2017

Simulating the effects of management practices on cropland soilorganic carbon changes in the Temperate Prairies Ecoregion of theUnited States from 1980 to 2012

Zhengpeng Li
South Dakota State University, zli2807@jacks.sdstate.edu

Shuguang Liu
USGS, EROS

Zhengxi Tan
ASRC Federal InuTeq

Terry L. Sohl
USGS, EROS

Yiping Wu
Xi'an Jiaotong University

Li, Zhengpeng; Liu, Shuguang; Tan, Zhengxi; Sohl, Terry L.; and Wu, Yiping, "Simulating the effects of management practices on cropland soilorganic carbon changes in the Temperate Prairies Ecoregion of theUnited States from 1980 to 2012" (2017). *USGS Staff -- Published Research*. 1021.
https://digitalcommons.unl.edu/usgsstaffpub/1021

Ecological Modelling 364 (2017) 68–79

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

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

Zhengpeng Li[a,*], Shuguang Liu[b], Zhengxi Tan[c], Terry L. Sohl[b], Yiping Wu[d]

[a] Geospatial Sciences Center of Excellence, South Dakota State University, Brookings, SD, 57007, United States
[b] U.S. GeologicalSurvey (USGS) Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD 57198, United States
[c] ASRC Federal InuTeq1, Contractor to the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center, Sioux Falls, SD 57198, United States
[d] Department of Earth & Environmental Science, Xi'an Jiaotong University, Xi'an, China

ARTICLE INFO

Article history:
Received 8 October 2016
Received in revised form
20 September 2017
Accepted 21 September 2017

Keywords:
Biogeochemical model
Cropland management
Soil organic carbon

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

---

[*] Corresponding author.
E-mail address: zli2807@jacks.sdstate.edu (Z. Li).
[1] Work performed under USGS contract G13PC00028.

https://doi.org/10.1016/j.ecolmodel.2017.09.017
0304-3800/© 2017 Elsevier B.V. All rights reserved.

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.,

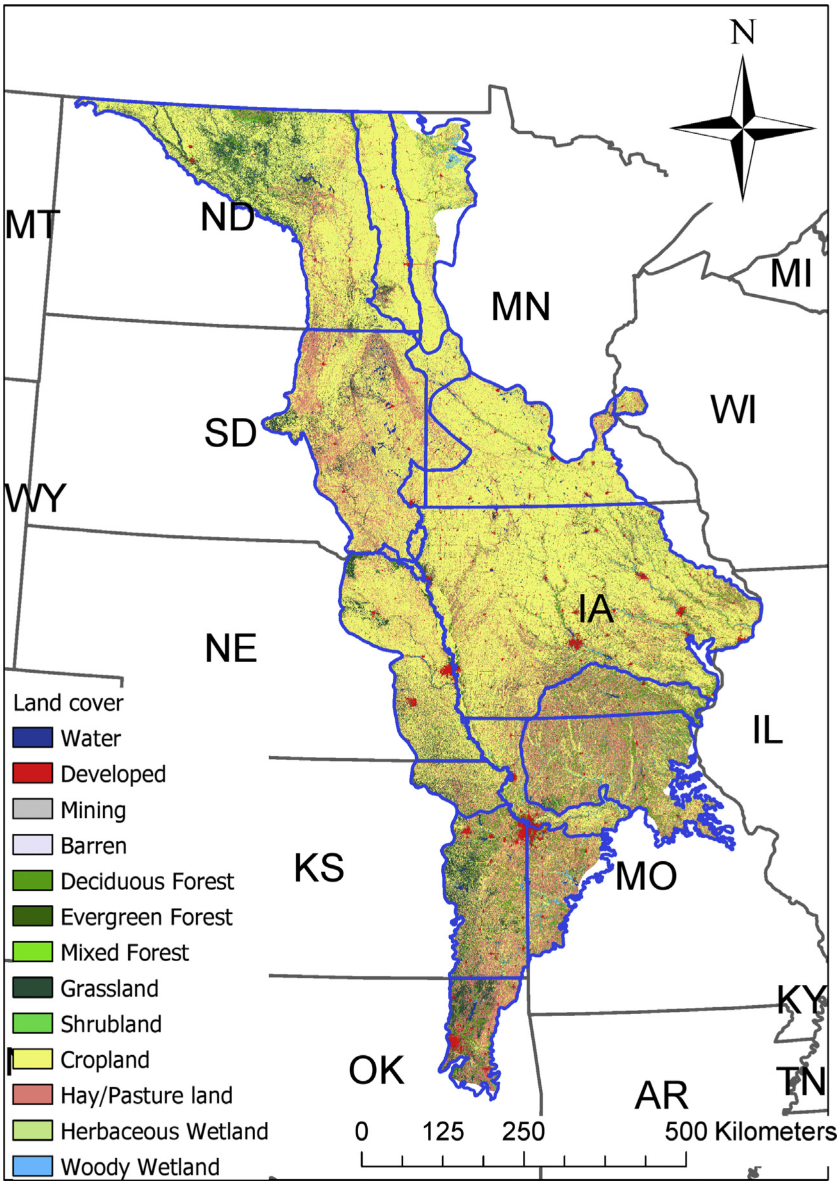

Fig. 1. Land cover types in the Temperate Prairies (Ecoregion 9.2).

2012). In A2 scenario outputs, the cropland area increase from 2006 to 2012, which matched the observations from USDA surveys in this region.

2.3.2. *Climate data*

For this study, we used climate data produced by the Parameter-elevation Regressions on Independent Slopes Model (PRISM) from Oregon State University (PRISM Climate Group, http://www.prismclimate.org, accessed Feb 2014). The PRISM data were downloaded from the Oregon State University ftp site and processed for the study area. The meteorological inputs to the GEMS model were monthly minimum temperature, maximum temperature and precipitation from 1980 to 2012 with 4 km spatial resolution.

2.3.3. *Soil data*

We used the spatial soil dataset generated for the LandCarbon project as the initial soil input for this study. The soil data from the Natural Resources Conservation Service SSURGO database (USDA-NRCS, 2009) were used to generate multiple maps at a 250 m resolution. The soil attributes included soil organic C content, bulk density, available water content and soil texture information.

