Chapter 4. The Potential of Agricultural Projects and Practices to Reduce Greenhouse Gas Emissions and Increase Carbon Sequestration

Enormous potential exists for farms and ranches in North America to reduce GHG emissions and increase carbon sequestration—potential found everywhere from intensive dairy operations to extensively grazed ranches, from prime cropland to marginally productive wet fields and drought-prone areas. The activities that can reduce emissions on farms range from cutting-edge innovations using biochar pyrolysis and anaerobic methane digesters to simple practices like adjusting crop rotations or setting aside marginal areas for habitat restoration.

The wide scope of climate-beneficial land use activities means that almost every farmer can benefit directly or indirectly from properly crafted incentives for emissions reductions. In some cases, farmers may choose to participate directly in an offsets program, in which case they would go through the necessary steps of monitoring and verifying their reductions, receiving offset credits, and selling the credits like other farm commodities. In other cases, farmers may not be interested in selling offsets but they may implement emissions-reducing activities because they make sense for other reasons, such as enhancing soil productivity or operational efficiency.

To capture the benefits of these activities for GHG mitigation, it is important to ensure a net benefit to the atmosphere. Thus farmers must manage all GHGs associated with their production practices, particularly carbon dioxide, nitrous oxide, and methane. Management choices may decrease some GHG emissions while increasing others, so it is important to look at all the impacts and do a net accounting. For example, managing land to increase soil carbon stocks by increasing plant growth might also increase emissions of N2O—a far more potent greenhouse gas. The cumulative impacts of a set of practices must be evaluated in each situation, as the impact of a suite of management practices on net GHG emissions varies by climate, soil type, and other conditions.

C-AGG intends to catalog these opportunities by producing a series of brief overviews of emission reduction/carbon sequestration practices and project types. These overviews will highlight the potential scope for emissions reductions/carbon sequestration, estimate the benefits and other environmental values to farmers and to society, and identify some of the barriers farmers may face in the near term in implementing these practices and projects. These overviews will be posted on www.C-AGG.com as they become available and C-AGG invites experts and practitioners to comment on them. The initial set of treatments included in this chapter is not intended to be an exhaustive list, but it is meant to be a "living document," with new information and activities added over time.

Cultivation Systems

SOIL MANAGEMENT, COVER CROPS, AND CROP ROTATION

Farmers can safeguard existing soil carbon and promote new accumulation (sequestration) by protecting the reservoir of carbon already in their soils (e.g., by reducing tillage and erosion) and by promoting conditions for the growth of roots and soil microbes (e.g., by using nutrient-retaining cover crops and rotating crops to diversify the demands on soil). Such practices as soil management, cover crops, and crop rotation can both protect and build soil carbon and can reduce the need for inputs, thereby lowering costs and potentially generating revenues from carbon offsets.

- **Soil management** involves several agricultural practices that have been found to increase soil carbon stocks by increasing plant biomass or slowing the rate of soil organic matter decay.[xi] Reducing tillage, using cover crops, changing crop rotations, planting improved crop varieties, and managing fertilizer use are all practices that can contribute to increased soil carbon storage.[xii]

- **Cover crops**, or crops planted during fallow periods, increase biomass production per unit of land, reduce erosion, and can improve soil structure and reduce compaction. Increased biomass makes more organic carbon available to the soil by increasing plant residue, reducing erosion, and slowing plant matter decomposition. These effects also reduce the amount of carbon that is released back into the air as CO2 from the oxidation process, and more biomass is converted to soil organic carbon. Improved soil structure and reduced compaction also improve soil fertility and reduce N2O emissions. Cover crops like hay fix carbon in the soil through their extensive root systems. Leguminous cover crops also replenish nitrogen levels in the soil, acting as a natural fertilizer.
- **Crop rotation** is the practice of sequencing dissimilar types of crops in the same area. The practice protects soil fertility by avoiding the buildup of pathogens and weeds, replenishing nutrients, alleviating compaction, and, in the case of legumes, replenishing nitrogen. Rotating crops helps ensure that nutrients are used efficiently, reducing the need for additional inputs. By reducing the buildup of weeds and pathogens, crop rotation helps farmers use less pesticides, creating a double benefit for the atmosphere: the demand for fossil-fuel-intensive pesticides is reduced, and the vigor of carbon-rich soil microflora is improved.

