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Simulating the effects of management practices on cropland soil organic carbon changes in the Temperate Prairies Ecoregion of the United States from 1980 to 2012

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ABSTRACT

Understanding the effects of management practices on soil organic carbon (SOC) is important for designing effective policies to mitigate greenhouse gas emissions in agriculture. In the Midwest United States, management practices in the croplands have been improved to increase crop production and reduce SOC loss since the 1980s. Many studies of SOC dynamics in croplands have been performed to understand the effects of management, but the results are still not conclusive. This study quantified SOC dynamics in the Midwest croplands from 1980 to 2012 with the General Ensemble Biogeochemical Modelling System (GEMS) and available management data. Our results showed that the total SOC in the croplands decreased from 1190 Tg C in 1980 to 1107 TgC in 1995, and then increased to 1176 TgC in 2012. Continuous cropping and intensive tillage may have driven SOC loss in the early period. The increase of crop production and adoption of conservation tillage increased the total SOC so that the decrease in the total SOC stock after 32 years was only 1%. The small change in average SOC did not reflect the large spatial variations of SOC change in the region. Major SOC losses occurred in the north and south of the region, where SOC baseline values were high and cropland production was low. The SOC gains took place in the central part of the region where SOC baseline values were moderate and cropland production was higher than the other areas. We simulated multiple land-use land-cover (LULC) change scenarios and analyzed the results. The analysis showed that among all the LULC changes, agricultural technology that increased cropland production had the greatest impact on SOC changes, followed by the tillage practices, changes in crop species, and the conversions of cropland to other land use. Information on management practice induced spatial variation in SOC can be useful for policy makers and farm managers to develop long-term management strategies for increasing SOC sequestration in different areas.

1. Introduction

Identifying the key processes and drivers controlling carbon (C) fluxes is critical to make C management decisions (Michalak et al., 2011). Soil organic carbon (SOC) is an important storage component of ecosystem C that is influenced largely by human activities in agricultural ecosystems. Many early studies showed that SOC declined after land use change from natural grassland to cropland (Follett, 2001; Lal et al., 2007a, 2007b). But studies have also shown that changing agricultural management practices can increase SOC in croplands (Ogle et al., 2003; US-EPA, 2012). There are also studies suggesting that croplands have a large potential to sequestrate C and mitigate greenhouse gas (GHG) emissions (Eve et al., 2002; Lal et al., 2007a). However, there are still substantial discrepancies among studies of C sequestration in croplands. For example, a study in Iowa found that the C sequestrated in cropland soils by reduction in tillage intensity was about 1.9 TgC based on 1998 data (Brenner et al., 2001). A later study showed that the increase in SOC may be much lower (0.6 TgC) by accounting for SOC loss due to the periodic alternating of low- and high-intensity tillage practices (West et al., 2008). But a study using a process model indicated that SOC

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in Iowa is a C source if the whole soil profile was considered instead of only the top 20 cm soil (Causarano et al., 2008). Another study using a process model also found that SOC in the whole soil profile decreased in Iowa due to the improvement of cropland soil drainage conditions (Liu et al., 2011).

In the Midwest temperate prairies of the United States, most of the native grasslands were converted to croplands after European settlement beginning in the 1860s (Parton et al., 2007). Grassland SOC declines by up to 50% after cultivation, but such losses could be overcome by improved cropland management. Past research suggests that increases in conservation tillage in croplands have sequestrated more SOC in croplands than other practices, such as land use change and crop rotation (Eve et al., 2002; Lal et al., 2007a; West et al., 2008). Several studies have shown that SOC increased on croplands in the United States due to conservation tillage and cropland restoration programs (Eve et al., 2002; Ogle et al., 2009; Ogle et al., 2003; West et al., 2008). However, about 37% of the croplands in the United States are still using intensive tillage (CTIC, 2008). These croplands may not sequester much SOC, or may even lose SOC since they have higher SOC decomposition rates and surface erosion (Auerswald et al., 1994; Leys et al., 2010). A study on the Midwest croplands found the change to less intensive tillage increased SOC by 45 TgC from 1990 to 2000 but that tillage intensification caused a SOC loss of 11.2 TgC during the same time period (West et al., 2008). Thus, when considering the effects of tillage management on cropland SOC dynamics at the landscape scale, it is necessary to include all the changes in tillage practices.

