United States Department of Agriculture
Natural Resources Conservation Service

CEAP Science Note
Conservation Effects Assessment Project
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Conserving Prairie Pothole Wetlands: Evaluating Their Effects on Carbon Sequestration in Soils and Vegetation

Summary Findings

Overall, previously farmed catchments in the Glaciated Plains had 12 and 26 percent less soil organic carbon (SOC) in the upland and wetland zones, respectively, than did native prairie catchments. Similarly, previously farmed catchments in the Missouri Coteau had 20 and 26 percent less SOC in the upland and wetland zones, respectively.

Restored wetland catchments had an average of 6.7 tons per acre less SOC in the upper 6 inches of the soil than did native prairie catchments.

Following restoration of semipermanent wetlands catchments, carbon was replenished at a maximum rate of 1.34 tons per acre per year in the top 6 inches of soil. Using this maximum rate, an average of 3.3 years is required to replenish soil carbon in the top 6 inches of soil through wetland restoration.

Based on a wetland catchment carbon sequestration rate of 1.34 tons per acre per year, carbon stocks in most restored prairie pothole wetland catchments for the PPR were estimated to replenish within 10 years following restoration.

In addition to soil carbon sequestration potential, sequestration of carbon through the emergent vegetation pool on restored catchments was estimated to be more than 788,000 tons for the PPR, or sequestration of 0.7 ton per acre of vegetative organic carbon in restored catchments.

Restoration age was hypothesized to be less of a factor on soil organic carbon sequestration rates than the vegetation/hydrologic phases occurring in the restored wetland basin. Study sites were restored over a 19-year period (1986–2004), a time span that included one of the most extreme dry and wet cycles recorded during the last 100 years in the PPR. This cycle potentially influenced SOC baselines, rates of carbon sequestration, and the hydro-geochemical processes in the wetland catchments.

Introduction

In response to concerns about global climate change, many countries are developing strategies to reduce emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). One strategy is to sequester atmospheric carbon (CO_2-C), by implementing conservation practices on agricultural lands to enhance soil organic carbon (SOC) sinks (Lal et al. 1998). Federal policies promoting wetland conservation and restoration, such as USDA's Conservation Reserve Program (CRP) and Wetlands Reserve Program (WRP), have led to the restoration of approximately 5.4 million acres of wetland and grassland habitats in the Prairie Pothole Region (PPR) of the United States. Restoration of grassland and wetland habitats (including wetland catchments) via the CRP or WRP is most often recognized for reducing soil erosion, improving soil and water quality, enhancing flood storage, and creating wildlife habitat (Knutsen and Euliss 2001); however, these restorations also have affected carbon sequestration and GHG emissions in the United States.

Shifting land use from cultivation to a more natural state often results in replenishment of SOC stocks and the capture and storage (sequestration) of CO_2-C. Undisturbed wetlands are generally sinks for CO_2-C and sources of CH_4, although levels depend on a variety of factors—and often their complex interaction—including soil physiochemical properties, sources of carbon, types and stability of microbes present in the soil, landscape position, length of time that reducing conditions exist, plant physiology, and hydroperiod (Altor and Mitsch 2008; Yu et al. 2006). Undisturbed peatlands have significant SOC pools and the capacity to sequester high levels of atmospheric carbon (Bridgham et al. 2007), although they accumulate carbon very slowly (Moore et al. 2007). Undisturbed freshwater mineral soil wetlands may accumulate and sequester significant amounts of CO_2-C but are thought to account for greater annual CH_4 fluxes than peatlands in the conterminous United States (Bridgham et al. 2007).

This study's objective was to evaluate the impact of conservation programs on carbon sequestration in the soils and vegetation communities of restored wetland catchments on WRP and CRP lands in the PPR. During 1997 and 2004, surveys of more than 400 catchments in the PPR were conducted to evaluate how SOC and vegetation organic carbon (VOC) stocks of restored catchments on program lands vary in relation to cropland and native prairie catchment baselines.

