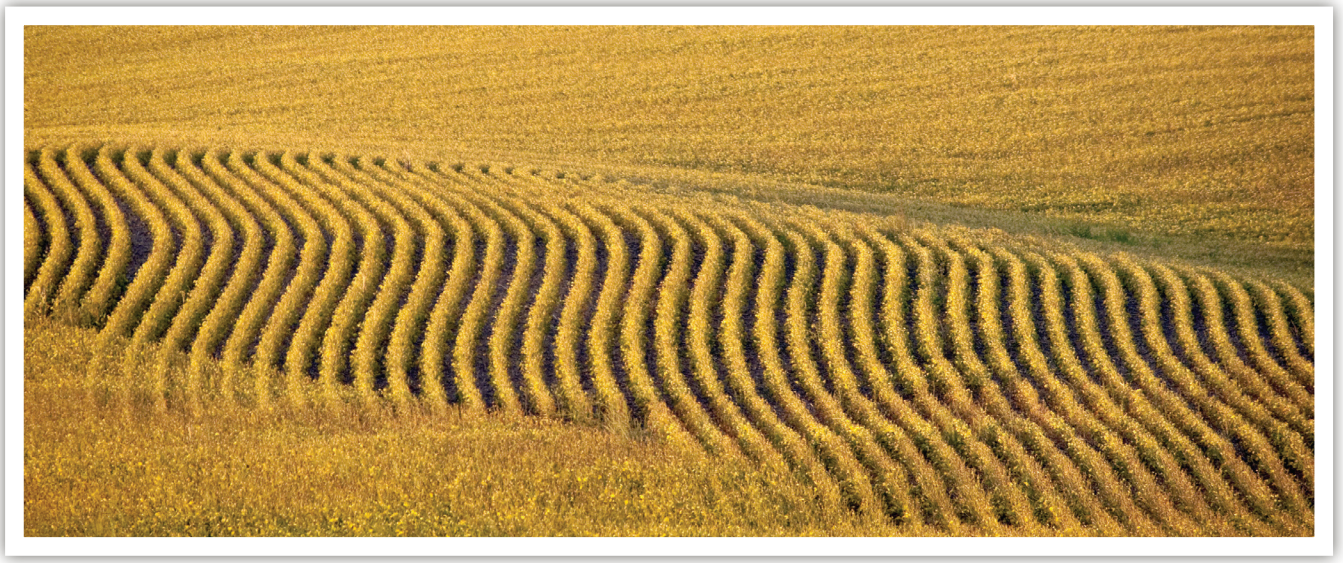
Banking on Carbon



Policy Considerations for Carbon Payments and Sequestration in Agriculture

a report by **Wyatt Fraas**
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All photos by Wyatt Fraas

Acknowledgements: Funding for this report was provided by the McKnight Foundation, Minneapolis, MN and the Center for Rural Affairs, Lyons NE.

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Executive Summary*



The climate is changing at a quickening pace as a direct result of human activities. Our actions cause increasing amounts of atmospheric greenhouse gases that trap solar energy, driving increasingly severe and frequent heat waves, droughts and strong storms. Agriculture contributes a relatively small portion of overall US greenhouse gas emissions. Reducing agricultural emissions will be beneficial, but the greater opportunity to use agriculture to mitigate climate change lies in the potential of agricultural soils to pull carbon out of the air, reducing greenhouse gas levels and gaining time to reduce overall emissions.

Following other countries' actions a decade earlier, the US government began to give serious consideration to greenhouse gas reductions in 2009, when it initiated major climate change legislation to cap carbon emissions and pay farmers who sequester and store carbon in the soil.

Though that legislation did not become law, several private organizations have established a market for "carbon credits," where farmers are paid to adopt certain practices believed to sequester or store increased carbon in the soil. These exchanges also pay for practices to reduce emissions of other greenhouse gases, particularly methane and nitrous oxide.

Integrity is critical to these payment systems. Carbon credits are designed to offset very real emissions of greenhouse gases. Credits must achieve real and permanent increases in soil carbon storage to effectively address climate change. Fortunately, we have the potential to substantially influence the amount of carbon captured on land through management of agricultural crops, livestock, soils and plant communities, but we are doing so at only a fraction of the rate possible.

Current agricultural recommendations to reduce global warming (as exemplified by these carbon offset payments and most USDA discussions) are to farm with no-till techniques, plant trees, reduce fertilizer use, and capture methane at confinement livestock operations. More and better approaches can greatly increase the carbon captured and emissions reduced. Most of these enhanced practices also allow farm and ranch land to better withstand effects of global warming.

Agricultural Carbon & Greenhouse Gas Management

• **Plant and root growth.** Plants capture carbon from the air by using photosynthesis to make plant tissues. However, over 80 percent of carbon in plants quickly returns to the atmosphere through microorganisms digesting plant materials and releasing carbon as a byproduct. Crops with lots of above-ground growth potentially contribute more carbon to the soil and cover crops capture carbon during extended growing seasons in the fall

* The purpose of this report is to present policy recommendations related to potential payments for carbon credits for effective climate change mitigation through agricultural practices. The full report presents those recommendations and a review of current scientific knowledge of the effects of agricultural practices. Funding for this report was provided by the McKnight Foundation, Minneapolis MN and the Center for Rural Affairs, Lyons NE.

and spring. However, the carbon most likely to remain in soil is sequestered underground, in plant roots, where decomposition occurs more slowly. Thus, deep-rooted crops and crop rotations with legumes increase deep soil carbon. Water and fertilizer management for optimum plant growth result in more plant materials above and below ground while soils without compaction allow deeper and more vigorous root growth. A fallow season with no plant growth generates no soil carbon.

• **Tillage.** No-till farming, which leaves a mulch layer of old plants on the soil surface, is often the primary recommendation for farmers to capture carbon. This is because tilling, plowing and other surface disturbances increase the breakdown of soil carbon near the soil surface while exposing surface-level carbon-containing particles to loss by erosion. Most research has found that no-till farming achieves substantial increases in carbon sequestration over conventional tillage systems in the top layers of soil.

However, scientists caution that it is not suited to every situation, particularly cold, wet soils where the heavy residue layer impedes seedbed readiness. In addition, carbon sequestered near the surface by no-till farming can be quickly lost as a result of a single tillage operation. Furthermore, long-term research in Nebraska found that certain tillage practices sequestered more carbon deep in the soil, below two feet, than no till. There is more to learn from additional research on the relationship between tillage and carbon sequestration, particularly deep in the soil where carbon is most stable. Optimal tillage management would reduce erosion and decomposition while increasing the deep root growth that contributes much of the stable deep carbon.

• **Fertilization.** Nitrogen fertilizers increase plant production, which increases the potential soil carbon contribution. However, these fertilizers emit nitrous oxide, a greenhouse gas nearly 300 times more potent than carbon dioxide, when applied to the soil and their manufacture from natural gas releases large amounts of carbon dioxide, which may offset any soil carbon gains of increased plant production. Adding fertilizers only in the specific amounts, locations and times needed by crops can limit excessive emissions. Adding legumes to a crop rotation, instead of using other nitrogen sources, also limits nitrous oxide emissions.

• **Livestock.** Ruminants (cattle, sheep, etc.) emit methane, a carbon-containing greenhouse gas, as digestive gas and in manure. Digestive methane can be reduced with higher quality feeds, both in feedlots and while grazing. Controlling feed rations with simple additives can also reduce digestive methane. Grazing management to provide higher quality feed, as in intensively managed pastures with mixes of legumes and grasses, also reduces methane production. Pasture-based dairy operations release fewer greenhouse gases from all sources than do confinement, grain-based operations.

• **Manure.** Manure applied to the soil from slurry pits, deep-bedded livestock buildings, feedlots, compost, and livestock droppings on pasture all substantially contribute organic matter to soil and release few greenhouse gases. The primary exception is anaerobic lagoons, which break down most organic matter and release it into the atmosphere as methane and nitrous oxide.

• **Erosion.** Most soil carbon is in the top few inches of soil, so it can be easily lost to water and wind erosion where it is likely to be quickly decomposed instead of being sequestered within the soil. No-till and other conservation tillage practices protect the soil surface, greatly reducing soil loss. Other farming practices that reduce erosion include use of small grain crops, cover crops, contour cropping, buffer strips and shelterbelts that cover the ground, slow runoff, or reduce wind speeds. Practices that build soil life increase the "glue" that holds soil particles together so they are less easily moved offsite, keeping the carbon-containing topsoil in place.

• **Organics.** Organic farming often includes multiple practices documented to increase carbon capture, reduce emissions, and provide other environmental services. However, evidence of improved carbon capture on organic farms has been limited. Measurements of energy use and resulting greenhouse gas emissions, however, are often lower for organic than conventional farms, primarily due to differences in fertilizer sources.

• **Land use change.** Land use change from forest to grassland or cropland results in carbon emissions from the site as soils are exposed to disturbance and as woody plant materials are burned or decomposed. Carbon losses may reach 30 to 50 percent in these transitions. Replanting (reforestation) or new forest plantings (afforestation) are means of reversing these losses and could, along with improved management of degraded lands, recapture at least half the carbon lost. However, well managed grasslands capture more total carbon than forests and have substantial potential to recapture atmospheric carbon.

• **Biomass energy.** Biomass materials such as wheat straw or switchgrass from agricultural lands have the potential to produce carbon-neutral energy when burned since their carbon comes from photosynthesis, not from fossil fuels. However, production, transportation and processing of biomass may significantly affect the carbon balance of the resulting energy supplies. In addition, a limiting factor is that much of each year's crop residue is required for erosion protection, and considerably more is needed to retain soil carbon. Only high residue crop systems provide a protective level of biomass, which few annual crops can supply. Perennial biomass crops, however, might be harvested at greater rates than the annual crops now being used.

• **Adding Charcoal to Soil.** Biochar (charcoal or terra preta) is a form of organic carbon found in many soils that can last for thousands of years. Controlled charcoal production may permit sequestration of more carbon than other agricultural practices for longer periods on some soil types. Biochar has been used in Japan for decades as a soil amendment, but scientific investigation of its properties has just begun. The "biogas" released in charcoal formation can be captured and used as a fuel source, typically for heating.

Carbon sequestration in soils provides numerous other benefits in addition to offsetting carbon emissions and reducing atmo-

spheric CO_2 concentration. These are truly win-win benefits - the practices and results of capturing carbon in the soil improve air quality, water quality, soil quality and biological diversity while making terrestrial ecosystems more resilient to the damaging impacts of global warming. Perhaps the most important effect is the increased ability of agricultural systems to continue to produce food for human use.

Policy Implications & Recommendations

• Build conservation and carbon payment programs that complement each other. Many conservation and carbon management practices achieve the same goals. Carbon practices should not impair other conservation objectives such as erosion control, water quality and wildlife habitat. Landowners should be allowed to "stack" payments for carbon management with incentives for conservation to achieve these broader benefits.

• Prioritize research to guide protocols for carbon payments. Current payments reward a narrow slice of practices while a wide array of practices with proven carbon sequestration potential (cover crops, crop rotations, diverse plantings, managed grazing systems, grass-based livestock systems, and combinations of such practices) go unrecognized. One "silver bullet" solution will not fit the variety of cropping systems, climates and soils across the country, but systems could be tailored to meet those requirements through targeted research.