The quantity of emission reductions from soil management, cover crops, and crop rotation will vary from farm to farm, soil to soil, and region to region. For example, U.S.-based studies show that altering the mix of crops or using cover crops can sequester an additional 0.37–1.1 t CO2e/ha/year.[xiii] Global studies show a slightly larger range of 0.3–1.16 t CO2e/ha/year.[xiv] Long-term (30-year) studies in Ohio have shown an increase of 1.08 t CO2e/ha/year from switching to a high-residue crop rotation (corn-oat-hay vs. corn-soybean).[xv]

It is difficult to cost-effectively quantify with a high degree of accuracy the amount of carbon in any particular field or the amount due to any particular management practice. Direct soil sampling can yield great accuracy, but it is prohibitively expensive. Furthermore, the effect of management is relatively small from year to year. As a result, scientists have difficulty quantifying the effect of changes in management without analyzing many samples of soil from fields. The costs of this analysis can easily outweigh the value of the additional carbon sequestered. Thus there is a scientific challenge to account for the spatial variability of soil carbon in more cost-effective ways than through direct soil sampling.[1]

No protocols currently exist for quantifying emissions or emissions reductions from the use of cover crops or crop rotations specifically. Several research efforts and protocol development processes are now under way in North America to address this challenge, including a draft quantification protocol for reduced summer fallow in Alberta, Canada, and two soil carbon sequestration quantification methodologies currently under peer review. In addition, process-based models are being tested for their ability to accurately quantify carbon sequestration for particular management processes.

TILLAGE MANAGEMENT

When soils are tilled, the decomposition of organic materials and soil organic carbon is accelerated, and a portion of the sequestered

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[1] “Soil carbon content can be accurately measured using modern dry-combustion carbon-nitrogen analyzers, and even older methods (e.g., wet-oxidation) provide acceptable accuracy and precision. Consequently, designing cost-effective sampling schemes is the main challenge in estimating carbon stock changes over larger areas.” K. Paustian et al., Agriculture’s Role in Greenhouse Gas Mitigation (Arlington, VA: Pew Center on Global Climate Change, 2006).

carbon is returned to the atmosphere. Conservation tillage, where the degree of soil disturbance is minimized, can reduce GHG emissions by slowing the decomposition of organic matter compared with conventional tillage. The amount of carbon stored through conservation tillage will depend on the crop type, the agro-climatic region, and the degree to which the tillage management system disturbs the soil.

A considerable number of U.S. farmers have adopted conservation tillage management because of other benefits, such as fuel savings from machinery, reduced labor costs, and increased soil quality. Conservation tillage may also create cost savings by lowering the amount of fertilizer that needs to be applied to achieve the same yield.

The emission reduction potential from conservation tillage per acre of cultivated land varies based on climate, soil, and crop type. According to the USDA's National Agricultural Statistics Service, approximately 320 million acres of land in the United States are current cultivated under principal crops (e.g., corn or soy). Since tillage management practices are most commonly and successfully applied to principal crops, there exists a large technical potential for emissions reductions from reduced tillage management. EPA analysis shows the total agriculture soil carbon sequestration potential to be 168 Tg CO2e per year (or 168 million metric tons of CO2e per year) net emissions below baseline, between the period 2010 to 2110 at a fixed carbon price of $15 per ton.[xvi] Farmers may achieve additional emission reductions from using less fuel and avoiding the emissions of applied soil nitrogen fertilizers.

In North America, two protocols have been developed for the quantification of emission reductions resulting from the implementation of tillage management practices. One, developed in Canada under a collaborative federal-provincial-territorial government process, has been adapted by the Province of Alberta's GHG Emissions Offset System. A second tillage management protocol was developed for the Chicago Climate Exchange, a voluntary and legally binding GHG reduction and trading system in North America.

FERTILIZER MANAGEMENT AND NITROGEN CONTROL

Agricultural use of nitrogen fertilizer plays a dominant role in generating agricultural emissions of nitrous oxide, a gas that is 310 times more potent for global warming than CO2. Excessive use of nitrogen in agricultural systems not only contributes to GHG emissions, it also impairs water quality, reduces biodiversity, and threatens human health.

