

## THE CONTRIBUTION OF SOILS TO CARBON SEQUESTRATION

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### EXECUTIVE SUMMARY

Soils are among the largest pools of carbon and hold great promise for mitigating increasing atmospheric concentrations of carbon dioxide (CO<sub>2</sub>) (Marland et al., 2001) (all references cited in the Executive Summary are found in the reference section of the report). In natural conditions, CO<sub>2</sub> from the atmosphere can be stored in the soil as a solid. When soils are managed to increase carbon uptake, it is commonly referred to as carbon sequestration. Carbon is stored in soils in two forms, as soil organic carbon or soil inorganic carbon. Soil organic carbon forms through plant uptake and decomposition, while soil inorganic carbon forms through mineralization. To take advantage of these natural processes that pull CO<sub>2</sub> from the atmosphere, alternate farming and resource management practices can be employed that increase the carbon stock in biomass and soils. The promotion and implementation of water and land management practices that enhance carbon buildup in biomass and soils include adopting conservation tillage, reducing soil erosion, and minimizing soil disturbance; using buffer strips along waterways; enrolling land in conservation programs; restoring and better managing

wetlands; restoring degraded lands; converting marginal croplands to wetlands or grasslands; eliminating summer fallow (Lal et al., 1999; Paustian and Cole, 1998), using perennial grasses and winter cover crops; and fostering an increase in forests (Peterson et al., 1999).

Carbon accumulation in soils is controlled by ecosystems, climatic conditions, and soil properties. Ideal settings to sequester organic carbon in soil are found in environments that promote minimal soil disturbance (Post et al., 2001; Paustian and Cole, 1998). Low aeration reduces the rate of decomposition, allowing more carbon to amass (Paustian and Cole, 1998); wetland soils and areas of poor drainage are effective in this aspect. Generally, with an increase in rainfall, there is an increase in carbon accumulation, and with a decrease in temperature, there is an increase in carbon accumulation. The growth of perennial grasses also contributes to below-ground carbon buildup (Paustian and Cole, 1998). Of the various ecosystems, wetlands, and forests are unique in that they have the potential for sustainable carbon

accumulation well over 50 years (Paustian and Cole, 1998). By comparison, cropland soil carbon accumulation will peak at about 20 years, while rangelands in North Dakota have the potential of increased carbon uptake for about 10–50 years.

The contribution of soils and biomass to carbon sequestration is unique in that it provides an immediate short-term response, buying time while evolving technologies emerge to address long-term measures (Lal, 2002). Most of the ideal conditions that favor carbon sequestration, such as soil types, climate conditions, and ecosystems, exist in the Plains CO<sub>2</sub> Reduction (PCOR) Partnership region.

PCOR Partnership Phase I work has indicated that the soils and biomass of the PCOR Partnership region can be managed to result in the uptake of significant amounts of carbon in soils. In this setting, the most promising practices with potential to sequester carbon are reduced-tillage management practices on agricultural lands (Leistriz, 2004); conversion of marginal agricultural lands and degraded lands to grasslands, wetlands, and forestlands (Paustian and Cole, 1998); and adoption of advanced grazing systems when favorable conditions exist (Faller, 2004). Furthermore, within the PCOR Partnership region, soil organic carbon and soil inorganic carbon have been observed to accumulate at depths below 50 cm (Cihacek and Ulmer, 2002; Cihacek, 2004). Therefore, the contribution of soil inorganic carbon, along with deep organic carbon sequestration in reducing CO<sub>2</sub> emissions may currently be underestimated for the PCOR Partnership region (Cihacek, 2004).

## **ACKNOWLEDGMENTS**

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## BACKGROUND/INTRODUCTION

As one of seven Regional Carbon Sequestration Partnerships (RCSPs), the Plains CO<sub>2</sub> Reduction (PCOR) Partnership is working to identify cost-effective carbon dioxide (CO<sub>2</sub>) sequestration systems for the Partnership region (Figure 1) and, in future efforts, to facilitate and manage the demonstration and deployment of these technologies. With CO<sub>2</sub> emissions from the PCOR Partnership region in 2001 approximating 13% of the total CO<sub>2</sub> emissions from the United States and Canada, resulting in discharges of 826.32 million metric tons of anthropogenic CO<sub>2</sub> (Jensen et al., 2005), in this phase of the project (Phase I), the PCOR Partnership is characterizing the technical issues, enhancing the public's understanding of CO<sub>2</sub> sequestration, identifying the most promising opportunities for sequestration in the region, and detailing an action plan for the demonstration of regional CO<sub>2</sub> sequestration opportunities.

This report represents an introduction to the topic of soil carbon sequestration. All information provided is derived from published literature and personal communication. The focus is on the potential carbon sequestration opportunity provided by alternative land management practices. Previous investigators have estimated that midwestern U.S. cultivated soils have been depleted of organic carbon by 10–16 metric tons of carbon per acre and that the conversion from natural to cultivated lands has resulted in soil organic carbon (SOC) reductions of  $3 \times 10^9$  metric tons to  $5 \times 10^9$  metric tons (Lal, 2002; Dumanski et al., 1998). In Canada, where nearly 80% of the land farmed is in the prairie provinces of Manitoba, Saskatchewan, and Alberta (Dumanski et al., 1998), similar trends are evident, with organic carbon reduced by 15% to 35% following cultivation.

Soils are among the largest pools of carbon and hold great promise for mitigating the increasing atmospheric concentrations of carbon through expanding soil carbon capture (Marland et al., 2001). Lal (2002) suggests that the present carbon storage of U.S. soils can be increased by 30%–50% in the next 50 years and will prove to be a cost-effective measure while technologies are developed to lessen emissions.

### **The Relationship between Carbon and Soil**

In natural conditions, CO<sub>2</sub> from the atmosphere can be stored in soil as solid forms of carbon, commonly referred to as carbon sequestration. Soil carbon sequestration has two primary mechanisms, direct and indirect. Direct fixation of atmospheric CO<sub>2</sub> in soils (Kimble et al., 2001) involves carbon stored as carbonates or biocarbonates and as inorganic carbon. Among the processes that foster inorganic carbon accumulation in soil are atmospheric CO<sub>2</sub> dissolving in rain water; the dissolution of decomposed organic carbon in the soil solution; dissolved plant system carbon bioproducts, such as carbonates from plant root respiration; and soil carbonate minerals dissolved by acidic soil solutions (Cihacek and Ulmer, 2002).