• Protect long-term results of carbon payments. Initial carbon trading protocols were for only five-year terms, with the credit recipient free to end the practice and return the sequestered carbon to the atmosphere. Measures that ensure sequestered carbon remains sequestered are necessary. However, current payments are inadequate incentive for landowners to enter into long-term agreements.

• Provide real "additionality" to carbon payments. Only new and "additional" efforts to reduce emissions or capture carbon should qualify for incentives. EPA and USDA should develop guidelines for determining when practices approach the usual and thus no longer require incentive and for addressing emissions caused by technologies that are in decline, such as anaerobic lagoons. This will eliminate payments for what would have been done anyway; a practice that wastes limited resources. In addition, it is critical to foster innovation by paying those who have led the way in the past with early adoption

• Incorporate agricultural resilience into carbon management. Many farming/ranching practices both sequester carbon and reduce the effects of climate changes. Increasing soil organic carbon improves crop yields, absorbs more water during storms and stores it longer, resists erosion, and reduces drought effects. While reducing emissions and capturing carbon are necessary to slow global warming, a simultaneous effort to deal with its impacts – which have already begun – is a realistic response to maintaining crop production, food supplies and the farm economy.

• Ensure that bioenergy production works in concert with soil carbon goals. When crop residues or dedicated energy crops are considered for cellulosic ethanol and biomass energy production, we risk losing carbon from the soil. We also remove the nitrogen in the crop residue. If that nitrogen is replaced by manufactured nitrogen, the practice will generate additional emissions of the potent greenhouse gas nitrous oxide. Much more crop residue is required to maintain soil carbon and fertility than to reduce erosion, which had been guiding plans for energy crops. USDA should also research the potential for other "win-win" options for sourcing biomass for biofuel production, such as limited biomass harvest from Conservation Reserve Program acres timed to minimize damage to wildlife.

Introduction

The climate is changing at a quickening pace. Human actions are the most likely cause of greenhouse gas buildup in the atmosphere, but altering agricultural practices can play a significant role in reducing or reversing greenhouse gas accumulation. Proposals to pay for these agricultural activities should be based on evidence that the most effective activities will be encouraged. This paper describes relevant agricultural practices and policy recommendations.

The Intergovernmental Panel on Climate Change, a group of 1,300 independent scientific experts from countries all over the world under the auspices of the United Nations, concluded there is a more than 90 percent probability that human activities over the past 250 years have contributed to greenhouse gas increases.

The leading nations of the world began to respond to climate change warnings in 1997. The US House of Representatives joined this trend in 2009 by initiating major climate change legislation. This proposed law would have capped carbon emissions, but would have allowed those who exceed limits to offset them by paying farmers (and others) to avoid emissions or to sequester and store carbon in the soil. In response to this legislation around the world, a number of organizations are certifying reductions or sequestration of greenhouse gases and are paying for these "carbon credits". These include payments to farmers to adopt certain practices believed to sequester or store increased carbon in the soil. These credits can also include payments for practices that reduce emissions of other greenhouse gases.

In order to deliver maximum benefits to farmers and the environment, carbon trading systems like these must have integrity. Carbon credits, for example, must achieve real and permanent increases in soil carbon storage or emission reductions beyond that which would be achieved in their absence. Carbon credits are designed to offset very real emissions of greenhouse gases. Therefore, the credits must achieve real and permanent greenhouse gas benefits if we are to effectively address climate change.

Most of the Earth's carbon spends long periods (centuries to millennia) in major reservoirs while small amounts cycle between these large stores. Two parts of the cycle, both controlled by humans, are rapidly transferring carbon out of long-term storage into the atmosphere: burning of fossil fuels and land use conversions of carbon-rich ecosystems like rainforests, wetlands and grasslands. When this carbon is released into the atmosphere, less heat from Earth's surface can escape through the atmosphere into space, resulting in warmer atmosphere and oceans, which is changing the global climate.

Two other portions of the carbon cycle relatively quickly remove carbon from the air: chemical absorption in the ocean and conversion of carbon dioxide (CO_2) into plant materials through photosynthesis. We have little control over carbon absorbed or released by the oceans. However, our management of agricultural crops, livestock, soils and plant communities gives us considerable opportunity to enhance the storage of carbon captured by plants.

Agriculture can play a role in reducing the amount of carbon-containing greenhouse gases in our atmosphere. While reducing agriculture-related greenhouse gas emissions is important and worthwhile, agriculture contributes a relatively small portion of overall US greenhouse gas emissions. Therefore, a greater opportunity lies in the potential of agricultural soils to pull carbon out of the air to reduce greenhouse gas levels and gain time to reduce overall emissions.

The purpose of this report is to present policy recommendations related to potential payments for capturing carbon or reducing emissions through agricultural practices. This document presents those recommendations and a review of current scientific knowledge of the effects of agricultural practices (mainly Great Plains and Midwest farming) on capture and release of soil carbon and release of nitrous oxide and methane. The greenhouse gas impacts of agriculture are greatly influenced by management of farming practices; in some cases there are difficult tradeoffs in emissions between alternative practices. It should also be noted that, while the scientific knowledge of these impacts has grown rapidly in the past decade, each new step in understanding has been accompanied by new questions about detailed workings of the atmosphere, soils, microorganisms and other elements of the carbon cycle.

Overview

Carbon is a very common element on Earth. All life is built from carbon molecules. Carbon is also the central element in discussion of climate change because carbon's presence in the atmosphere and ocean affects the entire planet's climate.

Carbon is stored throughout the planet in several primary reservoirs: the atmosphere, oceans, living organisms, soils and rock formations (Figure 1). Carbon cycles slowly through the reservoirs, except for very rapid cycling through plants and animals. The long-term capture of carbon (decades or longer) is termed "sequestration". Whether a reservoir removes carbon from the active cycle (as a "sink"), or releases carbon (as a source), can depend on human management.

Figure 1 depicts human management as burning of fossil fuels, land use changes and industrial processes, which all release greenhouse gases to the atmosphere. Small amounts of carbon are captured (sequestered) on land and in the ocean through photosynthesis and gaseous absorption into seawater. These amounts of capture are inadequate to offset the amounts of carbon released by human activities, resulting in greenhouse gas buildup in the atmosphere.

Several gases in the atmosphere are very effective at absorbing heat or reflecting it back toward the earth, a process known as the "greenhouse effect". Carbon dioxide (CO_2) is only a small fraction of atmospheric gases, but it plays a critical role in trapping heat, and it is produced in large amounts by human activities. Other significant greenhouse gases are methane (CH_4) and nitrous oxide (N_2O), which occur in smaller amounts but are 25 and 298 times more potent than CO_2, respectively, in trapping heat energy[2]. Water vapor also acts as a greenhouse gas and occurs in greater amounts than CO_2; while its proportion of the atmosphere is not affected directly by human activities, it does increase with higher temperature.

Since 1988[3], a consortium of scientists has reported on greenhouse gas changes and likely effects expected over the next century. These projections have become increasingly detailed, and the data supporting them have come from an ever-widening array of sources. And the timeframe for the onset of climate change has shrunk: the impacts of global climate change are already upon us. Ten of the warmest years on record have occurred since 1998[4]; sea levels have risen four to eight inches this past century[5]; animals have gone extinct as their habitat has changed[6]. This report addresses agricultural aspects of the only two options to relieve global warming: 1) curtailing emissions of greenhouse gases and 2) increasing carbon sequestration[7].

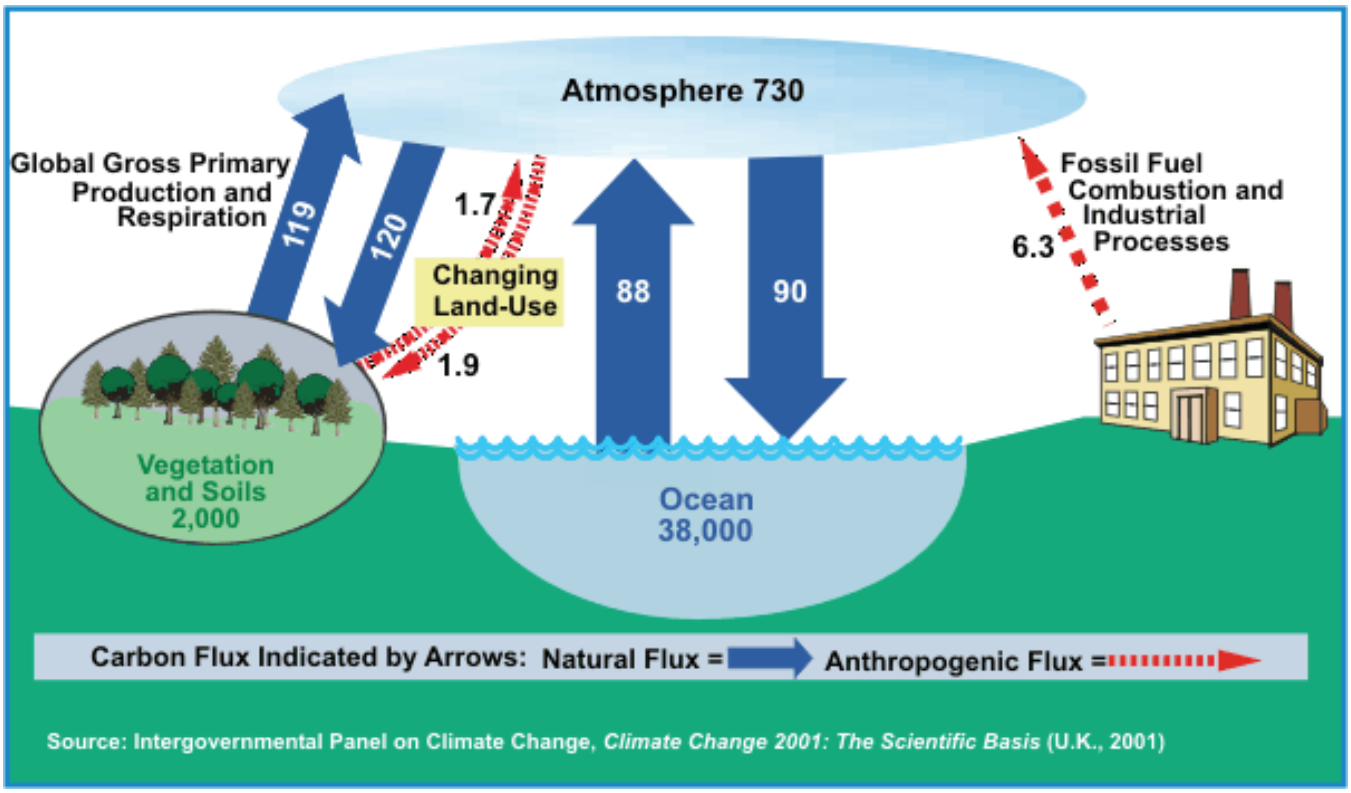


Figure 1. Current global carbon storage and flows (or flux, *from* emission sources or *into* "sinks"). Large amounts of carbon are stored in the soil, ocean, atmosphere, and rock formations (shown as million metric tons of carbon). Small amounts of carbon are captured (sequestered) on land and in the ocean. Human influences of land-use change and industrial processes release carbon that had been sequestered for millions of years (from IPCC 2001[1]).

