cropland that is vulnerable to erosion and add value to marginal cropland where crop growth is poor year after year. Because these practices are often used on strips of land adjacent to cropland, they are sometimes called "edge-of-field" practices.

Some of the practices in this category provide annual income, such as planting forages to be harvested, crops that can serve as feedstock for biomass production, or harvestable trees within cropland or pasture. Other practices involve converting cropland to permanent unharvested plantings that provide key environmental benefits, including intercepting agricultural chemicals and sediment at field borders, managing wind or stormwater and reducing stream erosion. These plantings can also attract pollinators and insects or other invertebrates that prey on or parasitize crop pests (often called "natural enemies"). Because these areas are generally unfertilized, they also reduce the overall use of synthetic nitrogen, which saves money, lowers nitrous oxide emissions, and reduces the carbon emissions from the production and transport of synthetic nitrogen fertilizer.

For all of the practices in this section, it is highly preferable to use ecologically appropriate native forbs, grasses or woody plants whenever possible because they provide important wildlife habitat and are well adapted to the soils and climate. Using these practices to add high quality patches of native habitat to agricultural lands will help to rebuild the biodiversity of microbes, insects and wildlife on agricultural lands while improving soil health and sequestering carbon. It is important that these plantings be ecologically consistent with the types of habitats present before conversion to agriculture. For example, because fire prevented trees from encroaching into native prairies, the invasive potential of trees planted in areas that were formerly prairie should be considered in any of the practices that involve adding woody plants.

Calculating the GHG impact of adding permanent herbaceous or woody cover. Except where noted, the COMET-Planner ERCs for the practices in this category are based on the conversion of conventionally managed cropland to permanent unfertilized herbaceous or woody cover. This results in increased soil carbon stocks from the cessation of tillage, additional plant residue, and reduced nitrous oxide emissions from the elimination of synthetic fertilizer. Where shrubs or trees are planted, the estimates include the accumulation of carbon in woody biomass.[105] The COMET-Planner ERCs measure the GHG impacts per acre of the practice, though individual strips or parcels may be less than an acre.[105]

ERCs estimated by COMET-Planner for alley cropping and multistory cropping are based on replacing 20% of the area of a conventionally managed crop field with woody plants. GHG impacts come from increased soil organic matter due to the cessation of tillage and increased carbon inputs from plant residues, decreased nitrous oxide emissions from reduced fertilizer application, and the accumulation of carbon in woody biomass.[105]

Conservation cover (CPS 327). This general category involves planting areas of perennial grass and/or herbaceous plants that attract wildlife, pollinators, and natural enemies of crop pests such as spiders and ground beetles. These areas of deep-rooted plants not only increase biodiversity, but they also sequester carbon, reduce erosion, improve stormwater infiltration and boost water quality by absorbing nutrients and chemicals leaching from adjacent fields. When possible, ecologically appropriate native plants are preferred to increase the biodiversity co-benefits.

An innovative program in the Midwest involves planting permanent strips of prairie plants (mixed forbs and grasses) between fields or strips of corn or soybeans to improve soil health, reduce flooding, and improve water quality by filtering runoff from fields (**Figure 35**).[169] The width and shape of these "prairie strips" depends on the amount of water draining from adjacent fields, with wider/larger strips used in areas with more runoff.

Prairie strips are growing in popularity because they help manage stormwater and reduce water pollution while having little average impact on yield.[170] Moreover, farmers can be compensated for the installation and maintenance of the strips through the USDA-Farm Service Agency (FSA) Conservation Reserve Program (CRP).[171]

Permanent forage and biomass planting (CPS 512). These plantings include mixtures of grasses and other plants that are adapted for pasture, hay or use as feedstocks for biomass production. Again, using native plants is preferred for the additional biodiversity benefits. These plantings will generally be either harvested or grazed, and are assumed to be unfertilized in order to reduce GHG emissions from manufacture, transport and application of synthetic nitrogen fertilizer.

Contour buffer strips (CPS 332). In this practice, narrow strips of herbaceous perennials are planted on the contour between wider crop strips (**Figure 36).** Buffer strips can be used on any sloping land including cropland, orchards, or vineyards, and are usually planted with deep-rooted grasses and/or legumes that increase infiltration and may add nitrogen. Planting the strips on the contour slows runoff and directs the water evenly across the strips to filter out sediment and agricultural chemicals.

Riparian herbaceous cover (CPS 390). This practice involves planting grasses, legumes or other plants that can tolerate periodic flooding on stream borders in order to reduce erosion and increase water quality (**Figure 36**). With the climate-related increase in heavy precipitation, riparian buffers are becoming an increasingly important tool for reducing stream erosion. Riparian buffers also reduce nutrient flow into streams from adjacent fields or pastures, provide food for fish or wildlife and can be used to restore plant communities that naturally occur in riparian areas.

Figure 35. *A "prairie strip" planted between crop strips on a Montana farm. Credit: Jennifer Hopwood, Xerces Foundation.*

Field border (CPS 386). Planting a strip of deep-rooted grasses or other perennials around a field can filter runoff and catch sediment that would otherwise enter surface waters.

Filter strip (CPS 393). Much like a field border, this practice involves planting strips of perennial grasses around fields near environmentally sensitive areas in order to filter contaminants and reduce sediment in surface waters (**Figure 36**).

Grass waterway (CPS 412). In this practice, perennial grasses are planted in a graded channel that serves as a temporary watercourse during heavy rains (**Figure 36**). Grasses used in this setting generally have weak stems and lay down under flowing water. Grass waterways reduce erosion and flooding of cropland while adding organic matter and increasing soil health.

Vegetative barrier (CPS 601). In this practice, dense plantings of stiff perennial herbaceous vegetation are made on hillsides or slopes to filter water and educe erosion. Native grasses are often used in this setting because they can grow more than 5-6' tall with stiff stems that interfere with water flow.

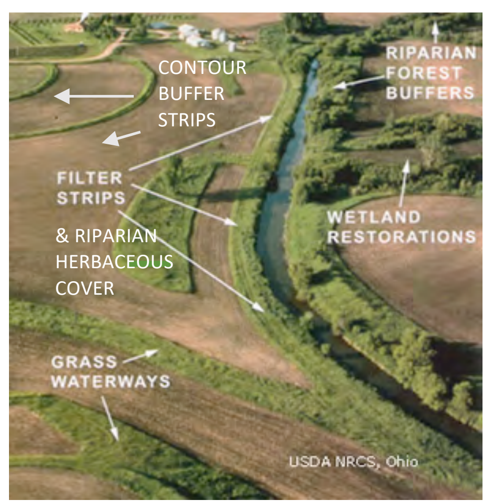


Figure 36. *Examples of several practices involving herbaceous cover, showing how their placement can intercept or direct water to filter out chemicals & sediment and reduce erosion. Modified from USDA NRCS.*

Tree and shrub establishment (CPS 612). This practice involves planting seedlings or cuttings or promoting natural regeneration in previously forested areas. Species selection depends on the site and purpose of the project, and ecologically appropriate native species are preferred when possible in order to provide useful habitat. Benefits of tree and shrub establishment include controlling erosion, improving water quality, enhancing wildlife habitat, and conserving energy when trees provide shade for buildings. It is important to recognize that planting trees should be undertaken with care in regions where the native vegetation was prairie or grassland. In such settings, woody plants may become invasive without the fire that historically prevented their encroachment, and trees and shrubs can be detrimental to grassland nesting birds and other species. Trees should only be planted in areas where the native vegetation was forest or included trees and shrubs in particular areas, such as around streams.

Hedgerow planting (CPS 422). A hedgerow is a linear planting of trees, shrubs or perennial bunch grasses of at least 3′ in height. A mixture of plant types is particularly effective at disrupting wind erosion and intercepting airborne particulates or chemical drift. A hedgerow can also provide a visual or sound barrier. Adding a strip of conservation cover including native forbs like those found in a pollinator meadow increases biodiversity and provides crucial food and habitat for pollinators and natural enemies of insect pests, which can increase crop productivity and profits (**Figure 37**).[172,172b,173]

Riparian forest buffer (CPS 391). Planting trees and shrubs along waterways can be combined with herbaceous riparian buffers, enhancing their benefits (Figure 37, above). Woody buffers can reduce aerial pesticide and herbicide drift as well as intercept the flow of agricultural chemicals into surface waters. They also add habitat elements that attract additional biodiversity. Moreover, because carbon is stored in the wood as well as in the roots, woody riparian buffers sequester more carbon per acre than do herbaceous buffers (see Table 1). Again, ecologically appropriate native species are preferred.

Alley cropping (CPS 311). This is an agroforestry practice in which strips of crops are alternated with strips of woody plants that shield the crop from wind (**Figure 38**). The trees and shrubs can produce additional products for sale.[174,175] If shading of the crop is a

Figure 38. *Alley cropping with cotton planted between strips of pine trees in Florida. Credit: National Agroforestry Center, USDA.*

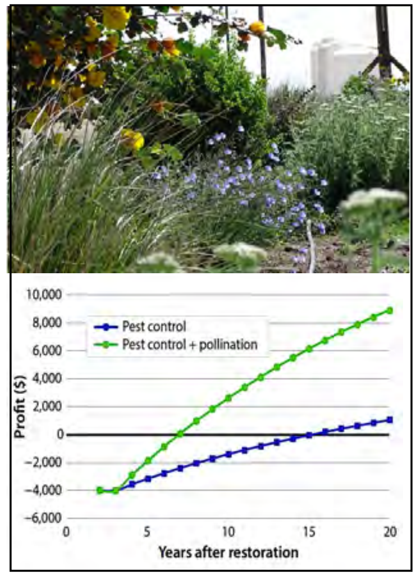


Figure 37. ***Top:*** *Hedgerows planted between fields can contain trees or shrubs as well as grasses and flowers, all preferably native. From Ref. 173.* ***Bottom:*** *Restoring hedgerows provides important habitat for pollinators as well as insects and spiders that help to control pests, boosting profits. When costs are covered by an incentive program, profits increase as soon as Year 2. From Ref.172.*

concern, a strip of herbaceous perennials (i.e., Conservation Cover, CPS 327) can be planted between trees and the crop. Alternatively, alley cropping can be used to shade crops that might be damaged by high summer temperatures.

Multistory cropping (CPS 379). By planting trees and shrubs of different heights with herbaceous understory plants in a way that mimics a forest, this practice improves crop diversity and makes maximum use of space (**Figure 39).** Multistory cropping is a common approach in international small-holder farming.[176] In the US, multi-layer cropping is associated with "permaculture", a farming strategy designed to combine fruit trees and shrubs of different heights with herbaceous vegetable or fruit crops that can tolerate shade beneath.[177] Increasing the use of permaculture for its carbon benefits could help organic growers and urban farmers who wish to improve soil health while maximizing productivity. This approach could potentially be scaled up for use in larger commercial farms after a demonstrated record of success in smaller settings.

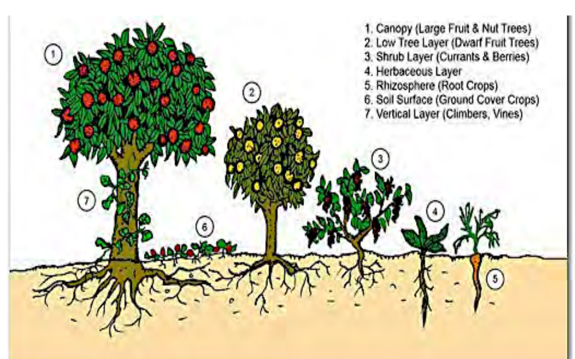


Figure 39. *Multistory cropping is one of the hallmarks of permaculture, a growing trend on small farms and in urban agriculture. Credit: The Permaculture Research Institute.*

2.4 Practices Involving Grazing

In conventional (continuous) grazing, animals are confined within a large pasture or section of rangeland and allowed to graze at will. This grazing strategy can lead to overgrazing and bare soil. It can also lead to overconsumption of favored plant species relative to disfavored ones, causing the plant community in the pasture to be become dominated by disfavored plants and weeds. Alternatives to traditional continuous grazing include silvopasture[174,175] and "prescribed grazing" or "management intensive grazing" (MIG).[178]

Converting conventionally managed cropland to grassland that is hayed or grazed can have a positive impact on GHG emissions (see Permanent Forage and Biomass Planting CPS 512 above) while improving water quality and reducing erosion. Using ecologically appropriate native plants in grazing lands boosts biodiversity by improving habitat for wildlife and pollinators.

Range Planting (CPS 550). This practice is used to restore the plant community in a grassland to one more typical of native conditions, and it is one of the most effective ways to sequester carbon in grazing lands (see Table 1). Range planting can involve adding adapted legumes or grasses, but planting grasses and forbs native to the site is preferred in order to support and increase local biodiversity. Range planting, particularly with native plants, improves forage for livestock and increases habitat for wildlife while reducing erosion, improving water quality and sequestering carbon.

Several recent studies have suggested that native warm-season grasses not only sequester more carbon but also enhance steer growth as compared to the introduced fescues that are often used for pasture.[179] Based on these studies, the USDA recommends planting these native grasses where possible to increase the quality summer forage in pasturelands, pointing out that these native grasses also provide valuable habitat for bird species with declining populations like the northern bobwhite.

