Annual budgets of soil organic carbon in North Dakota Prairie Pothole Region between 1998 and 2007

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Soil organic carbon (SOC) dynamics are critical to soil fertility and sustainability and are subject to land surface disturbances. To quantify the impacts of annual change in land use and contribute to the NACP Mid-Continent Intensive Campaign Interim Synthesis of Regional CO_2 Fluxes (MCI), we used historical climate variation and land use and management change as primary forces to simulate annual SOC budgets in a pilot study area of the Prairie Pothole Region from 1998 to 2007. We found that the baseline soil carbon level is also a critical factor in determining the annual soil carbon change rate caused by land surface disturbances.

Materials and Methods

Study Area

The study area is a typical representative of the North American Prairie Pothole Region, located in Stutsman County of North Dakota, USA, and the area covers 260 km^2. The western part belongs to the Missouri Couteau and the eastern part is glaciated depressional lowlands. The semiarid climate has a mean annual precipitation of 399 mm (±61 mm) and a mean annual temperature of 3.5°C (±2.1°C) averaged from 1998 to 2007. The land is mainly covered by agriculture (44%), grassland (26%), and water/wetlands (13%). The spatial patterns of land use types in 2001 are illustrated in figure 1.

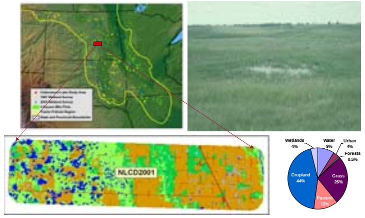

Figure 1. Location of the study area, with land use and land cover classes defined by NLCD 2001.

Modeling System

The General Ensemble biogeochemical Modeling System (GEMS) (Liu et al., 2004) (fig. 2) was used to simulate ecosystem carbon (C) dynamics.

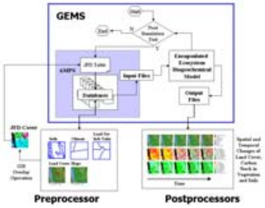

Figure 2. A diagram of GEMS. It consists of three major components: one or multiple encapsulated ecosystem biogeochemical models, a data assimilation system (DAS), and an input/output processor (IOP).

JFD: joint frequency distribution
AMPS: automated model parameterization system

Input Data

A joint frequency distribution (JFD) grid was generated as a simulation unit by overlaying the following GIS grids (60m): USDA NASS cropland grids from 1998 to 2007, PRISM climate map (mean monthly precipitation and mean monthly minimum- and maximum temperatures from 1972 to 2007), SSURGO soil database, nitrogen deposition map, drainage class map, and irrigation distribution. Attribute data include crop composition, crop rotation, FIA, tillage and residue management statistics.

Ensemble Simulations and Uncertainty Control

GEMS simulations of each JFD case were executed to incorporate the variability of inputs. Values of selected output variables were written to a set of output files after each model execution and then aggregated for the study area using SAS Macros program. Meanwhile, the uncertainty of simulations was evaluated in terms of the coefficient of variation (CV) with all model outputs. We used NASS grain yields of major crops (http://www.nass.usda.gov/Statistics_by_State/) and SOC information from literature as references to verify corresponding outputs. We repeatedly ran simulations by adjusting parameters after each run until the outputs matched the references as closely as possible. Figure 3 indicates that about 81% of the variance in the simulation of grain yield can be explained. The slope and intercept of the regression line are not significantly different from 1 and 0, respectively.

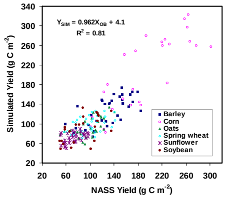

Figure 3. Comparison of simulated crop yields and NASS crop yields from 1998 to 2007.

Results and Discussions

Annual Land Use Change

The data derived from USDA NASS annual cropland maps indicate that the annual variation in cropland and grassland was associated with the rotation among cropping systems and the conversion between grassland and cropland. Planted areas for barley, spring wheat, and sunflower declined sharply from 1998 to 2007, while the areas for corn and soybean expanded from 0.5% to 13.5% and from 1.0% to 14.6%, respectively.