2.3.4. *Crop management data*

We used county-level USDA-reported yield data and the spatial LULC change data sets to create the annual crop rotations in the cropland. The reported yield data included the county Federal Information Processing Standards (FIPS) code, year, total acres planted for major crops, total acres harvested and yields for major crops within each county from 1980 to 2012. We grouped all the harvested crops into five major categories: corn, soybean, spring wheat, winter wheat and other crops. The planted area for each crop was converted to percentage of the total cropland area in the county. For each simulated cropland pixel, a Monte-Carlo method was used to decide the crop type for each year according to the county-level probability density function of planting areas of crops. A random number between 0 and 100 was generated first; the crop type chosen was the one that allowed the accumulated percent of composition (from 0 to 100) to exceed the random number (Schmidt et al., 2011). The reported yields for the major crops were

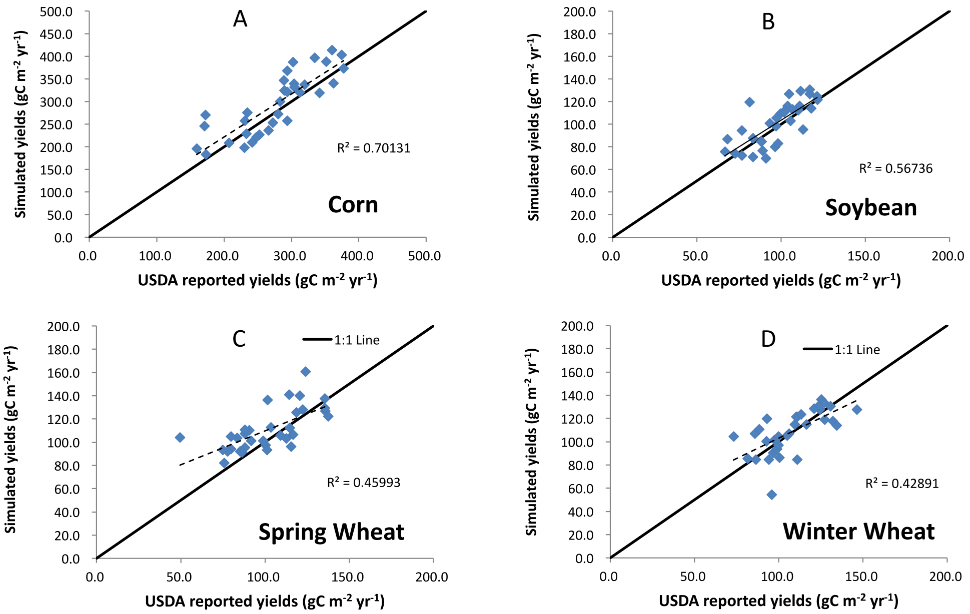

Fig. 2. Simulated annual crop yields compared with U. S. Department of Agriculture reported yields for (A) corn, (B) soybean, (C) spring wheat, (D) winter wheat.

converted to C using the conversion factors from earlier studies and compared with GEMS simulated yields (Li et al., 2014; West et al., 2010).

The tillage practice data were obtained from the National Crop Residue Management Survey collected by the Conservation Technology Information Center (CTIC) (CTIC, 2008). CTIC collected the area information for intensive tillage, reduced tillage and conservation tillage from 1989 to 2004 for corn, soybean and small grains for all the counties. We converted the tillage area to the probability of the tillage by dividing the planted area for each tillage type by the accumulated planted area (Schmidt et al., 2011). We used the county-level probability density function of the tillage practices and the Monte-Carlo method to decide the tillage type for each crop pixel in a given year. A random number was generated and then each tillage fraction was accumulated until the sum exceeded this random number. The tillage fraction that allowed the sum to exceed the random number was the tillage type returned for the current crop type in this year (Schmidt et al., 2011). Any years before 1989 used the tillage probability in 1989 and the years after 2004 used the information in 2004.

2.4. *Crop growth calibration and verification*

The major crop growth parameters were calibrated using state-level crop yield data (Li et al., 2014). A subset of points within the state were randomly selected and simulated to predict crop yields between 1980 and 2012. The simulated crop yields were compared with USDA-reported yield data in the state. The GEMS then adjusted the parameters by the difference and repeated this procedure until the overall prediction error was less than 5% (Li et al., 2014; Wu et al., 2014). The parameters for the major crops (corn, soybean, spring wheat and winter wheat) were adjusted using this method for all the states in the study area and the calibrated parameter values were stored in an external file to be used in the simulation.

The simulated crop yields of the four major crops were compared with the USDA-reported yield data (Fig. 2). Generally, the simulated grain yields achieved a good match with the observed crop yields for the four major crops. The GEMS simulated corn yields better than other crops ($R^2 = 0.70$). Compared with corn and soybeans, the simulated wheat yields showed poor performance for capturing annual variations. We encountered some difficulties in matching the planting date with winter wheat in the spring. For winter wheat, the typical planting date is usually in the fall and harvest date is in the late spring. The GEMS simulates crop growth at monthly time steps and this simplification may result in more bias in the spring than in the summer when temperatures are high. We also noticed some over estimation of crop yields for all the crops in certain years. GEMS simulations overestimated the crop yields under extreme climate conditions, such as drought and flooding. For example, in 2012, severe drought in the Midwest lowered the yields of major crops (Boyer et al., 2013), but the simulated crop yields were 5–20% higher than reported yields in 2012. The overestimation of crop yields in the model introduced more C into the soil and increased the SOC.

2.5. *Model simulation scenarios*

To assess the LULC and management practice impacts on SOC dynamics, we used five model scenarios based on data availability:

1. Historical scenario (HIST): This scenario used all the management information collected, such as historical LULC, crop growth information and CTIC data to estimate the carbon changes. The simulation was done by combining all the historical management data from 1980 to 2012. This scenario also considered cropland production increases under improved technology.
2. Tillage scenario (NOTILLCHANGE): This scenario assumed that all the tillage practices remained the same as the tillage practices in 1980. Other modelling data were the same as HIST.
3. Land cover scenario (NOLCCHANGE): This scenario assumed that cropland area remained the same as the cropland in 1980, without any land cover change to other land covers. Other modelling data were the same as HIST.
4. Crop composition scenario (NOCOMPCHANGE): This scenario assumes that the distribution of crop species planted in the cropland remained the same as in 1980. Other modelling data were the same as HIST.
5. Technology scenario (NOTECHCHANGE): This scenario assumes that technologies to increase cropland production remained the same as in 1980. All other modelling data were the same as HIST.