Other grassland birds also prefer the bunch-grass growth habit of the native grasses to the more continuous carpet of the introduced fescues, and the greater height at which native grasses are maintained provides enhanced cover for these bird populations.[179]

Calculating the GHG impacts of range planting. COMET-Planner calculates the ERCs for rangeland planting by assuming that degraded grasslands are restored to more native conditions or seeded with improved forages. This will increase productivity and add additional plant residues to the soil, boosting carbon storage.[105]

Figure 40. *Silvopasture for cattle. From Ref. 175.*

Silvopasture (CPS 381). Silvopasture is an agroforestry practice that is not yet commonly used in the United States, but one that could provide significant advantages if it were more widely adopted in regions where it is ecologically appropriate (**Figure 40**).[174,175] Silvopasture most commonly involves planting trees on pasture lands but can also be accomplished by planting pasture grasses after thinning existing forest stands (**Figure 41**). The trees store additional carbon in the wood and can provide an extra source of income from nuts or periodically harvested timber. Adding woody plants to grazing lands also provides habitat options that are likely to increase biodiversity.

Using silvopasture, grazing animals can be kept cool while feeding outdoors all summer. The ability to naturally cool large animals like dairy cattle or horses without requiring air-conditioned barns is likely to become increasingly important as summers become hotter and more humid under climate change. Silvopasture could become a particularly important tool for climate resilience in the dairy and horse industries and a good way to save energy and reduce GHG emissions in the agricultural sector.

Calculating the GHG impact of silvopasture. The COMET-Planner ERCs for silvopasture are based on the additional carbon accumulation in woody biomass from planting trees and/or shrubs on existing unfertilized grazing land, and assume little change in soil carbon or N_2O emissions.[105]

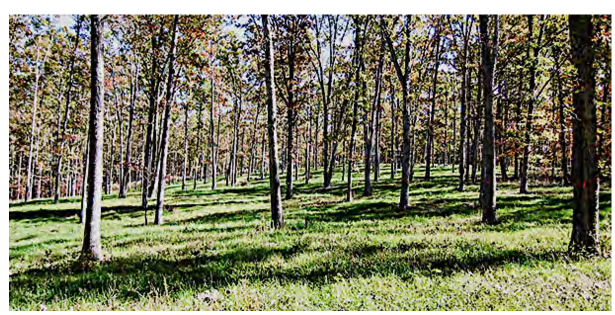


Figure 41. *Silvopastures can be made by thinning existing forest as well as by planting trees in pasture. Credit. Progressive Forage.com.*

Prescribed grazing, rotational grazing (CPS 528). Prescribed grazing is defined by NRCS as managing the harvest of vegetation with grazing by cattle, goats or sheep.[104] This definition has been broadened to include more intensive pasture management in which cattle are confined in a small area of pasture for a short period of intensive feeding before being moved to a new area.

This general strategy will be referred to here as rotational grazing, although several variations exist, such as adaptive multi-paddock (AMP) grazing, management-intensive grazing (MIG) and sometimes, "mob" grazing. These variants differ in the details of how often the animals are moved, stocking rates and recovery times for the pasture segments between periods of grazing.[178,180]

Despite some differences in the details, the various forms of rotational grazing all control the timing, intensity and/or duration of livestock grazing in a given areas to prevent overutilization or underutilization of available forage, reduce selective foraging on desirable plants, and limit access to sensitive areas. By preventing overgrazing, erosion is reduced and less bare ground is available for weed growth. By attempting to align livestock herbivory with active plant growth, provide plants adequate rest between grazing bouts, and avoid excessive selective pressure on desirable plant species, rotational grazing aims to improve the productivity, diversity, and composition of pastures and grasslands.[180,181]

Common to all forms of rotational grazing is the need for the grazier to continuously evaluate conditions as animals are moved among pastures.[180] This means that successful rotational grazing requires motivated and experienced graziers who are willing to actively manage their herds, sometimes on a daily or even hourly basis.[180]

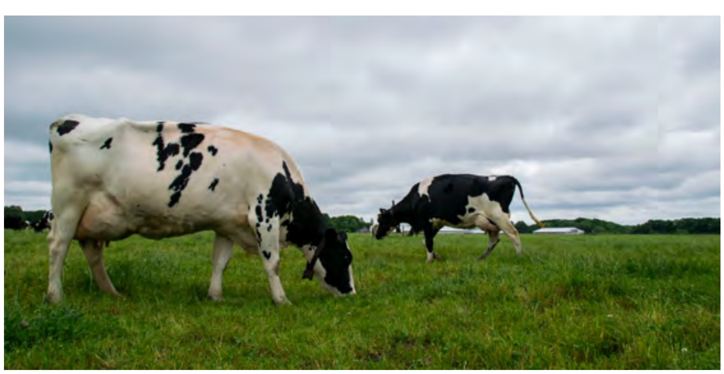
There are many non-peer reviewed extension reports, books, and articles in the popular press touting the carbon-sequestering benefits of various intensive grazing methods.[181,182] Among the handful of peer reviewed studies comparing carbon sequestration among different forms of rotational grazing, one study found significant carbon benefits in rotationally grazed pastures.[183]

Among other peer-reviewed studies, the impacts of rotational grazing on carbon sequestration depended on the type of grass, grazing intensity, regional climate and management practices. For example, results of one meta-analysis found no average increase in carbon storage across a variety of studies of rotational grazing. Instead, results showed an increase in soil carbon of 6-7% in pastures containing warm season grasses but a decline of 18% in pastures dominated by cool season grasses.[184] In another meta-analysis, pooling data across climatic conditions grazing resulted in a net loss of SOC,[185] but separating the data by climate type revealed that grazing increased carbon by 7.6% in most warm climates but decreased it by 19% in moist cool climates. The same study showed that in dry climates (both warm and cool), only low or low to medium grazing intensities led to soil carbon increases.[185] Increasing management intensity by fertilizing and irrigating pastures can also increase carbon sequestration.[186] These examples show the need to consider the heterogeneity of data from different situations before pooling studies into a single meta-analysis.

The large number of different strategies used for rotational or management-intensive grazing and the need for constant adaptive management has made it hard to accumulate a critical mass of peer-reviewed studies that use the same protocols to make controlled comparisons between carbon sequestration in conventional grazing and MIG systems. This is an important research need.

Calculating the GHG impacts of grazing. The COMET-Planner estimates of GHG reduction for prescribed grazing do not encompass the variety of rotational grazing strategies. They are based simply on the increase in soil carbon stocks expected to result from moving animals among pastures at 21-day intervals and allowing them to remove only 40% of available forage, instead of the 60% or more of the forage typically removed during conventional grazing.[105] These estimates do not yet capture the intricacies of all of the various ways that MIG can be implemented.

Grazing has the potential to be a useful carbon-sequestering practice. At this time, however, full evaluation of the possibilities awaits additional peer-reviewed studies of carbon sequestration in each of the various forms of rotational grazing when compared to the more traditional strategy of continuous grazing.



Credit: Kellogg Biological Station, Michigan State University

Part 3.

Environmental & Economic Co-benefits of Healthy Soil and Land-Based Carbon Sequestration

Co-benefits enhance the value of practices that sequester carbon in agricultural soil. In fact, many of these practices are already in use nationwide because of these co-benefits. For example, recognizing the ability of cover crops to reduce the flow of nutrients and sediment from cropland to Chesapeake Bay, Maryland established an incentive program in 2004 to increase the use of cover crops.[187] This program has been so successful that Maryland now leads the nation in cover crop use (see Figure 33 above).

In a similar way, no-till and reduced-till (sometimes called "conservation tillage") are currently valued primarily for their many co-benefits, not because they sequester carbon. Conservation tillage has become familiar through its beneficial impacts on soil health, water quality and the availability of water, and it also appeals to farmers because it saves time and money (**Figure 42**).

A comprehensive treatment of the environmental and economic co-benefits of the recommended practices is beyond the scope of this report. Our goal is simply to put these co-benefits into context and to provide a few examples that are particularly compelling and that may be useful in policy discussions and outreach efforts.

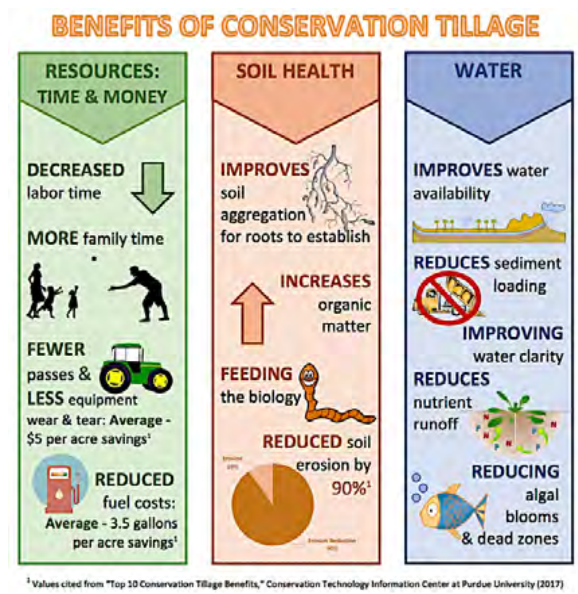


Figure 42. *Conservation tillage saves resources, improves soil health and increases stormwater control and water quality. Drawn by Fox Demo Farms. University of Wisconsin Extension.*

3.1 Environmental co-benefits of the carbon-sequestering management practices

The environmental co-benefits of the carbon-sequestering practices extend well beyond the farm by boosting the ecosystem services provided by healthy soil, which are important for all living things. These services include ensuring adequate nutrient and water cycling, reducing erosion, maintaining the quality of surface and coastal waters and increasing biodiversity.

Degraded agricultural soils cannot perform key ecosystem services. In undisturbed native soils, the carbon released as CO_2 by microbial respiration is balanced by new carbon sequestered in the soil, the loss of soil through erosion is balanced by the formation of new soil, and the loss of soil nutrients in ground and surface waters is balanced by the input of nutrients from decomposition[9] (**Figure 43,** next page, left). In contrast, the "domesticated" soils now found in agriculture are out of balance and losses of carbon, soil and nutrients

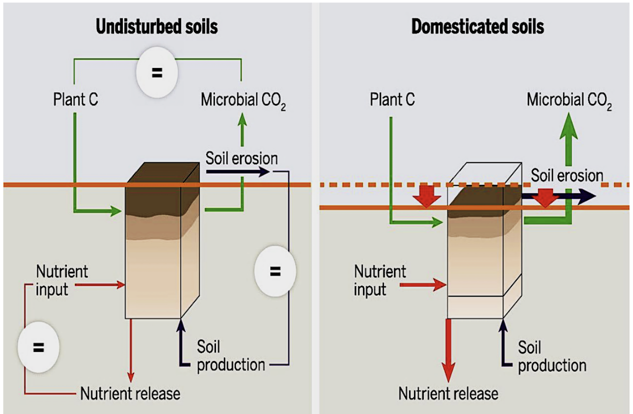


Figure 43. ***Left:*** *In undisturbed native soils, there is a balance between loss and gain of carbon, soil and nutrients.* ***Right:*** *In degraded agricultural ("domesticated") soils, this balance is lost, and the crucial ecosystem functions of nutrient cycling and water purification and flow management begin to fail. The recommended carbon-sequestering agricultural practices improve soil health and help to rebuild the balance seen in native soils, restoring the key ecosystem services. Source: Ref. 9. Used with permission.*

from the soil far exceed gains (Figure 43, right). By increasing resilience to dangerous floods and droughts, improving the cycling of key nutrients, and increasing the purity and availability of fresh water, rebuilding the soil benefits all organisms.

Restoring ecosystem services. Increasing the use of the agricultural practices recommended here for carbon sequestration will help to restore the crucial balances seen in native soils so that the two major "ecosystem services" of soil can once again operate effectively:

Nutrient cycling. The soil ecosystem is where nutrients are cycled, that is, where formerly living material is decomposed by microbes and its component nutrients (e.g., carbon, nitrogen, phosphorous, potassium) are released in forms that can be taken up by plants to continue the cycle. When nutrients are cycled effectively by a healthy soil food web, less synthetic nitrogen fertilizer is needed. This reduces GHG emissions from fertilizer manufacturing and transport, lowers water pollution from nitrate runoff and cuts air pollution from nitrous oxide, a potent greenhouse gas.

Water cycling and purification. Water readily infiltrates into healthy soil, reducing costly damages from flooding , lowering sediment erosion, and allowing natural filtration of the water. As described below, the aggregate structure of healthy soil acts as both a physical and biological water filter. Many soil microbes actually metabolize pesticides, fungicides, and herbicides, thereby reducing their concentrations in groundwater.[188] The organic matter in healthy soil holds water,[189] reducing the need for irrigation.

YEAR	RAINFALL (inches)	RUNOFF (inches)	
		NO-TILL	MOLDBOARD
1979	44	0.14	5.52
1980	46	0.19	12.47
1981	42	0.00	5.60
1982	35	0.00	4.46
Average		**0.09**	**7.01**

Figure 44. *Over 4 years, the average runoff (inches) from no-till fields was only 1.2% that seen in fields that had been intensively tilled using a moldboard plow. Source: Ref. 190.*

Improving soil health can therefore preserve limited freshwater supplies, avoid the expense of irrigation equipment, and reduce the use of electricity for pumping and spraying irrigation water. It is also becoming increasingly clear that microbes in healthy soil can confer drought tolerance on plants and even alter the nature of the soil to reduce evaporation and increase the retention of water.[63]

Erosion reduction. Erosion by water and wind causes the loss of rich topsoil and its carbon-rich organic matter. In conventional agriculture, tillage breaks up the aggregate structure of soil, leaving it loose and without the intricate system of pores that allow water to infiltrate into healthy soil as if it were a sponge.