Research also has shown that increasing C input through cropping practices is as important as reducing tillage intensity (Ogle et al., 2005). Increases in crop NPP not only produce more crop residues but also increase root biomass, both of which increase C inputs into the soil (Follett, 2001; Lal et al., 2007a). Using the U. S. Department of Agriculture (USDA) reported crop yields data, studies found the cropland NPP increased by about 50% between 1972 and 2001 in the Midwest region (Hicke et al., 2004; Prince et al., 2001). Given the large increase in crop production from 1972 to 2001, increased C inputs may become an important factor in the SOC dynamics in the Midwest region. A study on European cropland C dynamics using model simulations found that increasing crop residue return to the soil can build up the SOC, but this effect is compensated by other management practices, such as intensification of tillage and replacement of manure by mineral fertilizers (Gervois et al., 2008). A later study using multiple models and inventory data concluded that the agricultural management practices impacting litter inputs were as important as the decomposition of soil organic matter in European croplands (Ciais et al., 2010).

The goal of this research is to study the SOC dynamics for croplands in the Midwest temperate prairies from 1980 to 2012 and understand the mechanisms of SOC changes under the land use and land-cover change (LULC) and management practices. We used spatially explicit land cover data and available cropland management data to investigate two key science questions: Is the cropland soil in the region a C gain or loss, and what is the major driver of SOC dynamics in croplands? These findings will help to develop more effective C management plans for vulnerable soil C pools in this region.

2. Methods

2.1. Study area

The research area is the Temperate Prairies of the Northern Great Plains (Fig. 1). This area is defined as the Level III Ecoregion 9.2 and stretches across eastern North Dakota, Minnesota, eastern South Dakota, most of Iowa, Nebraska, Missouri, Kansas and northern Oklahoma (US-EPA, 1999). This ecoregion covers multiple major land resource areas (MLRA) and has large variation in climate, soil, and cropping systems (USDA, 2006). Eastern North Dakota and eastern South Dakota are in the Northern Great Plains Spring Wheat Region (USDA, 2006). The dominant soil types are Mollisols and the major cropping system is dry-farmed spring wheat. Iowa and western part of South Dakota, Nebraska and Kansas are in the Central Feed Grains and Livestock Region (USDA, 2006). This region has the most favorable climate and soil for agriculture. The major cropping systems are continuous corn and a corn-soybean rotation. Southern Nebraska and Kansas belong to the Central Great Plains Winter Wheat and Range Region (USDA, 2006). The dominant soil types are Mollisols with large areas of Alfisols, Entisols, and Inceptisols. Grazing and dry-farmed winter wheat are the major land uses in this region.

2.2. GEMS modelling framework

The General Ensemble Biogeochemical Modelling System (GEMS) is a regional modelling framework that uses spatially explicit LULC data and biogeochemical models to study C dynamics in large regions (Liu, 2012; Liu et al., 2004). GEMS applies LULC data from remotely sensed products along with information on soils, terrain, and other environmental factors, to provide spatially explicit inputs of vegetation biomass, soil nutrient status, and management practices to biogeochemical models. The GEMS model has been extensively tested for crop management to enable automated processes for calibrating the biogeochemical model parameters with crop inventory data and the explicit inclusion of the major types of management and disturbances on ecosystems (Li et al., 2014; Liu, 2012; Wu et al., 2014).

This study used the biogeochemical model Erosion-Deposition-Carbon-Model (EDCM) in GEMS to simulate the LULC and management impacts on SOC. The EDCM is an ecosystem model that simulates the dynamics of C and nitrogen in vegetation biomass and soil (Liu et al., 2003). It simulates cropland soil C dynamics based on multiple processes such as crop production, residue inputs and soil decomposition at monthly time steps.

2.3. Input data sets

2.3.1. Land use and land cover data

Two LULC spatial data sets published by the U.S. Geological Survey (USGS) were used to construct the LULC history from 1980 to 2012 in the region. Both data sets were simulation results of the forecasting scenarios of land-use change (FORE-SCE) framework (Sohl et al., 2010; Sohl et al., 2007). The first data set was developed to study the ecological processes driving landscape changes in the Great Plains and provided LULC data from 1938 to 1992. The second data set was generated for the USGS Land Carbon project and was used for assessing LULC impacts on ecosystem C dynamics and C sequestration potential (Zhu et al., 2010). This LULC data set was also simulated using FORE-SCE and provided historical data from 1992 to 2005 and future scenario data from 2005 to 2050 (Zhu et al., 2011).

Both data sets have the same spatial resolution (250m) and land cover classifications. To save computation time and matching with climate data, we used the 4 km instead of 250 m spatial resolution. We downloaded the original data sets from the USGS land cover modelling website (http://landcover-modeling.cr.usgs.gov). The two data sets were combined using a python programs and a nearest neighbor method to generate a land cover time series from 1980 to 2012 in the study area with a 4 km spatial resolution. For the years from 2006 to 2012, we used the A2 scenario results. The A2 scenario simulated dramatic increases in anthropogenic land covers and corresponding declines in natural land covers (Sohl et al.,