Emission reduction opportunities in fertilizer usage fall into the following categories:

- Altered quantity of fertilizer applied,
- Altered placement of fertilizer application,
- Altered timing of fertilizer application,
- Altered type of fertilizer,
- Altered crop management practices (e.g., use of cover crops), and
- Management of runoff/leaching and associated indirect emissions.
- Adjusting fertilizer use is among the most cost-effective ways for farmers to reduce emissions of greenhouse gases into the atmosphere.

Because direct field measurement of N2O emissions is prohibitively expensive,[xvii] researchers continue to focus on building process models or simplified defaults based on direct measurement in experimental plots in various locations globally. Though the IPCC has issued guidelines for reporting N2O emissions under national GHG inventories, and EPA has adapted these guidelines for use in preparation of the U.S. inventory, the guidelines are based on highly simplified default data and therefore have not been accepted as a way to measure project-level benefits. Several other methodologies for more accurate model-based estimation of N2O emissions are under development, including the DNDC (de-nitrification and de-composition) model, the Alberta Nitrous Oxide Emission Reduction Protocol, the Winrock-Packard simplified methodology, and the DAYCENT model.

Recently, a protocol for emissions reductions credits from nitrogen fertilizer management for

N2O mitigation in corn production was proposed for use in the U.S. Midwest.[xviii]

BIOCHAR

Biochar, a fine-grained charcoal product made of carbon, can be used as a soil amendment, where it degrades very slowly and holds considerable promise for reducing GHG emissions while enhancing soils and increasing biomass and crop productivity. Biochar is produced by the thermal degradation of biomass (crop or forest biomass, animal manures, or other biomass wastes) in the absence of oxygen, via pyrolysis or gasification. This process effectively condenses carbon into a high-surface area charcoal product that decreases the decay rate of the carbon for millennia, greatly slowing the breakdown and release of carbon back into the atmosphere. Biochar has a mean residence time of 1,000 to 2,000 years in soils,[xix] thus creating "virtually permanent" soil carbon.

Biochar production technologies can be categorized into slow pyrolysis, fast pyrolysis, and gasification, and they may be stationary or mobile. The amount of bioenergy co-produced by biochar production systems will vary with the system and the production parameters, but the optimization of biochar production will reduce the energy co-product, and vice versa. Biochar systems may allow farmers to adjust their production to take advantage of changes in prices of carbon, energy, crop inputs, and biomass, though they may encounter trade-offs between flexibility and efficiency.

In addition to its capacity to reduce GHG emissions, biochar has many ancillary agronomic and environmental benefits. It is more stable than other soil amendments and has been shown to increase nutrient availability beyond a fertilizer effect, potentially making it more efficient at enhancing soil quality than other organic soil amendments.[xx] In preliminary studies, biochar has been shown to reduce nutrient leaching and N2O and methane emissions from soil, to enhance fertilizer-use efficiency, to improve soil nutrient retention and bio-availability of nutrients to plants, and to increase soil moisture retention, crop productivity, soil fertility, and soil structure.[xxi] Biochar production and utilization systems also offer significant waste management opportunities, both on-farm and off. However, biochar has not been thoroughly or systematically studied in all soils and climates, and differences in the pH or nutrient content of some products might make them more advantageous in some soils than in others.

Biochar systems are currently being used in industrial-scale and farm-scale applications, showing demonstrable benefits, including income generation, biochar for land application and/or sale, bioenergy co-production (bio-oils, syngas, thermal energy for on-farm utilization), and agronomic benefits. However, there is a need for continued development of biochar demonstration projects at all scales, including on the farm, to establish better data on all aspects of production and utilization, including data on the economics of various biochar systems.

Emission reductions associated with the carbon sequestration portion of biochar are relatively straightforward. Scientific evidence demonstrates that biochar is a very stable form of organic matter when added to soils, with an estimated mean residence time of 1,000 to 2,000 years.[xxii] However, biochar products have both a labile component and a stable component, and quantification (through testing) of the labile component is necessary to establish the proportion of carbon in the stable fraction of biochar for carbon trading schemes.[xxiii]

The technical global carbon reduction potential of biochar is conservatively estimated to be as high as 1 gigaton per year by 2054 (one "wedge").[xxiv] This estimate includes only the direct carbon reduction benefit of biochar, without accounting for renewable energy production and fossil fuel displacement, increased net primary productivity, or reduced soil N2O or CH4 emissions. Emissions reductions associated with the other climate mitigation aspects of biochar depend on the biochar system and environmental factors, but they can include avoided emissions from conventional use of feedstock biomass, avoided emissions of N2O and CH4 from soils amended with biochar, displaced fertilizer and agricultural inputs, and fossil fuel displacement (from syngas, bio-oils, and/or thermal energy created by biochar production technologies).