After tillage, wind can carry the loose topsoil away, while stormwater that can't infiltrate gathers on the surface and runs off, carrying the topsoil with it, clogging streams and other surface waters. No-till reduces runoff, the first step in erosion (**Figure 44**). In tilled fields, as much as 4000 lbs. of soil per acre can be washed into streams and waterways after a single heavy rain (**Figure 45**, left). When fields are tilled in the fall and left fallow until spring, this erosion can continue for months. Not only does erosion choke surface waters with sediment and cause massive water pollution, it reduces the organic matter in agricultural fields that is required for a healthy soil food web and compromises the potential for future carbon sequestration.

Simply reducing tillage lowers sediment loss through runoff (compare the muddy water running off the tilled field in the left panel in Figure 45 with the reduced runoff in block #1 in the right panel).

Figure 45. ***Left:*** *Water streaming off a flooded field that has been tilled, illustrating the magnitude of sediment loss from water erosion in tilled fields left fallow. NRCS; Photo credit: USGS.* ***Right:*** *These flumes measure surface water movement and nutrient concentrations in runoff from experimental fields in Iowa containing different percentages of prairie plants. Even including a strip of prairie plants comprising only 10% of a corn or soybean field has a dramatic impact on the amount and quality of the water leaving the field. Source: Ref. 169.*

By including just 10% conservation cover in corn and soybean fields using "prairie strips" of native plants, researchers in the Midwest documented a 60% reduction in runoff and a 95% reduction in sediment loss (Figure 45, right #2).[169] Even greater water quality benefits can be obtained by planting larger tracts of deep-rooted perennial prairie plants (Figure 45, right #3).

No-till and cover crops together are powerful tools for reducing erosion and sediment loss. In no-till, 30% of the residue from the previous crop is left on the surface, reducing erosion by 70%.[190] Live roots in cover crops hold the soil during the winter, and living above-ground vegetation adds to the physical buffer from rain provided by the crop residue left on the surface by no-till. By channeling runoff from fields with different management histories to adjacent ditches, USDA-NRCS demonstrated that a no-till field with a winter cover crop produced less runoff with a smaller sediment load (**Figure 46,** note clarity and low volume of water in ditch on left) than did a conventionally tilled field (Figure 46, ditch on right).

Between 1982 and 2012, the use of NRCS conservation practices resulted in an estimated 35% reduction of soil erosion[191] **(Figure 47**). Even so, the 2012 national average rate of erosion was still 4.6 tons per acre per year, a significant annual loss of organic matter from agricultural fields. The greatest erosion (7-8 tons/acre annually) is seen in the upper Mississippi River drainage (Figure 47), where the use of no-till and cover crops and even crop rotation remain at relatively low levels.[192]

Water that infiltrates into soil is filtered and purified.

As discussed in **Part 1**, the aggregate structure of healthy soil includes stable pores that allow water to infiltrate. When this aggregate structure is disrupted by tillage, water runs off rather than infiltrating (Figures 45, 46).

Figure 46. *Demonstration of the impact of soil health practices on runoff quantity and sediment load. The field on the left was planted using no-till while the field on the right was conventionally tilled in the fall and left fallow over the winter. Runoff from the no-till field contained visibly less sediment than runoff from the conventionally managed field. Credit: Arnold King, NRCS.*

Runoff not only facilitates erosion and damages water quality by adding sediment to waterways, it also reduces the natural ability of soil to purify water.

Both the physical properties of the soil and the actions of soil microbes help to clean water that infiltrates into the soil.[193] The physical structure of soil traps sediment, while soil particles bear negative charges that attract and bind to various toxic chemicals, removing them from groundwater. Soil microbes play an active role in water purification in soil by breaking down some organic chemicals, including some pesticides and herbicides.

Healthy soil can even reduce pathogens. As pathogenic bacteria move through the soil in groundwater, they are attacked and degraded by soil microbes. Water-borne pathogens can become adsorbed onto clay particles in soil, be trapped in tiny spaces within soil aggregates, or die because the soil environment is so different from that of their host. The microbial, chemical, and physical processes involved in the soil-based purification of groundwater are essentially the same processes by which household wastewater is treated in a residential septic field.

1982 **2012**

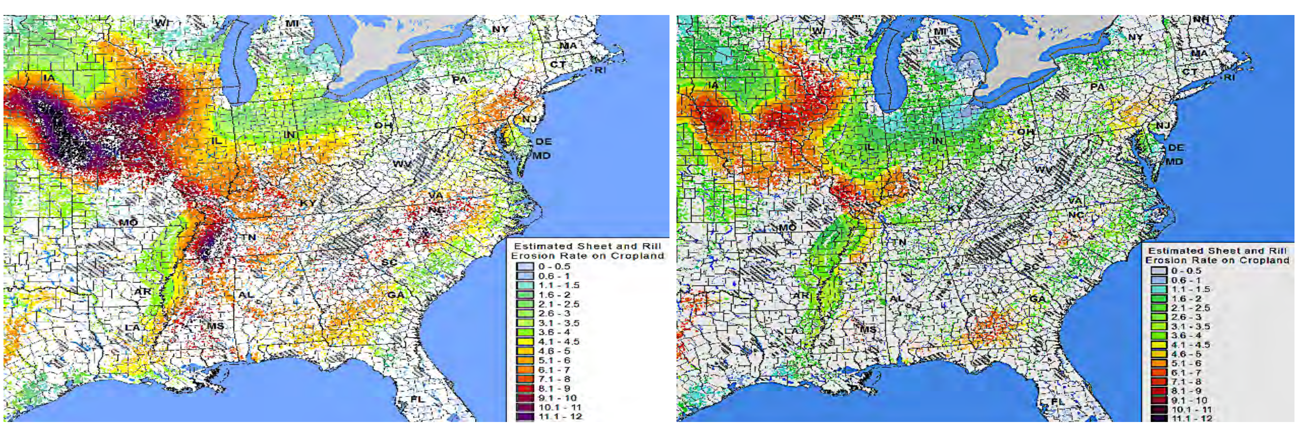


Figure 47. *Rates of erosion (tons/acre per year) improved between 1982 and 2012, but are still at very high levels in the Midwest, where the use of tillage and fallow periods are common and adoption of cover crops and crop rotation is still relatively rare. Source: Ref. 191.*

Figure 48. *Adding a strip of native prairie plants to provide food and habitat for pollinators and other insects increases the populations of pheasants and quail on this farm. Credit: NRCS*

Agricultural practices that sequester carbon also boost biodiversity. We are in the midst of a worldwide decline in insect diversity spurred by both intensive agriculture and climate change.[194,195] Insect populations have been decimated by the widespread use of agricultural chemicals, the spread of invasive species, the loss of habitat from climate change and ongoing land conversion for agriculture and development.

Contrary to popular belief, most insects are neither crop pests nor vectors of disease. The majority are highly beneficial, and their contributions to a vibrant planet cannot be overestimated. The loss of insect pollinators and natural enemies of crop pests not only jeopardizes agricultural productivity, it also threatens populations of birds and other creatures that depend upon them for food.[194,195]

Increasing the use of the recommended carbon-sequestering practices will not only improve soil health and water quality, it will also provide crucial habitat to support increased biodiversity. Practices that add permanent sources of herbaceous and woody cover (see **Part 2**) provide habitat that can help to rebuild the populations of beneficial insects (**Figure 48**). Other practices such as crop rotation and the use of multispecies cover crops increase the diversity of soil microbes and other soil organisms, a crucial component of rebuilding soil health. Using cover crops, converting cropland to grassland, trees or shrubs and planting trees on grazing lands (silvopasture) also provide important habitat for birds, mammals and other wildlife.

3.2 Economic co-benefits of the carbon-sequestering management practices

The economic value to society of restoring soil ecosystem services. This is a complex topic and a full review is beyond the scope of this report. To provide a general idea of the value of ecosystem services, we discuss just one recent estimate of the value of ecosystem services from improved soil health.[173]

Farmland LP is an investment company that manages two sets of farms in ways meant to increase soil health and sustainability on both cropland and non-farmed areas. To estimate the value of ecosystem services from healthy soil, Farmland LP used a comprehensive database, the Ecosystem Valuation Toolkit,[196] that was developed through examination of the peer-reviewed literature on this topic. Using this toolkit, the value of ecosystem services on farmland managed for soil health was compared with the value of farmland that was under conventional management.[173]

One of Farmland LP's funds includes 5705 acres of farmland with an estimated total Ecosystem Services Value (ESV) of $2261/acre for the five years ending in 2017. This compares to an estimated Ecosystem Services Loss (ESL) of $1500/acre if the land had been left under conventional management, for a net ESV of $3762/acre. These results suggest that managing farms for increased soil health can produce significant economic value in terms of improved ecosystem services.

Recognizing that these services are of value to society as a whole, incentivizing the use of practices that build soil health with public funds is a way to share the cost of improving soil health among all those who benefit.

The economic value of soil health to farmers.
Building soil health with USDA-NRCS conservation and carbon-sequestering practices improves nutrient cycling, protects plants from pathogens and reduces water and temperature stress. Healthy soil also boosts water infiltration and water-holding capacity. These outcomes increase crop productivity and can reduce the need for costly inputs.

The overall economic value of healthy soil has been estimated as $40/acre-$140/acre.[197] Itemizing the economic value to farmers of specific benefits of soil health improvement reveals:

- 1% increase in soil organic matter: $15.70/acre[198]
- Soil saved from erosion: $2.10 in plant nutrient benefits + $5/ton in water quality benefits[194]
- Nutrients in cover crops (hairy vetch): $18/acre[194]
- Nutrients in cover crops (alfalfa): Year 1 $96/acre, Year 2 $30/ac.[194]
- Increased crop yield from boosting pollinators: $29/acre[199]
- Reduced need for pesticides from boosting natural enemies of crop pests: $5/acre.[199]

TABLE 2. Percent increase in corn and soybean yields after one, three and five years of consecutive cover crop use on a field, based on a regression analysis of data for crop years 2015 and 2016[1]			
	One Year	Three Years	Five Years
Corn	0.52%	1.76%	3%
Soybeans	2.12%	3.54%	4.96%

[1] Figures shown are an average of yields from the 2015 and 2016 growing seasons, with yield data obtained from about 500 farmers each year through the SARE/CTIC National Cover Crop Survey.

Source: Ref 151.

Soil health increases climate resilience, reducing risk. Healthy soil provides resilience to the impacts of variable and severe weather by allowing excess water to infiltrate while holding water for plants to use during droughts. Largely through its impacts on water availability, healthy soil stabilizes yields across years, reducing risk and providing farmers with important economic benefits.[200,201]

Improving soil health is therefore considered to be a relatively inexpensive and reliable "no-regrets" strategy for risk reduction and adaptation to the increasing flood/drought cycles that are now increasing due to climate change.[6] Consistent with the reduced risk of healthy soil, Iowa provides a $5/acre crop insurance credit for planting cover crops,[202] and many soil health proponents agree that crop insurance rates in general should be lowered for farmers who prioritize soil health.[203]

Cover crops pay for themselves over time by reducing input costs. Given the number of factors involved in cover crop management, farmers find that some experimentation is generally required to settle on an integrated rotation of cash and cover crops that works on their farms. Despite the learning curve, a 2019 report from USDA Sustainable Agriculture Research & Education (SARE) revealed that corn and soybean farmers who were willing to explore cover crops saw slightly greater yields the first year that continued to increase over time (**Table 2**).[151]

By the third year in corn, increases in yield plus the savings obtained from reduced inputs and less need for erosion repair produced a net profit that continued to grow over time (**Table 3**). Also in the third year, the cost savings from inputs and fewer erosion repairs ($26.10-$43.10) overshadowed the value of the yield gains ($12.32, Table 3), showing that net profit may be a more accurate metric for quantifying success than is yield alone.

Table 3. *Savings over time from reduced inputs when using cover crops in corn. Despite the added expense of seed and an additional planting, farmers used less fertilizer and herbicide and needed to make fewer repairs for erosion. These savings offset the cost of cover crop use by Year Three and continued to add to profits through time. Lower section: Four situations that accelerate the economic benefits of cover crops, with the estimated the benefit for each. Source: Ref 151.*

BUDGET ITEM — CORN		YEARS OF COVER CROPPING		
All figures are per acre		One	Three	Five
Estimated input savings when using cover crops				
Fertilizer[1]		$0	$14.10	$21.90
Weed control[2]		$0–$15	$10–$25	$10–$25
Erosion repair[3]		$2–$4	$2–$4	$2–$4
Subtotal		**$2–$19**	**$26.10–$43.10**	**$33.90–$50.90**
a. Savings on inputs (the low end of the subtotal range from above)		$2	$26.10	$33.90
b. Income from extra yield in normal weather year (survey data)[4]		$3.64	$12.32	$21
c. Cost of seed and seeding (survey data)[5]		$37	$37	$37
Net return in a normal weather year (a + b – c)		**-$31.36**	**$1.42**	**$17.90**
Special situations that accelerate the economic benefits of cover crops				
I. When facing severe herbicide-resistant weeds[6]	Benefit	$27	$27	$27
Adjusted net return		**-$4.36**	**$28.42**	**$44.90**
III. Compaction addressed by cover crops[8]	Benefit	$15.30	$15.30	$15.30
Adjusted net return		**-$16.06**	**$16.72**	**$33.20**
V. Income from extra yield in a drought year (survey data)[10]	Benefit	$58.70	$75.73	$92.55
Adjusted net return		**$27.34**	**$77.15**	**$110.45**
VII. Federal or state incentive payments received[12]	Benefit	$50	$50	$50
Adjusted net return		**$18.64**	**$51.42**	**$67.90**

Special situations accelerate cover crop benefits. In **Part 2**, several situations that accelerate the economic benefits of cover crop use for farmers were discussed. These include the presence of herbicide-resistant weeds, soil compaction and flooding or drought. In each case, the income saved or added by cover crops (Table 3, bottom) accelerated the basic return on investment expected from cover crop use (Table 3, top).