Methods

The North American PPR covers about 350,000 square miles and includes portions of Iowa, Minnesota, Montana, North Dakota, and South Dakota in the United States and Alberta, Manitoba, and Saskatchewan in Canada. Both countries are conducting studies to better understand carbon dynamics and GHG fluxes in prairie wetlands (Gleason et al. 2005). The PPR is also one of the most critical breeding grounds for numerous species of waterfowl in North America (fig. 1). The thousands of pothole wetland catchments on the PPR landscape exhibit dynamic hydro-geochemical characteristics that support diverse food webs and habitat conditions to meet waterfowl requirements for courtship, breeding, feeding, molting, and migration. Recently, however, other ecosystem services provided by prairie pothole depressional wetlands are being documented, including their role as a potential sink for CO_2-C.

The 1997 study, totaling 204 sample wetland catchments, focused on restored prairie wetland catchments on CRP, WRP, and Department of the Interior lands, and on native prairie wetland catchments (Gleason et al. 2008a). The 2004 study expanded the 1997 sample population to include farmed wetlands and hydrologically altered wetlands (presumed drained) on cropland, and increased the total number of sample wetland catchments on WRP and CRP lands to 130 sites for a total of 270 wetland catchments (table 1). Approximately 49 of the restored wetlands sampled in the 2004 study also included lands restored through other programs, such as the Water Bank Program and the U.S. Fish and Wildlife Service Partners for Fish and Wildlife Program. Distribution of the 1997 and 2004 sample populations are shown in figures 1 and 2 as it relates to the USDA major land resource areas and physiographic regions.

The 2004 sample included catchments containing temporary, seasonal, and semipermanent wetlands in hydrologically restored and non-drained restored catchments on program lands; drained and non-drained catchments on croplands; and native prairie catchments. Samples of soil and vegetation were collected along four transects that radiated from the center of the wetland and extended in the cardinal directions to the catchment boundary. Along each transect, soil samples were collected to a depth of 12 inches in each catchment subzone (shoulder-slope, mid-slope, toe-slope, wet-meadow, shallow-marsh, and deep-marsh). (See fig. A–6 in Gleason et al. 2008b.)

Previous work demonstrated that most differences in SOC between farmed and non-farmed wetlands occur within the upper 6 inches (Euliss et al. 2006); however, soil samples were collected to a depth of 12 inches to ensure compatibility with current and future carbon sink and source inventories for the United States. A separate soil sample from each subzone was collected for determination of bulk density (total mass per unit volume) to convert nutrient concentrations to mass per unit area.

The four soil samples from each subzone were composited by 0- to 6- inch and 6- to 12- inch depth increments for determination of physical (particle size) and chemical attributes (extractable phosphorus [P], total and inorganic carbon [C], total and extractable nitrate [NO_3^{-1}], and ammonium [NH_4^+]) using standard methods (Page et al. 1982; Klute 1986). However, the vegetation samples were collected from subzones on only one of the four transects by clipping all aboveground biomass (live and dead) within a 2.7 square-foot quadrat. Total dry mass, total carbon, total nitrogen, and total phosphorus for vegetation samples were determined by standard methods (Page et al. 1982; Klute 1986).

Table 1. Number of wetland catchments sampled in the Prairie Pothole Region in 2004, by physiographic region, catchment type, and land-use treatment

Physiographic region catchment type	Restored lands[1]								
	Hydrologic restoration			Nondrained restoration			Croplands		Native prairie
	Years restored			Years restored					
	1–5	5–10	>10	1–5	5–10	>10	Drained	Nondrained	
Missouri Coteau									
Temporary	5	4	7	4	3	8	5	5	5
Seasonal	4	8(2)	6(4)	6	6	8(5)	7	6	5(4)
Semipermanent	3	1	5(3)	3	3	5(4)	3	5	5(4)
Glaciated Plains									
Temporary	6	1	0	5	7	8	4	6	5
Seasonal	9	4(2)	7(6)	4	2	7(2)	5	6	5(3)
Semipermanent	5	5(3)	7(5)	4	4(1)	5(1)	3	6	5(3)