Carbon offset accounting methodologies for biochar are currently being considered by the Climate Action Reserve of the California Climate Action Registry and the Climate Trust of Oregon. In addition, a biochar offset accounting methodology has been submitted to the Voluntary Carbon Standard, where it is under review.

CROP RESIDUE AND WASTE MANAGEMENT

Crop residues from the field (e.g., leaves, seed pods, stalks, and stubble) and crop process waste (e.g., husks, seeds, bagasse,[2] and roots) can be managed in ways that reduce GHG emissions.

Management options for crop residue include leaving it on fields, plowing it back into soil, composting and then applying to soils, putting into landfills, or burning it in the field.[xxv] The material can also be used as fuel (feedstock), animal bedding material, supplemental animal feed, or construction material.[xxvi]

Depending on which management practice is used, varying amounts of GHG emissions may be released. Crop residue and other agricultural waste management practices can increase the nitrogen in the soil, thereby increasing the amount available for nitrification and denitrification, eventually resulting in the release of nitrous oxide. Based on its global warming potential, N2O is the dominant GHG released from crop residue.[xxvii]

Other management options include using crop residue as a biomass feedstock for liquid fuel or electricity production or for cellulosic ethanol. Though energy content varies among crop species, cereal crop residues have on average a heating value of 18.6 gigajoules per ton, which is 50% that of coal and 33% that of diesel, and a maximum biofuel energy of 5 exajoules per year.[xxviii]

However, the removal of crop residue can have a deleterious effect on soil quality. Returning crop residues to the soil improves its quality by controlling erosion, maintaining structure, moderating moisture and temperature regimes, providing energy for microbial processes, providing an important source of macro and micronutrients, and conserving organic matter content.[xxix] Conversely, removing crop residues can have negative effects on all these processes with important consequences for both soil health and agricultural productivity,[xxx] and it can transform soils from significant sinks of atmospheric CO2 to large sources.[xxxi] Studies have thus found that only 40% of corn residue can be collected without adverse effects on soil under continuous production[xxxii] and mulch-till[3] conditions, compared with 70% under no-till conditions.[xxxiii]

The United States accounts for 13% of the global 3.8 billion tons of residue produced each year, of which 300 million tons are from cereals,[xxxiv] which is the most usable form of residue. Some 33% of U.S. residues are produced in the Corn Belt and 25% in the Great Plains. For corn alone, over 90% of the 68 million tons of annual corn stover[4] is left in the fields[xxxv] and less than 1% is collected for reprocessing.[xxxvi]

As a whole, agricultural soils were responsible for 261.6 teragrams of CO2e in 2004,[xxxvii] with approximately 4% coming from crop residue.[xxxviii]

The amount of crop residue converted into soil organic carbon is largely dependent on a number of ecological factors, such as temperature, soil moisture content, and soil type, as well as

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[2] Bagasse is the fibrous residue remaining after sugarcane or sorghum stalks are crushed to extract their juices.

[3] Full-width tillage involves one (or more) tillage trip that disturbs the entire soil surface and is done prior to and/or during planting. Tillage tools such as chisels, field cultivators, disks, sweeps, or blades are used. Weed control is accomplished with crop protection products and/or cultivation.

[4] Stover consists of the leaves and stalks of corn (maize), sorghum, or soybean plants that are left in a field after harvest.

management practices that determine the amount and quality of residue left on the land, tillage techniques utilized, and the use of fertilizer, irrigation, and crop type.[xxxix] Some studies have shown that the lignin content of residue is strongly positively associated with soil organic carbon content.[xl]

It has been estimated that the U.S. technical potential of carbon sequestration through residue management on croplands is 22.5 million metric tons of carbon per year.[xli]

The IPCC 2006 guidelines include recommendations on measuring emissions reductions associated with crop residue management. (See http://www.epa.gov/climatechange/emissions/downloads09/Agriculture.pdf.)