Soils are a major pool of carbon, as are plants and other forms of life. Together they hold about three times the amount of carbon as the atmosphere[1]. The organic matter that ends up in the soil each year contains about 58% carbon, but much of that is quickly returned to the atmosphere through decomposition. Agricultural soils may have lost one-quarter of their carbon[8]; some of this carbon may potentially be re-sequestered with proper management. Management approaches are primarily 1) increasing plant biomass that captures carbon, 2) reducing greenhouse gas emissions and 3) increasing the soil residence time of carbon.

Agriculture is also a source for the three primary greenhouse gases influenced by human activities: carbon dioxide, methane, and nitrous oxide. The agricultural component of greenhouse gas emissions is about 30% globally and 6% of US emissions[9] (Figure 2)**. US agricultural components are primarily methane from livestock manure and nitrous oxide from nitrogen fertilizer[4], while carbon dioxide emissions are a far smaller component. Land-use change from native prairie and forest to intensive agriculture was the greater component of US greenhouse gas emissions before the 1960s, but since that time, fossil fuel emissions have surpassed agricultural activities in emissions[10].

Our management of agricultural soils is a key element in greenhouse gas management. Recapturing the carbon that has been lost from soil is one promising way to reduce carbon dioxide in the atmosphere. Current efforts to do so are meager: we may be managing soils to capture carbon at a rate only 6% of what we could achieve[15].

Most agricultural practices affect carbon sequestration or emissions. Modification of each of these practices can individually and cumulatively reduce greenhouse gases. However, their effective-

**This report deals primarily with agricultural, or on-farm, practices and does not address "downstream" activities of the food system such as processing and shipping, which could constitute over 85% of the food system energy use[11] and substantial greenhouse gas production potential[12]. Portions of this report discuss "upstream" farm inputs, such as fertilizer contributions to greenhouse gas production potential.

Projected Climatic Changes & Impacts

The effects of global warming will affect not only our climate but where and how we live. The specifics of what places will receive more or less moisture, or which will be hotter or more humid are difficult to pin down due to the limited understanding of detailed climate interactions. However, predictions of region-specific climate changes demonstrate the potential risks of climate change to leading agricultural areas. Scenarios developed by the US Global Climate Change Research Program[138] and Union of Concerned Scientists[139] predict that nationally:

- Heat waves will be 10 degrees hotter and three times more frequent as warm regions get warmer and dry areas get dryer.
- As ocean temperatures increase, hurricanes will gain 8% more wind speed and drop 18% more rain.
- Inshore rainstorms will become more severe, resulting in larger, more frequent floods.
- Roads and bridges will be damaged by floods and higher temperatures.
- Food poisoning will be more frequent at higher temperature, while diseases will spread and allergy season will expand.
- Summertime energy demand may increase by 20%.
- Ocean levels will rise by 10 inches to 2 feet, flooding some coastal areas and increasing damage from storm surges.

For the Great Plains and Midwest, farming stands to lose far more than it could gain this century with warmer temperatures and "CO_2 fertilization" of plants at higher atmospheric carbon dioxide levels:

- Plant hardiness zones may move north 150 miles, allowing weeds, insects and diseases to overwinter in larger numbers and to survive further north than at present.
- Total precipitation may increase 13-20%, coming in larger storms and creating wetter winters and springs – delaying planting of grains and harvest of high value, early season produce.
- Wind damage in severe storms will occur more often, and crops will experience heat stress more frequently due to more frequent temperatures over 90 degrees and higher evaporation rates.
- Drought conditions will occur more often, and aquifer levels will fall, making irrigation more difficult and costly.
- Livestock production will add costs as animals suffer heat and humidity stress as temperatures rise and nights no longer cool off.

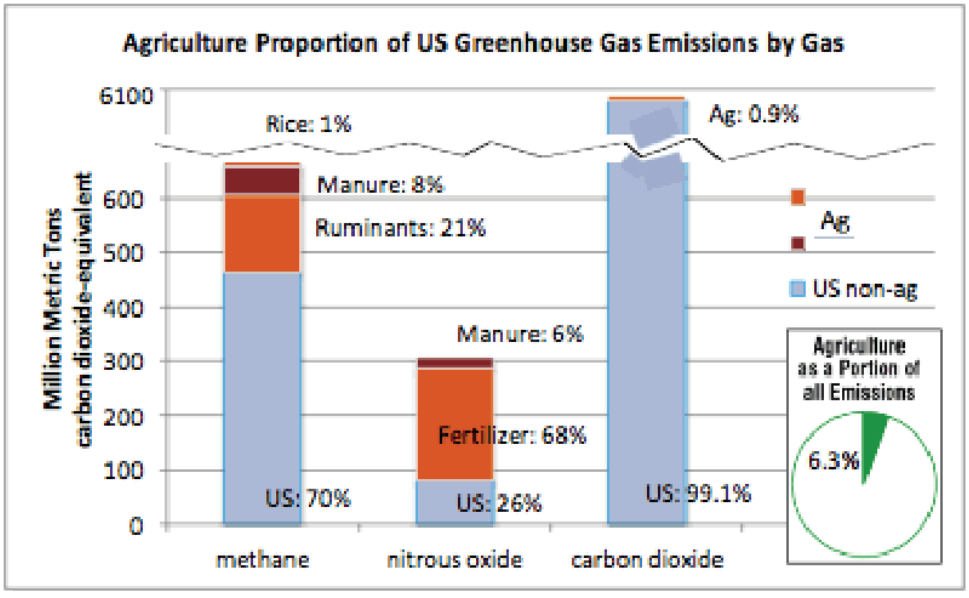


Figure 2. Agriculture proportion of US greenhouse gas emissions.

Agriculture is responsible for nearly one-third of methane emissions, three-quarters of nitrous oxide emissions and a small fraction of carbon dioxide emissions in the US. Agriculture contributes about 6% of total US greenhouse gas emissions (data from US EPA 2012[9]).

ness varies with site specific conditions and may involve tradeoffs between different greenhouse gases[16, 17].

European Union sequestration programs do not currently include agriculture due to the difficulty of quantifying greenhouse gas capture as well as verifying its extent. A group of leading agricultural researchers concluded that success of programs to encourage agricultural carbon sequestration may well hinge upon achieving effective measurement and verification of claims[18], which are under study.

Soil Carbon & the Effects of Farming Practices on Atmospheric Carbon Dioxide

Many aspects of agriculture can be modified to affect rates of carbon sequestration: plant residues, tillage, water management, grasslands, manure application and land use.

Plant Residue Management

Plant photosynthesis is a primary means of capturing atmospheric carbon. Photosynthesis turns sunlight and carbon dioxide into carbon-containing plant sugars, which are used to build stems, leaves and roots. As plant parts die, over 80% of their carbon content quickly returns to the atmosphere as microorganisms digest the plant materials. The remainder resides in the soil for varying lengths of time[19]. Several "pools" of carbon are usually recognized based on their residence time, such as active or "labile" pools (microbial biomass, water soluble carbon and particulate carbon), with a monthly turnover; slow pools (most plant parts within several inches of the soil surface and many other soil organic carbon compounds), with turnover measured in decades; and passive pools (larger or perennial roots, deeper materials, or partially decomposed plant and microbial materials), measured in hundreds of years[20].

The carbon most likely to remain in soil is that from plant roots[21] and partially decomposed materials. The carbon in surface crop residues is more likely to be released as carbon dioxide, although a small amount may be gradually incorporated into the soil, primarily in the upper soil layers.

Greater amounts of plant production result in greater amounts of carbon available to store as soil organic matter[22]. Several farming practices effectively increase plant material, such as planting crops with higher biomass production (e.g. corn vs. soybeans), replacing fallow periods with crops, lengthening the growing season with cover crops, fertilization for bigger, healthier plants, etc.

These techniques may be necessary to overcome inherent soil carbon shortcomings of annual cropping systems. In a number of trials, annual crops do not appear to provide the amounts of plant material necessary to maintain soil carbon levels present in untilled grassland or forest[23, 24]. Conversion of perennial grasslands or forests to short-season annual crops can result in less photosynthetic carbon capture during the growing season. After conversion, soil carbon may continue to decompose at previous rates, which gradually depletes soil carbon stocks. This may be particularly apparent at depths where annual crops do not supply as many roots at the range of depths and densities as a native plant community composed of a variety of perennial and annual species[25]. The observed loss of soil organic carbon following conversion to annual, monocrop agriculture may therefore be due to an imbalance between carbon input and carbon decomposition in the soil[26], regardless of tillage or fertility source[27]. For example, 100-day corn crops in effective 240-day growing seasons could supply less belowground biomass than the previous long-season native plant communities.

Fertilizing with nitrogen affects the quantities of both crop biomass and soil organic matter. Nitrogen is essential for plant growth and comprises a significant portion of both living and dead plant tissues; the carbon to nitrogen ratio is generally in the range of 10-40 to 128. Up to a point, an increase in nitrogen increases plant production; beyond that point, nitrate forms of nitrogen readily leach into groundwater, wash off into surface waters, or are emitted as gas[29], with undesirable effects on human health, aquatic ecosystems and the atmosphere[30] (nitrous oxide is discussed the following section, **Effects of Farming Practices on Nitrous Oxide Emissions**).

Measuring Greenhouse Gases

The amount of greenhouse gases is written in several measurement units. "Gigatons" (Gt) and "teragrams" (Tg) are used interchangeably to refer to the weight in metric tons or grams (a metric ton is 10% larger than a US ton). Other terms include million metric tons (mmt) and megatons (Mt or thousand metric tons). Since CO_2 is the major greenhouse gas of concern, amounts of the many others (particularly nitrous oxide and methane) are measured as "carbon dioxide-equivalents" (CO_2e or CO_2 Eq) for their effectiveness at trapping heat in the atmosphere. Combinations of gases, such as emissions from a cropping operation, are often lumped together for a simpler measurement of carbon dioxide-equivalents.

Carbon is measured both as gaseous carbon dioxide and as elemental carbon, such as in global carbon sinks or the gallon of gasoline (6.3 pounds) that contains 5.5 pounds of carbon. That gallon of gasoline burns to yield 20 pounds of CO_2 as its carbon combines with atmospheric oxygen; CO_2 contains only 27% carbon by weight.

Figures in this report refer variously to CO_2e or to C amounts, depending on the original author. When possible, metric measurement units have been converted to standard US units for land, volume and distance.

Conversions:

Gigaton = Teragram (10^{12} g) = 1000 million (billion) metric tons	
Metric ton = 1000 kilograms = 1 million grams	
Metric ton (or tonne)	1.1 US (short) ton
Hectare	2.47 acres
1 pound carbon	3.67 pounds carbon dioxide

Nitrogen-use efficiency (NUE), or the amount of applied nitrogen that results in crop biomass, has been estimated at less than 50%[34]. Long-recommended practices of matching fertilizer rates to crop needs, banding fertilizer application, making split fertilizer applications through the growing season, etc. improve NUE, reduce nitrogen losses to the environment, limit microbial decomposition of soil organic matter, and cut farm costs. Application of nitrogen to create additional plant material for carbon capture, beyond the fertilizer needed for normal crop production, is often counterproductive[35].

The utility of replacing inorganic nitrogen fertilizer with organic sources is under debate. Alternative nitrogen sources would be expected to retain crop yield levels, which is difficult for nitrogen-producing crops in rotation, as a year of non-food crop is required. Legume cover crops during fallow periods (winter or growing season) may meet this requirement, particularly if used as a green manure crop[36].