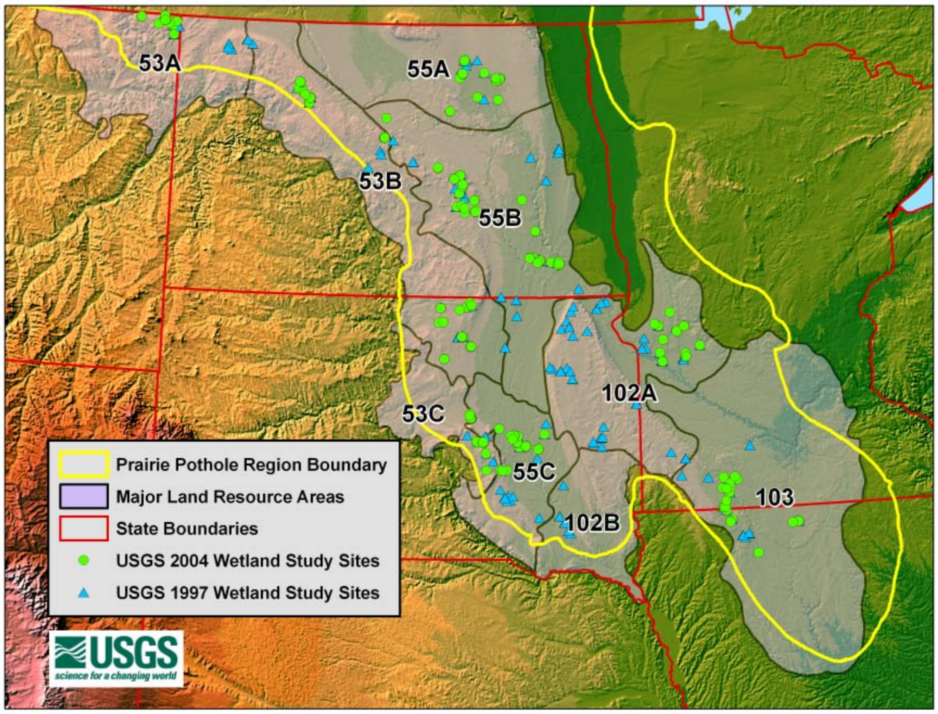
Numbers in parentheses are wetland catchments that were also sampled during the 1997 survey (Gleason et al. 2008a).
[1]One hundred thirty of the restored wetlands were on lands enrolled in the Farm Bill conservation programs Conservation Reserve Program (CRP) or Wetlands Reserve Program (WRP), and 49 wetlands were on sites restored through other, non-USDA programs.

Results

Sample results indicated that SOC stocks in the surface soil (0–6 inches) of wetland and upland zones in both physiographic regions were significantly lower in restored catchments than in native prairie catchments. In nearly all cases, cropland catchments also had significantly lower SOC stocks than did native prairie catchments; however, for one comparison in the Glaciated Plains, SOC in the wetland zone of cropland catchments (average = 23.58 ± 1.47 tons per acre) was not significantly lower than that in native prairie catchments (average = 26.22 ± 1.68 tons per acre). Collectively, results suggest that catchments with a cultivation history have lost SOC relative to a native prairie baseline. Overall, previously farmed catchments in the Glaciated Plains had 12 and 26 percent less SOC in the upland and wetland zones, respectively, than did native prairie catchments. Similarly, previously farmed catchments in the Missouri Coteau had 20 and 26 percent less SOC in the upland and wetland zones, respectively, than did native prairie catchments. These findings are consistent with other studies demonstrating that conversion of native prairie to cultivated agricultural land often reduces carbon stocks by 20 to 50 percent or more (Mann 1986; Anderson 1995; Cihacek and Ulmer 1995).