IRRIGATED RICE CULTIVATION

Virtually all domestic rice is grown in flooded conditions. This presents unique circumstances for GHG emissions compared with most other agricultural commodities. Anaerobic decomposition, which occurs in flooded fields, generates significant amounts of methane, while aerobic decomposition associated with non-flooded agriculture produces CO2. In 2005, rice emissions were 56 million metric tons of CO2e in the United States (1% of total U.S. agricultural emissions).[xlii]

The literature on emission reduction opportunities associated with flooded rice derives primarily from studies in Asia, which has significantly different cultivation practices than the United States.[xliii] Within the United States, attention on GHG emissions reductions in rice has centered on California. Rice cultivation in the U.S. South entails different practices and growing conditions, and further research is needed before concluding that the experience in Asia or California will translate to that area.

Emissions reduction opportunities in rice include:

- **Altered paddy flooding (timing and duration).** Activities that shift decomposition from anaerobic to aerobic conditions can shift emissions from methane to carbon dioxide. DNDC modeling and experimental results indicate that on certain soil types in California, emission reductions of nearly 1 ton CO2e/acre/year are possible, largely from reductions in methane emissions.[xliv]
- **Residue management**. Practices for removal of postharvest rice straw residue vary by region in the United States but fall into three general categories: burning, anaerobic decomposition (i.e., incorporation of residue and re-flooding fields), and rice straw harvesting. Burning rice straw has air quality side effects and is in decline in some rice production areas, namely California. Anaerobic decomposition of rice straw results in significant CH4 production and a net increase in GHG pollution. Rice straw harvesting can result in a net emissions reduction when it displaces anaerobic decomposition and when the ultimate decomposition of the rice straw produces CO2 rather than CH4.
- **New varieties**. Use of higher-yielding varieties can reduce CH4 emissions compared with lower-yielding varieties.[xlv] Higher-yielding varieties direct more carbon into grain production and therefore leak less into the atmosphere via anaerobic decomposition. Specific quantification of this potential is not yet available.

Direct field measurements of CH4 and N2O emission reductions can be quite expensive, and therefore researchers have focused on building process models based on direct measurement in experimental plots in various locations globally. Quantification methodologies for emissions reductions from rice cultivation are currently based primarily on the DNDC model being developed by the Environmental Defense Fund and the California Rice Commission through a joint project funded by USDA.

Livestock Systems

DAIRY AND INTENSIVE LIVESTOCK OPERATIONS

GHG emissions from the raising of livestock can include emissions associated with enteric fermentation processes in addition to the decomposition of manure, among other sources. Farmers may be able to reduce GHG emissions by focusing on lowering the emissions intensity or improving the efficiencies of retained energy in the feed of livestock.

Emissions intensity is a measure of the amount of greenhouse gases produced by an animal for each unit of production (e.g., gallon of milk, pound of live weight). For ruminants, such as cattle, the emissions with the greatest impact are methane produced through enteric fermentation. These emissions are the by-product of digestion that are exhaled or eructated (belched) by ruminant animals like dairy and beef cattle. One strategy to reduce emissions from cattle is to use feed additives, such as edible oils, ionophores, or distiller's grains, which can inhibit the formation of methane by rumen bacteria. Other methods, such as adjustments to the lifecycle (e.g., moving cattle through the system to slaughter at earlier ages) or reducing the days in the feedlot by increased efficiencies, may also reduce related emissions. Another strategy, where cattle are selected for their net feed intake (i.e., breeding those cattle that gain more weight with similar amounts of feed as their neighbors) is under development in Alberta.[xlvi]

Alternatively, for non-ruminant animals such as swine, manipulations in feed rations or improvements in feeding technologies increase the feed conversion efficiency (FCE) rates for these animals. (FCE is a measure of an animal's efficiency in converting feed mass into increased body mass.) FCE gains decrease the amount of manure that is excreted by a pig, resulting in fewer manure-related emissions from decomposition (i.e., during the spreading of manure on fields).

In addition, other methods that increase feed efficiency or manage emissions related to the production of dairy cattle feed can be implemented. Potential opportunities for efficiency gains can be achieved in the following areas:

- Milk productivity: better genetics or husbandry to achieve equal milk with less feed,
- Diet modification: higher-quality feed or supplements (edible oils or ionophores) to decrease enteric methane per unit feed,
- Replacement rate: fewer non-productive cows, and
- Pasture: avoid emissions associated with processing feed.