Deforestation

Land use change from forest to grassland or cropland results in carbon emissions from the site as soils are exposed to disturbance, as woody plant materials are burned or decomposed, and as new land uses fail to maintain forest-level soil carbon inputs[23, 24] (as described above in **Plant Residue Management**). Some 60% of forest carbon is in the soil (excluding roots), with 18% in tree parts[37]. With deforestation, overall carbon losses may reach 30 to 50%[32], with much of the loss coming from the soil.

A suite of approaches could recapture at least half of the carbon lost through deforestation[8]. Replanting (reforestation) or new forest plantings (afforestation) are means of reversing these losses by capturing carbon in the soil and in woody material over periods of decades[38]. Shorter term impacts on greenhouse gases are also possible through improved management of degraded forest lands (which increase growth rates and carbon capture), retention of existing forests (which maintain carbon sequestered above and below ground), and prescribed use of forest products as biomass fuels (which offset fossil fuel use)[39].

Grasslands

Grasslands worldwide contain 10-30% of the world's soil organic carbon[40]. Temperate grasslands in the US contain 35% more carbon per acre than US forests[26]. Many grasses are deep-rooted and add carbon to the soil through the yearly cycle of root growth, death and decay[41, 42].

Wet grasslands like swamps and tundra create "organic soils" (histosols) with extremely high carbon content. Many wet grasslands worldwide are degraded and others are being drained for use as cropland, both of which can release large quantities of stored carbon.

Several management practices can improve or restore carbon sequestration on grasslands[43]. Management to increase production can increase soil carbon as it does with cropland. Restoring grass cover on cropland can increase carbon capture[44, 45]. Grazed grass-

Nitrogen Cycling in Soil

(descriptions after Aulakh et al. 1982[31], O'Leary et al. 1994[32], Bouwman et al. 2002[33], Cassman et al. 2002[34], Galloway et al. 2003[30], Lin et al. 2011[29])

Plants use nitrogen to build proteins and other essential compounds within cells, and they cannot grow or mature without an adequate supply. Nitrogen cycles through the atmosphere, soil and living organisms in several molecular forms, a few of which are useable by plants. Over three-quarters of the atmosphere is gaseous nitrogen (N_2), but plants cannot use this form directly. The N_2 molecule must be broken apart and recombined for plant use, which occurs with two species of microbes in the "nitrogen fixing" process or with high temperatures (such as lightning reactions in the atmosphere or the Haber-Bosch industrial process). Along with producing nitrogen in a form that plants can use, parts of this cycle can create nitrous oxide (N_2O), a greenhouse gas 298 times more potent than carbon dioxide (CO_2).

Soil organic matter contains 4-6% nitrogen, but only about 5% of this becomes available to plants each year through microbial breakdown. Leguminous plants (and some other species) have developed symbiotic relationships with nitrogen-fixing bacteria to get an enriched supply of nitrogen. Leguminous roots provide a rich source of nitrogen when they decompose; hence the purpose of farming systems that use legumes in rotation with other crops. Humans have supplemented these natural processes with fertilizers containing readily (or nearly so) plant-available forms of nitrogen.

Nitrogen in plant or microbe cells is bound to carbon and other elements as organic compounds. Microbes break down these compounds (as well as ammonia (NH_3)-based fertilizers) to create inorganic or "mineral" forms. Plants can make use of mineral nitrogen (such as gaseous nitrogen in the atmosphere), only in an ionized, or electrically charged, form, primarily ammonium (NH_4^+) or nitrate (NO_3^-).

Ammonium is the product of nitrogen fixation as well as a major product of organic nitrogen decomposition, and can be directly absorbed by plant roots. In aerated soils, "nitrification" by a limited set of microbes quickly converts ammonium to nitrite (NO_2^-), then to nitrate, a plant-accessible form. Plants and microbes compete to use up the available ammonium; excess ammonium can support a "bloom" of microbial populations that create nitrate. At times, nitrous oxide can be a byproduct of ammonium breakdown.

A wide range of other bacteria breaks down nitrate to create gaseous nitrogen through "denitrification", which usually occurs in oxygen-deprived conditions such as inside soil particles or in waterlogged soils. Nitrous oxide is produced as an intermediate step in denitrification and can be lost to the atmosphere. Under some of these conditions denitrifying bacteria can consume nitrous oxide in addition to producing it, to the extent of pulling it from the atmosphere, creating a "sink" for N_2O. The specific population composition of denitrifying microbes can alter the rate and quantity of nitrous oxide production. These populations are modified by crops, temperature, fertilizer types, tillage, and other management choices and environmental conditions.

Ammonium is readily adsorbed by soil particles and stays in place. Nitrate, however, is water soluble and is easily leached to lower soil levels or the water table, or can be dissolved in precipitation runoff to surface waters. Many widely used nitrogen fertilization practices do not maintain levels of plant-available nitrogen without fostering N_2O production or nitrate losses. Nitrogen-use efficiency (ratio of nitrogen applied to nitrogen in crop material) is estimated at less than 50%, as nitrogen is lost to the atmosphere, leaching, runoff, or incorporation into other organisms.

Carbon Storage: Forests, Grass and Croplands

Carbon is captured in forests, grasslands or croplands in aboveground and belowground locations in varying amounts and lengths of time. The relative amounts of total carbon captured on a site generally follow the trend of forest > grassland > cropland.

Only forests store substantial amounts of carbon in aboveground materials. Trees may sequester carbon in woody stems for tens to hundreds of years while growing, dead or harvested (if for long-lived wood products). Grasslands also sequester carbon for long periods, but do so primarily in the soil.

Note: Considerable uncertainty surrounds the numbers because of ambiguity in definitions of biomes. They are useful as an overview of the magnitude of carbon stocks in terrestrial ecosystems. Data are from IPCC 2000[23].

Global carbon stocks in vegetation and soil carbon pools to a depth of 39 inches (1 meter):

Biome	Area (billion acres)	Global Carbon Stocks (GtC)			tC per hectare
		Vegetation	Soil	Total	
Tropical Forests	4.35	212	216	428	98
Temperate Forests	2.57	59	100	159	62
Boreal Forests	3.39	88	471	559	165
Tropical Savannahs	5.56	66	264	330	60
Temperate Grasslands	3.09	9	295	304	98
Deserts & Semideserts	11.24	8	191	199	18
Tundra	2.35	6	121	127	54
Wetlands	0.86	15	225	240	278
Croplands	3.95	3	128	131	33
Total	37.36	466	2,011	2,477	

land captures more carbon and methane than does undisturbed grassland[45, 46].

Intensive rotational grazing techniques can sequester substantially more carbon than extensive grazing practices[47]. Intensive techniques reduce grazing periods, increase plant recovery periods, and increase stock density. Several differences on intensively managed grazing areas have been identified that affect soil carbon levels: changes in plant species composition, distribution of manure, rapid root turnover, rapid litter decomposition, changes in soil surface microclimate, and other mechanisms[47].

Grassland fires historically formed part of an evolutionary-scale process of plant and animal community development that also cycled carbon between the atmosphere, soil and plants. Fires contributed charcoal to prairie soils (see Adding Charcoal to Soils, below). Grassland fire is now often used to release nutrients for short-term production gains; however, fires emit substantial amounts carbon, methane and nitrous oxide into the atmosphere[16].

Tillage

Tillage affects soil carbon in several ways. It exposes the surface layer to wind and water erosion, it exposes buried organic matter to water, air and microorganisms, and it moves surface material below ground.

Conventional or inversion tillage (moldboard plowing or multiple disc/cultivation passes) buries surface materials. Typically less than 15% ground cover remains after such practices, which provides little protection against wind or water erosion. The surface layers of soil contain the highest amounts of plant materials, so wind or water erosion of the top few inches can remove a high percentage of a site's carbon-rich particles.

Conservation tillage encompasses a range of practices designed to leave at least 30% of the soil surface covered with crop residue[49]. No-tillage, chisel plowing, single disc passes, and other techniques are considered reduced or conservation tillage practices. These practices, especially no-till, are very effective at reducing erosion and loss of surface carbon-bearing crop residues and soil.

Bacteria, fungi and other microorganisms that digest plant materials are most numerous and active just below the soil surface where temperature and moisture levels are more constant. Microbial digestion of organic matter is often limited by oxygen availability, so tillage allows digestion (decomposition) to occur more rapidly. This process also releases some carbon dioxide to the atmosphere. No-tillage, which does not throw open or invert the soil, limits aeration-related carbon dioxide release.

Compaction by heavy farm machinery often destroys soil structure, limiting root penetration and water percolation, which is sometimes a problem with no-till systems[50]. Tillage can break up compacted soil and allow deeper root growth, which is beneficial to carbon capture. Roots below the biologically active plow layer (top 15 inches) are exposed to less microbial digestion and are likely to remain in the soil longer than are plant materials at the surface.

While there is widespread acceptance among researchers and soil conservation agencies of conservation tillage as a beneficial practice for many conservation outcomes, there is less certainty over its value for capturing soil carbon[55, 56]. The majority of studies (but not all[57, 58, 59]) have found higher amounts of soil carbon in

Plants & Carbon Sequestration

Plants capture carbon from the air through photosynthesis, the process that creates sugars that become the building materials of plant structures.

Plant roots, stems and leaves (and manure from animals) all contribute to soil organic carbon, but not all of this contributes to "sequestration," or long-term storage. Some 80% of each year's plant carbon is returned to the atmosphere as carbon dioxide. How much carbon remains in the soil or how long it stays there depends on the chemical compound in which it is found.

Plant stems with high lignin content are more resistant to decomposition48. Partially decomposed materials such as compost are more stable than whole leaves and stems. Plant roots secrete carbohydrates, enzymes and other substances, many of which are quickly broken down by bacteria, soil animals, and fungi (which produce glomalin, a long-lasting, high-carbon "glue" that holds soil particles together). Digestion of secretions and other plant materials by these organisms quickly releases carbon dioxide.

Waste and body parts from these creatures remain in the soil and often decompose at a slower rate. Subsequent decomposition takes longer still, or deeply buried plant parts may remain for tens to hundreds of years due to the lack of organisms or suitable conditions for further decomposition. Burned plant material may also become buried. When this is a form of charcoal, it can resist decomposition for thousands of years.

Emissions by Bushel or Acre?

Greenhouse gases, as with other emissions, can be measured by the unit of production or by the site. For agriculture this is either by the bushel, pound and gallon (termed "emissions intensity"[91]) or by the farm or acre. The former approach emphasizes efficiency while the latter emphasizes the absolute quantity of emissions.

Both yield- and area-scaled measurements of greenhouse gases are important to the human food supply. Yield-based comparisons allow crop-to-crop contrasts but also reflect immediate effects on the food supply. Per-acre comparisons, in contrast, address actual changes in emissions. Both approaches need to include a time element to address rotational effects of varying acreages of food and non-food crops over the entire farm or over the entire rotational cycle.

Potential USDA policies for carbon sequestration currently identify greenhouse gas reductions by the ton[92]. Those tons may be measured absolutely on each acre or relatively by efficiency improvements. However, reductions in greenhouse gases per bushel may not result in overall reductions; for example fertilizer use per bushel of corn has declined 36% since 1970 but pounds of fertilizer applied per acre have increased by 22%[93].

Acreage-based reductions may not be absolute, either, if practices at one location affect decisions at another. On the global level, "leakage", or displaced emissions, can occur[94] in this way. For example, if it became US policy to reduce total emissions per farm, a perennial legume crop in rotation with corn might be chosen to cut greenhouse gases associated with synthetic nitrogen production. But that legume crop reduces production of human-food calories for that period. The market impact of reduced food crop production may lead to cropping on farmland cleared from forest in Brazil at a higher greenhouse gas impact[94].