No-till saves on fuel, labor and equipment maintenance. Because tractor time and fuel use are reduced by eliminating plowing, disking, and other steps to prepare tilled fields for planting, no-till saves money and reduces vehicular emissions. In 2016, NRCS estimated the economic value of saved time and avoided fuel use,[204,205] showing that no-till can save an average of 4.16 gallons of diesel/acre for each tillage pass not needed for field preparation. Assuming an average off-road diesel fuel price of $2.05 per gallon, planting a 100-acre field using no-till would save more than $850/acre in fuel costs for every eliminated pass across the field. As discussed above in **Part 2** (see Figure 21), preparing a seedbed in a conventionally tilled field may require 5-6 passes for a total savings from no-till planting of more than $5100/acre. The more passes eliminated by no-till, the greater the savings.

By adopting no-till, a farmer who plows 15 acres per hour would also save roughly 6.7 hours of labor and machinery use for every avoided pass over a 100-acre field.[124] A 2015 Iowa State University Extension report estimating the monetary value of avoided labor and machinery costs assumed $16.50/hr saved for avoided labor (total labor cost/hr of field operations is 1.1 x labor rate of $15/hr) and $12.37/hr saved on lubrication and maintenance of the 180-hp 2-wheel drive tractor that was used in the example, for a total savings of $28.87/hr (https://www.extension.iastate.edu/agdm/crops/pdf/a3-29.pdf). Thus, practicing no-till on a 100 acre field would save about $193 in labor and maintenance costs (or about $1.93/acre) for every avoided pass (6.7 hrs x $28.87/hr).

By reducing fuel use, no-till also reduces vehicular emissions. For each gallon of diesel saved by no-till, emissions are reduced by 22.4 lbs CO_2e (0.0102 t CO_2e/gallon). By reducing fuel use by 4.16 gallons/acre for each tillage pass, adopting no-till on millions of acres could produce a substantial reduction in agricultural emissions.

Adoption of carbon-sequestering management practices requires that they be economically advantageous. Because farmers often operate on small margins, the economic benefits that the recommended carbon-sequestering practices can provide often make the difference between whether they are used or not. By offsetting the additional costs of planting a cover crop, incentives can significantly accelerate the return on investment for cover crops and provide an economic buffer while farmers learn to use cover crops successfully (bottom of Table 3).[151] Where state, federal or private incentive payments for cover crops are unavailable, many farmers are hesitant to take on an additional expense that might not pay off right away, and this is reflected in low cover crop usage.[161]

A diverse mix of cover crop species used for overwinter weed control in North Carolina. Credit: Zeb Winslow, www.farmers.gov

Part 4.

Increasing Adoption of the Carbon-Sequestering Management Practices

To sequester significant amounts of carbon in the soil, the practices must be used widely. The recommended practices for improving soil health and sequestering carbon not only benefit society as a whole, they also confer many direct benefits to farmers (see Part 3). Despite these benefits, however, adoption rates of even the most fundamental of the recommended practices are low (see Figures 30, 33). Given the current state of the climate crisis,[1,3] understanding how to motivate increased use of the carbon-sequestering NRCS practices is critical.

A recent report on negative emissions strategies from the National Academy of Sciences[30] identified the willingness of American farmers to adopt the carbon-sequestering practices as the largest potential barrier to achieving significant soil carbon sequestration in agriculture. Although the scientific evidence has revealed which agricultural practices are effective and how much GHG reduction we can expect from each (Table 1), this knowledge only translates to achieving negative emissions if agricultural producers actually embrace the practices and use them widely.

Because soil carbon sequestration is one of a small handful of effective and affordable negative emissions strategies currently available,[30] designing and implementing effective outreach programs that boost adoption of the recommended practices nationwide must be a high priority. We don't yet fully understand how agricultural producers decide to replace a familiar management practice with a new one, nor is there a clear strategy for producing the widespread behavior change required. Simply providing information about how to implement the practices or about their economic and environmental benefits is necessary but clearly not sufficient for successful outreach programs.[206]

4.1 Understanding decision-making by agricultural producers

Our knowledge of factors that affect farmers' decisions about a new management practice comes from three sources in the social sciences: analyses of data such as participation in conservation programs, quantitative surveys of farmers, and qualitative interview-based research exploring the individual bases of particular decisions.[207,208] This rich literature reveals how heterogeneity among farmers and their perceptions of the various practices shape adoption decisions. One finding is clear. We must add a social science component to soil health outreach.

Information transfer alone is insufficient to increase adoption of new practices. It is crucial to provide farmers with high quality evidence-based information about how specific management practices work to benefit the environment and increase productivity. Specific examples of the timetable and magnitude of expected benefits must be provided and the attendant economic costs and possible demands on time management disclosed. Clear and accurate information is necessary to provide motivation and it can allay simple concerns. However, it is clear that decades of providing farmers with information about environmentally beneficial agricultural practices has not produced widespread gains in the adoption of key practices like no-till and cover crops.

To be effective, outreach programs must also address social and psychological barriers that arise when farmers consider a new practice. These barriers include concern about the time required to master a new system or a commitment to maintain entrenched family or community management traditions. These and other barriers to adoption are particularly unlikely to have been adequately explored in marginal communities where farms are small and many farmers have been overlooked by traditional outreach programs.

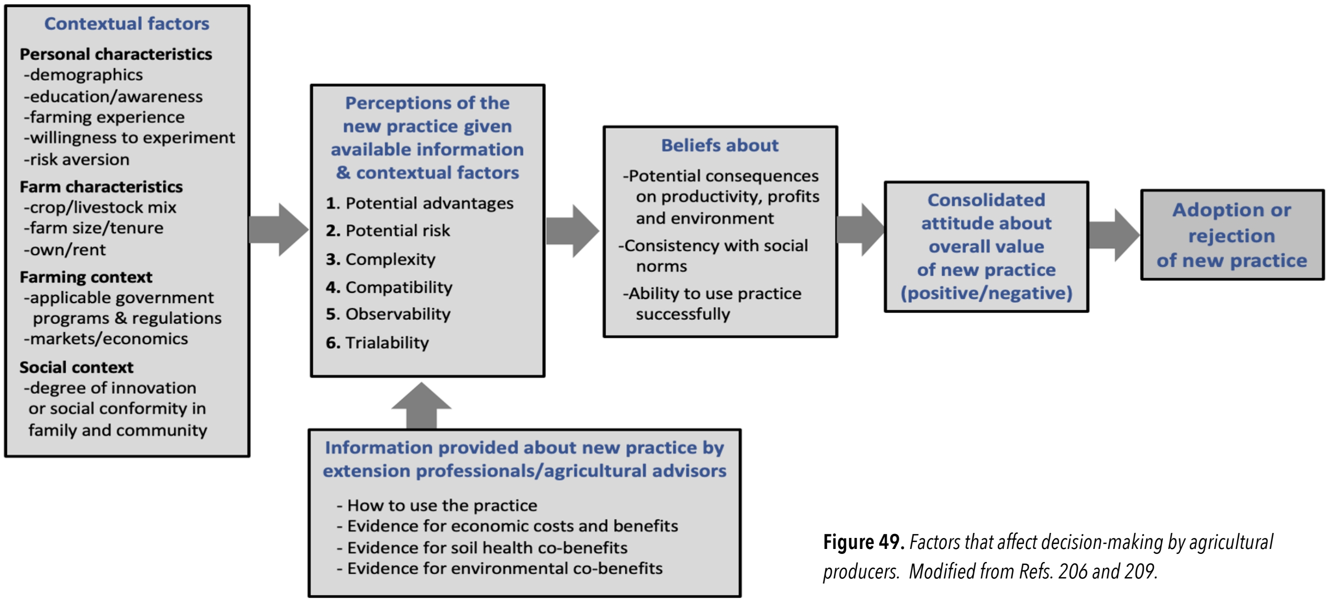


Figure 49. *Factors that affect decision-making by agricultural producers. Modified from Refs. 206 and 209.*

During the decision-making process, factual information about a new practice is filtered through a meshwork of social and psychological factors specific to each individual, resulting in a set of fundamental perceptions about the new practice (**Figure 49**). These perceptions involve the potential benefits of the practice, its potential risks, the complexity of the practice, its compatibility with current farming practices, its "observability" (can the practice be seen in use on a nearby farm), and its "trialability" (can the practice be tried out in a limited way).[206,,209]

These fundamental perceptions are then consolidated over time by each individual into beliefs about the potential consequences of adopting the behavior, how others in the community will regard the change, and a personal assessment of the ability to use the practices successfully. Eventually, these beliefs consolidate into an attitude about the overall value of the practice and the personal intention to either adopt or reject it (Figure 49). Understanding the way that perceptions about a new practice are integrated into a consolidated attitude about the overall value of the practice is central to adoption and cannot be overlooked in outreach programs.[207,210]

Specific issues that may affect adoption of the recommended carbon-sequestering practices. Some of the factors outlined in Figure 49 that could be involved in the decision to adopt a new soil health practice are organized into a set potential "barriers and benefits" in **Table 4**.

Table 4. Factors affecting the decision to adopt a new soil health practice

Perceived benefit of adoption[1]	*Perceived barrier to adoption*	*Reducing the barrier*
Increases production, yield or soil health ***(1)***	No obvious yield benefit, fear reduced yield	Demonstration on local farm
Monetary incentive or inexpensive ***(1)***	Costs too much	Provide incentive, cost-share
Saves time or money ***(1)***	Takes too much time	Provide technical assistance
Provides a clear environmental benefit	Environmental benefit unclear	Demonstration on local farm
Solves a problem like soil compaction, weeds, flooding, drought) ***(1)***	Don't have the problem or solve it another way	
Reduces a risk ***(1)***	Don't feel at risk	
Easy to implement ***(3)***	Complicated to implement	Provide technical assistance
Relatively sure of success ***(2,3)***	Not sure about success	Demonstration on local farm, peer mentoring
Needed equipment is available ***(3,4)***	Equipment not available	Increase access to equipment
Compatible with current management (***4)***	Inconsistent with current management	
Family/community support the practice ***(4)***	Conflicts with family/community traditions	Arrange for community thought leader to demonstrate practice
Already know how to do the practice ***(2,3)***	Don't know how to do the practice	Provide technical assistance
Friend or neighbor does it & had success ***(5)***	Don't know anybody who does it	Demonstration on local farm
Respected person does it & had success ***(5)***	Never heard anyone discuss it	Demonstration on local farm
I can try it on a few acres at low risk ***(6)***	I need to make a big investment to try it	

[1]Numbers in parentheses refer to specific perceptions in Figure 49

Identifying such barriers and benefits in the target population is a core concept in "Community Based Social Marketing" (CBSM). Based in the social sciences, CBSM is a well-tested strategy to encourage increased adoption of environmentally desirable behaviors.[210] After identifying the barriers and benefits to a behavior as perceived by the target group, the goal is to design messaging and, when possible, implement changes that reduce the commonly perceived barriers while increasing its perceived benefits (Table 4).

For example, some producers considering a new practice may not have crucial pieces of equipment, such as a planter appropriate for no-till or strip-till, or an interseeder that allows cover crop seed to be sown into the standing cash crop. Devising programs to make such equipment available to farmers can reduce key barriers and increase adoption rates of no-till or cover crops. Uncertainty about the benefits of a practice or fear that it is complicated and hard to learn may be reduced by a field day at a local farm hosted by a producer who has used the practice successfully. Other possibilities for reducing specific barriers to adoption of soil health practices are listed in Table 4.

BENEFITS OF REDUCED TILLAGE
Soil Erosion: • Crop residue on fields acts as a mulch to **protect soil** from erosion
Soil Organic Matter: • Crop residue on fields promote soil productivity by **"feeding the biology,"** which increases the soil's organic matter • Organic matter promotes **healthy soil structure** and **improves crop production** • Organic matter supports the development of **stable soil aggregates**, which **increases soil absorbency** and **infiltration rates**, while **fostering root establishment** and **growth**
Infiltration Rates: • Increased infiltration rates **reduce soil erosion** and **agricultural runoff** • Increased infiltration rates promote water conservation by reducing evaporation, which is important for arid regions or areas affected by severe drought
Time and Resources: • **Less time** and **resource intensive**, which improves overall quality of life
BARRIERS TO USE OF REDUCED TILLAGE
Tradition: • Difficult to break from traditional practices
Learning Curve: • Due to the relatively steep learning curve, transitioning from traditional to conservation tillage takes time and dedication • The drastic change in soil structure, which overall is a positive outcome, may present new challenges (i.e., different pests and weeds)
Equipment: • Planting into a no-till system may require different equipment (i.e., closing wheel)

Figure 50. *Perceived benefits and barriers to the adoption of reduced tillage. Source: Fox Demonstration Farms, University of Wisconsin Extension.*

Identifying barriers and benefits to address in outreach.