A Dairy Management Protocol has been approved in the Alberta Offset System.

In 2007, enteric fermentation and manure management were responsible for 131 million tons and 59 million tons of CO2e emissions, respectively, in the United States.[xlvii] With U.S. cattle and hog inventories of approximately 94 million and 9.6 million heads, respectively, small reductions in emissions associated with each animal could lead to noteworthy reductions overall.

Four protocols have been adapted and developed under the Alberta Offset System in 2007–08, addressing the GHG emission reductions that could be achieved from the following activities:[xlviii]

- Reducing the slaughter age of cattle,
- Reducing the days cattle are on feed,
- Feeding edible oils to cattle, and
- Innovative feeding of swine.

MANURE MANAGEMENT

The decomposition of manure can result in the release of methane, nitrous oxide, ammonia, and carbon dioxide into the atmosphere. A number of factors are responsible for GHG emissions from livestock manure, including the quantity of manure produced, the manure's characteristics, how the manure is managed and stored, and geographic location.[xlix]

Over the past few decades, manure management systems have seen a marked increase in emissions due to a variety of factors, including a shift from small farms that generally use dry manure management systems to larger farmers that tend to use liquid systems (usually in the form of open lagoons). In traditional management systems, the manure was deposited in pastures or corrals and subsequently collected and applied as a fertilizer to croplands, thus allowing it to decompose aerobically or to remain in constant contact with air, which releases very small amounts of methane.[l] However, larger dairy and swine farms—which have become more common over the past two decades—often use liquid manure management systems that use water to flush the alleyways or pits where the manure is deposited.[li] In these liquid or "slurry" systems, the manure is then collected and stored in concrete tanks or lagoons until it can be applied to cropland through irrigation methods. This process creates optimal conditions for methane production, since the manure is stored is a water-based environment with high level of nutrients for bacterial growth.[lii] Methane production is especially prominent in dairy and pig farms, whereas beef, poultry, and other livestock farms do not generally use liquid manure systems.

Anaerobic manure digesters offer significant GHG emissions abatement potential. Manure digesters are specially designed insulated tanks that are used to facilitate the anaerobic digestion process under a controlled atmosphere. These tanks decompose the manure in a controlled environment, recover the methane produced (known as biogas), and either combust it or capture it and use it as an energy source. A variety of anaerobic digestion technologies are available.

Rising fuel costs and growing concerns about the environment have increased recent interest in biogas as a potential renewable fuel source to displace fossil fuels in heat and electricity production. As such, the anaerobic treatment of agricultural wastes, including manure and crop residues, presents an opportunity to reduce methane emissions associated with the decomposition of organic matter, in addition to reducing emissions from the combustion of fossil fuels in the generation of heat and electrical energy. The digestate, or solid material, produced as a by-product of anaerobic digestion can also be applied as a fertilizer, displacing fossil-fuel-based chemical fertilizers.

In the United States, livestock produce over 1 billion tons of manure on an annual basis.liii According to a study conducted by the University of Texas, much of this manure is either stored in lagoons or left outdoors to decompose.[liv] The decomposition of animal waste is a large source of U.S. GHG emissions, accounting for approximately 14% of GHG emissions from the agriculture sector between 2005 and 2007.[lv]

As of February 2009, EPA estimated that only 125 farm-scale anaerobic digesters were operating at commercial livestock farms in the United States.[lvi]

Riparian Areas and Wetland Restoration

Wetlands naturally sequester atmospheric carbon and perform other valuable ecological functions. The latest inventory of GHG emissions and sinks for the United States listed prairie wetlands in Conservation and Wetland Reserve Program lands as carbon sinks.[lvii] Restoring wetlands can sequester atmospheric CO2 and mitigate GHGs generated by agriculture, in addition to having other important ancillary benefits, such as enhancing organic stocks of soils to ensure the sustainability of food production, providing habitats critical to the maintenance of biodiversity, retaining surface water to mitigate flooding, and improving water quality in streams and rivers.