Life-cycle analysis[48, 93] is an emerging technique to measure direct (on-farm) and indirect (off-farm, supply chain) greenhouse gas emission and sequestration to estimate total global warming potential[95] of management alternatives.

the upper soil layers under conservation tillage systems[60, 61]. Soil research has historically sampled only the upper levels of the soil (typically to 12 inches in depth)[61, 62], but studies of deeper levels (three feet or more) suggest that subsoil contains from 30 to 60% of total soil carbon[25]. Some studies that include more than the top foot of soil have found no difference in total carbon between conventional and no till systems[63, 64, 65]. However, one long-term study found that carbon at depths greater than two feet varied between tillage practices. Several tillage practices were associated with less carbon than no-tillage, but disking and deep subsoil tillage accumulated more carbon than no-till[66].

While some proponents recommend no-tillage as a widespread "best management practice", its use may not be appropriate on all soils. Some indications are that no-tillage is suitable for only a portion of cropped soils(for example, just 40% of soils in Ohio), and seems to be unsuitable for clay soils, poorly drained soils and cool soils[67].However, these depth and exclusion results are in dispute as additional refinement of sampling procedures may be needed to verify these findings[68, 69].

Tillage differences may be less important to soil carbon levels[27] than the cropping systems put in place during conversion of grassland and forestland to crops. Erosion losses, coupled with reduced carbon inputs from annual agricultural crops (as discussed above in **Plant Residue Management**), could account for a large proportion of the historic (and ongoing) loss of soil carbon from US farmland[26].

Conservation tillage has several benefits: it reduces soil carbon dioxide emissions, reduces fuel use, increases soil water storage, and limits surface erosion on all soils. But its effectiveness in capturing carbon in soil and varies with soil type and conditions. Continuous no-till may not be superior to all other tillage systems deep in soil where sequestered carbon is most stable and least likely to be subsequently lost[66].

Manure Application

When animals eat the carbon in plants, it becomes body tissues, is exhaled to the atmosphere as carbon dioxide, or is excreted in manure or digestive gases. Manure contains 40-60% carbon by dry weight[70].

Soil application of manure from slurry pits, deep bedded livestock

buildings, feedlot manure, compost and livestock droppings on pasture all make substantial contributions of organic matter to soil. The primary exception among manure handling systems is anaerobic (oxygen-free) lagoons, which break down most organic matter and release it into the atmosphere as methane[71], which has a greater climate impact than carbon dioxide. (Additional discussion of manure is found in the following section **Effects of Farming and Ranching Practices on Methane Emissions**.)

Cover Crops

Cover crops serve numerous purposes[72]: to supply organic matter, to either provide or immobilize nitrogen and other nutrients, to provide weed control, to cover soil for erosion protection during a nongrowing season (i.e. summer fallow or during winter), etc. Cover crops also make use of sunlight and capture carbon during extended growing seasons in the fall and spring.

Any crop on the land is more valuable for capturing carbon than no crop at all: fallow fields contain less soil carbon than fields continuously cropped[73]. Continuous or intensified cropping in this sense includes winter in northern areas as well as fallow years in dry regions. Carbon capture is related to the volume of aboveground[74] and root-related[75] plant material produced by the cover crop[74], just as it is with primary crops of corn, beans, wheat.

Cover crops are often tilled into the soil (as a "green manure") but can also be left on the surface. In no-till systems, cover crops not incorporated into the soil can add carbon both through surface residue and through root decomposition. Most combinations of cover crops and tillage[72], including the combination of no-till and legume cover crops[46], were found to increase soil carbon amounts.

Soil nutrient effects vary with the cover crop[72]. Cereal crops (annual, grain-producing grasses) produce carbon-containing biomass and can take up excess soil nitrogen so it does not leach or volatize. Legumes (clovers, vetch, peas, etc.) produce subsoil nitrogen as well as surface and root biomass. Brassica (radish, turnip) and mustard crops add biomass while deterring weeds and pests. A mix of species often results in higher biomass production and soil carbon. For example, legume and cereal mixes increased soil carbon content under several tillage practices[76] more than cereals alone[77, 78]. Specific mixtures resulted in varying carbon capture rates[79].

Carbon Markets

Markets for carbon work on the premise that those who want to offset some of their carbon emissions (individuals or businesses) may purchase an amount of carbon sequestered or not emitted from someone else. Markets are either voluntary, in which buyers do so for public relations value or personal interest, or regulatory, in which governments limit allowable emissions.

In the European Union, the EU Emissions Trading System has capped (limited) industrial carbon emissions (with a 21% reduction between 2005 and 2020). Companies may purchase ("trade") a block of sequestered or un-emitted carbon through national or private Exchanges to help meet their emissions target. Agricultural sources or sinks of carbon are not recognized by the EU at this point. Prices for EU Allowances (one metric ton of CO2) have ranged from $8 - $19 since 2005.

In the United States, a number of voluntary frameworks for carbon offset projects and carbon exchanges have been established[51]. Only two regulatory programs are currently in place. The Regional Greenhouse Gas Initiative (www.rggi.org) in the Northeast plans to limit power plant emissions by 10% between 2009 and 2018. Its carbon emission credits have averaged $1.98/t CO_2. The California Air Resources Board started its carbon offset program in 2012, designed to reduce emissions from a broad range of industries to 1990 levels by 2020[52] (agriculture remains a voluntary-reduction program). Initial carbon allowances were auctioned at an average of $15.60/t CO_2 while 2015 allowances were auctioned at $11.07[53].

In the US, approved sequestration projects for agricultural activities currently include methane capture from manure facilities, reforestation, reduction of nitrogen fertilizer use, and rice farm water management. Previous practices (from the now-dormant Chicago Climate Exchange) included no-till cropping, alfalfa seeding, grass seeding on cropland, improved management on rangeland, tree planting, and methane digesters.

Acceptable practices are limited by these criteria: additional, measurable, verifiable, and permanent[54].

Ecosytem Services

Carbon sequestration in soils provides numerous other benefits in addition to offsetting carbon emissions and reducing atmospheric carbon dioxide concentration. These are truly win-win benefits[8]: the practices and results of capturing carbon in the soil improve air quality, water quality, soil quality, and biological diversity while making terrestrial ecosystems more resilient to the damaging impacts of global warming. Perhaps the most important effect is the increased ability of agricultural systems to continue to produce food for human use.

These co-benefits include[80]:

(i) improved quality of soil and water resources,
(ii) decreased nutrient losses from ecosystems,
(iii) reduced soil erosion,
(iv) better wildlife habitat,
(v) increased water conservation,
(vi) restored degraded soils, and
(vii) increased use efficiency of inputs.

These benefits come about through the physical and chemical attributes of soil organic matter, as well as the agricultural practices that enhance sequestration. Practices that add residue to the soil surface mitigate temperature extremes, reduce evaporation of soil moisture, minimize soil and chemical runoff, and allow water infiltration to occur. Practices that vary the cropping sequence or add grasses put roots into varied depths of soil. These roots add organic matter and pores when they die and provide food, oxygen and water to the decomposition microbes.

Soil organic matter adds bulk and pore space to the soil, allowing air and water easy movement into and out of the soil. Fungal decomposition of this organic matter creates glomalin, a major glue for holding soil particles together, reducing erosion and maintaining pore spaces, while also providing food for soil microbes[81].

Crop yields appear to increase on all soils as soil organic carbon levels improve[80].

Cover crop use is generally low across the US[82, 83], averaging 10% of farmers raising major crop species. Organic farmers are an exception, using cover crops at twice or more of that rate[83]. Vegetable farmers are another exception: 69% of western New York vegetable farmers reported experience with cover crops[84]. Farmers cite a number of obstacles to using cover crops[72]: seed and seeding incurs costs; late or wet spring weather may inhibit killing or incorporating winter cover crops; some species are difficult to kill and may compete with the subsequent cash crop; soils may be cooler or wetter in springtime under cover crops; establishment time is lacking after a main crop; planting is difficult through residue, etc. Cover crops use water, and where water is limiting, yield of subsequent crops can be reduced[85]. In addition, use of cover crops over an entire growing season to enhance soil fertility obviously displaces yield and income from cash crops[72].

Cover crops can also affect yield of the primary cash crop. With proper timing and choice of species, yield may be unaffected or may increase due to soil effects[72]. However, some studies have shown yield declines following cover crops[86]. Resource, cost and yield considerations all affect choice or use of cover crops.

Organic Farming Systems

"Organic" farming systems are characterized by limitations on allowable crop inputs and by emphasis on practices intended to improve soil quality[87]. Use of the "organic" label in the US is regulated by the USDA National Organic Program[8]8, which enforces these limitations, such as prohibition of synthetic nitrogen fertilizer and synthetic pesticides. Practices to improve soil quality are often those recommended to reduce greenhouse gas impacts of agriculture, such as surface mulching, continuous cropping, cover cropping, legumes in rotation, and manure application[70]. While these practices are not limited to organic production (and some farmers apply these practices without certifying as "organic"), their use is less common in conventional production systems, either singly or in combination[89].

Many ecosystem benefits are often attributed to organic systems. Such benefits include reduced nitrogen losses, enhanced biological diversity, improved support for pollinators, and improved soil health[90].

Research into the expected soil carbon and greenhouse gas benefits of organic crop production systems has produced mixed results. For example, some studies have found increased soil carbon under organic management[96, 97, 98]; a later review concluded that many studies had insufficiently accounted for manure inputs and were invalid comparisons[99]; another partially refuted that study, finding inherently higher carbon levels in organic farming systems, but concluded that very few adequate studies comparing organic to conventional systems have yet been conducted100.

However, organic systems could use up to 20% less total energy than conventional farming systems[101], largely as a result of fertilizer differences[102]. Use of manure and legume-based fertilization in organic systems represents less energy use than synthetic nitrogen fertilizer production, delivery and application in conventional farming systems. While organic systems frequently use cultivation for weed control, energy use for tractor fuel represents a very small fraction of total farm energy use on both organic and conventional farms[101]. Despite probable energy savings, greenhouse gas emissions related to organic crop production range from no difference to 25% less than conventional practices[101, 102].

Conclusions about organic systems' energy usage and greenhouse gas production are also debated when compared by acre or amount of crop. Organic crops are generally recognized as producing from 5 to 20% fewer bushels or pounds per acre than conventional crop and livestock systems, depending on the crop[103]. This can result in higher greenhouse gas emissions totals per bushel for organic systems. A counterargument holds that a disparity in research attention between organic and conventional systems limits knowledge of "best" organic practices in research trials. For example, when crop varieties are designed for specific organic systems, yield increases of 8 to 15% over varieties used in conventional production have been found[104].

While no-till farming has increased among conventional farmers in much of the country, those who choose certified organic practices usually avoid no-till, and in fact are barred from using the synthetic herbicides associated with conventional no-till methods. However, research into 'no-chem' or organic no-till is identifying methods of using cover crops to achieve similar reductions in tillage to reduce erosion risk and to cut fuel use for cultivation[105].

Practices in Combination

Numerous farming practices affect soil carbon capture and release (Table 1). These practices can be combined to reduce carbon dioxide emissions and to increase soil carbon sequestration[95, 107]. For example, in Michigan, minimum tillage captured carbon belowground while legume-rotation both captured carbon and offset carbon dioxide loss from lime application[108].