Historical SOC Stock Change Trends

Table 1 shows that the average SOC stock in the top 20 cm of soil for the whole study area declined from 85.8 Mg C ha^{-1} in 1972 to 75.9 Mg C ha^{-1} in 1998 with an annual loss rate of 0.38 Mg C ha^{-1}yr^{-1}. But the average SOC stock varied with land use types; agricultural land experienced the maximum reduction (0.45 Mg C ha^{-1}yr^{-1}). Since 1998, the whole study area has turned out to be a SOC gain at an annual rate of 44 kg C ha^{-1}yr^{-1}. The SOC sources and sinks (spatial patterns) as of 2007 compared with the baselines in 1998 are illustrated in figure 4.

Table 1. The baseline SOC stocks of major land use classes and their change rates

Land use type	Number of pixel			Change in pixel	Base 1972	1972-1998	Base 1998	1998-2007
	1972	1998	2007	1998 - 2007	Mg C ha^{-1}	Mg ha^{-1}yr^{-1}	Mg C ha^{-1}	Mg ha^{-1}yr^{-1}
Forest	275	237	297	60	74.0	-0.22	75.0	-0.02
Grassland	7344	6618	4865	-1753	81.9	-0.11	76.1	0.04
Agriculture	26327	24342	22705	-1637	86.6	-0.45	75.9	0.07
Wetland	1836	1684	3309	1625	95.9	-0.38	75.6	0.04
Mean					85.8	-0.38	75.9	0.04
Stdev					22.9	0.27	19.7	0.40

Pixel size = 60 x 60m^2.

Figure 4. SOC sources or sinks as of 2007 in comparison with the baseline in 1998.

Annual Net Ecosystem Exchange in Croplands

As illustrated in figure 5, counting the biomass removed by harvesting, the ecosystem was a C sink with increasing strength from 1998 to 2007 because of the increase in above-biomass production even though there were annual variations. Meanwhile, SOC stock had varied about the neutral line but still followed the net ecosystem carbon flux pattern and trend. Such annual variation can be attributed to the annual land use alteration, especially the crop rotation between corn and other crops.

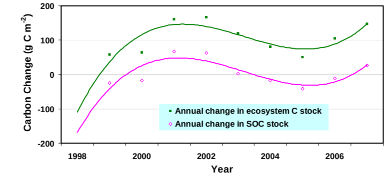

Figure 5. Annual ecosystem C and SOC balances within the study area (SOC balance means the difference in soil organic carbon stock from the previous year, and system C balance refers to the sum of SOC balance and removed C by harvesting grain and straw).

Annual SOC Change Rate as Related to the Baseline

The annual SOC change rate is logarithmically functional of the baseline SOC magnitude despite a fairly good linearity (see fig. 6). Averaged over the whole study area, this kind of regression model can explain about 63% of all variance. However, the model varies with land use type, and the coefficient of determination (R^2) ranges from 0.31 for forestland to 0.69 for cropland. In general, the soils having higher baseline SOC tend to be more sensitive to the disturbances and to become greater carbon sources (Tan et al., 2006).

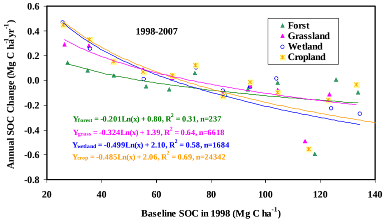

Figure 6. Annual SOC change rate in the top 20 cm of soil compared to the baseline SOC in 1998.

Conclusions

1. An increase in corn area and other favorite management practices from 1998 to 2007 led to a remarkable increase in biomass production which, coupled with extension of conservation residue management, significantly mitigated soil carbon emissions and altered cropping systems from carbon sources to small carbon sinks.
2. The annual change in the cropping system was a major force driving ecosystem carbon fluxes and resulting in spatial variability of annual SOC budgets across all croplands.
3. The annual change rate of SOC stock in all kinds of land significantly depends on the baseline SOC levels, and soils with higher carbon stock (about 70 Mg C ha^{-1} in this case) tend to be carbon sources, while soils having lower C contents likely turn out to be carbon sinks following conservation management.

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References

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