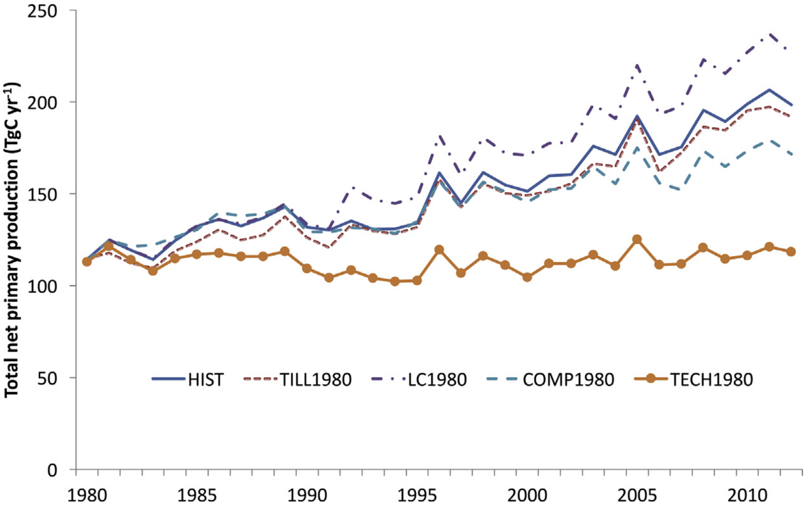

Fig. 3. The percentage of the total planted area changes in (A) conservation tillage and (B) intensive tillage for corn, soybean and small grain between 1989 and 2004 in the study region.

For each simulation, GEMS was first run for 10 years to initialize the C pools and other state variables. The preliminary run used the PRISM climate data in 1980 and applied the same land cover and management practices in 1980. After the preliminary run, GEMS was run with the climate and LULC data from 1980 to 2012 to simulate the SOC dynamics under each scenario. The simulation results from these scenarios were compared to estimate the effects of management practices on SOC dynamics.

The spatial distribution of SOC changes was analyzed at the pixel level in the HIST scenario. The change of SOC in the HIST scenario was calculated for each pixel as:

$$\Delta \mathrm{SOC} = (\mathrm{SOC}[2012] - \mathrm{SOC}[1980])$$

In order to demonstrate the consequences of the different land management practices on ecosystem SOC, we examined the simulated impact of these practices on SOC for all the counties. To make the results comparable, we used the relative change instead of actual change values. For the HIST scenario, we calculated the relative SOC changes in each county between1980 and 2012 by:

$$\mathrm{RatioHIST} = \mathrm{SOC}[2012]/\mathrm{SOC}[1980]$$

For all the other scenarios, we computed the ratio of the 2012 SOC values between each scenario and the HIST scenario to assess the change of SOC in the scenario in each county.

$$\mathrm{Ratio} = \mathrm{SOC_{sce}}[2012]/\mathrm{SOC_{HIST}}[2012]$$

If the ratio value is lower than 1.0, this means either less SOC was accumulated or more SOC was lost than the HIST scenario. If the ratio value is higher than 1.0, then more SOC was accumulated or less SOC was lost. Thus, the scenario impacts on SOC can be observed from the ratio values, where ratio values higher than 1.0 are positive impacts and ratio values less than 1.0 are negative impacts.

3. Results

3.1. Land-use land-cover and management practice changes

Cropland occupied about 60% of the total land area and 74% of the agricultural area in Ecoregion 9.2. The LULC changes in crop area from the FORE-SCE model results were small and the amount of change varied in different time periods. The total cropland area decreased about 1.8% between 1980 and 2001, from 32.03 Mha in 1980 to 31.46 Mha in 2001. After 2001, the total cropland area

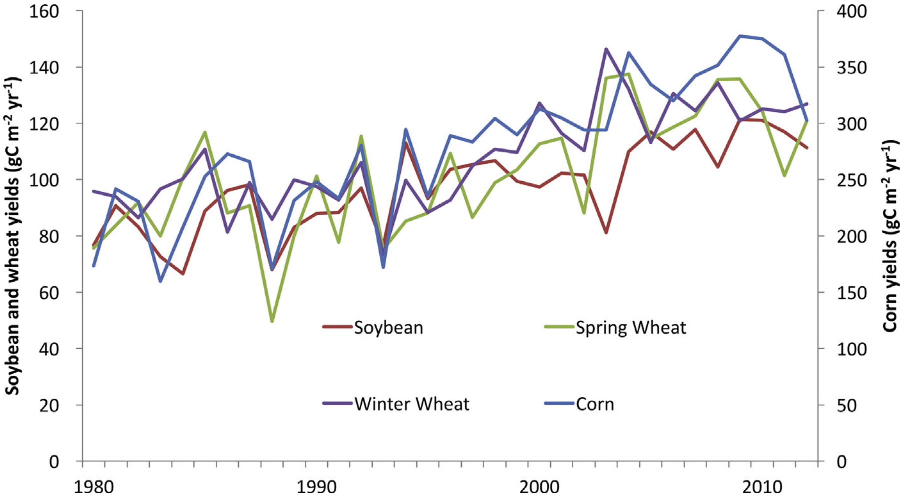

Fig. 4. The percentage of the total planted area changes between 1980 and 2015 for the major crops.