With an average net primary productivity of 1,180 grams of carbon per square meter per yearlviii and a surface area of 7–9 million hectares,[lix] wetland ecosystems store more carbon per hectare than any other ecosystem.[lx] The size of the historic wetland carbon sink in the prairie pothole region of North America was recently estimated at 378 million tons CO2e,[lxi] with over half (197 million tons) of the total carbon stores lost to the atmosphere from cultivation of farmed or drained wetlands. An Agriculture–Wetlands GHG Research Initiative, involving multiple benchmark sites in the prairie pothole region of Canada, recently showed that newly restored wetlands were found to sequester 0.86 tons of CO2e per hectare per year.[lxii] In other areas of the United States, the wetland losses and carbon sinks were significantly larger than in the pothole region of the Great Plains.

Agricultural management practices can also affect the carbon sequestration taking place in remaining wetlands. In sediments from eroded soil that migrates to wetlands, organic carbon decomposes and liberates methane, while nitrous oxides from agricultural fertilizers are emitted along wetland margins. Existing carbon sinks in wetlands have and continue to be lost through four primary mechanisms:

- Drainage of wetlands,
- Farming of wetlands,
- Decomposition of historic soil organic materials,
- Application of fertilizers, which increases the emission rates of trace GHGs.

The following management strategies can help farmers reverse the continued deterioration of wetlands and emissions of GHGs from them and can reverse these trends to begin sequestering and rebuilding soils in wetlands:

- **Cease Artificial Drainage of Wetlands and Hydric Soils**. Draining historic wetland soils and exposing deeper soils to the decomposition process can be avoided by farming historic wetlands soils only when they seasonally dry down and by confining the agricultural uses to only those areas that dry down adequately to support agricultural uses. Farming these wetlands will release the stored carbon they accumulated in prior wet periods when they were not farmed. Also, unless protected with grassy buffers, farmed wetlands have the potential to emit large quantities of N2O from their margins and methane from the anoxic portions of the flooded basin.[lxiii] For GHG management, these systems may fare best if not farmed.
- **Reduce Mechanical Disturbance of Soils**. Existing carbon stocks found in the soil can be protected from decomposition and the release of carbon into the atmosphere by reducing the mechanical disturbance of seasonally drained wetland soils by annual tillage (disking, plowing, rototilling, etc.). The use of no-till seeding techniques may, for example, allow for the continued use of seasonally dry wetland soils while minimizing carbon loss.
- **Restore Hydrology of Wetlands**. Restoring degraded wetlands, particularly wetland hydrology, may be the most effective way to influence carbon sequestration in wetlands. In fact, ongoing studies show a general reduction in GHG emissions from most wetland restorations and suggest wetland restoration to be a most important strategy for enhancing carbon sequestration in wetlands.[lxiv] Once hydrology is restored, the water-saturated and waterlogged environment reduces the decomposition potentials and rates annually as plant matter dies back. A very rapid accumulation of plant matter (sequestered carbon) can build up, and in the least affected currently drained wetlands significant levels of lost carbon may be replaceable by hydrological restoration over a decade or so.
- **Buffer Wetlands from Fertilizer and Nutrients**. Wetland buffers can be used to mitigate sediment and nutrient import into wetlands and to curtail the subsequent wetland enrichment process and the release of trace gas emissions (CH4 and N2O). The buffer idea can be extended into the upland drainage areas to retain topsoil, reduce runoff to wetlands in high-gradient areas, and hence reduce sediment and nutrient import into wetlands.
- **Restore the Biodiversity of Wetlands**. Relationships between biotic and hydrogeochemical attributes in healthy wetlands contribute to reduced emissions of trace GHGs. The soil bacteria and fungi, and some plants, have the capacity to use nutrients very effectively, making them less vulnerable to releasing trace gas emissions. Disturbances can reduce their efficiency at removing available nitrogen declines, causing an increase in nitrous oxides, methane, and other trace gases.

Programs such as the Wetland Reserve Program of the Natural Resources Conservation Service, U.S. Fish and Wildlife Services programs for wetland protection and restoration, and numerous ones administered by private organizations (e.g., Ducks Unlimited, The Nature Conservancy, Prairie Enthusiasts, LandKeepers, and farm organizations) can facilitate wetland restoration and management efforts by farmers. However, the costs of monitoring and verification are likely to be high for GHG reductions from wetlands, because trace gas emissions are ephemeral and costly to measure.