Production/Grazing Practice Changes	t CO_2eq/ ac/yr
Grazing Management	1.1 - 4.8
Use of Manure/Byproducts on Pasture	0..07 - 1.8
Pastureland Management	0.04 - 1.8
Reduced/Conservation Tillage	0.3 - 0.7
Rangeland Management	0.02 - 0.06
Improved Roations, Cover Crops, Elimination of Summer Fallow	0.2 - 0.4
Improved Irrigation Management	0.2
Improved Fertilizer Management	0.1 - 0.2

Table 1. Carbon Sequestration Potential of Agricultural Practices
The net capture and release of all greenhouse gases of varying potencies is expressed as CO_2- equivalents (metric tons CO_2-equivalent per acre per year). (Data from Lewandrowski et al. 2004[92] in Johnson et al. 2009[106].)

Planting Former Farmland to Grass under Long-term Conservation Reserve Program Contracts

The general trend for soil carbon content is for more carbon to be captured under grasslands than in crop fields. Planting grass on cropped land is therefore a recommended practice for carbon sequestration[38].

Conservation Reserve Program (CRP) grass plantings are a special instance of grass planting in which highly erodible or other sensitive crop fields are placed in extended grass cover (or occasionally in tree cover)[109]. These Federal contracts prescribe limited vegetative disturbance (e.g. mowing, grazing or burning) for 10 to 15 years.

Former croplands planted to grass may sequester carbon at rapid rates during the first few years[75] but eventually approach saturation or equilibrium near the level of untilled native grassland. The recovery period has ranged from 12 to 50 years[110, 111] under typical, limited management under CRP contracts.

Soil carbon can be managed on cropland converted to grassland. CRP plantings, for example, with more productive grass species and "management for high production" yielded greater soil carbon gains[38] in the eastern Great Plains. Diverse plantings, including the addition of legumes to the CRP seeding mix, can sequester even more carbon[112, 113]. However, when CRP fields are returned to crop production, carbon accumulated during the contract years is generally lost rapidly[114], particularly under conventional tillage.

Management with periodic harvest (grazing, mowing) has been shown to increase carbon sequestration. Grazed compared to ungrazed sites had more live roots and greater root biomass[115, 116], but carefully managed harvest is needed to protect against erosion and wildlife habitat loss[117, 118].

Biomass Energy

Biomass materials (crop residues, bioenergy crops, etc) from agricultural lands have the potential to be burned or gasified to produce carbon-neutral energy since their carbon content derives from current cycles, not fossil carbon flows. Proposals to harvest biomass would collect and remove residues such as corn stover and wheat straw or would harvest dedicated biomass crops for consumption at centralized facilities. However, export of residues can leave soils vulnerable to erosion and deplete soil carbon stocks, or have other adverse agronomic effects such as reduced water infiltration, increased soil temperature, or loss of crop nutrients. In addition, the specific practices in production, transport and processing of biomass may significantly affect the greenhouse gas balance of the resulting energy supplies[119].

Soil conservation regulations currently address protection against wind and water erosion on farmland[120]. A substantial amount of each year's residue is required for erosion protection for tillage systems (Table 2), particularly for sloping or erodible soils. Many crops, such as soybeans, sunflowers, dry beans, sugar beets, etc. may not provide enough residue for erosion protection even if all residue is retained. Even heavy residue no-till corn[123] or wheat[124] systems may need to retain at least 75% of annual residues for erosion control.

If soil carbon levels are to be maintained, additional residue beyond that required for erosion protection is advised:

- Low residue crops in Colorado don't produce enough plant material to maintain soil carbon levels[125];
- 25% residue removal is the suggested limit for 160-bushel no-till corn in Ohio[123];
- 0% removal is recommended for corn-soybean rotations under tillage with less than 270 bu/ac corn yield[121].

Crop biomass production, amount of tillage, soil type, and field slope are major factors affecting residue-harvest limits on soil carbon protection.

Residue needed to protect soil (t/ac)

Crop Sequence	Tillage	Wind	Water	Soil Carbon
Corn-Corn	Plow	0.77	1.39	3.38
	No-till	0.08	0.29	2.34
Corn-Soybean	Plow	1.22	3.56	5.56
	No-till	0.07	0.43	3.52

Table 2. Amount of Standing Crop Biomass (tons/ac) Needed to Protect Soil Resources
These quantities of residues limit wind or water erosion to the "T" rate (equal to soil formation) and maintain the soil carbon content (from Johnson et al. 2006[121] and Wilhelm et al. 2007[122].)

If an increase in soil carbon levels were desired, additional residue would need to be retained on the field. Adding conservation practices to biomass crop management, such as cover crops[126], could mitigate loss of residue due to biomass crop harvest.

While the energy balance (amount of energy used compared to energy produced) of corn-based and cellulosic ethanol is now widely accepted as positive[127], the decision to remove potential biomass feedstocks has environmental impacts beyond energy and carbon: erosion, water quality, wildlife habitat, soil fertility, etc.[128]. Biomass harvest from perennial crops, particularly grasses, is more likely to result in soil carbon accumulation[129] due to more effective use of the full growing season, greater root biomass, lack of tillage, and reduced opportunity for erosive loss of soil.

Adding Charcoal to Soil

Charcoal is a long-lived form of organic carbon found in many soils, with longevity in the soil of tens to thousands of years[130]. Controlled charcoal formation may be a means to sequester larger amounts of carbon for longer terms than most other biological means; for example, open-air burning retains 3% of initial carbon, plant decomposition retains 10-20%, while controlled charcoal production can retain up to 50%[131]. Its presence in the soil may

also reduce emissions of methane and nitrous oxide, although research results are limited[132].

Known variously as biochar, black carbon, pyrogenic carbon, or terra preta ("black earth" in reference to dark Amazonian soils formed under prehistoric human influence), charcoal can also improve soil fertility and crop production. It has been a commercial soil amendment in Japan for decades[133]. Charcoal has high pore space and permeability, and increases the exchange capacity of the soil, resulting in both higher nutrient adsorption and nutrient release capability for plant use[134].

Source materials and heating technique affect the chemical and physical composition of the charcoal, making it possible to control its final properties[104]. Little long-term research has been completed on these variations, however, leaving charcoal's efficacy as a soil amendment still in question. For example, it may be ineffective in soils high in organic matter[135].

Production of charcoal yields both carbon and combustible gases or oils. The pyrolosis process of heating organic material at low oxygen levels produces 35% charcoal and 65% biogas/oil at 350 to 500 degrees F, and 80% biogas/oil with 10% charcoal at higher temperatures[132]. The biogas released in charcoal formation can be captured and used as a fuel source, typically for heating.

Effects of Farming Practices on Nitrous Oxide Emissions

Nitrous oxide (N_2O) accounts for 4.5% of human-caused greenhouse gas emissions in the US. Agriculture contributes nearly three-quarters of US nitrous oxide emissions, primarily from fertilizers and manure management (Figure 3). These nitrogen sources fuel natural microbial reactions in the soil[136] that can emit N_2O.

Nitrogen application as crop fertilizer nearly always results in nitrous oxide emissions, at an average rate of 1.00% of the applied amount for all nitrogen sources[137]. However, the emission rate can be several times that amount where anaerobic conditions occur due to saturated or compacted soils[17]. In addition, higher application rates yield higher emissions[17] and application at rates greater than plant needs can double the emissions from cornfields[138]. Since N_2O has a high greenhouse gas effect (298 times that of CO_2), these N_2O emissions can easily negate any gains in soil carbon from increased plant mass, unless fertilizer is carefully managed[17].

Fertilizer sources vary in emissions of N_2O.Inorganic nitrogen and liquid manure emit higher levels of N_2O than solid manure while legume-based fertility systems emit least[17]. In addition to N_2O emission from fertilizer application, production of ammonia fertilizer emits substantial amounts of carbon dioxide (1.2 metric tons CO_2 per ton of ammonia, for the roughly 20 million metric tons of ammonia used in the US in 2007)[139]. This amount of CO_2 can equal 30 to 100% of annual carbon sequestered under crops such as corn and soybeans[10]. Making efficient use of nitrogen fertilizer is therefore beneficial to carbon management in addition to its economic importance.

A more efficient use of nitrogen meets crop demands, increases crop growth and yield, and leaves less nitrogen to be lost as N_2O or as a surface or groundwater pollutant. Nitrogen use efficiency is a measure that represents the effective conversion of soil nitrogen into crop plants, specifically into harvested yield. Application of fertilizer nitrogen sources, whether synthetic nitrogen or manure, can be targeted to times and locations where crops can use them. These techniques include banding applications to the crop row, spring rather than fall application, multiple application times, injection rather than surface application, etc[34].

Nitrous oxide can be released any time soil conditions are suitable for microbial activity. Significant emissions occur during freeze-thaw cycles[141]. The nitrogen-emissions pathways may favor N20 over nitrogen gas (N_2) emissions at low temperatures[142], which suggests that fall or winter application of nitrogen fertilizer and manure may result in greater N_2O emissions than applications during other seasons.

Tillage methods have variable effects on nitrous oxide emissions. Comparison of no-till practices and inversion tillage found that nitrous oxide was generally less with no-till use in dry (aerated) soils but higher in wet soils[143].

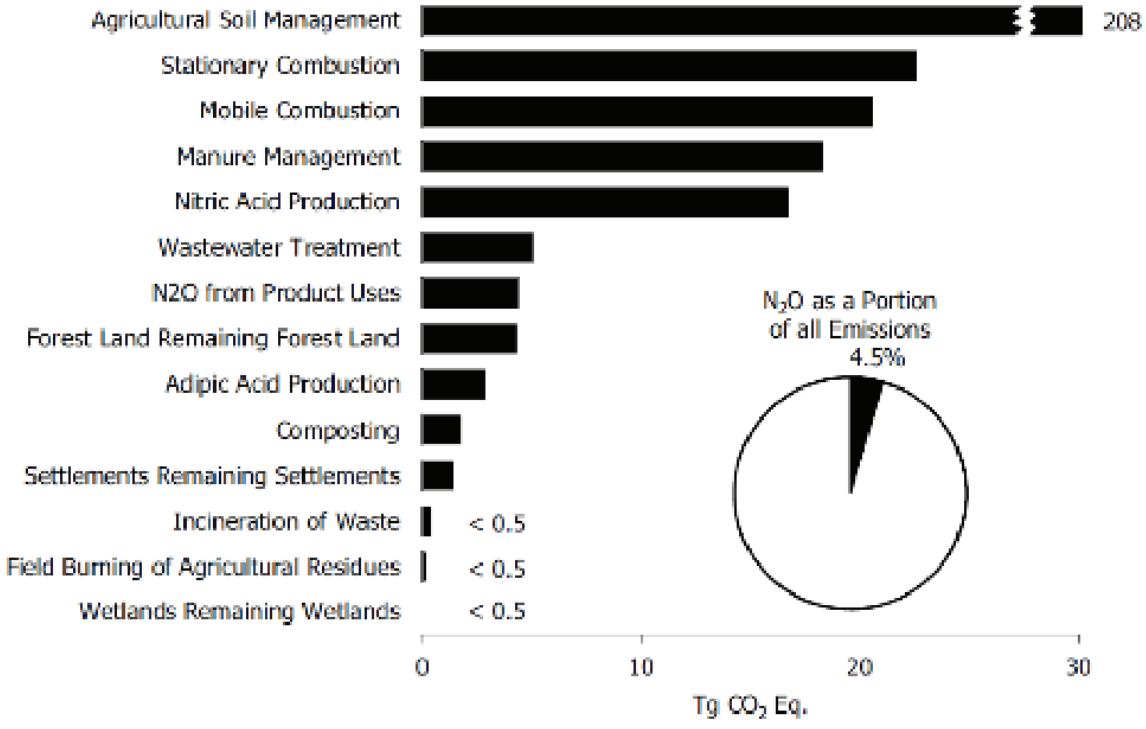


Figure 3.
2010 sources of nitrous oxide (N_2O) in the US.