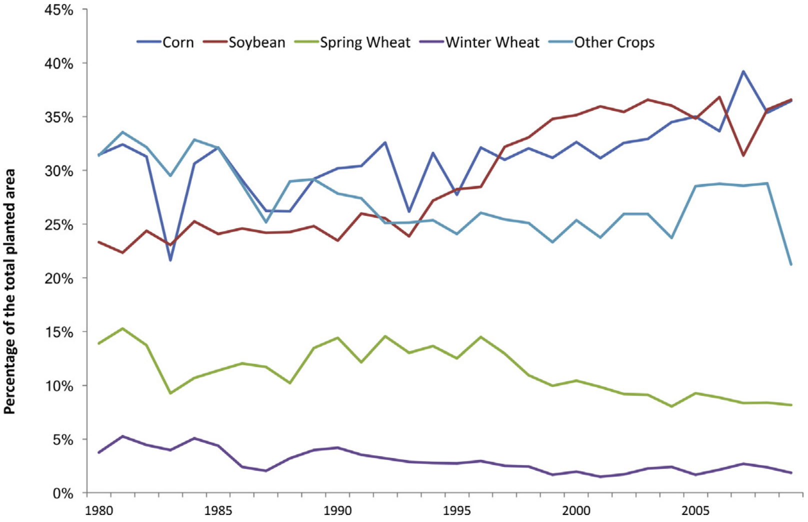

Fig. 5. The changes in yields from 1980 to 2012 for corn, soybean, spring wheat and winter wheat.

increased slightly to 31.52 Mha in 2012. In all the modelled cropland pixels, 77% of them had no land-use change for the 33-year period. 23% of the cropland pixels experienced some type of land-use change between 1980 and 2012, with most of the changes happening between 1989 and 2000. Of the cropland pixels that changed to other land cover types, about 84% of the pixels changed to grassland/pasture, 10% changed to wetlands, 5% changed to developed land, and only 1% changed to forest land.

The fractions of conservation tillage and intensive tillage in the total cropland area are shown in Fig. 3. The conservation tillage fractions for three crop categories showed clear increases from 1989 to 1994 (Fig. 3A). The soybean crop type had the highest increase in conservation tillage, while the small grains had the lowest. Between 1994 and 2004, only the soybean crop type had some increase in the fraction of conservation tillage. The fraction of conservation tillage of the corn and the small grain both decreased from 1994 to 2004. The intensive tillage fractions exhibited different trends from the conservation tillage (Fig. 3B). Between 1993 and 2004, the intensive tillage on soybean fields had the largest decrease. For the small grains crop type, intensive tillage decreased between 1989

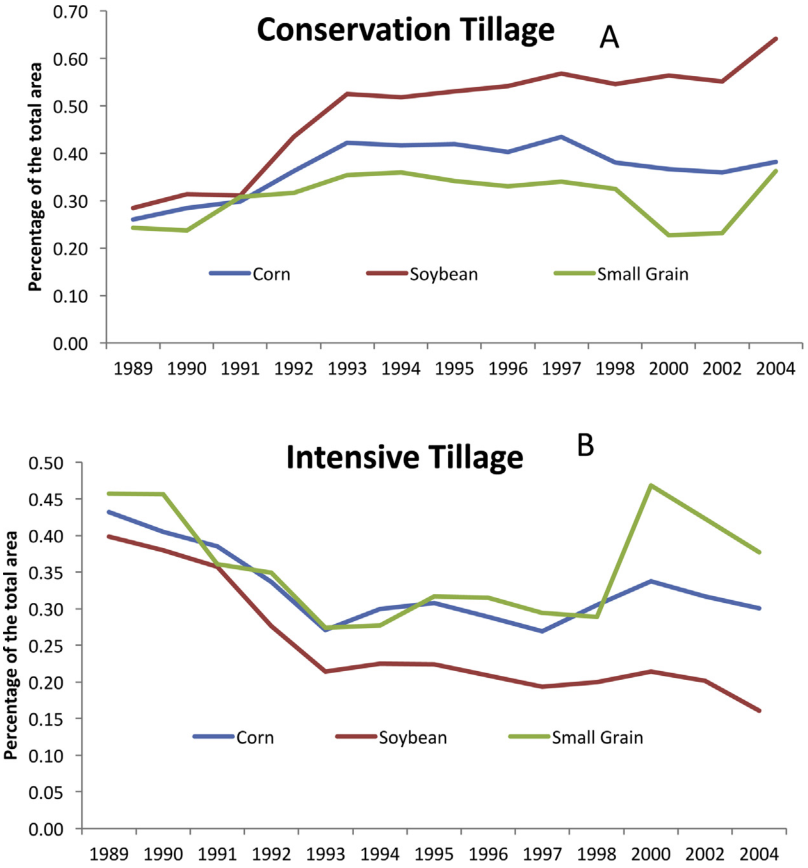

Fig. 6. Simulated cropland total net primary production change from 1980 to 2012 in the 5 scenarios described in Section 2.5.

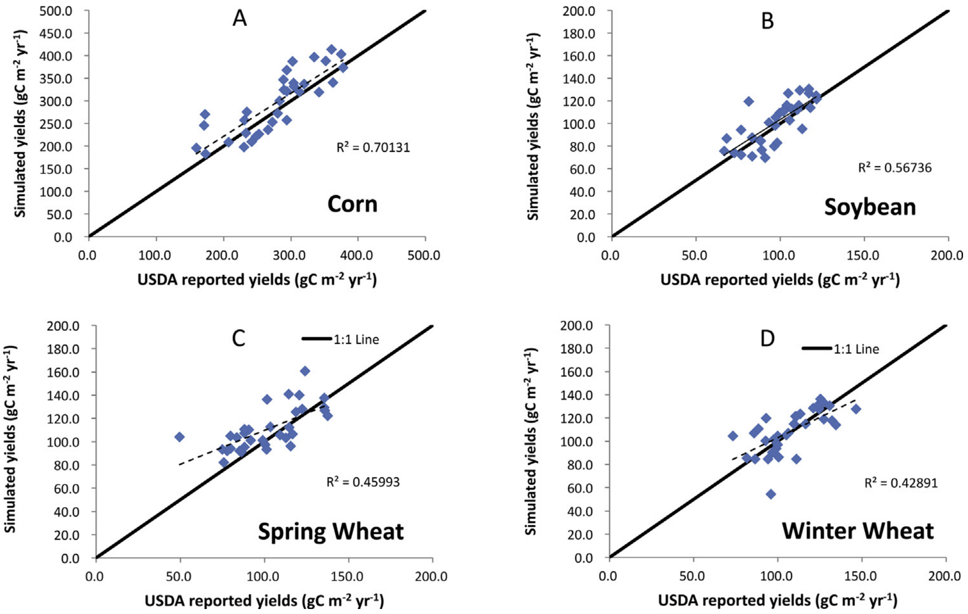

Fig. 7. Simulated cropland total soil organic carbon change from 1980 to 2012 in the 5 scenarios described in Section 2.5.

and 1993, but increased thereafter to 47% in 2002 and declined 37% in 2004.