The lowered SOC in previously farmed wetlands presumably represents carbon losses from oxidation. On average, restored catchments had 6.7 tons per acre less SOC in the upper 6 inches of soil than did native prairie catchments. On the basis of this estimate, the 1,098,542 acres of catchments on program lands in the PPR would have a total of 7,341,915 tons less SOC than would an equivalent area of native prairie catchments.

The above estimate of total SOC loss represents the potential amount of SOC that could be replenished through carbon sequestration on program lands, but it does not address the rate of SOC sequestration. When grasses and forbs are reestablished in the upland zone of croplands, SOC stocks generally increase as a result of carbon sequestration by plants. Though estimates are highly variable, studies have demonstrated that conversion of cropland to grassland on CRP lands results in carbon sequestration rates of approximately 0.22 to 0.45 tons per acre per year; for example, see Follett et al. (2001). A commonly used method to estimate carbon sequestration rates is to compare SOC stocks on restored lands to cropped sites that are as similar as possible with respect to ed-



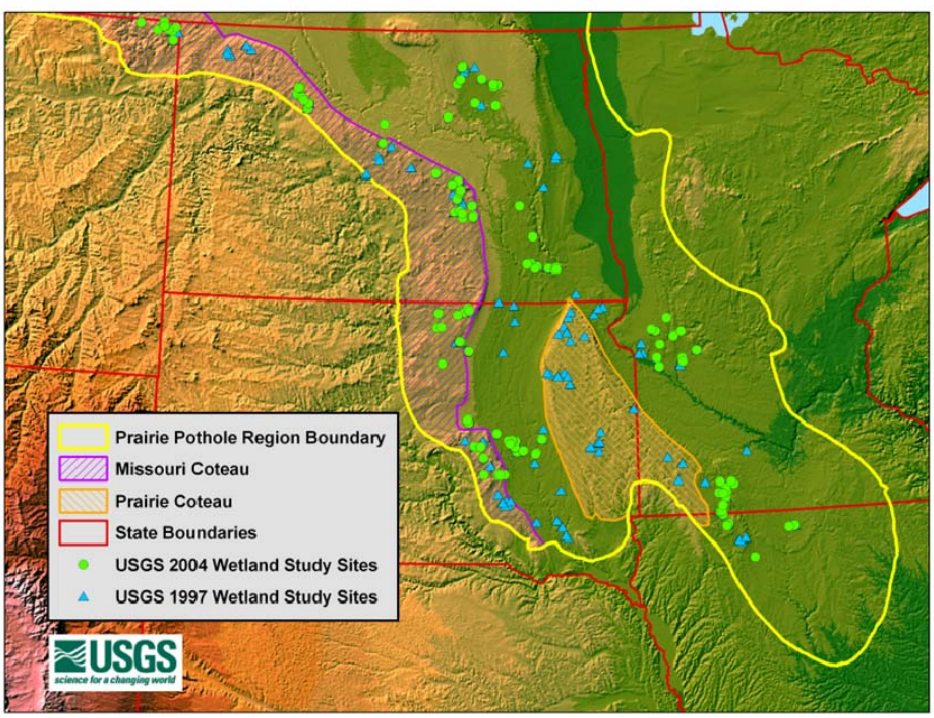


Figure 1 (top). Extent of the U.S. Prairie Pothole Region and distribution of 1997 and 2004 sample wetland catchments

Figure 2 (bottom) Distribution of 1997 and 2004 sampled wetland catchments relative to physiographic regions aphic (soil-related) and climatic factors. In this study a similar approach was used to estimate carbon sequestration rates; however, researchers were unable to detect a significant increase in SOC of restored catchments relative to a cropland baseline for all regions and time periods.