Indirect fixation of atmospheric CO<sub>2</sub> in soils (Kimble et al., 2001) involves photosynthesis and allows plants to remove CO<sub>2</sub> from the atmosphere and convert it into carbohydrates and oxygen. This process takes place in leaves, with some of the carbohydrates stored in the root system. When the plant dies and decomposes, the carbon enters the soil. It is estimated that, in this way, 20 million metric tons of carbon per year is naturally stored on U.S. farms and grazing land soils (Comis et al., 2001). With improved management practices, it is estimated that an additional 180 million metric tons of carbon sequestration per year could occur in U.S. farms and rangelands. This would offset approximately 12%–14% of total

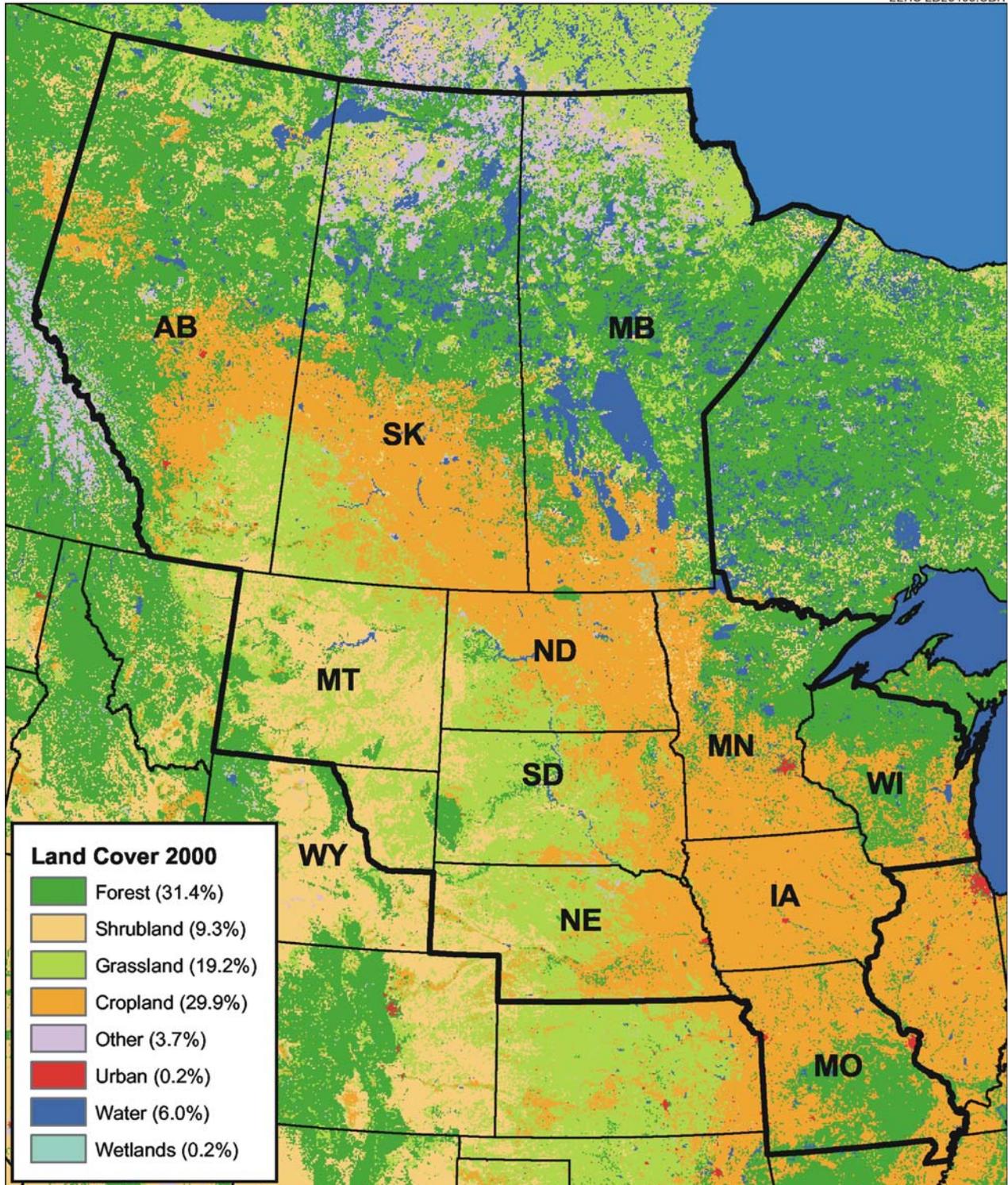


Figure 1. Land cover for the PCOR Partnership region (European Commission Joint Research Centre, 2003).

current U.S. carbon emissions (Comis et al., 2001).

### **Greenhouse Gases**

For targeted emission reductions, the Intergovernmental Panel on Climate Change (IPCC) focuses on six greenhouse gases, CO<sub>2</sub>, methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF<sub>6</sub>) (Environmental Defense, 2004). Within the United States, for 2001, the anthropogenic greenhouse gas emissions reported (million metric tons of carbon equivalents), carbon dioxide from fossil fuel combustion at 82% (1547), other CO<sub>2</sub> contributed 2% (31.7), methane contributed 9% (175.8), N<sub>2</sub>O accounted for 5% (97.5), and HFCs, PFCs, and SF<sub>6</sub> represented 2% (31.4) (National Energy Information Center, 2004).

While produced in lesser quantities than CO<sub>2</sub>, the additional greenhouse gases mentioned above are of importance because of their long duration in the atmosphere, coupled with their powerful infrared absorption characteristics that make them more potent than CO<sub>2</sub>. For example, the heat-trapping ability of CH<sub>4</sub> and N<sub>2</sub>O are regarded as 21 times and 310 times as potent as CO<sub>2</sub>, respectively. As a result, if these greenhouse gas emissions are not also offset, benefits gained through carbon dioxide-reduced emissions, and gains through trading carbon credits, will be lost (Miller et al., 2004).

Both N<sub>2</sub>O and CH<sub>4</sub> emissions occur from industrial- and agricultural-related activities. Agricultural nitrogen sources are typically from biological nitrogen fixation, dung and urine, effluent and slurry, and fertilizer manure, with gaseous nitrogen losses occurring as N<sub>2</sub>O, nitrogen oxides, and ammonia volatilization (Manaaki Whenua – Landcare Research, 2005). The IPCC uses a general ratio (1.25:100) for

N<sub>2</sub>O emission from soil: soil nitrogen input (Miller et al., 2004).

Nonindustrial CH<sub>4</sub> releases occur through rumination from cattle, rice production, and the decomposition of organic waste such as in wetlands. Vast amounts of CH<sub>4</sub> are also produced by termites and as gases released from the sea floor (Manaaki Whenua – Landcare Research, 2005).