Even a general review of the literature on the barriers and benefits to adopting a new practice can be a starting point for designing outreach programs. Such a list was compiled by extension personnel in Wisconsin in an effort to encourage farmers to switch from conventional tillage to reduced-till or no-till (**Figure 50**). The major benefits identified for reduced tillage include reduced soil erosion, improved soil health from increased soil organic matter, increasing water infiltration and the ability to save time and resources. The barriers to adoption included the psychological adjustments required to break from tradition, the potentially steep learning curve involved in switching tillage practices, and the need for additional specialized equipment such as no-till planters, roller-crimpers or attachments for strip tillage.

General barriers like these that are identified through a literature search can then be tested and tuned for a particular community through discussions, surveys or focus groups of farmers who closely resemble the group targeted by the outreach program.

The use of surveys. Between 2012 and 2019, the Sustainable Agriculture Research and Education program (SARE) and their partners conducted six National Cover Crop Surveys to explore farmers' attitudes about cover crop use.[164] These surveys have provided very useful insight into how farmers themselves perceive the benefits and barriers to using cover crops across different years and situations.

Surveys can be valuable resources for those designing outreach programs, with several major qualifications. First, it is important for the group who receives and returns the survey to accurately represent the group targeted by the outreach program. It is also crucial to obtain survey responses not only from people who have already adopted the target practice (adopters) but also from those who have not (non-adopters). Given a sample meeting both of these criteria, the surveyors can draw valid inferences about what factors best differentiate adopters from non-adopters. These factors are then the target of the outreach program.

Obtaining survey responses from a representative sample of farmers that includes both adopters and non-adopters can be a significant challenge. Adopters of a particular practice are often easier to identify than non-adopters and are more likely to respond to a survey because they are already interested in the topic.

Of the 1172 farmers who returned a National Cover Crop survey in 2019, 94% had used cover crops on their farms at least once.[164] The authors of the 2020 National Cover Crop Survey discuss this issue and acknowledge the difficulty of obtaining information from farmers who do not currently use cover crops.

In addition, farmers who work with SARE or other individual farming organizations may not be a random sample of all farmers who might use the practice. Finding ways to ensure a representative sample and increase survey participation by non-adopters can require significant creativity and is likely to increase the cost and time required to produce a survey.[211]

Even though the 2020 National Cover Crop Survey includes responses from only 77 farmers who did not use cover crops (non-adopters), some useful information was obtained about the barriers that dissuaded this group from using cover crops.

Table 5. Perceived barriers to cover crop use[164]

	major concern	*minor concern*
• Too much time or labor required to use cover crop:	*49%*	*21%*
• No clear positive economic return:	*42%*	*27%*
• Reduced yield in the following cash crop:	*39%*	*26%*
• Increased overall crop or production risk:	*38%*	*30%*
• Cover crop might use too much moisture:	*35%*	*25%*
• Might not be able identify the best cover crop for my farm:	*35%*	*26%*
• Might not achieve an acceptable stand:	*38%*	*30%*

The issues in **Table 5** were expressed by a majority of non-adopters in that survey as either a major or minor concern (see Ref. 164 for the full table of responses).

Some of these concerns can be addressed during information sessions by providing information such as the timetable for economic return experienced by similar groups of farmers, impacts on yield of various crops and the effects of cover crops on soil moisture, as discussed in **Part 2** of this report. Concerns about time requirements or the potential for success can be at least partially addressed using information in case studies, demonstrations, or peer-to-peer learning from local producers who have used the practices.[211]

This national survey echoes the finding that cover crops are often perceived by farmers as complex and difficult to manage.[209] In addition to the management complexity and time requirements to establish this practice, extension personnel have noted other specific concerns about cover crops from producers:

- Winter cover crops can keep the soil too cool in spring and delay planting of early spring crops. This is a valid concern, yet there are solutions. For examples, in fields earmarked for spring crops, tillage radish could be used as a cover crop because it generally winterkills and decomposes early enough in the spring to avoid a delay in soil warming.[212,213] Alternatively, strip-tillage could be used to form a narrow seedbed that will warm quickly, as if no cover crop had been planted.[109]

- Planting cover crops early enough for best growth requires specialized equipment. Planting into standing corn or soybeans requires either aerial seeding or specialized equipment that may not be readily available such as a Highboy broadcast air-seeder or a high clear drill interseeder (**Figure 51**).

- Termination of cover crops without herbicide requires a roller-crimper, another piece of specialized equipment that is not widely available in many locations (see Figure 28 in **Part 2**).

- Pest organisms. Some farmers are concerned that pests such as slugs are likely to move from cover crops into the following cash crops, where they can damage seedlings. A recent extension bulletin suggests that planting into living cover crops ("planting green") and increasing the diversity and length of crop rotations are effective ways to reduce slug populations.[210]

In the 2020 National Cover Crop Survey, the farmers identifying themselves as non-adopters were also asked what might increase their use of cover crops.[164] The two most common responses were (with the percentage of respondents expressing each as either a major or minor concern):

- Evidence that cover crop use would allow reduced need for fertilizer, herbicides and other inputs: 75%
- Information clarifying how cover crops would benefit his/her farm economically: 70%

Addressing these concerns can easily be incorporated into information sessions using examples from peer- reviewed research, reports from agricultural groups and case studies. Once again, however, this information alone may not resolve social or psychological issues, so it is still important to provide opportunities for local demonstrations and/or collaborative, peer-to-peer learning.

Figure 51. ***Left:*** *Interseeder used at Penn State to drill cover crop seed between rows of corn.* ***Right****: Three rows of cover crop seed drilled between rows of standing corn will emerge before the corn canopy closes. Credit: Greg Roth, Penn State.*

4.2 Understanding how behaviors spread can increase the effectiveness of outreach programs

Social scientists know that behaviors tend to spread through communities in a predictable way.[214] New behaviors are generally pioneered by a small group of "innovators" who are open to new ideas and practices and are willing and eager to experiment. Through their examples, the behavior may spread moderately easily to some "early adopters." These are people in the community who are generally aware of new developments and willing to explore them if encouraged by a locally trusted innovator. Innovators and early adopters readily identify and embrace the benefits of a new behavior and may be able to independently acquire much of the information required to implement the behavior.

Once this small core of people in the community adopts a new behavior, the time required for it to be adopted by the majority of the community depends on the rate of "social diffusion," the process through which an initially novel behavior becomes accepted in a community as the norm.

The next groups to adopt the new practice, the "early majority" and "late majority", are likely to be motivated by different factors than the innovators and early acceptors. This majority population is likely to be more risk averse and less willing to experiment than were the early adopters. They are also likely to be more affected by the opinions of others, to feel too busy to take on something new, or to be fearful of the risk associated with replacing an established practice.[215] This large group is likely to be deterred by outreach emphasizing the innovative or experimental nature of the behavior.[215] Instead, outreach to this group should focus on providing local evidence of success by the early adopters and citing well-designed case studies that describe the experiences of farmers in other nearby or similar communities.[216] As more and more people in a community adopt the behavior and it becomes the accepted social norm, peer pressure may then play a role in the decision-making of the last adopters. Inevitably, however, some fraction of the community will continue to resist the behavior regardless of outreach efforts and the new social norm.

Case studies can speed the social diffusion of new practices. Several recent case studies of farmers who have successfully improved soil health clearly show that lower input costs and increases in yield from healthy soil practices usually soon outweigh the expense of cover crop seed, initial failures, and time spent on education.[151,200,211,217] Having farmers describe their successes in their own words in such case studies is an extremely powerful communication tool.

Recent case studies by the American Farmland Trust[217] describe the paths taken by three row crop farmers to increase their use of no-till and cover crops and reduce fertilizer use. Each farmer had to experiment with implementation details over several years, and each invested time in learning activities (estimated at $0.44 to $10.35 per acre). Yet in less than 10 years, they all had yield increases of 2-22% attributable to soil health and an average increase in net income of $42 per acre per year. All three farmers reduced fertilizer use (mostly phosphorous and potassium), which saved $17-$66 per acre per year. Reducing tillage saved them an average of $26/acre per year on fuel, machinery use, and labor although several had some initial costs involved with modifying equipment. These farmers also all saw improved water quality and reduced carbon emissions on their farms. These examples of success by real farmers are important outreach tools.

Another very valuable set of case studies focused on the economic value of the types of conservation practices we recommend.[211] The farmers involved in these case studies testify to experiencing a cascade of savings across their farms rather than just isolated benefits from specific practices. These whole-farm benefits included overall increases in soil health, reduced variation in yield between years, and significantly increased profits at the farm scale.

Trade periodicals can help to publicize farmers' experiences. Nationally distributed trade periodicals such as *No-Till Farmer* and regional papers like *Lancaster Farmer* (Pennsylvania) or *The Delmarva Farmer* (Maryland, Virginia, Delaware) are valuable sources of information and social influence for farmers.[218] These periodicals and websites such as USDA's www.Farmer.gov commonly run stories about farmers who have successfully begun to use no-till or strip-till, cover crops, or other practices that boost soil health. Although these are generally anecdotal reports rather than more authoritative controlled studies, they are highly accessible to farmers and can be very useful outreach tools when appropriately vetted for accuracy.

For example, after the massive Midwest flooding in Spring 2019, several of these sources ran stories about farmers who noted lower erosion and improved infiltration.[219,220] Moreover, it was clearly evident to many residents that farmers in flooded areas who had planted cover crops could re-enter fields for planting much sooner than could farmers whose fields were bare. For Midwest farmers who couldn't get into flooded fields in time to plant corn or soybeans, incentives were provided to plant cover crops instead. This provided farmers with a valuable opportunity to witness the benefits of this key practice first hand.[221] Similar examples distributed by other media sources provided powerful examples of how adopting healthy soils practices can reduce flood risk.

Figure 52. *After harvesting millet from the field on the left, the farmer seeded it to a cover crop mix of oats, barley, pea, radish and rapeseed, while the adjacent field on the right was left fallow. Using a remote sensor to measure soil moisture revealed that more moisture was retained in the cover-cropped field during the summer heat. In addition, weed control by the cover crop allowed two fewer herbicide passes. From Ref. 222.*

Droughts can provide additional useful examples of the value of soil health. During dry periods, improved water-holding capacity in healthy soil can reduce the need for irrigation, lowering fuel use and equipment maintenance and sometimes allowing farmers to avoid using or even installing irrigation.[6] One case study described a Colorado dryland farmer who found that more water was retained during the summer in a field planted with a spring cover crop mixture than in an adjacent field left fallow (**Figure 52**).[222] He also noted that improved weed control in the field with the cover crop allowed him to reduce herbicide use. A North Carolina farmer also reported that better weed control in fields with cover crops allowed him to reduce herbicide use by 50%.[223]

Opinion pieces in these trade publications can also highlight ways in which commonly held beliefs may slow the adoption of beneficial practices. For example, practices like no-till and cover crops often increase profits despite short-term yield declines. An editorial *in No-Till Farmer* noted that this benefit is likely to be missed by farmers whose definition of success remains focused on yield rather than on profit.[224] Providing farmers with concrete examples of how the recommended practices can reduce input costs and raise profits despite small initial yield declines could help to change the definition of success and facilitate increased adoption of the recommended carbon-sequestering practices.

The collective experience of farmers across the country can be used to illustrate that no-till, cover crops and other NRCS conservation practices can solve problems and boost farm incomes while improving soil health. Many case studies reveal that despite short term problems that might arise, most farmers who are willing to try the soil health practices will succeed and come to recognize the significant benefits that healthy soil provides. Their testimonials in trade publications and elsewhere can serve as motivating examples for other farmers and should be included in outreach programs.

4.3 Incentives can help farmers overcome barriers to adopting soil health practices

Extra costs, a steep learning curve and/or short term yield drag can discourage farmers from adopting NRCS conservation practices that improve soil health and sequester carbon. When profit margins are slim, the potential for even small economic losses during the transition to no-till and/or cover crops can be a deterrent to farmers, making federal and state incentives for the use of soil health practices crucial. The cover crop program in Maryland, which propelled Maryland farmers into national leadership for cover crop use, is a prime example of the power of incentives.[187,225]

Providing incentives for the recommended soil health and carbon-sequestering practices in Table 1 reflects a recognition of shared responsibility that is likely to be regarded positively by farmers. Publicly funded incentives send the message that because the benefits of improving soil health and sequestering carbon extend beyond the farm to society as a whole, it is reasonable to spread the costs among all beneficiaries.

Designing incentive programs. The design of incentive programs, including the structure and source of funding, the administrative and paperwork requirements, and the time frame for support, can all affect how farmers perceive and utilize incentives.[226,227] Additional research to discover the most effective incentive programs in different settings and to identify ways to adjust current subsidy programs to encourage management for soil health would be very worthwhile.[228] Examples of issues to consider may include:

Incentives for transitioning to a new practice. When adopting a new management practice like no-till or cover crops, the need for financial assistance is largest in the first few years of the transition. During that time, farmers must learn how to successfully implement a new practice and may need new or modified equipment. Incentive programs in which initial payments are large enough to cover the initial expenses may reduce some of the barriers to making a change and increase adoption rates. Because most farmers who stick with the transition to one of these practices find improvements in soil health and increased profitability after the first few years (Tables 3, 4 above), reducing incentives after the transition period seems reasonable. Then, offering a smaller but ongoing incentive reflects the importance of maintaining the practices over the long term and rewards farmers for the social value of carbon sequestration, improved water quality and contributions to stormwater management.

Incentives to reward ongoing testing of practices that increase soil health. Incentive programs can also be structured to help farmers, agencies and others better track the results of soil health practices. Providing payments to farmers to undertake and share the results of annual soil health testing (e.g., infiltration rate, bulk density, phospholipid fatty acid) as part of their incentive agreement would give them more information about the success over time of soil health practices on their farm, and would provide USDA with many more data points to help assess the benefits of different combinations of soil health practices in different soil types, climates, and farming systems.