Carbon stocks were significantly higher in cropland than in restored catchments in the Missouri Coteau, whereas carbon stocks were statistically similar between restored and cropland catchments in the Glaciated Plains. Researchers were unable to detect a linear increase in carbon with restoration age. Therefore, the 2004 study was unable to estimate carbon sequestration rates by using a paired-sampling design for restored and cropland catchments, nor was it able to estimate rates by using a relationship between carbon stocks and restoration age. In contrast, the 1997 PPR study showed a positive relationship between wetland zone SOC and restoration age for semi-permanent catchments but not for seasonal catchments, while upland zones were not examined (Euliss et al., 2006).

Carbon Sequestration in Prairie Pothole Wetlands

The rate at which SOC stocks change is a function of climate, cropping history, type of plants seeded, landscape position, hydrology, soil characteristics, and time. Other studies that used paired-sampling designs also observed variable SOC sequestration rates, including SOC estimates for cropland sites that exceed those for restored grassland sites on CRP lands (for example, Follett et al. 2001).

The 2004 study indicated that wetland catchments with a cultivation history (i.e., wetland catchments in cropland and restored wetland catchments) had significantly lower SOC stocks than native prairie wetland catchments (i.e., wetlands with no known cultivation history), with the exception of one cropland wetland zone sampled in the Glaciated Plains sub-physiographic province. This finding suggests that agricultural activities in the PPR have resulted in substantial SOC losses compared to the historical native prairie condition from the combined effects of altered hydrology and cultivation.

Restored wetland catchments had a mean of 6.7 tons per acre less SOC in the upper 6 inches of the soil than did native prairie catchments. There are approximately 1.1 million acres of wetland catchments on lands enrolled in WRP and CRP in the PPR. Using the mean estimate of 6.7 tons SOC per acre, restored wetland catchments were estimated to have 7.3 million fewer tons of SOC than an equivalent area of native prairie catchments in the PPR. This estimate represents the potential amount of atmospheric carbon that could be sequestered on wetland catchments restored on CRP and WRP lands.

Published carbon sequestration rate estimates for conversion of cropland from conventional tillage to no-till range from 0.22 to 0.33 ton per acre per year, with an estimated saturation time range of 15 to 50 years (U.S. EPA 2006). The 1997 PPR study showed that restoration of semi-permanent wetlands stored carbon at a rate of 1.34 tons per acre per year in the top 6 inches of soil (Euliss et al., 2006). Based on this rate, carbon decreases in the top 6 inches assumed lost from oxidation associated with cultivation would be replenished in an average of 3.3 years (range 1.5 to 5.1 years).

It has been estimated that the average sequestration rate for formerly cultivated grasslands enrolled in CRP is 0.22 ton per acre per year (Follett et al. 2001). Using this more conservative sequestration rate, restored wetland catchments on WRP and CRP lands in the PPR potentially sequester 244,960 tons per year of SOC, with a total of 2.9 million tons of SOC potentially sequestered in restored wetland catchments on all WRP and CRP lands in the PPR between 1986 and 2004. The more conservative sequestration rate was used because the 2004 study could not replicate the sequestration rate calculated in 1997. This difference was postulated to result from variations in the study design as well as the influence of climate.

Study Design Effects on Calculating Carbon Sequestration Rates

While the 1997 study was designed similarly to the 2004 study, there were significant differences. The 2004 study sampled farmed and drained wetland catchments on cropland as well as restored wetland catchments on CRP and WRP lands, and the 1997 study sampled only restored and native wetland catchments. The 2004 survey included the upland zone, whereas the 1997 study included only the wetland zone.

The paired-site design used in the 2004 study is a commonly used approach to estimate SOC sequestration rates and has been used in other carbon sequestration studies. This approach involves comparing SOC stocks on restored lands to stocks measured from cropland sites that are similar in edaphic and climatic factors. However, the results from the 2004 study found carbon stocks to be significantly higher in cropland than in restored catchments in the Missouri Coteau and statistically similar between restored and cropland wetland catchments in the Glaciated Plains (fig. 3).