Significant contributions of CH<sub>4</sub> and N<sub>2</sub>O are created by bacteria in soils and wetlands (Energy Information Administration, 1994). Key factors influencing the soil atmosphere N<sub>2</sub>O and CH<sub>4</sub> flux in ecosystems are water, nitrogen, oxygen, and the dynamics of the ecosystem. As with CO<sub>2</sub>, offsetting N<sub>2</sub>O and CH<sub>4</sub> emissions is dependent on management practices and tends to be quite variable with time (Liebig et al., 2005).

Generally, with wetter soils, there is an increase in N<sub>2</sub>O emissions. Liebig et al. (2005) indicated that irrigated cropland emitted more N<sub>2</sub>O, 7.5–10.0 grams of nitrogen acre per day (g N ac<sup>-1</sup>d<sup>-1</sup>) in the case of corn from Colorado, compared to nonirrigated cropland, that emits approximately 2.0 g N ac<sup>-1</sup>d<sup>-1</sup>. Added soil wetness attributed to spring thaw, showed 16–60% of released N<sub>2</sub>O from the Parkland region, Alberta. And in western Nebraska, the N<sub>2</sub>O emissions increased by a factor of 5, when the soil surface of winter wheat was wetted (Liebig et al., 2005).

There is a relationship between soil carbon and nitrogen as indicated by the fact that nitrogen, as a fertilizer tends to increase biomass and SOC. Quantitatively, there is an 8–10:1 carbon:nitrogen ratio, so that as 8–10 metric tons of carbon (mTC) is sequestered, 1 metric ton of nitrogen (mTN) is also tied up in the soil. This depletes nitrogen for crop availability (Miller et al., 2004).

Regarding CH<sub>4</sub>, although limited research exists, there are studies that show dryland cropping systems sequestering CH<sub>4</sub> at a rate of  $1.5 \pm 0.9 \text{ g C ac}^{-1}\text{d}^{-1}$ . Both rangelands and nonirrigated croplands are presumed to act as sinks for CH<sub>4</sub>. However, the application of nitrogen fertilization generally reduced soil carbon uptake on the order of  $0.1 \pm 0.2 \text{ g C ac}^{-1}\text{d}^{-1}$  (Liebig, 2005).

Clearly, additional research is needed to fully understand the N<sub>2</sub>O and CH<sub>4</sub> flux in the extensive PCOR Partnership region. However, future research through the PCOR Partnership Phase II work will quantify N<sub>2</sub>O and CH<sub>4</sub> flux in wetlands and study how this is affected by land use in the Prairie Pothole Region (PPR) (PCOR Partnership, 2005).

#### **Terrestrial-Based Approaches Used to Reduce Atmospheric Carbon**

Presently, there are two primary terrestrial-based approaches used to reduce atmospheric carbon. One approach is to reduce net carbon emissions to the atmosphere that result from farming operations, such as machinery use and heating and drying of crops (Paustian and Cole, 1998), and to minimize the agricultural use of fossil fuels by substituting biofuel. The other approach, which is the focus of this paper, removes CO<sub>2</sub> from the atmosphere by increasing the carbon stock in biomass and soils and promotes management practices that foster increasing the soil carbon pool (Paustian and Cole, 1998). An example of a means of increasing carbon in the soil would be adopting no-till practices that would minimize soil disturbance and leave soil residue in the topsoil (Paustian and Cole, 1998), rather than the conventional practice of plowing and disking fields before planting (Fawcett and Towery, 2002).

#### **Management Practices That Enhance Carbon Accumulation**

Land cover and land use define the ecosystem type, such as agricultural land, wetlands, grasslands, and forests. The properties of these ecosystems and their vegetation are indicators of potential carbon accumulation and the extent to which the soil-carrying capacity can be increased through ecosystem management. Such management changes include water (Metting et al., 2001) and land management practices. For example, water management might incorporate changes such as the use of packed snow to increase soil moisture (Dumanski et al., 1998) by trapping snow with grain stubble in no-till settings. Among the proven land management practices that have a high potential of enhancing carbon accumulation are the following: adopting conservation tillage practices, reducing soil erosion, and minimizing soil disturbance; using buffer strips along waterways; enrolling land in conservation programs, such as the U.S. Conservation Reserve Program (CRP); restoring wetlands; restoring degraded lands; converting marginal lands to wetlands or grasslands; eliminating summer fallow (Lal et al., 1999; Paustian and Cole, 1998), using perennial grasses and winter cover crop; fostering afforestation and reforestation; and light to moderate grazing of rangelands to promote plant growth (N.D. Farmers Union and U.S. Geological Survey, 2003a).

#### **Ideal Settings to Sequester Organic Carbon**

A number of natural processes beyond management practices affect the rate at which organic carbon can accumulate in soils, including key variables such as soil conditions and climate (Centre for Ecology and Hydrology, 2002). Through an assessment and understanding of these primary variables governing soil carbon, the conducive environment and processes for enhanced carbon can be promoted.

Soil order, soil texture, drainage, and acidity of soil are the primary soil conditions affecting the accumulation of soil carbon (Cihacek, 2004). By knowing the soil order, the native environment under which the soil was formed can be determined, along with the soil's innate capacity to sequester organic carbon under ideal conditions. Soil texture is indicative of the aggregate structure of soil and its moisture-holding capacity (Johnson et al., 2000). Continuously wet soils with limited oxygen capacity, such as those found in wetlands and areas of poor drainage, provide an ideal setting for slowing decomposition, thereby increasing the carbon stock (Paustian and Cole, 1998). Research also indicates that soil wetness, as indicated by drainage classes, is an ideal indicator of organic carbon accumulation (Davidson, 1995).

Soil acidity is presumed to play an important role in the accumulation and decomposition of organic matter in soils, and the effects of soil acidity on carbon uptake are under investigation. While some soil scientists have observed organic matter accumulating relatively quickly in acidic soils (Collins and Kuehl, 2001), others have observed carbon accumulating in moderately acid to slightly alkaline (pH 5.6–7.8) soil conditions (Cihacek, 2004).

Ideal settings to sequester organic carbon in soil are found in environments that promote minimal soil disturbance (Post et al., 2001; Paustian and Cole, 1998). Low aeration reduces the rate of decomposition, allowing more carbon to accumulate (Paustian and Cole, 1998). Wetland soils and areas of poor drainage are effective in this aspect. Enhanced precipitation often provides the needed moisture to maintain an increase in plant growth and SOC (Collins and Kuehl, 2001). Generally, with an increase in rainfall, there is an increase in carbon accumulation (Natural Resource Management, 2004). Under water-saturated soil conditions, the lack of

oxygen over time prevents complete microbial decay of biomass over a wide temperature range. Collins and Kuehl (2001) point to research on soils in the midwestern United States that show the effect of climate on soil organic matter. They emphasize that when there is a 10°C decrease in mean annual temperature, the soil organic matter increases by a factor of 2 or 3. Thus a soil in the northern portions of the PCOR Partnership region would be expected to have a significantly higher organic matter content than a soil in Texas.