Alternative funding mechanisms. Program designs that merit further exploration include mechanisms such as discounts on federally subsidized crop insurance for farmers who adopt one or more soil health practices. Such discounts reflect the increased resilience to drought, flooding and extreme temperatures provided by increased soil health.[202] Evidence for this resilience is provided by the reduced use of prevent planting resources after the devastating 2019 Midwest flooding by farmers who used cover crops,[164] and a reduction in crop insurance claims in the Northeast by farmers managing for healthy soil.[6]

Direct incentives or payment for carbon offsets?

Voluntary carbon markets that pay farmers to adopt carbon-sequestering practices in order to sell carbon offsets are gaining momentum. Several commercial ventures exist, such as Indigo Agriculture, Nori and TruCarbon, and non-profit groups such as the Ecosystem Services Market Consortium are working to build the offset market.

The relative costs and benefits of funding carbon-sequestering soil health practices through the market for carbon-offsets rather than with direct incentives should be carefully considered. The ability of farmers to sell carbon credits into the offsets market could certainly increase the adoption of the recommended practices which would result in improved soil health. However, unless the carbon credits are purchased to be retired, offsets do not reduce GHG emissions, and some argue that their use early on the path to net-zero can justify weakened efforts to curb GHG emissions at their sources.[36,37]

In contrast to selling credits for carbon offsets, offering direct incentive payments reflects a recognition that increasing the adoption of carbon-sequestering practices is of value to society as a whole.

The management practices recommended in this report will not only reduce future climate change and provide multiple additional environmental benefits, they also increase food security by increasing the climate resilience of agriculture and reversing the dangerous degradation of our agricultural soils. Using public funding for incentives to increase adoption of the recommended practices spreads the costs among all who receive these important benefits.[211]

4.4 Developing outreach programs to increase adoption of NRCS carbon-sequestering practices.

As discussed in **Part 4.1**, improving soil health and sequestering carbon is a national need and it is important to increase the adoption of appropriate management practices across all commodities and farmer groups. To accomplish this increase, it would be useful to develop a comprehensive program of soil health outreach that introduces farmers to soil health and carbon sequestration in ways that facilitate the social and psychological mechanisms of behavior change.

Outreach programs must be local, equitable and inclusive. Just as our nation's farms vary widely in size, geography, local climate and agronomic factors, our farmers also vary in their goals, values and experiences. Outreach efforts must be attuned to differences among farmers just as they are to differences in soil, commodities and farming systems. It is particularly important to increase soil health outreach to farmers in minority and underrepresented groups and to design and deliver outreach programs tailored to their specific needs.

To develop this type of comprehensive and inclusive outreach, it would be useful to form a community of practice in which conservation practitioners, farmers, researchers and outreach professionals work together. This group could develop templates for outreach programs to increase the adoption of the soil health practices, providing a basic evidence-based framework that could be augmented and refined for different locations and commodity groups by local outreach experts. Such a community of practice could offer valuable opportunities for co-learning when people share research and ideas. It would also provide a platform for sharing successful outreach strategies, as well as for reviewing and analyzing strategies that have not produced the desired results.

Communities of practice among university extension personnel are already being developed in many areas of Cooperative Extension within the Land Grant University system. One example outside Extension is a collaboration in the watershed management arena between NGOs, watershed managers and commodity groups.[229]

Emerging best practices for outreach. Above all, information about the targeted soil health practices and their benefits must be evidence-based and provided accurately and concisely in plain language that is understandable to all. In addition:

- Information should be illustrated with carefully chosen examples and clear graphics.
- The information and examples should be relevant to the particular audience, as specific as possible, and derived from peer-reviewed journals or other trusted sources.
- Demonstrations during information sessions can be very useful as long as they are carefully designed and the point is clearly explained. The NRCS and other soil health organizations have devised several very powerful demonstrations of the differences between healthy and unhealthy soil, such as the slake test (**Figure 53**). These demonstrations are easy to perform, and provide powerful and immediate visual examples of why improving soil health is worthwhile.
- Information should be provided by "trusted messengers" who, if needed, have been trained to provide the outreach program by experienced personnel using a train-the-trainer model. These trusted sources depend on the information domain. Some research has suggested that farmers tend to rely more on private sector sources (agricultural retailers, agronomists) for production-related information,[218] while Extension and resource agencies are more trusted for conservation-related information.[230]
- Field days hosted by adopters on local farms are effective ways to illustrate the successful use of soil health practices as well as to convey technical details about implementation. Demonstrations of how the necessary equipment is used in unfamiliar practices such as strip- tillage can be particularly useful. Gathering farmers on local farms for field days is a good way to generate discussion and answer questions in a familiar setting.
- The community of practice or local outreach professionals can place articles in agricultural media, social media and podcasts to spread information about the practices and their benefits, and provide examples of farmers who have used them successfully.

Figure 53. *In the slake test, dried chunks of soil from fields under different management are suspended in columns of water. Soil from fields managed with reduced tillage and other healthy soils practices remains intact for long periods in water (**left**), while unhealthy soil from conventionally tilled fields quickly falls apart in water because the soil structure has been damaged (**right**). This simple test is a compelling visual illustration of how no-till reduces erosion. Source: NRCS.*

Using collaborative learning as an outreach tool.

Traditional outreach programs operate primarily as one-way information exchanges: from educator to farmer. This approach can be successful in transferring basic information, but it is less successful in helping farmers design, implement, and adjust plans for their land and farming system on an ongoing basis. Although ongoing conversations with public and private sector advisors can help, the number of such advisors experienced in soil health practices falls far short of the capacity needed for widespread, rapid adoption of soil health systems. Collaborative learning and peer teaching can ease the burden on these educators.

Collaborative learning models could be a useful addition to traditional outreach and education as a means to promote faster and more successful adoption of conservation practices.[231] Farmers enjoy peer teaching, and value participatory research,[232] and discussions among peers can help resolve concerns about new practices. Organizing groups of farmers or ranchers in an area who share similar soils, climate, and/or farming systems can provide opportunities to test multiple techniques simultaneously and share results, hastening learning and the adoption of best practices for that area. Collaborative groups may also be able to share the cost of acquiring needed equipment like a roller crimper or high-boy seed planter, can create a larger local market for inputs like cover crop seeds, and can address some of the social barriers to adoption (see Table 4).

In sum, time and resources invested in developing comprehensive and evidence-based outreach programs will be well-spent. Large investments have already been made in research to discover how to improve soil health and sequester carbon. However, unless farmers can be encouraged to adopt these practices, research advances will be wasted and the potential to improve the health of the nation's soils and reduce the risks of climate change cannot be realized.

Part 5.

Conclusions and Recommendations

5.1 Conclusions

The recommended NRCS practices for sequestering carbon in agricultural soils (Table 1) are effective and supported by robust scientific evidence. Increasing their use by US farmers could make a significant contribution to the nation's GHG reduction goals.[30] Widespread adoption of these practices will not only fight climate change and help to rebuild the health of our agricultural soils, it will also provide both farmers and ordinary citizens an array of important economic and environmental co-benefits.

The carbon-sequestering practices recommended in this report for use on cropland (Table 1) can produce direct positive economic benefits for farmers through improved soil health, reduced input costs and increased crop productivity. These practices also reduce soil erosion, improve water quality and increase stormwater infiltration, which reduces both inland flooding and stream erosion. By increasing the amount of organic matter in the soil, the cropland management practices in combination with increased use of deep-rooted herbaceous plants at field borders and in marginal areas enhance the water-holding capacity of soil.

Practices that increase tree and shrub planting reduce erosion and help to purify surface waters. Woody riparian buffers not only stabilize stream banks and sequester carbon, they also protect aquatic biodiversity by shading and cooling streams that have warmed to damaging levels from the increased summer temperatures under climate change.

The improvements in soil health produced by using the recommended carbon-sequestering practices will increase the resilience of US agriculture to risks from the increasingly damaging impacts of climate change. Many of the practices also help to restore biodiversity by providing winter cover, restoring and improving grassland habitat, providing habitat for pollinators, and reducing runoff of agrichemicals and sediment into wetlands and streams.

Together, the practices recommended in this report provide a low-cost and immediately available way to reduce atmospheric carbon. Given the wide array of co-benefits associated with these practices, increasing their use is an investment in US agriculture that will pay economic and environmental dividends for years to come.

5.2 Recommendations for agricultural agencies and policymakers at federal, state and local levels

The time is right to promote soil health and carbon sequestration in agriculture as a cost-effective natural climate solution[30] and to establish policies that will increase the number of acres on which the recommended carbon-sequestering practices are used.

It is our hope that this report will help agency personnel and policymakers at federal, state and local levels to recognize not only the climate-related benefits of the recommended practices but also their extensive environmental and economic co-benefits. The following recommendations are meant as guidelines for developing evidence-based programs that will increase the adoption of carbon-sequestering agricultural practices by producers across the United States.

1. Make soil health a central focus of USDA programs. Rebuilding the health of our agricultural soils not only sequesters carbon but also provides multiple environmental and economic co-benefits for producers. By making soil health a central organizing principle of its new focus on climate friendly agriculture, the USDA could amplify the key role of healthy soil in climate resilience and increase awareness of the scientific evidence for its valuable co-benefits.

2. Boost efforts to increase soil health and carbon sequestration at all governmental levels. To date, soil health programs have focused primarily on erosion and water quality. They are only recently broadening to include the urgent need to address climate change. State, tribal and local governments are often hampered in efforts to expand into this new area both by reduced staffing after decades of funding cuts and by insufficient knowledge about climate change and its connections to soil health among the remaining personnel.

i. Train federal, state, tribal and local soil health personnel about soil carbon sequestration and its importance as a climate solution. In order to develop effective and attractive programs to increase the use of the recommended practices, soil health professionals and agricultural advisors need to be fully aware of why it is important to increase soil carbon sequestration on farms in their state. Where this is not already the case, NRCS could educate local personnel in state agencies and local conservation districts on the fundamentals of the climate crisis and how using NRCS conservation practices can improve agricultural climate resilience, increase soil carbon sequestration and allow agriculture to be part of the climate solution.

ii. Establish a State & Tribal Soil Health Grant Program. Such a program would provide states and tribes with matching funds to design and implement a cohesive strategy to improve soil health and increase soil carbon sequestration while acknowledging all of the other environmental co-benefits of rebuilding the soil. These grants would allow each state or tribe to address its most critical needs in research, training, outreach and education, technical assistance, or financial incentives. This approach would help states and tribes take a leadership role, focus their efforts, and leverage state and local resources to promote soil health practices in integrative ways.

iii. Expand training programs for agricultural advisors to ensure accurate knowledge of mechanisms of soil health and carbon sequestration. Target groups would include governmental soil health personnel, university extension, non-profit organizations, farm cooperatives and private crop advisors. NRCS has established a suite of soil health training workshops and materials and could update and expand these to provide basic and advanced training for the people who advise farmers on the cropland and grazing practices that boost soil health and sequester carbon. Such programs, perhaps provided by state NRCS personnel, would help to ensure that accurate and evidence-based advice is provided to farmers about soil health, carbon sequestration and their environmental and economic benefits.

3. Build soil health education and outreach programs that will increase adoption of the recommended practices. In a recent report from the National Academy of Sciences,[30] the willingness of farmers and ranchers to adopt the key carbon-sequestering practices was identified as the largest single barrier to reaching the potential of land-based carbon sequestration as a negative emissions strategy. Although NRCS and various conservation-oriented NGOs have been encouraging farmers for years to use the management practices that improve soil health and sequester carbon, the adoption of these practices remains low. This suggests that simply increasing the magnitude of outreach is not going to be enough. We need to revamp the outreach approach.

i. Fund local efforts to identify barriers and benefits to adopting carbon-sequestering management practices. Increasing adoption requires understanding how local farmers and ranchers view the benefits of changing management practices as well as the perceived barriers to making such changes. Funding to states and tribal governments for focus groups, surveys and other analyses of how farmers and ranchers in specific localities view the barriers and benefits to key practices could reveal the types of interventions that could dramatically increase adoption.

ii. Develop outreach materials that combine accurate information with an understanding of the social/psychological dimensions of decision-making. Outreach programs must be formulated and delivered in ways that combine information about the agronomic, economic and environmental benefits of the recommended practices with evidence-based approaches to behavior change from psychology and the social sciences. This combined approach is essential to identifying and overcoming perceived barriers that keep farmers from adopting the recommended agricultural practices. Reducing issues perceived as barriers while enhancing the benefits is pivotal to increasing adoption rates.

iii. Collate updated information about economic and environmental co-benefits of soil health practices for use at the local level. Although outreach programs are of necessity local, federal NRCS and organizations like USDA-SARE could assist states by providing basic training materials that will ensure a common knowledge base on basic soil health, how agricultural practices affect soil carbon, the clear economic co-benefits of the practices and the role of carbon sequestration in soil as a climate solution. This training material, when combined with key insights about behavior change from social science, would provide state and local outreach professionals in soil conservation districts and non-governmental organizations with a common knowledge base to which additional localized information could be added as needed.

iv. Pay attention to the message. Education and outreach programs should be developed with an understanding of how information about soil health and carbon sequestration can be framed in ways that will be well-received by farmers and ranchers.

v. Promote a Community of Practice (COP) for soil health outreach specialists. National extension leadership could promote a community of practice among University and agency soil health outreach specialists who coordinate local outreach programs. This group could help to develop and implement effective programs designed to increase the adoption of the recommended carbon-sequestering practices.