In addition, the 2004 study did not find a linear increase in carbon with restoration age, although the 1997 carbon study in the PPR did find a relationship between restoration age and wetland zone SOC for semi-permanent wetlands (Euliss et al. 2006). As a result, SOC sequestration rates could not be estimated for restored wetland catchments using the 2004 study paired-approach design (i.e., cropland and restored wetlands), and rates could not be estimated for restored wetland catchments based on a relationship between carbon stocks and restoration age (fig. 4). Estimating the SOC sequestration rate for WRP or CRP wetland catchments may require a long-term monitoring approach that includes measuring SOC stocks before, during, and after restoration activities on individual Farm Bill program wetland catchments.

Climate Effects on Carbon Sequestration Rates

Climate variability (both spatial and temporal) is another factor that was hypothesized to affect calculation of carbon sequestration rates for restored wetland catchments on WRP and CRP lands for the 2004 study. The climate of the PPR is extremely variable inter- and intra-annually, and exerts a profound influence on ecosystem processes, including carbon dynamics, as well as on cropping practices. During dry conditions, many wetland catchments in the PPR are farmed, with a subsequent loss of SOC. However, during wet conditions, the same catchments are left idle, enhancing vegetation re-establishment and carbon sequestration.

The variable wet-dry conditions also affect SOC sequestration rates in restored wetland catchments. It is hypothesized that the primary source of SOC in prairie pothole wetlands that leads to SOC sequestration is the belowground biomass of emergent vegetation. This occurs during dry to moderately wet conditions. During increasingly wet conditions, emergent vegetation is replaced by floating aquatic communities, and sedimentary carbon sequestration becomes the primary process of sequestration. As such, it is likely that restoration age is less of a factor on SOC sequestration rates than the vegetation/hydrologic phases occurring in the restored wetland basin.

Restored wetland catchments sampled for the 2004 study spanned 19 years (1986–2004), and included one of the most extreme drought and deluge periods in the past 100 years for the PPR. The influence of climate on SOC was interpreted by plotting the Palmer Drought Severity Index against SOC and