The growth of perennial grasses contributes significantly to below-ground carbon accumulation (Paustian and Cole, 1998). Grasslands are exceptional when compared to agricultural and forest ecosystems in having significant portions of total biomass below-ground, attributing to the dense fibrous root system of grassland (Reed et al., 2001; see Figure 2). In contrast, temperate forests make substantial carbon contributions both in above-ground materials and below-ground accumulations.

Comparisons of ecosystems of the earth by Houghton (1995) indicate that wetlands (swamp and marsh) have significantly higher mean carbon content in vegetation and in soil than temperate grassland and pasture. Through ongoing research, PCOR Partnership wetland scientists are determining the mean carbon content of vegetation and soils in the PPR (Figure 3) an area with thousands of freshwater marshes.

### **Time Factors Associated with Organic Carbon Sequestration in Soils**

Managing soils for increased carbon uptake will pull CO<sub>2</sub> from the atmosphere for a 50–100-year time frame after which the soils will have reached a new equilibrium. Equilibrium refers to the point at which the total amount of carbon in the soil does not change over time. Once a steady state has been reached, the carbon

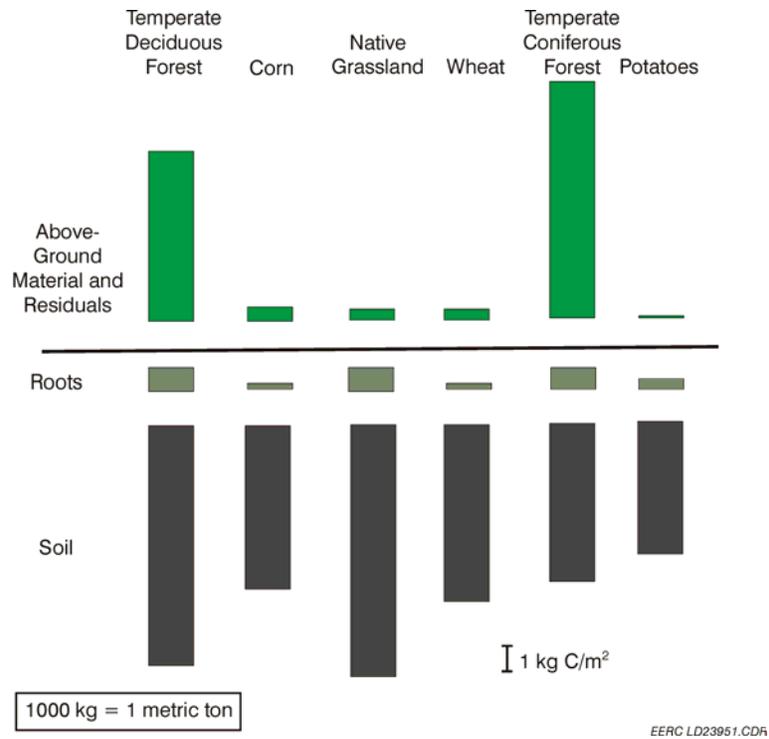


Figure 2. Distribution of SOC in above-ground plants, roots, and surface soil to a depth of 30 cm (modified from Gregorich et al., 1995).

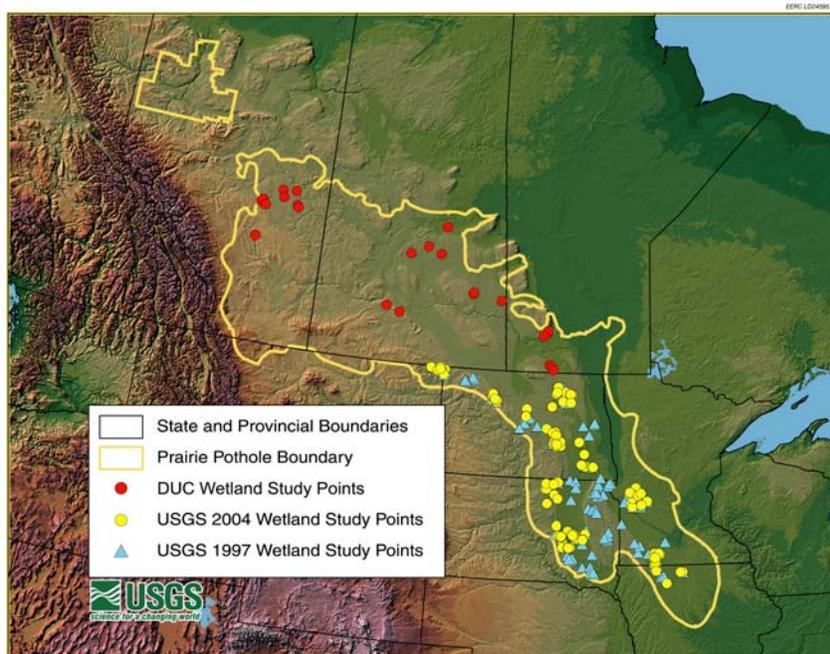


Figure 3. PCOR Partnership study sites in the PPR conducted with Ducks Unlimited Canada (DUC) and U.S. Geological Survey (USGS) (PCOR Partnership, 2005).

will remain sequestered until the land management practices change or some other event occurs. The manipulation of soils and biomass for carbon sequestration has the advantage that it can be implemented immediately without the need for new technologies. This will allow for the concurrent development of:

- 1) Technologies to lessen carbon and other greenhouse gas emissions (Lal, 2002), such as more fuel-efficient vehicles.
- 2) More efficient technologies for the capture of CO<sub>2</sub> from large sources.
- 3) Emerging alternative energy sources.
- 4) Carbon credit-trading markets for geologic storage.
- 5) Infrastructure and monitoring technologies to support geologic storage.

Time frames and estimates of organic carbon storage potential in soil for a selection of PCOR Partnership states and provinces are shown in Tables 1–5.