Agriculture contributes nearly three-quarters of US N_2O emissions through fertilizers and manure management (from US EPA 2012[9]).



As mentioned earlier, manure from confined livestock operations is largely handled in liquid form. Slurry systems (pit storage) limit manure exposure to the air to reduce nitrogen losses. This liquid manure is annually applied to the land, usually by injecting it into the soil to retain its value as nitrogen fertilizer. This process also limits nitrous oxide losses to the atmosphere.

In contrast, anaerobic (oxygen-limited) "lagoon" systems are open-air storage to encourage evaporation, settling of manure solids, and microbial digestion of carbonaceous material, resulting in substantial loss of nitrogen to the air as ammonia. The liquids are eventually sprayed or spread on farmland in ways that also increase evaporation losses and limit nitrogen application to the ground[144]. The remaining solids may be applied to crop fields every 15 to 25 years with little additional nitrogen loss.

Both the storage and application from anaerobic lagoons result in high nitrogen emissions, primarily as gaseous nitrogen (N_2) and ammonia (NH_3), rather than as nitrous oxide[145]. However, nitrous oxide emissions may be high in soils where lagoon liquids are applied.

There seems to be a trend away from spraying manure liquids and toward injecting manure slurry as a soil amendment, due to demand for lower cost fertilizer and to more stringent environmental regulations[144].

Liquid manure contains water-soluble carbon compounds that are readily decomposed by denitrifying bacteria. Most nitrous oxide emissions from applied slurry occur within a few days, in conjunction with increased carbon dioxide emissions[146]. Liquid manure application for crop fertilization should therefore occur at rates and times that can be immediately used by crops[147].

Solid forms of stored manure (including compost) emit less N_20 than liquid forms. Solid forms contain less soluble carbon[145], so nitrous oxide production is one-half the level of liquid manure[17]. Manure from livestock on pasture is also in solid form and emits nitrous oxide at low rates[140].

Effects of Farming & Ranching Practices on Methane Emissions

Methane (CH_4) emissions account for about 15% of the global greenhouse gas impact, compared to the 60% attributed to carbon dioxide[148]. US EPA (2012)[9] estimates that 32% of US methane emissions, the largest single source, are due to livestock (Figure 4).

Agricultural methane is produced by bacteria under oxygen-limited conditions in wet soils, the rumens of cattle, sheep, goats, etc. ("enteric" methane) and from stored manure from all classes of livestock[16].

Ruminant livestock can eat feeds not suitable for human consumption, often from lands not suitable for tillage agriculture. Enteric (intestinal) methane production is associated with digestion of these coarse plant materials and emission of methane in the breath or via flatulence. Additional processes affect methane emission from manure management.

Management of feeds for livestock both in confinement and on pasture can reduce enteric methane emissions[16, 149]. Cattle produce less methane on high energy diets such as corn compared to lower energy feeds such as barley or forages[150]. Feed additives such as ionophore antimicrobials or sunflower oil can reduce methane production by 11 - 22%[151, 152].

Extensive (grazing-based) livestock operations lack the ability or finances to replace grazed forages with high energy concentrates or feed additives. Grazing management that reduces the fiber content of forages, such as addition of legumes to the pasture[153], and short duration, low frequency grazing cycles can reduce methane emission by over 20%[154]. Such techniques to improve management and quality of grazed lands can enhance livestock growth and weight gains, reducing the time-to-slaughter of livestock, and thereby reducing lifetime methane emissions for those animals[155].

As US livestock operations have grown in size, confinement facilities that flush manure with water have become more common[9]. As described under **Nitrous Oxide**, these systems are either limited (deep pit, slurry) or full atmospheric (lagoon) exposure, but both limit aeration of the material, creating suitable conditions for methane production.

Lagoon systems emit roughly twice the amount of methane as deep pit systems (Figure 5). Deep pits are managed to retain nutrients for use as crop fertilizer and are emptied at least annually,

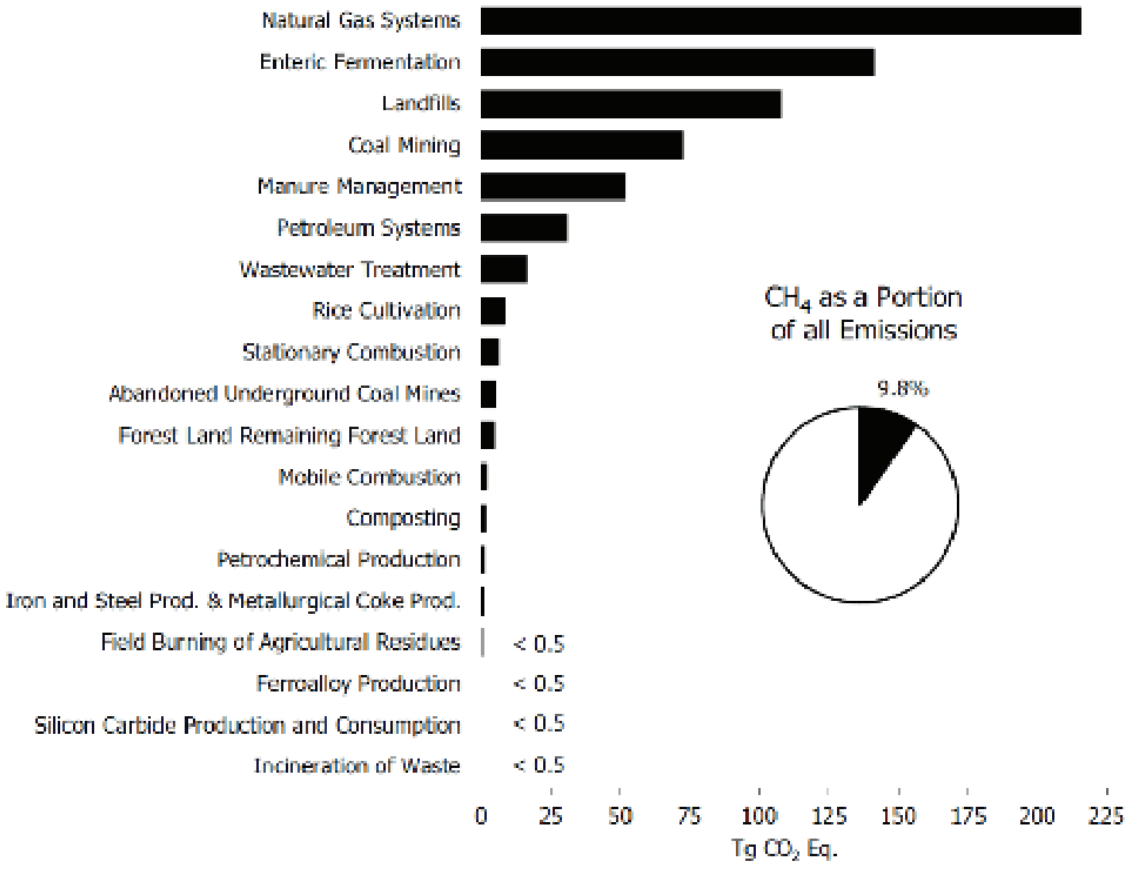


Figure 4. 2010 sources of methane emissions in the US.

One-third of US methane emissions are due to agriculture, primarily from enteric fermentation (ruminant livestock) and manure management (from US EPA 2012[9]).

while lagoon solids may be removed every 15 to 25 years.

Stored liquid manure contains a high content of methane for both hogs and cattle, with hog manure emitting a higher amount[157].

Lagoon systems result in such high emissions of methane that US EPA[158] encourages the use of "methane digester" technology to capture and burn methane, either to produce supplemental electricity or as "flaring" that results in carbon dioxide release (with less greenhouse effect than methane).

Solid manure packs, such as those in deep-bedded confinement dairy operations, can also emit methane due to the anaerobic conditions in the manure pack. In contrast, "compost dairy barns" (while not actually forming compost[159]) and deep-bedded hog barns aerate the manure pack and maintain aerobic conditions throughout the pack, reducing the amount of methane production. In the former, daily tillage adds air, while in the latter, hogs root or dig through the surface layers.

Controlled composting of manure similarly maintains aerobic conditions that reduce methane production by 50 to 100%[160, 161].

Manure deposited in pasture and range conditions is nearly completely aerobic (oxygen-available) and produces little methane – at most one-tenth the amount of liquid systems[148, 156].

Some soil bacteria digest methane. Grasslands often absorb methane, although the net amount is small[45]. Tilled soils absorb methane intermittently; they absorb less when subjected to inorganic fertilizer applications[162].

Soils with high water tables or seasonal flooding are natural sources of methane as soil pores are filled with water instead of air. Decomposition of organic matter in such anaerobic conditions emits methane. Rice farming typically creates ponded conditions favorable to methane production[163], but contributes a small portion of US methane emissions.

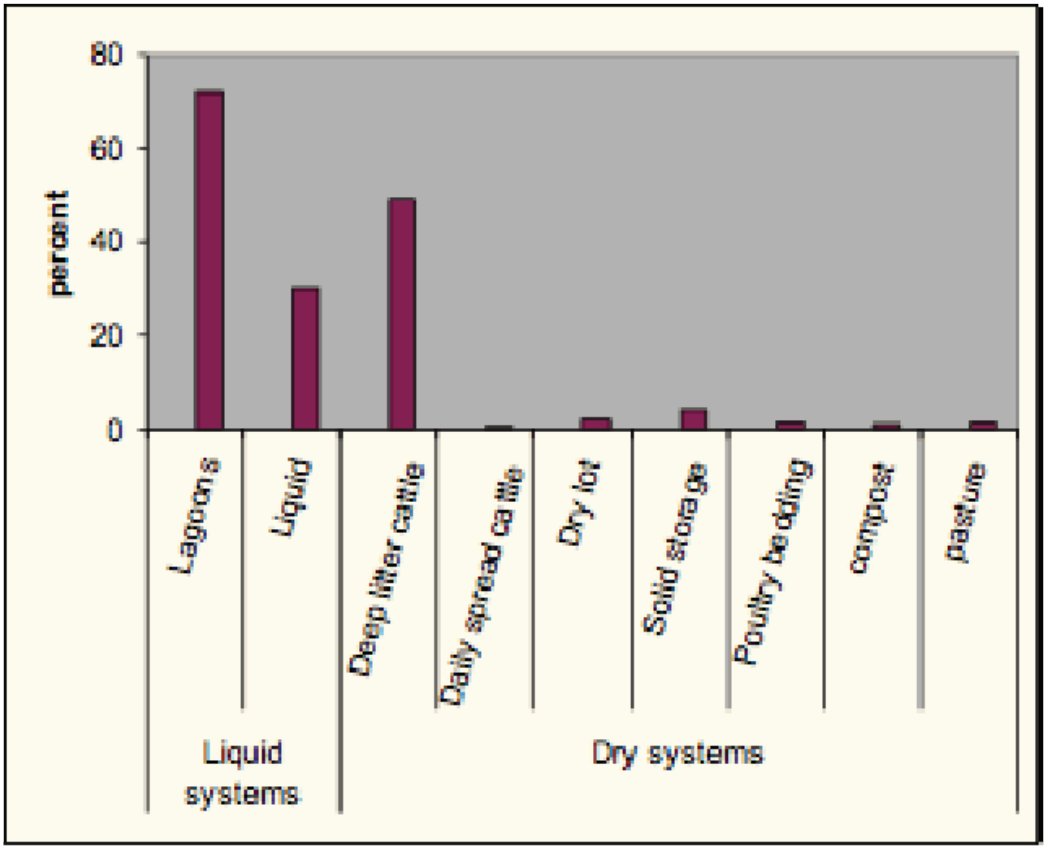


Figure 5.
Methane emission potential (percent of initial content) for manure management systems, Midwest and Great Plains.