The planted area for the major crops also changed from 1980 to 2012 in the region. We calculated the percentage of the total planted area for the major crops using the data from USDA reported crop planted areas. The results showed that the percentage of the total planted cropland area for the two major crops, corn and soybean, steadily increased from 1980 to 2012 (Fig. 4). The percentage of the corn-planted area increased from 30% in 1980s to 34% in 2000s. The percentage of the soybean-planted area also increased from 24% in the 1980s to 35% in the 2000s. Meanwhile, the total percentage of the planted wheat (spring and winter) and other crops decreased from 45% in the 1980s to 30% in the 2000s.

We calculated the major crop yields in the amount of organic carbon using the data from USDA reported crop yields with the method from the previous studies (Li et al., 2014; West et al., 2010). Overall, yield of the four major crops increased between 1980 and 2012 (Fig. 5). The corn yields were much higher the other three crops and had the largest increase between 1980 and 2012 (Fig. 5). At the same time, the yields of soybean increased only 30%. The spring wheat increased 41% between 1980s and 2000s and the winter wheat yields increased only 32%.

3.2. Simulated cropland C dynamics under the scenarios

The simulated cropland total NPP increased from 1980 to 2012 for all the scenarios except NOTECHCHANGE (Fig. 6). The annual total NPP for cropland increased about 43% over time in the HIST scenario, from 128.1 ± 9.5 TgC yr^{-1} (1980–1990) to 183.3 ± 15.8 TgC yr^{-1} (2000–2012). This increase agreed with previous studies which found that the cropland production in the Midwest has increased since 1980 (Hicke et al., 2004; Prince et al., 2001). The simulated NPP was slightly lower for the NOTILLCHANGE than HIST scenario, probably caused by the lower SOC levels in the NOTILLCHANGE scenario. Out of all the scenarios, the highest NPP was in the NOLCCHANGE scenario, which had the largest cropland area of all the scenarios. Other studies also showed that restoring grassland/pasture on previous cropland caused a large decrease in plant production (Hartman et al., 2011). The NOCOMPCHANGE scenario had lower total NPP than the HIST scenario after 1995 because less corn was planted in the NOCOMPCHANGE scenario than in the HIST scenario. Since corn has much higher production than all the other field crops, less corn planted area produced lower values of total NPP than the HIST scenario. The NOTECHCHANGE scenario had the lowest NPP since it excluded the technology improvement effects on crop production.

SOC changes generally followed the same trend, with the significant exception of the NOTECHCHANGE scenario (Fig. 7). In the HIST scenario, the total SOC decreased about 6% between 1980 and 1996, from 1190 TgC to 1107 TgC, and then increased about 5% to 1176 TgC in 2012 (Fig. 7). The annual decrease rate of SOC in the HIST scenario was 5.1 TgC yr^{-1} from 1980 to 1996 and the mean rate of increase was 4.3 TgC yr^{-1} from 1996 to 2012. The other three scenarios: NOTILLCHANGE, NOLCCHANGE and NOCOMPCHANGE all exhibited similar trends but with different turning points and SOC levels in 2012. In the NOTILLCHANGE scenario, the total SOC kept decreasing until 2000 and increased to 1133 TgC in 2012. The total SOC in the NOLCCHANGE scenario decreased from 1980 to 1992 and increased to 1212 TgC in 2012. The total SOC in the NOCOMPCHANGE scenario decreased from 1980 to 1996 and increased to 1144 TgC in 2012. In all the scenarios, the NOLCCHANGE had the highest SOC after 32 years, about 2% higher than the SOC in 1980. The HIST scenario had about a 1% loss in SOC, followed by the NOCOMPCHANGE (4%) and NOTILLCHANGE (5%) scenarios. The NOTECHCHANGE scenario had the largest SOC loss (14%) between 1980 and 2012. These results indicate that technology improvements, which increased cropland production, may contribute more to the total SOC changes in the region than other management practices.

3.3. Spatial distributions of soil organic C changes

The highest amounts of SOC were found in North Dakota, Minnesota and Iowa (Fig. 8A). The SOC losses were mainly in the northern part of the region and the SOC gains were in the central part of the region (Fig. 8B). Out of the cropland pixels simulated, 47.8% had SOC losses higher than 5% and 37.5% had SOC gains higher than 5% after 32 years, and the rest of the pixels (14.7%) had smaller changes (< 5%) in SOC after 32 years. SOC gains were mainly in the regions with lower initial SOC and SOC losses were in the region