### **Wetlands**

Wetlands provide the opportunity for more sustainable carbon accumulation (Paustian and Cole, 1998). They have the potential of storing carbon long after 50 years (Table 1), with restored wetlands reaching natural wetland soil carbon levels within 10–20 years (N.D. Farmers Union and U.S. Geological Survey, 2003c). Studies indicate that wetlands in the PPR of the PCOR Partnership region sequester carbon on average at a rate of 1.2 metric tons of carbon per acre per year (mTC ac<sup>-1</sup>yr<sup>-1</sup>) (N.D. Farmers Union and U.S. Geological Survey, 2003c). With wetlands containing large carbon reservoirs among terrestrial ecosystems over the long term and with carbon

accumulating at a greater rate in these ecosystems when compared to no-till agricultural fields (N.D. Farmers Union and U.S. Geological Survey, 2003b), the sequestration potential of the PPR looks very promising.

The land area with frequent wetland occurrence covers more than 118 million acres of the PCOR Partnership region (National Resources Canada, 1993; N.D. Farmers Union and U.S. Geological Survey, 2003b; Iowa State University, 2005; U.S. Fish & Wildlife Service, 2005a) and includes primarily peat lands and prairie potholes.

The Peat Land Region covers well over 100 million acres within the PCOR Partnership region. The vast expanse of land that comprises the peat lands does make a substantial contribution to the naturally occurring accumulation of carbon. Preliminary estimates suggest that peat lands are expected to store approximately 12 million mTC yr<sup>-1</sup> (N.D. Farmers Union and U.S. Geological Survey, 2003b; Iowa State University, 2005; U.S. Fish & Wildlife Service, 2005a). Relative to the PPR, peat lands have high methane emissions and tend to accumulate carbon at rates tenfold slower than the PPR.

The PPR is estimated to include 17 million acres of wetlands (Euliss et al., in press; U.S. Fish & Wildlife Service, 2005a) within Alberta, Saskatchewan, Manitoba, North Dakota, South Dakota, Minnesota, Iowa, and Montana (Figure 3). But the acreage may be substantially larger (43 million acres) if one includes drained or altered wetlands (Euliss et al., in press). Through the PCOR Partnership, the potential of the PPR wetlands to sequester carbon is being determined. Preliminary PCOR Partnership research indicates that farmed PPR wetlands, if restored, could sequester as much as 378 million metric tons of organic carbon over the next decade, if contributions from the soil, sediment

**Table 1. Estimates of Carbon Storage Potential for North Dakota**

Ecosystem	Terrestrial Sequestration		
	Wetlands	Rangeland	Agricultural Land
Area Available for Carbon Sequestration	<sup>1</sup> Approx. 2.4 million acres <sup>1</sup> (with large potential for adding acres in restored wetlands)	<sup>2</sup> Approx. 10.3 million acres <sup>2</sup> (additional 1.2 million in tame grass pastures)	<sup>3</sup> Approx. 28 million acres (land presently being farmed)
Amount of CO <sub>2</sub> That Can Be Sequestered	Natural prairie potholes: <sup>1</sup> Average: 1.2 mTC ac <sup>-1</sup> yr <sup>-1</sup> Range: 0.6 to 2.1 mTC ac <sup>-1</sup> yr <sup>-1</sup>  After restoration: <sup>1</sup> Carbon stock increases at a rate of 2.1 mTC ac <sup>-1</sup> yr <sup>-1</sup> .  After replenishment of lost CO <sub>2</sub> : <sup>1</sup> Rate slows to 0.4 mTC ac <sup>-1</sup> yr <sup>-1</sup> .	<sup>2</sup> Average: 0.04 mTC ac <sup>-1</sup> yr <sup>-1</sup> <sup>2</sup> Range: 0 to 0.12 mTC ac <sup>-1</sup> yr <sup>-1</sup>	Changing field crop type and rotational cycles on carbon storage: <sup>4</sup> Results in an increase in all crop rotations (average) 0.08 ± 0.05 mTC ac <sup>-1</sup> yr <sup>-1</sup> , except where summer fallow is practiced and continuous corn is changed to corn-soybean.  Converting from conventional to no-till: <sup>4</sup> Results in an increase in all crop systems (average) in 0.23 ± 0.06 mTC ac <sup>-1</sup> yr <sup>-1</sup> , except where summer fallow is practiced.
Length of Time Before Sink Reaches Capacity	<sup>2</sup> Long after 50 years	<sup>2</sup> 12–56 years	Croplands: <sup>2</sup> From 0–5 years, little to no carbon storage. From 5–15 years, rapid increase of carbon accumulation. From 15–20 years, a decline in carbon storage. <sup>2</sup> After approx. 50 years, croplands stop storing additional carbon.  Changes in rotation cycles and cropping types of no-till: <sup>4</sup> Peaks in the 5–20 years after first implemented. <sup>4</sup> Then declines to zero between 40 and 60 years.

<sup>1</sup> N.D. Farmers Union and U.S. Geological Survey, 2003b.

<sup>2</sup> N.D. Farmers Union and U.S. Geological Survey, 2003a.

<sup>3</sup> Association of State Foresters, 2005.

<sup>4</sup> N.D. Farmers Union and U.S. Geological Survey, 2003c.

buildup, and plant ecosystem are accounted for (Euliss et al., in press). This research suggests that a substantial contribution to store additional carbon in soil can be made throughout the PPR by converting nonproductive or marginal croplands and restoring degraded lands to wetlands when favorable conditions exist.

### **Forest**

The PCOR Partnership comprises over 249 million acres of forestland not including other wooded land of 75 million acres (Canadian Forest Service, 2001; National Association of State Foresters, 2005). The PCOR Partnership states and provinces that are major contributors of forest and other wooded land (in millions of acres) are Alberta (90), Manitoba (89), Saskatchewan (60), Montana (22.5), Minnesota (16.5), Wisconsin (16), Missouri (15), and Wyoming (11) (Canadian Forest Service, 2001; National Association of State Foresters, 2005). With forests representing 31% of the land cover of this region (Figure 1) and with temperate forests contributing a substantial quantity of SOC in aboveground materials and surface soil to a depth of 30 cm (Figure 2) in comparison to other ecosystems, reforestation and afforestation provide some of the best options to sequester additional carbon.

When a tree reaches maturity, its net photosynthetic capacity has reached its peak. As the tree ages and woody biomass accumulates, the fixed photosynthetic capacity is taxed. Both carbon and biomass increase at a declining rate over time, until carbon storage reaches steady state (Lertzman, 2005). This is maintained unless there is a substantial change to the ecosystem, such as through fires or logging. As such, older trees, in contrast to young trees, do not maintain their rapid carbon accumulation, but are able to store substantial quantities (Ryan, 2005). However, Anwar (2001) has shown that young forests may have more trees and greater diversity than an older forest, leading

to more carbon storage in young forests compared to old forests. As the tree dies, tree litter and woody debris are added to the forest floor; some CO<sub>2</sub> is released into the atmosphere, and some carbon accumulates in soil.