Methane emission (volatilization) varies with residence time and temperature (e.g. lagoons emit 9% more methane in TX than ND) (data from EPA 2009c[156]).

Policy Implications & Recommendations

Rationalize Soil Carbon Credits with broader conservation policies

Ensuring that carbon credits complement, rather than detract from conservation objectives is critical to the long-term productivity of agriculture and the protection of water, wildlife and other environmental assets.

It is important to allow producers to receive conservation payments and carbon credits on the same practice – often called "stacking" credits. That would enable conservation programs to pull producers seeking carbon credits in directions that also enhance water quality and wildlife habitat.

In addition, USDA and EPA should be explicitly directed by statute to deny payment of carbon credits on any practice proved to have significant adverse affects on wildlife or water quality.

Prioritize research on soil carbon sequestration

The Department of Agriculture should make it a high priority to invest in research to improve the scientific understanding of carbon sequestration and use that knowledge to broaden and fine tune the carbon trading protocols.

This must be done to create the knowledge to develop a broader and more accurate protocol for soil carbon sequestration. As reported above, current protocols ignore some practices that sequester carbon and reward others of uncertain contribution to sequestration.

The first attempts at payments for agricultural carbon offsets after 2000 included only a few practices: continuous no-till, strip-till, multi-year plantings of grass or legume forages, methane capture, tree plantings, and grazing management to improve rangeland. Since the Chicago Climate Exchange ended its program in 2010, the list of practices approved by the remaining carbon markets shrank still further to include only fertilizer reduction, rice water management, tree planting and methane capture. These programs omit practices proven to improve carbon sequestration such as cover crops and use of certain crop rotations. Carbon markets' protocols should include a broader range of proven carbon sequestering practices.

Tillage is clearly an important factor in soil carbon sequestration. But the impact of no-till systems on carbon sequestration varies by soil type and conditions. And even in areas generally suited to no-till, the effect of tillage on carbon sequestration deep in the soil profile is not fully understood. For example, eastern Nebraska research found that deep subsoil tillage and surface disking each resulted in more deep soil carbon sequestration than continuous no-till[66]. More research is needed to understand the effects of tillage on carbon sequestration.

There is also a need to refine tillage practices that sequester carbon in farming systems, such as organic systems, that are generally beneficial for carbon sequestration but rely on some tillage for weed control. Organic farmers are among the most attentive to environmental concerns. They would likely be rapid adopters of new tillage practices that enable them to increase carbon sequestration while maintaining organic weed control.

Are there optimal tillage practices to provide weed control in organic systems and move residue deeper in soil, while minimizing the destabilizing effects on soil organic matter? The public agricultural research system, made up of USDA and land grant colleges, should research potential optimal systems.

Carbon credit protocols must secure more permanent benefits

The early attempts at carbon markets involved five-year contracts or similarly short-term timeframes, with the recipient of carbon credits required to maintain practices for the full five years. However, after five years, contract holders were free to end the practice and return the sequestered carbon back to the atmosphere.

It is hard to find much benefit for society in that outcome. The carbon dioxide from the coal burned in an offset trade will be in the atmosphere for the long term. Its offset must be equally long term.

In the case of continuous no-till, it was assumed that most farmers who adopted it would never go back to tillage. However, that may not be a safe assumption. It is not unusual for farmers who adopt "continuous" no-till to disk once every five or more years to deal with pH, nutrient stratification or weed issues. When that happens, much of the carbon sequestered in preceding years by no-till is lost (personal communication, Gary Varvel, USDA ARS, Lincoln, NE).

The Department of Agriculture and Environmental Protection Agency should develop options for a carbon credit easement program. Landowners and buyers would be held responsible for a combination of requirements, such as landowners making legally binding commitments to maintain carbon sequestering practices over the long term, or buyers committing to purchase replacement credits when a credit reaches its time limit.

Ensure carbon credit protocols really provide "additionality"

The existing protocols reward farmers to adopt no-till farming practices that they were already rapidly adopting in many locales prior to carbon credits. "Additionality" – the benefit provided beyond "business as usual"— is a fundamental objective of carbon credits. To offset increased emissions elsewhere, as intended, the credits must induce practices that would not otherwise be implemented.

However, we strongly recommend **against** simply denying credits to those who adopt practices that reduce greenhouse gases early or without the incentive of carbon credits. That would have the perverse effect of placing the most environmentally responsible producers at a competitive disadvantage in land markets. In this undesirable case, the best environmental stewards would be denied the payments received by other farmers, and thus would be placed at a competitive disadvantage in buying and renting land. Thus more land would move into the hands of those willing to adopt environmentally beneficial practices only when explicitly paid. Penalizing early adopters could even encourage land managers to replace carbon sequestering practices with carbon-releasing practices so they too could become eligible for carbon contracts.

A better alternative is to pay past and future adopters, but only for practices that go beyond the norm in carbon sequestration. Paying a farmer to achieve the average level of carbon sequestration on farmed soil will not add the tons of soil carbon needed to offset increased emissions from the coal burners paying for the credits.

This raises some vexing issues with regard to no-till. No-till adoption is exploding— tripling to over 22% of all US farmed acres from 1991 to 2006[164]. On the Canadian Prairies, it increased from less than 10% in 1991 to 50% in 2006[165]. A recent Conservation Tillage Information Center survey found that 45% of crop acres were no-tilled in 43 counties that account for 53% of Nebraska cropland[166].

In recent years, no-till adoption has accelerated as more farmers plant glyphosate resistant crops. Researchers found that use of glyphosate resistant crops "resulted in a large increase in the percentage of growers using no-till and reduced-till systems"[167].

At what point should no-till be considered the standard practice, rather than additional, in regions where it is well adapted and widely adopted? We recommend that USDA and EPA develop guidelines for determining whether a practice is the standard practice in a given area and soil type, or soon to be so, rather than "additional".

Likewise, additionality is called into question by protocols that pay for methane digesters on anaerobic lagoons, particularly newly installed anaerobic lagoons. Anaerobic lagoons are the methane problem. Methane emissions are relatively insignificant when manure is stored in deep pit systems, which are regularly emptied with manure knifed into cropland. Deep bedded systems such as hog hoop houses, where manure is aerated by rooting hogs and applied in solid form to land, also have low methane emissions.

Installing methane digesters on new lagoons gains little added benefits over use of deep pits or deep bedded systems without digesters. In fact, the industry is trending away from anaerobic lagoons due to the increasing economic value of the nitrogen in manure applied to farmland from deep pits and deep bedded systems.

It makes little sense to pay farmers to add methane digesters to new lagoons, if in the absence of the payment, they would use deep pit or deep bedded systems that avoid the problem altogether.

It should be noted that while deep bedded systems for hogs can reduce greenhouse gas emissions compared to anaerobic lagoons, methane emissions appear to be more significant in deep bedded systems for other livestock such as cattle that don't root in the bedding. The absence of rooting allows anaerobic conditions to be created in the bedded system that can release methane.

Design carbon protocols to complement measures that make agriculture more resilient and productive in the face of climate change

Some of the practices that have been demonstrated to sequester carbon also hold promise for enhancing the resiliency of agricultural systems in the face of climate change.

As agriculture strives to meet society's need to sequester carbon, in addition to providing food, fiber and fuel, it will likely face new constraints on productivity from the extreme weather events expected to result from climate change. Policy should encourage approaches that enhance the resiliency of agricultural production systems, as they sequester carbon.

Carbon sequestration, in the form of increased soil organic matter, in and of itself adapts agriculture to extreme weather events by increasing soil water holding capacity. Increased soil organic matter generally enables soil to capture and store more of the precipitation from normal rainfall. That both stores water for subsequent dry periods, and allows soil to absorb more water from heavy downfalls, reducing flooding and soil erosion. Soil carbon also contributes to accumulation of glomalin[81], the glue that holds soil particles together, which increases porosity of the soil while resisting erosion.

Payments for planting grass, for example, should at least allow and perhaps encourage producers to rotate grass over different portions of their farm to improve the water holding capacity of the soils of the entire farm over time. Grass planted and left in one spot would sequester carbon, but not improve the resilience

of soils across the farm to extreme weather events. Thus, rotating grass has a more beneficial effect.

Tree plantings should be allowed and encouraged to be configured as field windbreaks in areas susceptible to drought. Trees in windbreaks reduce moisture requirements and drought stress on the crops in between, by protecting them from stress-inducing winds. At the same time, these trees sequester carbon in wood and roots[168].

In more arid regions of the Great Plains, tall grass windbreaks could serve the same function and, if moved across the farm over time, serve the additional function of enhancing the soil water holding capacity and drought tolerance of the soils of the entire farm[169].

Rationalize policy on carbon sequestration and production of biofuels from cellulose

Recent research suggests that, in many circumstances, it is possible to remove only a modest portion of crop residues while maintaining soil organic matter levels. It would be highly inefficient, and not very sensible, to pay farmers to sequester carbon (through carbon credits) while other policies reward them for reducing soil carbon by removing all crop residue for biofuel production.

Policy should restrict the application of incentives for cellulosic biofuels to only biofuels produced from facilities that acquire feedstock in a manner that does not detract from building soil organic matter. USDA and EPA should establish clear guidelines for how much residue can be harvested under different conditions, without jeopardizing soil organic matter formation.

In most grain cropping systems, it is probably most practical to limit the collection of residues to those which actually pass through the combine. Taking additional residues would involve additional field operations that would likely not be profitable unless a large portion of the remaining residue were harvested.

Policy makers should also support research of the potential for other "win-win" options for sourcing biomass for biofuel production. For example, analysis is needed for different regions of the nation on whether and when biomass could be harvested from Conservation Reserve Program acres, without reducing soil carbon sequestration, damaging bird nesting or winter cover. Periodic harvest may actually increase soil carbon sequestration on land enrolled in the program.

USDA should also explore the feasibility of producing and applying "biochar" (charcoal) as a means of simultaneously sequestering carbon and producing biofuel. Biochar is made by heating biomass to very high temperatures in an anaerobic (oxygen free) condition. It produces a gas that can be captured and used as a fuel (a process also known as wood gasification).

As reported in the preceding review of literature, preliminary research suggests that biochar returned to soil is one of the most stable forms of carbon that has been found. USDA and EPA should examine whether it is feasible to harvest biomass, turn it into charcoal while producing a fuel gas, and then return it to the soil, without adverse impacts on wildlife, water quality or soil productivity.

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