4. Expand the capacity to deliver accurate and up-to-date technical assistance on soil health and carbon sequestration. Outreach and education can help teach principles and practices, but farmers and ranchers also need technical assistance to implement carbon-sequestering practices successfully on their farm or ranch. In many cases, the lack of such assistance becomes a powerful barrier to practice adoption by reducing confidence that a management change will be successful.

i. Substantially increase the NRCS budget for Conservation Technical Assistance. A severe shortage of field staff with adequate training in soil health and carbon sequestration has hampered the ability of NRCS to deliver the technical assistance that farmers and ranchers need to increase adoption rates of carbon-sequestering practices. State and local agencies, farm cooperatives, non-profit organizations and various agricultural service providers are trying to meet the need but often lack adequate training and experience. Many of the private advisors, such as fertilizer or seed dealers and equipment salespeople, have a financial interest in the outcome. Increasing the availability of NRCS field staff would add more science-based information to the mix.

By helping farmers transition to practices that improve soil health and sequester carbon, additional NRCS staff could increase farmer confidence in a successful outcome and remove a key barrier to adoption.

ii. Promote practice implementation that increases the effectiveness of carbon sequestration. For example, cover crops sequester carbon best when managed to produce high biomass. Incentives and education should therefore focus on early cover crop planting and late termination in order to maximize cover crop biomass. This will increase carbon sequestration as well as add additional organic matter and help with weed control.

5. Develop and fund new incentive programs to ease the transition to carbon-sequestering management practices. Adopting new agricultural practices that improve soil health and sequester carbon can involve a transition period and upfront investment of time and capital. Farmers must often learn how to integrate the new practices into the existing management dynamic, and it can take time for new practices to produce a visible economic benefit. Incentives can reduce these key barriers to adoption by providing the economic certainty required for a farmer to risk a change in management.

i. Greatly increase funding for USDA's five major conservation programs. Current demand far exceeds funding available for existing USDA programs: the Conservation Stewardship Program (CSP), Environmental Quality Incentives Program (EQIP), Regional Conservation Partnership Program (RCPP), Conservation Reserve Program (CRP), and the Agricultural Conservation Easement Program. Time-consuming applications and funding rates below 50% in most of these programs discourage farmers from participating. Significantly increasing the funding for these five programs so that most applications can be funded would increase enthusiasm among farmers and facilitate adoption of the full suite of carbon-sequestering practices.

ii. Make the paperwork for enrollment as simple as possible, but verify practice implementation. Many producers shy away from requesting NRCS funds because the paperwork is extensive and the probability of funding is uncertain. Streamlining the paperwork may reduce an important barrier to adoption. In addition, providing for automatic enrollment for high-priority soil health practices, as the USDA does for Continuous Conservation Reserve Program practices, could reduce the uncertainty that farmers face when attempting to access programs like the CSP, EQIP, and RCPP. The USDA also needs to ensure inadequate enforcement of Conservation Compliance provisions and provide a clear expectation that equitable standards will be used to verify that practices funded with public monies are implemented as intended.

iii. Promote innovative evidence-based incentives that leverage existing USDA programs. Use available research and fund new analyses to determine the most effective ways to use incentives to drive adoption of particular practices. Providing a carbon sequestration 'bonus payment' to landowners who enroll land in Conservation Reserve Program contracts would boost demand for the CRP practices that sequester large amounts of carbon. Providing a discount on federal crop insurance for farmers who adopt soil health practices would recognize the impact these carbon-sequestering practices have in reducing yield loss (and thus reduce crop insurance payout) during exceptionally dry and wet years.

iv. Consider incentive programs that fund the transition to new practices, then taper to a maintenance level. Enhanced funding during a transition period is important to increase adoption because it may take 3-5 years for the carbon sequestering practices to produce visible improvements in soil health and crop productivity and enough savings in time and input costs to significantly increase net profits.. Incentives could potentially be reduced or eliminated once the practices have visibly increased profitability. However, the environmental benefits of some of these practices to the public as a whole may justify continuing payments at a maintenance level for as long as practices are continued.

v. Provide more attractive incentives for underutilized practices that sequester significant carbon. Increase NRCS and state incentives beyond current levels for practices that sequester a lot of carbon and that are not yet in common use.

vi. Facilitate farmer access to key equipment. Access to inter-seeders, high-boys, roller-crimpers, no-till drills, and other key equipment is important to help farmers adopt and adapt soil health practices. This assistance is particularly important for small farmers or those in historically disadvantaged groups who have often been left out of assistance programs. The need for specialized equipment could be met through subsidized equipment rentals through local soil conservation districts, and tax or low-interest loans for purchasing needed equipment. Easy access to specialized equipment will help to lower another key barrier to adoption of the recommended practices.

6. Increase equity and inclusion in USDA programs and make outreach results more accessible. A brief examination of "Outreach and Advocacy" on the NRCS website suggests that NRCS has been aware of the equity issue since at least the mid 1990s. The NRCS 2014 Farm Bill Outreach Strategy[233] specifies a number of outreach actions designed to increase outreach to underserved groups, though it is unclear how many of these actions were implemented. An analysis of participation in NRCS programs between 2013 – 2015[234] revealed that the fraction of all NRCS applications that came from historically underserved producers (31.6%) was less than expected based on their representation in the overall producer population (41.6%). This disparity was compounded by a lower approval rate for applications from the historically underserved producers (37.6%) when compared to approvals for non-underserved farmers (40.7%). These disparities must be corrected.

i. Require NRCS to analyze data on outcomes of all outreach efforts and make results accessible. Apparently much of the outreach to under-represented groups is conducted by third parties through grants. It is critical to analyze the effectiveness of this outreach work by documenting the yearly application and approval rates for farmers from each of the historically underserved communities identified by NRCS. Using an iterative process, the results on outcomes could be used in combination with periodic barrier analyses in underserved populations in each geographical area to determine a set of best practices for outreach to underserved communities that can be tested during the next Farm Bill. The results of these analyses and the best practices for outreach should be published on the NRCS website.

7. Establish a National Soil Monitoring Network to track impacts of management on soil carbon sequestration. Many states are struggling with how to measure changes in soil carbon resulting from implementation of carbon-sequestering management practices. Routine in-field soil sampling by farmers can track changes in soil health through standard measurements such as soil organic matter and bulk density. However, it is an illusion that the highly variable and generally shallow samples taken by farmers can accurately quantify changes in soil carbon after changing management practices.

i. Measuring changes in soil carbon from new management practices requires a careful and statistically sophisticated sampling strategy. The changes in soil carbon from using the recommended practices are small relative to the vast amount of carbon already in the soil. Accurately measuring the carbon impact of the practices is made even more difficult by variability in soil carbon both across single fields and at different depths.

Establishing a coordinated National Soil Sampling Network modeled after one already tested by NRCS[235] would ensure that data on the time course of soil carbon sequestration is accurate and repeatable. Having standard sampling and testing protocols for changes in soil carbon that are used by states and the federal government will greatly increase the accuracy of land-based GHG inventories.

Establishing a permanent grid of sites that is resampled over time in a standardized way is the most effective means of tracking changes in soil health and soil organic carbon.[235,236] This National Soil Monitoring Network would provide a rich source of high quality data that will capture key trends in soil health and provide data that will make current models of GHG reduction from soil carbon sequestration more accurate and thus more valuable.

ii. Effort already invested in the pilot sampling project means that a National Soil Monitoring Network could be established quickly. From about 2007-2016, NRCS piloted a national soil monitoring system based on the permanent grid of sites in the National Resource Inventory

(NRI). The NRI is a vast set of 800,000 sites for which data on land use, cropping patterns and other key information have been recorded since the 1980s. This pilot project led to the development of a sampling protocol that minimizes variation and targets the sampling strategy in ways that provide the most information for a given number of samples.[236,237]

Having the monitoring network in place as farmers and ranchers increase the use of the NRCS conservation and carbon-sequestering practices means that the time-course of carbon sequestration and the rebuilding of soil health can be monitored from an early stage, allowing the full time course of changes in soil health to be captured. The value of such high-quality data on a national scale can hardly be overestimated.

NRCS should work with state officials and local conservation districts to coordinate the identification of sites, the installation of the GPS-linked permanent site markers and the timing of the sampling efforts. In the pilot work, NRCS personnel were trained to establish the plots, take the samples and package them for analysis by soil health and modelling experts from Colorado State University.[235,236] Using this approach in the new National Soil Monitoring Network would get the maximum value from this previous work. It would also ensure that the sampling is done in a way that will help to refine the COMET models[105] that provide the key estimates of how much GHG reduction is attained from each practice (see Appendix 2).

8. Fund regular soil testing by farmers at a field level to monitor changes in basic soil health.

National and state cost-share and incentive contracts should include and fund regular soil health testing by producers, preferably using a common set of soil health metrics that are reliable and easy to measure. Results of these tests would then be reported to the agency that administers the incentives, and would ideally include detailed information about the management history of each field. Although this testing is likely to be focused on surface layers, it will be very useful for measuring basic aspects of soil health, such as changes in organic matter. It will be less useful for measuring changes in soil carbon, but these tests could provide many data points at a field level that, even if highly variable, might complement the more standardized soil carbon testing from the National Soil Monitoring Network.

9. Increase the availability of USDA data for research purposes. USDA agencies have a wealth of information that could yield important insights about soil health and carbon sequestration, but which is not currently available to researchers. In some cases, the data are housed at different agencies or on different systems, while in others, access even to anonymized data is denied. This information includes data on yield, participation in conservation programs, land use and management practices. The ability to analyze a consolidated database could reveal key information about conservation outcomes. Adding information collected by states would be even more useful. Making these data available to researchers while ensuring strict producer privacy protections could be done through creation of a data warehouse. The availability of these data for research purposes would greatly increase the value of conservation investments already made by allowing the impacts of conservation practices on carbon, water quality and other co-benefits to be rigorously tested.

10. Increase funding for key research in soil health and carbon sequestration. There is still much to learn about improving soil health, maximizing its economic benefits and how to increase farmer adoption of key practices. We also need to develop additional effective carbon sequestering practices and to determine best practices for keeping sequestered carbon in the ground. Some key areas of research that need further investment include:

i. Soil microbial ecology research to increase our understanding of the interactions of soil microbes with their environment and how these networks of interactions can be most effectively restored in degraded soils. We also need to better understand the implications of "biostimulant" products that introduce non-local microbes into agricultural settings.

ii. Economic research to collate and analyze the economic costs and ROI for use of the carbon sequestering practices.

iii. On-farm research to identify locally appropriate soil health practices in the highly variable soils, climates, and agricultural systems across the nation.
The USDA Sustainable Agriculture Research & Education program (SARE) is an example of a farmer-driven program that helps farmers and ranchers interact with university researchers to develop, test, and educate each other about locally successful soil health and carbon sequestration practices and systems. Increasing funding for this program could allow more on-farm research.

iv. Social science research to better understand why farmers adopt soil health practices and how we can ensure that the behavioral changes endure.

v. Impacts of periodic tillage on soil carbon stocks.
Reducing the intensity of tillage can increase carbon stocks by reducing disturbance of the soil ecology. However, in some settings, periodic tillage is advantageous. More research is needed to understand the impact of both periodic tillage (e.g. every 5 or 10 years) and tillage of different intensities on long-term carbon stocks.

vi. Controlled tests of the GHG impacts of management intensive grazing. There is little peer-reviewed research on the soil carbon impacts of various types of rotational grazing and the key grazing management factors that influence carbon sequestration. This should be a high priority for research. The 400 million acres of private pasture and rangeland in the US could potentially sequester significant carbon under some grazing regimes. To quantify the carbon impacts of management intensive grazing, however, additional well-controlled research studies are required that compare specific intensive grazing systems to conventional grazing management.

vii. Breeding deeper rooted annual crops and perennial grains. Annual crops with deeper roots would put organic material and carbon deeper into the ground where it is less likely to be disturbed and released as CO_2. Replacing annual grains with perennial grain crops would be even more significant by greatly reduce erosion, adding organic material to deeper soils and avoiding the costs and carbon emissions from planting grain crops each year

This comprehensive set of recommendations can help federal, state and local policy-makers design policies and programs that will accelerate the adoption of the carbon-sequestering practices recommended in this report.

By increasing the adoption of carbon-sequestering conservation practices nationwide, agriculture can become a significant part of the American climate solution.

Credit: STRIPS Program, Iowa State University

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Appendix 1:
Methods used for the Literature Review

In recent years, carbon sequestration has become a topic of interest in the popular press. Unfortunately, scientific evidence for the effectiveness of the practice(s) under discussion is not always presented. For a carbon sequestration program to become valid policy and be regarded as credible, the effectiveness of the recommended carbon-sequestering practices must be supported by scientific evidence. Evaluating and summarizing this evidence is one of the goals of this report.

Between 2010 and 2013, four major reports were published that outlined agronomic practices useful for GHG mitigation in agriculture. Together, they provide a solid baseline of evidence for a set of recommended agronomic practices for carbon sequestration. State-of-the-art estimates of the annual GHG reduction achieved per acre for each practice were obtained from COMET-Planner (see Appendix 2). More current literature was selectively reviewed to clarify particular topics. The baseline reports used are:

Olander, L.P. et al. 2011. *Assessing Greenhouse Gas Mitigation Opportunities and Implementation Strategies for Agricultural Land Management in the United States.* Nicholas Institute for Environmental Policy Solutions Report, NI R 11-09.[130]

This report puts the various carbon-sequestering agronomic practices into a broader policy context. It considers not just each practice's potential for GHG reductions, but the degree of scientific certainty for the efficacy of each practice, economic issues, barriers to acceptance and issues associated with implementation and accounting.