In the afforestation program of the Canadian PCOR Partnership provinces, the lifespan of trees, specifically white spruce, green ash, and hybrid poplars, is estimated at between 50 and 100 years old. White spruce and green ash are expected to reach maturity at approximately 50 years of age, while hybrid poplars reach maturation by approximately 20 years (Peterson et al., 1999). These time frames are very general and do vary among species and climatic regions (Roulet and Freedman, 1999). The afforestation rate of carbon accumulation for white spruce, green ash, and hybrid poplar in the Canadian PCOR Partnership provinces at ages 5 and 10 ranged from 0.113 to 2.12 mTC ac<sup>-1</sup>yr<sup>-1</sup> (Peterson et al., 1999; see Tables 2 and 3).

Since afforestation can store more carbon than other ecosystems, such as agriculture lands, afforestation has great potential for mitigating carbon in the atmosphere (Plantinga et al., 1999). Through afforestation programs such as in the PCOR Partnership region of Canada, Canada may be able to address some of its commitment under the Kyoto Protocol to reduce carbon emissions. For example, afforestation in the PCOR Partnership's Canadian portion can offset carbon emissions by approximately 2 million metric tons of CO<sub>2</sub>. Peterson et al. (1999) estimate that this can be accomplished in the 2008–2012 Kyoto Protocol reporting period.

### **Rangeland**

Nineteen percent of the PCOR Partnership region is made up of grassland, while 9% is shrubland (European Commission Joint Research Centre, 2003) (Figure 1), representing over 208 million acres in aggregate (National Association of State Foresters, 2005; European Commission.

**Table 2. Estimates of Carbon Storage Potential for Manitoba**

Terrestrial Sequestration				
Ecosystem	Forestland	Wetlands	Rangeland	Agricultural Land
Area Available for Carbon Sequestration	<p><sup>1</sup> Approx. 89 million acres (land presently being forested).</p> <p>Forestland (in Saskatchewan, Alberta, and Manitoba combined)</p> <p>Afforestation (forests in areas where trees have not previously grown):</p> <p><sup>5</sup> Approx. 14 million acres estimated to be biophysically available.</p> <p><sup>5</sup> Approx. 1.9 million acres total amount of land that can be realistically afforested over a 15-year period.</p>	<p><sup>2</sup> Approx. 55.5 million acres</p>	<p><sup>3</sup> Approx. 28 million acres</p>	<p><sup>4</sup> Approx. 11.7 million acres</p>
Amount of CO <sub>2</sub> That Can Be Sequestered	<p><sup>6</sup> Total Surface SOC content for the Manitoba PPR (southern section of Manitoba) is estimated at 100.6 million mTC.</p> <p>Forestland (in Saskatchewan, Alberta, and Manitoba combined)</p> <p>Afforestation:</p> <p><sup>5</sup> White spruce, green ash, and hybrid poplar at age 5 and age 10 sequester 0.113–2.12 mTC ac<sup>-1</sup>yr<sup>-1</sup></p>	<p><sup>6</sup> Total surface SOC content for the Manitoba PPR (southern section of Manitoba) is estimated at 25.1 million mTC.</p>	<p><sup>6</sup> Total surface SOC content for the Manitoba PPR (southern section of Manitoba) is estimated at 115.0 mTC for grassland and 8.0 million mTC for forage.</p>	<p><sup>6</sup> Total surface SOC content for the Manitoba PPR (southern portion of Manitoba) is estimated at 361.6 million mTC.</p>
Length of Time Before Sink Reaches Capacity	<p>Age at which tree type reaches maturity:</p> <p><sup>5</sup> White spruce: 50 years</p> <p><sup>5</sup> Green ash: 50 years</p> <p><sup>5</sup> Hybrid poplar: 20 years</p>	See Table 1	See Table 1	See Table 1

<sup>1</sup> Canadian Forest Service, 2001.

<sup>2</sup> Natural Resources Canada, 1993.

<sup>3</sup> European Commission Joint Research Centre, 2003.

<sup>4</sup> Statistics Canada, 2002.

<sup>5</sup> Peterson, et al., 1999.

<sup>6</sup> Lacelle, 1996.

**Table 3. Estimates of Carbon Storage Potential for Saskatchewan**

Terrestrial Sequestration				
Ecosystem	Forestland	Wetlands	Rangeland	Agricultural Land
Area Available for Carbon Sequestration	<p><sup>1</sup> Approx. 60 million acres (land presently being forested)</p> <p>Forestland (in Saskatchewan, Alberta, and Manitoba combined)</p> <p>Afforestation (forests in areas where trees have not previously grown):</p> <p><sup>5</sup> Approx. 14 million acres estimated to be biophysically available.</p> <p><sup>5</sup> Approx. 1.9 million acres total amount of land that can be realistically afforested over a 15-year period.</p>	<p><sup>2</sup> Approx. 23.9 million acres</p>	<p><sup>3</sup> Pasture and rangelands total more than 24 million acres.</p>	<p><sup>4</sup> Approx. 38.0 million acres</p>
Amount of CO <sub>2</sub> That Can Be Sequestered	<p><sup>6</sup> Total Surface SOC content for the Saskatchewan PPR (southern half of Saskatchewan) is estimated at 96.9 million mTC</p> <p>Forestland (in Saskatchewan, Alberta, and Manitoba combined)</p> <p>Afforestation:</p> <p><sup>5</sup> White spruce, green ash, and hybrid poplar at age 5 and age 10 sequester 0.113–2.12 mTC ac<sup>-1</sup>yr<sup>-1</sup></p>	<p><sup>6</sup> Total surface SOC content for the Saskatchewan PPR (southern half of Saskatchewan) is estimated at 41.7 million mTC.</p>	<p><sup>6</sup> Total surface SOC content for the Saskatchewan PPR (southern half of Saskatchewan) is estimated at 316.9 million metric tons for grassland and 23.4 million mTC for forage.</p>	<p><sup>6</sup> Total surface SOC content for the Saskatchewan PPR (southern half of Saskatchewan) is estimated at 1037 million mTC.</p>
Length of Time Before Sink Reaches Capacity	<p>Age at which tree type reaches maturity:</p> <p><sup>5</sup> White spruce: 50 years</p> <p><sup>5</sup> Green ash: 50 years</p> <p><sup>5</sup> Hybrid poplar: 20 years</p>	See Table 1	See Table 1	See Table 1

<sup>1</sup> Canadian Forest Service, 2001.