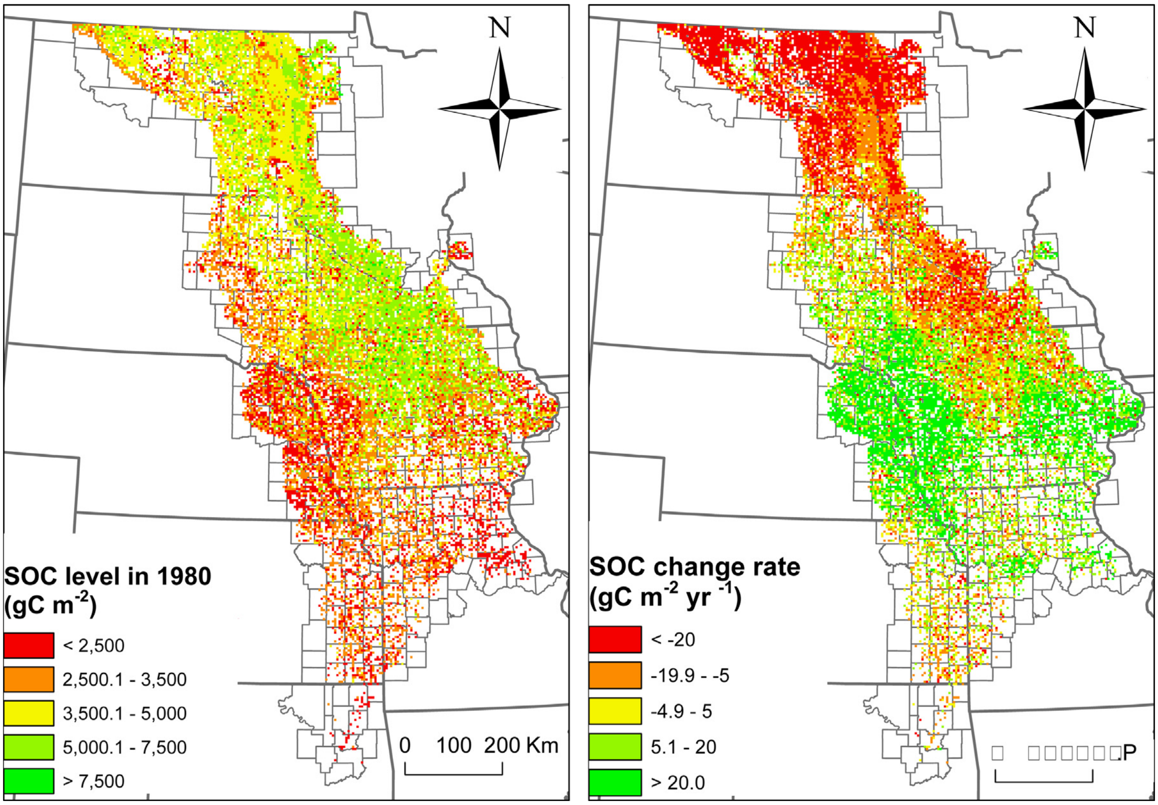

Fig. 8. Cropland (A) soil organic carbon stocks (top 20 cm) in 1980 and (B) the soil organic carbon change rate in the HIST scenario. Scenario details are described in Section 2.5.

with high initial SOC. The spatial patterns indicate that the croplands in the northern and southern parts of the region generally lost soil C, while the croplands in the center of the region sequestrated soil C.

The HIST scenario exhibited the same spatial pattern as the pixel-level results. At the county level, 31% of the counties had a SOC losses higher than 5% after 32 years and 45% of the counties had SOC gains higher than 5% after the same period. SOC losses tended to occur in the northern and southern parts of the region, including North Dakota, Minnesota, and Oklahoma. SOC gains were concentrated in Nebraska, Iowa, and northern Missouri (Fig. 9A).

The ratio of the SOC between the HIST and other scenarios for 2012 had very different spatial patterns. In the NOTILLCHANGE scenario, 43% of the counties had lower SOC values in 2012 than in the HIST scenario but there were also 13% of the counties that had higher SOC values (Fig. 9B). The CTIC survey data showed that the intensive tillage area increased in some counties even though the intensive tillage area decreased in the whole region. In the counties with high initial SOC values in 1980, we found the fraction of intensive tillage increased instead of decreasing. For example, in Decatur County, Iowa, the intensive tillage area for corn increased from 2505 ha in 1989 to 6788 ha in 2004, and the conservation tillage area also increased from 3147 ha to 4963 ha. Thus, the fraction of intensive tillage increased from 25% to 51% in this county. Another example is in McHenry County, North Dakota. The intensive tillage area for the small grains decreased from 47200 ha in 1989 to 40028 ha in 2004, while the conservation tillage area decreased from 28800 ha to 21596 ha at the same time. The fraction of the intensive tillage thus increased 2%, while the conservation tillage decreased 1%. The different changes of the tillage practices in the HIST scenario caused the lower SOC values in these counties (13% of the total counties) than in the NOTILLCHANGE scenario.

In the NOLCCHANGE scenario, less than 2% of the counties had lower SOC than the HIST scenario and 42% of the counties had higher SOC in the cropland in 2012 (Fig. 9C). About 56% of the counties had small changes (<5%) comparing with the HIST scenario after 32 years. This result indicates that the conversion of cropland to other land cover types, such as grassland, did not increase the SOC as much as the improved management practices. These counties are located mainly in Iowa, Nebraska and Missouri, where croplands have high production and use more conservation tillage. Generally, SOC increases when there are more C inputs into the soil. Since 1980, both the increased cropland production and the improved conservation tillage increased C inputs into the soil. This may sequester more SOC than the natural ecosystems that were present before cropland conversion. The counties with lower SOC values were mainly in North Dakota which had a relatively small area of planted corn, but a higher percentage of the intensive tillage. In these regions, converting cropland to other land cover types sequestered more SOC than keeping the cropland as cropland. The results also showed that where cropland had higher yields and more conservation tillage, such as Iowa, Nebraska, and northern Missouri, keeping cropland with crops sequestrated more SOC than converting cropland to other land cover types.

In the NOCOMPCHANGE scenario, about 76% of the counties had small SOC changes (<5%) compared with the HIST scenario. A total of 23% of the counties had lower SOC than the HIST scenario, and only 3 counties had higher SOC, after 32 years (Fig. 9D). The results indicate that the changes in crop composition did not have large effects on SOC changes compared with the other management practices. The counties with low SOC are located in the northern part of the region, including South Dakota, North Dakota and Minnesota. In these counties, we found the corn planted area increased more than other counties in the HIST scenario. The counties with higher