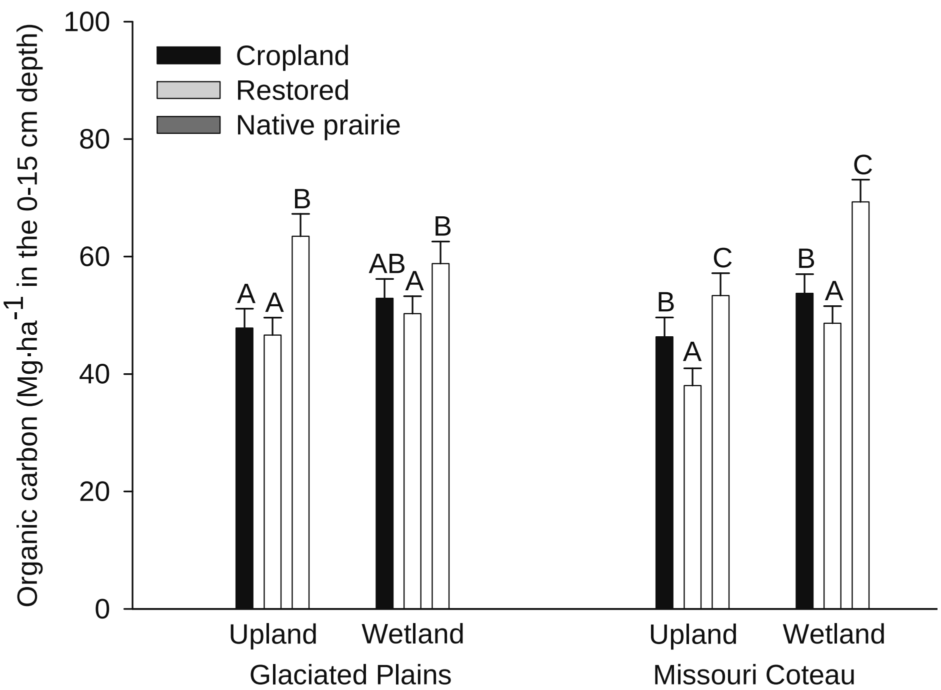
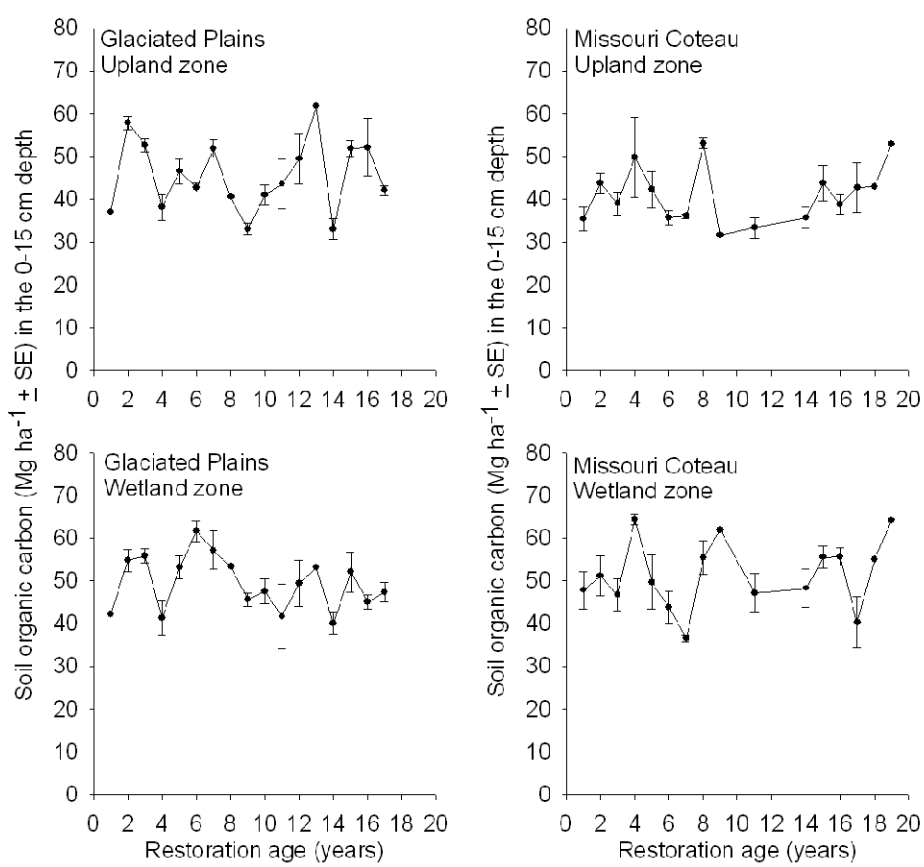


Figure 3 (top). Soil organic carbon in the surface soil (0–6 in; 0–15 cm) among land use treatments (cropland, restored, native prairie) in the upland and wetland zones of sampled catchments in the Glaciated Plains and Missouri Coteau physiographic regions of the PPR. Bars with a common letter (A, B, C) within a catchment zone and physiographic region are not significantly different ($P > 0.05$) (Gleason et al. 2008b).

Figure 4 (bottom). Relationship between SOC in the soil surface (0–6 in; 0–15 cm) and age of restored catchments by catchment zone (upland and wetland) and physiographic region (Glaciated Plains and Missouri Coteau) (Gleason et al. 2008b).



age for the restored wetland catchments sampled during the 19-year period (see figure C-4 in Gleason et al. 2008b). There were two dominant climatic phases during this time: The first phase occurred during the period 1986–96, and included a period of extreme drought (1986–92) that was followed immediately by an extreme wet period (1993–96). The second phase (1997–2004) showed a gradual change from extreme wet conditions to more normal hydrologic conditions.