<sup>2</sup> Natural Resources Canada, 1993.

<sup>3</sup> Government of Saskatchewan, 2004.

<sup>4</sup> Statistics Canada, 2002.

<sup>5</sup> Peterson, et al., 1999.

<sup>6</sup> Lacelle, 1996.

Joint Research Centre, 2003). Major amounts of grassland and scrubland can be found in Saskatchewan, Manitoba, and Alberta with over 60 million acres combined, and Montana (50 million), Nebraska (20 million), North Dakota (12 million), Missouri (14 million), South Dakota (24 million), and Wyoming (28 million) (National Association of State Foresters, 2005, European Commission Joint Research Centre, 2003)

The rangelands of the PCOR Partnership region are dominated by mollisols. Mollisols are soils characterized as having a high potential for accumulating SOC. These soils are native to the prairie grassland ecosystems and are notable for being typically black and fertile. The high concentrations of organic carbon in the surface soils and lesser concentrations in the deeper soil depths are attributed to the death and regrowth of the fibrous root systems of native grasses (Collins and Kuehl, 2001) and contribute to the substantial below-ground carbon accumulation (Figure 2). For example, dry, temperate rangelands in North Dakota have the potential of sequestering carbon for approximately 12–56 years before equilibrium is established, with an average storage rate of  $0.04 \text{ mTC ac}^{-1}\text{yr}^{-1}$  (N.D. Farmers Union and U.S. Geological Survey, 2003a). The conversion of marginal cropland to grasslands may prove to be a feasible option to promote carbon buildup in biomass and soils. Sequestration rates modeled on 1998 data for Iowa estimated carbon yields at a rate of  $0.53 \text{ mTC ac}^{-1}\text{yr}^{-1}$  for conversion from cropland to CRP (Brenner et al., 2001a; Table 4). Even the conversion of continuously cropped land to a managed grazing system increases efficiency of soil carbon sequestration because there is less soil surface disruption, increased root biomass production, and the return of organic matter in the form of animal dung and urine to the soil (Faller, 2004; Schuman et al., 2001; Schnabel et al., 2001).

### **Agricultural**

Agricultural lands in the PCOR Partnership region are primarily found in the following states and provinces (in millions of acres): Saskatchewan (38), North Dakota (28), Iowa (25.4), Alberta (24), Nebraska (22.4), Minnesota (21), Montana (17.5), South Dakota (17), Missouri (12.3), Manitoba (12), and Wyoming (2) (National Association of State Foresters, 2005; Statistics Canada, 2002). With much of the PCOR Partnership region already in the agricultural land base, expansion of agricultural activities is unlikely (Paustian and Cole, 1998).

For croplands in general, there will be a peak in the rate of carbon accumulation within the 5–20-year time frame, followed by a decrease in the rate of carbon accumulation. For Nebraska, modeled cropland carbon sequestration rates for 2000, showed estimated yields of  $0.06 \text{ mTC ac}^{-1}\text{yr}^{-1}$  across the state, with a range of  $0.01\text{--}0.25 \text{ mTC ac}^{-1}\text{yr}^{-1}$ . This range was influenced primarily by water management and tillage practices (Brenner et al., 2001b; Table 5).

On average, when converting from conventional farming to no-till for all crop systems in North Dakota, the carbon storage rate is  $0.23 \pm 0.06 \text{ mTC ac}^{-1}\text{yr}^{-1}$  (N.D. Farmers Union and U.S. Geological Survey, 2003a). However, summer fallow does not increase organic soil carbon; only a change to no-till practices achieves that result (N.D. Farmers Union and U.S. Geological Survey, 2003a).

### **Key Factors Affecting Carbon Storage in the Soils of the PCOR Partnership Region**

- Approximately 31% of the land cover that makes up the PCOR Partnership region (Figure 1) is forestland, approximately 30% is considered cropland, about 19% is classified as grasslands, and 9% shrubland (European Commission Joint Research Centre, 2003). While only 0.2% of wetlands appear to be represented in

**Table 4. Estimates of Carbon Storage Potential for Iowa**

Terrestrial Sequestration				
Ecosystem	Forestland	Wetlands	Rangeland	Agricultural Land
Area Available for Carbon Sequestration	<sup>1</sup> Approx. 2.5 million acres in forest	<sup>2</sup> Approx 0.6 million acres of vegetated wetlands  <sup>2</sup> Approx. 0.3 million acres of pond, lake, and reservoir habitats, and 0.1 million acres of river and stream habitats	<sup>1</sup> Approx. 3.5 million acres in pasture and rangeland	<sup>1</sup> Approx. 25.4 million acres in cropland
Amount of CO <sub>2</sub> That Can Be Sequestered	<sup>3</sup> Based on modeled 1998 data, tree conversion in Iowa accumulated soil carbon at a rate of 0.01 million mTC yr <sup>-1</sup> .	<sup>3</sup> Based on modeled 1998 data, wetlands conversion in Iowa accumulated soil carbon at a rate of 0.02 million mTC yr <sup>-1</sup> .	<sup>3</sup> Based on modeled 1998 data, CRP land in Iowa accumulated soil carbon at a rate of 0.8 million mTC yr <sup>-1</sup> , with grass conversion yielding 0.4 million mTC yr <sup>-1</sup>  <sup>3</sup> Based on modeled 1998 data, conversion of cropland to CRP was estimated to yield carbon at a rate of 0.53 mTC ac <sup>-1</sup> yr <sup>-1</sup> , with a range of 0.49–0.69 mTC ac <sup>-1</sup> yr <sup>-1</sup> .	<sup>3</sup> Based on modeled 1998 data, cropland in Iowa accumulated soil carbon at a rate of 1.9 million mTC yr <sup>-1</sup> .  <sup>3</sup> Based on modeled 1998 data, conversion from corn–soybean under intensive tillage to no tillage, soil carbon accumulated at a rate of 0.20–0.26 mTC ac <sup>-1</sup> yr <sup>-1</sup> .

<sup>1</sup> National Association of State Foresters, 2002.

<sup>2</sup> Iowa State University, 2005.

<sup>3</sup> Brenner, et al., 2001a.