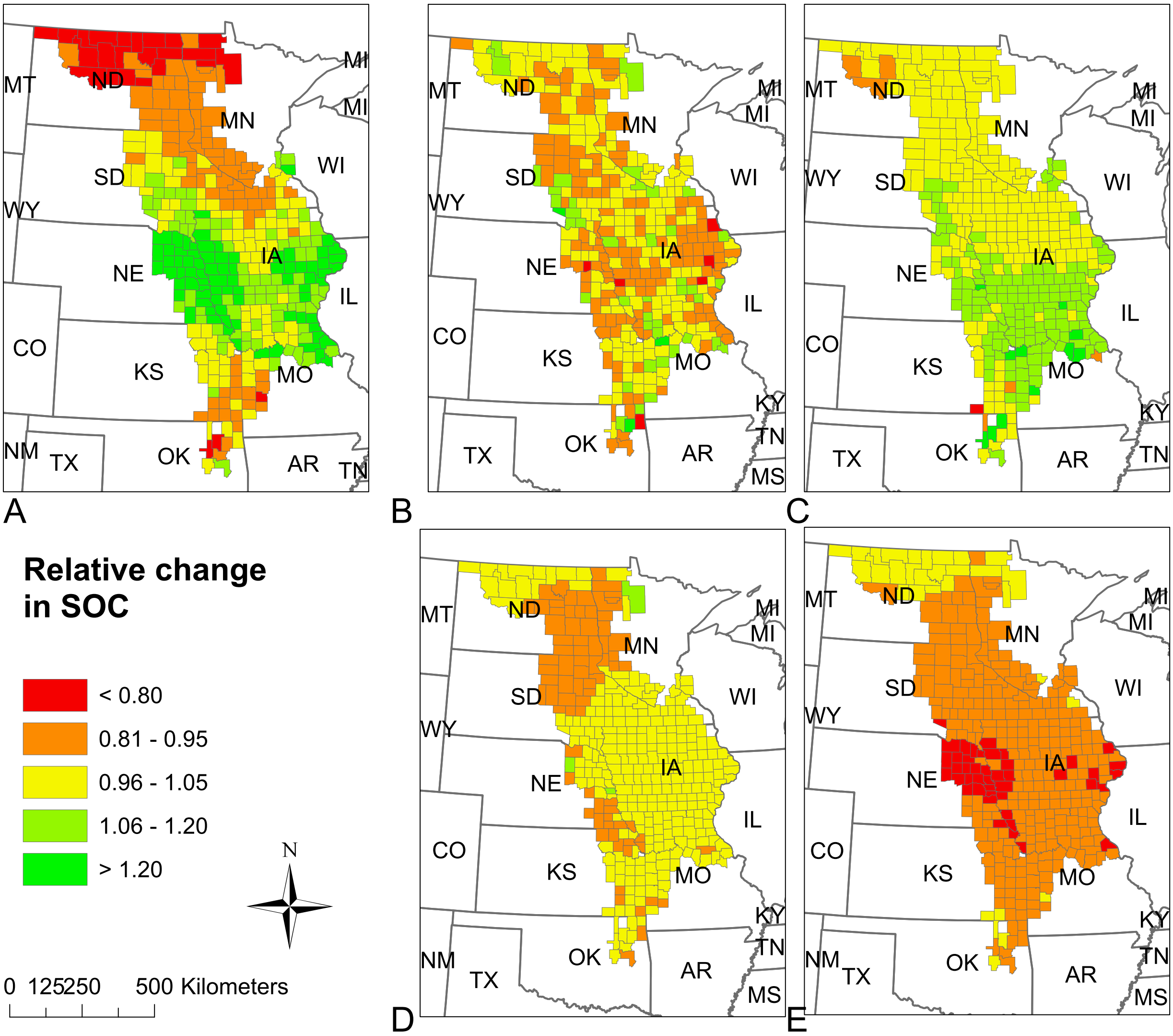

Fig. 9. Ratio of soil organic carbon (A) between1980 and 2012 in the HIST scenario; Ratio of soil organic carbon in 2012 (B) between HIST and NOTILLCHANGE; (C) between HIST and NOLCCHANGE; (D) between HIST and NOCOMPCHANGE; (E) between HIST and NOTECHCHANGE scenario. Scenario details are described in Section 2.5.

SOC had the soybean planted area increase and the corn planted area decrease, during the 1990s in the HIST scenario. For example, in Antelope county, Nebraska, the soybean planted area increased from 14000 ha in the 1980s to over 48000 ha after 2000, more than 300%. During the same time, the corn planted area decreased about 15%, from over 80000 ha in the 1980s to 70000 after 2000. The simulated result in this county showed that the cropland could have 8% higher SOC stocks if the planted area for crops was kept the same as in 1980. Thus, switching to high production crops instead of low production crops would be more likely to increase the SOC carbon stocks.

The NOTECHCHANGE scenario had the largest SOC changes compared with the other scenarios, 91% of the counties had more SOC loss than the HIST scenario and the rest of the counties did not have large differences (Fig. 9E). The counties that had 20% less SOC than the HIST scenario were mainly in Nebraska and Iowa. In these counties, the corn planted area was large and showed SOC gains in the HIST scenario (Fig. 9A). The lower SOC changes in the NOTECHCHANGE scenario suggested that if corn production was kept at the same level as in 1980, these counties would have had much lower SOC gains. The counties with smaller changes in SOC were mainly planted with low yield crops, such as spring wheat and winter wheat. The yields of corn increased about 100 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ between 1980 and 2012, while the yields of wheat increased only about 30 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ (Fig. 5). Large increase in corn production could bring much more C into the cropland soil and increase SOC.

4. Discussions

Characterization of land-use change activities in space and time are usually not available, but our study showed that they can be major factors affecting the C cycle at the landscape scale. Therefore developing relevant geospatial data layers characterizing not only land-cover change but also land-use change represents a major challenge in advancing C cycle research at regional and global scales, consistent with the conclusion of the North American Carbon Program interim synthesis (Liu et al., 2011).

Our study indicated a large increase in cropland production in this region, which agrees well with previous observations (e.g., Parton et al., 2007), and the increased productivity had the largest impact on SOC among all factors we investigated. Enhancement of long-term crop production in the Great Plains can be attributed to increased irrigation, pest management, fertilizer applications, improved tillage practices, and improved plant varieties (Parton et al., 2007). The increase of crop NPP can in turn produce more aboveground residue and root biomass inputs into the soil, resulting in higher levels of SOC (Johnson et al., 2006; Lokupitiya et al., 2012; Wilts et al., 2004). An assessment of European SOC also found that enhanced NPP slowed the loss of SOC and may further increase SOC (Smith et al., 2005). However, some field studies show NPP increase had only limited impacts on SOC as other factors (e.g., crop rotation) might be changing as well. For example, after reviewing the effects of enhancing crop rotations on SOC dynamics, West and Post (2002) found changing wheat-fallow rotation to continuous wheat did not increase SOC even though the cropland production increased. In addition, SOC dynamics is confounded by other important factors such as initial SOC level. NPP increase might lead to SOC increase in less fertile regions, as shown in this study and others (Tan and Liu, 2013).