It is hypothesized that the high SOC stocks measured for the wetland zones in the catchments on cropland during the 2004 study reflected the inability of producers to cultivate the basins within the catchments during the extreme wet period, and because cultivation of many of these catchments occurred only recently so that tillage practices eventually resulted in incorporation of wetland emergent vegetation that became established and survived during the wet period. However, with continued dry conditions, it is hypothesized that most of the SOC that resulted from incorporation of the emergent vegetation into the soil will be oxidized with CO_2 released to the atmosphere.

The spatial-temporal variability that characterizes the PPR appears to exert a profound influence on ecosystem processes such as carbon cycling and on the ecosystem services produced such as SOC sequestration. Additional studies are needed to understand the spatial and temporal effects of climate on carbon stocks and sequestration dynamics in PPR restored wetland catchments.

Sequestering Carbon in Prairie Pothole Wetland Vegetation

In addition to soil carbon sequestration potential, sequestration of carbon in vegetation through the emergent vegetation pool on restored wetland catchments was estimated to be 788,034 tons. This estimate equates to VOC sequestration of 0.7 ton per acre of restored catchment. While disturbance to the emergent vegetation on restored sites is likely through human management activities or natural events, the vegetation reestablishes quickly to serve as a long-term, continuous sink for CO_2-C storage.

Conclusions

A regional assessment of SOC stocks was conducted in the PPR to evaluate how soil and vegetative carbon in restored wetlands varied in relation to cropland and native prairie catchment baselines. The study showed that SOC stocks in the surface soil (0–6 inches) of wetland and upland zones in both physiographic regions were significantly lower in restored catchments than in native prairie catchments.

In nearly all cases cropland catchments also had significantly lower SOC stocks than native prairie catchments; however, for the Glaciated Plains SOC in the wetland zone of cropland catchments was not significantly lower than that in native prairie catchments.

Sequestration of CO_2-C in soils and plants following restoration was not an intended outcome when the WRP and CRP were originally implemented. Hence, this benefit is considered an additional ecological service that may contribute to offsetting GHG emissions.

In addition to sequestering carbon, restored catchments also may result in reduction of other greenhouse gas emissions, such as N_2O and CH_4, according to studies that have demonstrated nutrient enrichment from agricultural runoff can enhance emissions of greenhouse gases (Merbach et al. 2002). Consequently, converting cultivated cropland to permanent grassland within restored catchments should reduce nutrient enrichment in restored wetlands and lower emission of N_2O, and possibly CH_4 relative to a cropland baseline.

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The Conservation Effects Assessment Project: Translating Science into Practice

The Conservation Effects Assessment Project (CEAP) is a multi-agency effort to build the science base for conservation. Project findings will help to guide USDA conservation policy and program development and help farmers and ranchers make informed conservation choices.

One of CEAP's objectives is to quantify the environmental benefits of conservation practices for reporting at the national and regional levels. Wetland ecosystems provide valuable ecosystem services such as carbon sequestration in a variety of landscapes, the wetland national assessment draws on and complements the national assessments for cropland, wildlife, and grazing lands. The wetland national assessment works through numerous partnerships to support relevant studies and focuses on regional scientific priorities.

This assessment was conducted through a partnership among USDA-NRCS, USDA Farm Service Agency, and USGS Northern Prairie Wildlife Research Center. Personnel from the USDI-FWS, various state agencies and many landowners who granted access to private lands are gratefully acknowledged.

Primary investigators on this project were Robert A. Gleason, Ned H. Euliss, Jr., Murray K. Laubhan, Brian A, Tangen, and Kevin E. Kermes (USGS).

S. Diane Eckles (NRCS, retired) was the CEAP Wetlands Science Leader for this project. William Effland (NRCS) is the current CEAP Wetlands Component Leader.

For more information:
http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/ceap