Eagle A. J. et al. 2012. *Greenhouse Gas Mitigation Potential of Agricultural Land Management inthe United States: A Synthesis of the Literature, Third Ed.* Technical Working Group on Agricultural Greenhouse Gases (T-AGG) Report.[238] This detailed literature review supports Olander et al. (2011).[130] It provides brief descriptions of each carbon-sequestering agricultural practice, the most recent estimates of the of the estimated GHG reductions for each practice (both mean and range), and a comprehensive review of the literature as of the date of publication.

Denef et al. 2011. Greenhouse Gas Emissions from US Agriculture and Forestry: A Review of Emission Sources, Controlling Factors and Mitigation Potential. Interim report to USDAunder Contract #GS-23F-8182H.[13]For carbon-sequestration in agriculture, this report covers much of the same ground as Olander et al. (2011)[130] and was published the same year. Although the reports do not cite or refer to one another, the evaluation of the various practices and their potential for GHG reduction are similar.

ICF International, for the USDA. 2013. *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States*. Report in support of the work done under USDA Contract No. AG-3142-P-10-0214 [239] This report has very detailed discussion of each of the practices considered in Olander et al. (2011).[130] It also considers other practices associated with animal not considered here and various cost scenarios and the "break-even" points for each practice. A break-even point is the value of an incentive that would be required for a farmer to either implement the practice on cropland acres or to take an acre out of commodity production and shift it into one of the longer term carbon-sequestering practices involving perennial plants.

Information from these four reports was used to evaluate the carbon-sequestering potential of agronomic practices in three general areas: cropland management, grazing land management and land-use changes (e.g., conversion of marginal cropland to conservation cover, riparian buffer, pasture or forest), and to assess the level of scientific support for each practice. These reports show broad agreement on the effectiveness of the recommended practices listed in Table 1.

These reports define the various carbon-sequestering agronomic practices vary slightly, making it difficult to develop precise standards for each practice. To overcome this issue, we aligned the recommended practices to NRCS specifications and standards,[104] which are already familiar to many farmers. These standards outline the requirements for each practice, simplifying implementation and standardizing the assessment of GHG reductions for each practice.

Appendix 2:

GHG Reduction Estimates From COMET-Planner

Expected GHG reductions from using the recommended NRCS conservation practices can be obtained from [COMET-Planner](), one of the COMET tools for GHG analyses in agriculture developed at Colorado State University.

The COMET tools use a combination of empirical data and process-based computer models to combine the changes in soil carbon, methane [CH4], and nitrous oxide [N2O] that result) from using one of the recommended soil health practices instead of a conventional agricultural practice on a particular farm (COMET-Farm), or in a small geographical region (COMET-Planner). Because the global warming potential of methane and nitrous oxide are greater than that of carbon dioxide, their impacts are expressed on a common scale as "carbon- dioxide equivalents", and the resulting GHG reduction from using a given practice is expressed as a single value: metric tonnes of carbon dioxide equivalent per acre per year (Mt CO2e/acre-year).

As described in detail in the documentation,[105] COMET-Farm and COMET-Planner utilize the best available science for GHG accounting and are coupled to databases that specify climate, soil and land cover for all US locations. They use both process-based models (DAYCENT) and empirical emissions factor models to evaluate the GHG consequences of using a soil health management practice instead of a conventional practice (the baseline). For each of the recommended carbon sequestering practices, the COMET-Planner documentation specifies the baseline practice to which the recommended practice is compared.

COMET-Farm provides estimated GHG reductions for a single farm. The GHG impact of adopting one of the soil health practices is calculated in COMET-Farm using data specific to that farm. The farmer inputs information about the management history of fields on the farm as well as the details of the new practice(s) that will be used instead of the baseline practices (**Figure A2.1**). This information is then combined with data on climatic conditions, soils and land use specific to that farm that comes from remote sensing

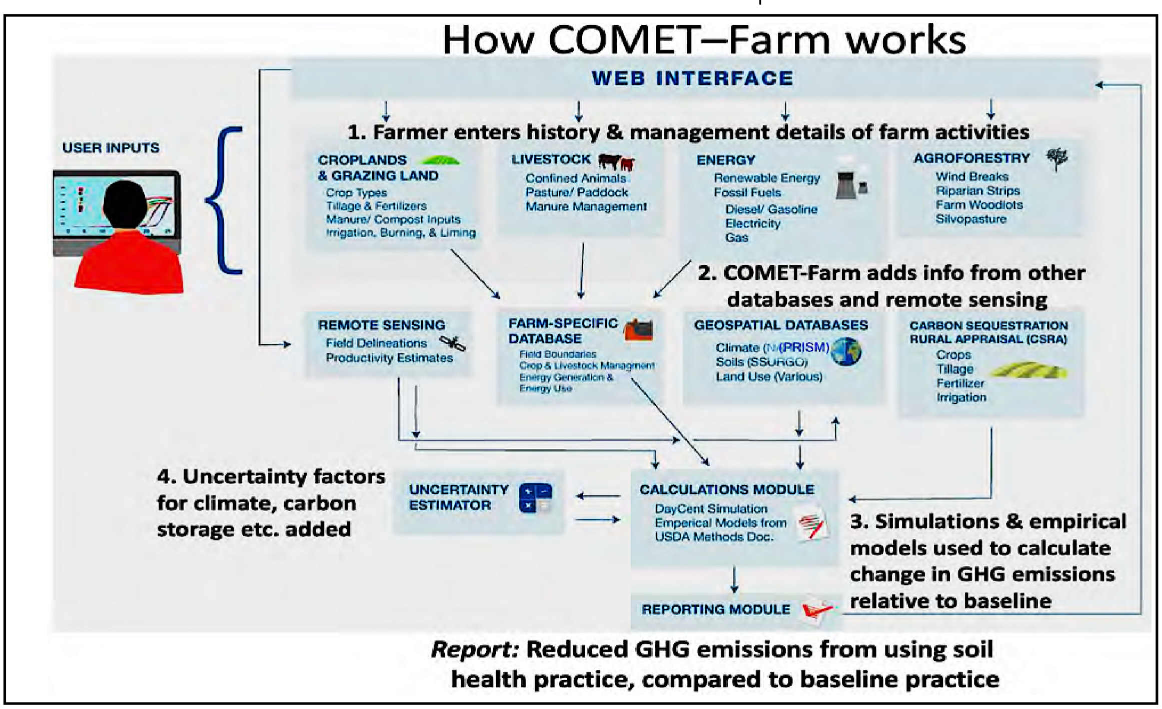

Figure A2.1. *COMET-Farm is a tool that estimates the GHG consequences of using one of the recommended soil health practices instead of a conventional "baseline" practice on a specific farm. See text for explanation. Graphic modified from a briefing for the US Climate Alliance Natural and Working Lands Workgroup, 4/8/2020, by Dr. Keith Paustian, Colorado State University.*

and various linked databases. All of this information then serves as input to a set of simulation and empirical models to produce an estimate of the GHG consequences of each new management practice substituted for the "baseline" practice. After incorporating a certain level of uncertainty into the estimates, a report is issued of the net GHG reductions expected if carbon-sequestering practices are used instead of the "baseline" practices for that area (for example, using no-till instead of conventional intensive tillage).

COMET-Planner provides estimated GHG reductions that are resolved to multi-county groups but are not specific for any particular site within a local region. COMET-Planner uses the farm-specific computational machinery from COMET-Farm to derive representative average values for GHG reduction after a change in management strategy for a localized region of several counties rather than for a particular farm. Counties in a given state within the same Major Land Resource Area (MLRA) are in the same multi-county group (**Figure A2.2**), and are similar in physiography, soils, climate, biological resources and land use.[105]

For each practice, COMET-Planner infers details about historical land use and management practices from national databases on soils, land use and climate for approximately 100 randomly chosen points in each MLRA. Each point is essentially a simulated farm (illustrated for California in **Figure A2.3**). For each of these simulated farms, remote sensing data is used to obtain a historical record of the crops grown and details of their management such as tillage, crop rotation, fertilization regime. Then averages are taken across all the points in a given MLRA to determine the typical practices and average inputs used in that locality.

These locale-specific averages are then entered into COMET-Farm as if they were data for a specific farm and are combined with information from COMET-Farm's soil, climate and land use databases. Finally, the GHG consequences of changes in management practices are modeled using the entity-specific computational machinery of COMET-Farm.

This results in estimates of the expected annual GHG reduction per acre (the ERC) when the NRCS carbon-sequestering practices are used in place of the "baseline" practices in that local region (i.e., if no-till is used instead of conventional tillage). All counties in the same multi-county region have the same ERCs.

The reported consequences of using a new practice are interpreted just as in COMET-Farm, except that the resulting GHG reduction for each practice represents an average for a several-county area rather than calculations for a specific farm.

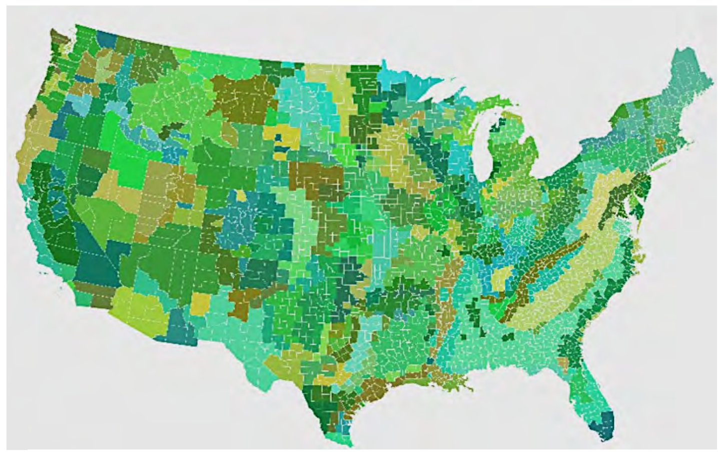

Figure A2.2. *U.S. counties in the coterminous U.S., grouped by Major Land Resource Areas. From the COMET-Planner Report.*[105]

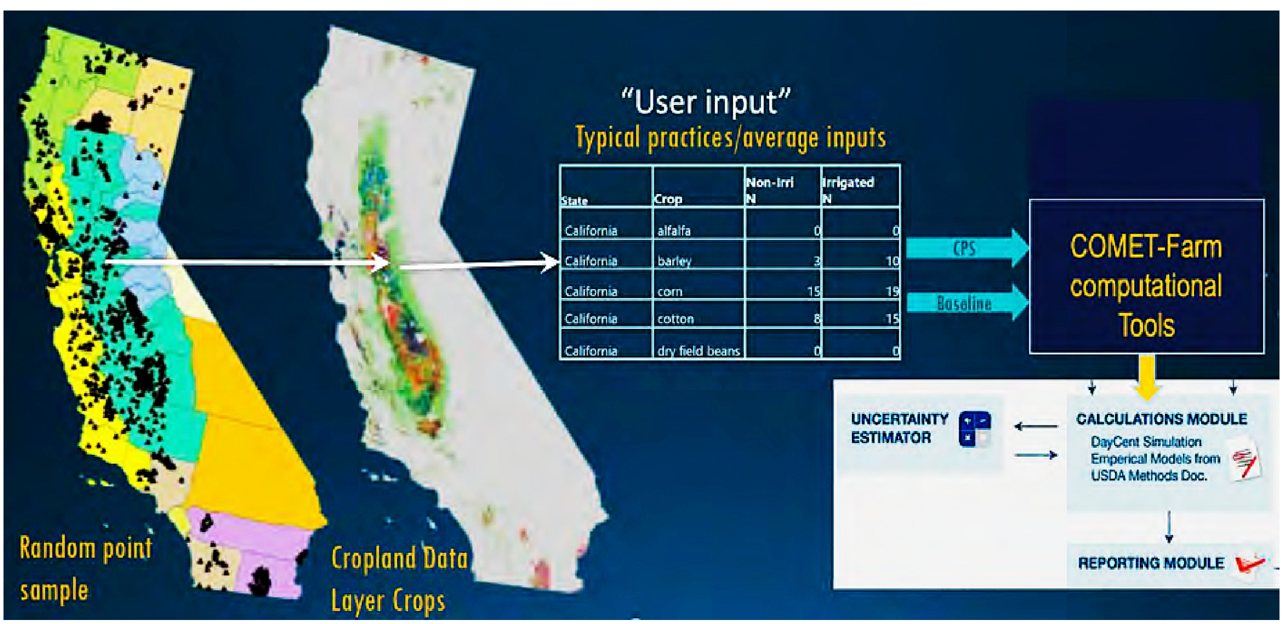

Figure A2.3. *The process used by COMET-Planner to estimate GHG reduction from using soil health and carbon sequestering agricultural practices in place of "conventional" practices. Random points placed on a map serve as locations for simulated farms, for which the historically used agricultural practices and inputs, which act as the "baseline" for the simulated farm at each point. COMET-Farm then uses the same computations and models as in Fig.* ***A.2.1*** *above to estimate the net reduction in GHG emissions from using one or more of the soil health/carbon sequestering NRCS practices ("CPS") instead of the "baseline" practices. Graphic modified from a briefing for the US Climate Alliance Natural and Working Lands Workgroup, 4/8/2020, by Dr. Keith Paustian, Colorado State University.*

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