**Table 5. Estimates of Carbon Storage Potential for Nebraska**

Ecosystem	Terrestrial Sequestration			
	Forestland	Wetlands	Rangeland	Agricultural Land
Area Available for Carbon Sequestration	<sup>1</sup> Approx. 1.2 million acres in forest	<sup>2</sup> Approx 1.3 million acres of scattered wetlands  <sup>1,4</sup> Acreage deemed negligible	<sup>3</sup> Approx. 20 million acres in rangeland	<sup>3</sup> Approx. 22 million acres in cropland
Amount of CO <sub>2</sub> That Can Be Sequestered	<sup>1</sup> Although tree conversion and wetland restoration add to the carbon pool, the contributions are considered minor since the area accounts for only 38,934 acres.		<sup>1</sup> Carbon sequestration rates, modeled on 2000 data for conversion from cropland to CRP grasses accumulated soil carbon at a rate of 0.23 mTC ac <sup>-1</sup> yr <sup>-1</sup>	<sup>1</sup> Carbon sequestration rates, modeled on 2000 data for cropland suggest soil carbon accumulated at a rate of 1.0 million mTC yr <sup>-1</sup> . <sup>1</sup> Carbon sequestration rates, modeled on 2000 data for cropland yield approx. 0.06 mTC ac <sup>-1</sup> yr <sup>-1</sup> across Nebraska. <sup>1</sup> Nonirrigated cropland in modeled on 2000 data under: Intensive tillage system – 0.01 mTC ac <sup>-1</sup> yr <sup>-1</sup> . Moderate – 0.04 mTC ac <sup>-1</sup> yr <sup>-1</sup> . No till – 0.15 mTC ac <sup>-1</sup> yr <sup>-1</sup> . <sup>1</sup> Irrigated cropland in modeled on 2000 data under: Intensive tillage system – 0.07 mTC ac <sup>-1</sup> yr <sup>-1</sup> . Moderate – 0.08 mTC ac <sup>-1</sup> yr <sup>-1</sup> . No till – 0.25 mTC ac <sup>-1</sup> yr <sup>-1</sup> .

<sup>1</sup> Brenner, et al., 2001b.

<sup>2</sup> U.S. Fish & Wildlife Service, 2005b.

<sup>3</sup> Association of State Foresters, 2005.

<sup>4</sup> European Commission Joint Research Centre, 2003.

Figure 1, it should be noted that the PPR wetlands overlap several ecosystems, incorporating drained and/or altered wetlands, and if restored, could potentially sequester 378 million metric tons of organic carbon over the ensuing decade, if contributions from soil sediment buildup and plant ecosystems are accounted for (Euliss et al., in press).

- The temperate to subarctic winter climates of the PCOR Partnership region demonstrate that this climatic environment fosters reduced microbial activity and significantly minimized carbon decomposition (Collins and Kuehl, 2001), making it ideal for organic carbon soil accumulation. Within natural ecosystems, SOC is inversely related to temperature. As temperatures decline, SOC increases exponentially (Lal, 2002). When conservative agricultural practices are incorporated, there is a noticeable difference between the potential rate of SOC in cool and humid climates ( $0.16\text{--}0.32\text{ mTC ac}^{-1}\text{yr}^{-1}$ ) and warm and dry climatic conditions ( $0.08\text{--}0.16\text{ mTC ac}^{-1}\text{yr}^{-1}$ ) (Lal, 2002).
- The PCOR Partnership region provides a unique research opportunity to study the diverse settings of the prairie wetlands, contrasted with the large semiarid region of southwest North Dakota, northeast South Dakota, northwest Wyoming, and southeast Montana. Such research should provide diverse land management practices to optimize carbon storage throughout the region (Faller, 2004).
- Cihacek and Ulmer's (2002) study of cultivated soils, specifically from crop-fallow rotations within the PCOR Partnership region, show that, while the surface 15 cm of soil has a reduced annual carbon accumulation, significant contributions can be made by soil inorganic carbon storage at

depths greater than 15 cm to offset carbon emissions.

With the favorable carbon-sequestering conditions of the PCOR Partnership region—cold winters and irregular precipitation patterns and the crop-fallow system, primarily practiced to reduce weeds and promote soil moisture—inorganic carbon precipitates as carbonates. These inorganic carbonates often infiltrate the soil profile and can accumulate as carbonate formations when calcium is present and as soil inorganic carbon at depths below 50 cm (Cihacek and Ulmer, 2002).

Organic carbon has been observed to accumulate below 50 cm in some circumstances (Cihacek and Ulmer, 1997). Since depths greater than 15 cm are less oxygenated, less subject to decomposition, and have a greater potential of remaining in storage (Dumanski et al., 1998), the potential for soil inorganic carbon, along with deep organic carbon, to offset carbon dioxide emissions may currently be underestimated (Cihacek, 2004).

#### **Ancillary Cost and Benefits of Management Practices Designed for Increased Carbon Storage in Soils**

Additional expenses may be incurred when a change in land management practice occurs to enhance soil carbon accumulation. For example, as a farmer changes from conventional till to no-till farm practices, increased costs associated with the adoption of new machinery, techniques, and increased use of herbicides may result (Paustian and Cole, 1998; Fawcett and Towery, 2002), and additional resources such as time will be essential to learn new methods (N.D. Farmers Union and U.S. Geological Survey, 2003c). However, increasing the soil carbon stock by removing  $\text{CO}_2$  from the atmosphere provides added benefits to the land, including more nutrient-enriched soil

resulting in the same or improved agricultural productivity, enhanced soil moisture, less soil erosion, improved soil quality, and increased numbers of beneficial soil microbes and earthworms.

Beyond the benefits to the soil, additional environmental benefits have been determined, including the return of beneficial wildlife, birds, and insects in and around the fields; a decrease in sediment and chemical runoff entering streams; less potential for flooding; and a reduction of dust in the air (Fawcett and Towery, 2002). There may also be financial rewards: reduced fuel consumption and the opportunity to “sell” the sequestered carbon as carbon credits to companies interested in offsetting their carbon emissions (N.D. Farmers Union and U.S. Geological Survey, 2003c).

## CONCLUSION

The soils of the PCOR Partnership region hold great promise for sequestering carbon. Conducive soil conditions and cold winter climates of the region provide an ideal setting to increase soil carbon stock.

Potentially, significant sustainable quantities of carbon could accumulate through restoration of wetlands over the next decade in the PCOR Partnership region. Through afforestation and reforestation, the region can make great strides in mitigating carbon in the atmosphere through substantial buildup of SOC in aboveground materials and belowground accumulations. Additionally, restoring degraded lands and converting marginal croplands to native grasslands or even grazing pastures can increase efficiency of soil carbon sequestration. For productive croplands, the adoption of water and land management practices that promote buildup of biomass and soils would help realize the PCOR Partnership’s terrestrial sequestration potential by facilitating immediate soil carbon pools without the need for new technology.

With the additional benefits to the soil and the environment and the possibility of financial incentives, sequestering carbon in soil may prove to be a win-win situation for the PCOR Partnership region.

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