We found the change of tillage practices had the second largest impact on cropland SOC in this region. Past studies have found that increased use of conservation tillage in cropland has sequestrated more SOC in the cropland than other management practices (Lal et al., 2007a, 2007b; Smith et al., 2008; West and Post, 2002). Several studies also found that SOC has increased on cropland in the United States due to conservation tillage (Ogle et al., 2003; West et al., 2008; Ogle et al., 2009). In this study, we found that while overall conservation tillage increased in the region, intensive tillage increased in some areas as well. These local increases in intensive tillage may reduce the impact of conservation tillage effect at the regional level, as suggested by an earlier study (West et al., 2008). The usage of conservation tillage may also cause lower crop productivity under certain conditions. A review of no-till management impacts on crop productivity found that corn yield could be reduced considerably with no-till under low nitrogen fertilization rates (Ogle et al., 2012).

The temporal patterns of SOC change under various scenarios showed two general temporal patterns of SOC change in our study (Fig. 7). The first was the continuous decrease of SOC under NOTECHCHANGE, which might be caused by instability in the simulated soil C pools. In our study, we used 10 years as the initialization time, which is a common pre-run time in the regional studies (Potter et al., 2009; Zhang et al., 2015). Some studies used long initial time from 2000 to 7000 years and assumed the long-term land use as grassland (Ogle et al., 2007; Ogle et al., 2009; Hartman et al., 2011). The second was the decrease-increase pattern under the other scenarios. The decrease of SOC that occurs before 1995 was shown in some studies to be possible but with high uncertainty. For example, a study of C balances in croplands in the United States found the total C stock slightly decreased prior to 1990 (Lokupitiya et al., 2012). But another study using a process-based model reported that SOC increased in US croplands from 1990 to 2000 (Ogle et al., 2009). The U.S. Environmental Protection Agency (US-EPA) reported that cropland remaining cropland sequestrated 14.2 $\mathrm{TgC\,yr^{-1}}$ in 1990 in the United States (US-EPA, 2012). The differences in the results may be driven by the differences in initial conditions, model inputs, and spatial coverage. Studies with long-term land-use data showed that the increase in SOC could have started earlier in the dryland, roughly in the 1950s. A simulation of 120 years of dryland cropping in the Great Plains suggested that cropland SOC declined since 1890 but increased after 1950 (Hartman et al., 2011). One major discrepancy is that our study showed large SOC loss in poorly-drained soils in the northern part of the region. These poorly-drained soils contained much higher initial SOC than drylands, and that their large SOC decreases could have resulted from drainage for cropping (Lal et al., 2007a). Combining the decreased SOC in these poorly-drained soils with the SOC gains in drylands might have resulted in a net loss of SOC in this region before 1995. This finding agrees with an earlier study which found the land-use and management practice changes on croplands increased SOC in mineral soils by about 6.5–15.3 $\mathrm{TgC\,yr^{-1}}$ but decreased SOC in organic or poorly-drained soils by 6.4–13.3 $\mathrm{TgC\,yr^{-1}}$ from 1982 to 1997 (Ogle et al., 2003).

In our simulations, we found that the effect of different management practices were geographically variable across the region. For example, SOC loss was dominant in the northern part of the study area and SOC gain was evident in the south-central region (Fig. 8B). This spatial pattern of SOC change agrees well with previous studies (Liu et al., 2011; Zhu et al., 2011). The reasons that define the spatial pattern are multifold including initial SOC storage, change of site drainage conditions, and crop species distributions that are dictated more by climate regimes. The north part of the study area was dotted by numerous prairie potholes with poorly drained conditions that promoted high SOC storage (Fig. 8A). The installation of tile drainage in the region for agricultural purposes along with relatively low ecosystem productivity due to climate conditions has led to a loss of SOC (Liu et al., 2011). Therefore the loss of SOC in the north resulted from land-use legacy, and it is unlikely that current agricultural land-use change activities can reverse this trend. In contrast, the high productivity of crops in the south-central part of the region, particularly in Iowa, can maintain or increase SOC.

The area of crop land conversion to other land covers in the region was small during the study period. Consequently, the impact of conversion on SOC dynamics was minimal. Our study highlights the importance of considering land-use change activities for C cycle research in agricultural regions. It is apparent that one cannot assume C gains or losses are neutral in areas experiencing little change in land covers because the ecosystem C conditions (i.e., C stocks and fluxes) under the same or similar land covers might be altered by a suite of other agents.

This study included several limitations. This study did not include the estimates of all GHG emissions from croplands. Past studies showed that when cropland production increased, the net GHG emissions also increased (Hartman et al., 2011). Such increases will reduce the effect of increasing in SOC stocks to mitigate GHG emissions. Another limitation is the changes to soil drainage conditions in the region. Earlier studies showed installation of drainage system could lead to large C losses from deep soils (Liu et al., 2011). These limitations could be addressed in future studies by integrating more data sets, such as the historical change in nitrogen fertilization or cropland drainage map.

Using spatial explicit LULC data inputs and county level survey data, we were able to simulate the SOC changes at a relatively high spatial resolution. Land managers can use such information, as well as local observations, to choose the best management practices in the region for cropland SOC sequestration.

5. Conclusions

The GEMS modelling framework with a coupled biogeochemical EDCM was utilized to investigate management impacts on cropland SOC in the Midwest temperate prairies of the United States from 1980 to 2012. Our simulation results showed that total SOC declined in the temperate grassland region from 1980 to 1995 and then rose again to 2012. Overall the cropland soil in the region lost a small amount C over the 32 years but the results also showed clear spatial differences in SOC changes. Large SOC losses occurred in northern North Dakota and Minnesota and large SOC gains occurred around Iowa. The simulation of multiple management scenarios showed that the technologies used to increase cropland production had the largest impacts on cropland SOC changes, followed by the tillage practices, planted species change and cropland change to other land cover. There was large spatial variation in the effect of these practices on SOC changes. Understanding the spatial patterns of management impacts is important to quantify SOC dynamics at the landscape scale and to provide useful information for better SOC management.

Acknowledgments

We thank Dr. Michael C. Wimberly, Dr. Xiaoyang Zhang and two reviewers for their specific comments and helpful suggestions in improving the manuscript. Any use of trade, firm, or product names is for descriptive purpose only and does not imply endorsement by the U.S. Government.

References

Auerswald, K., Mutchler, C.K., McGregor, K.C., 1994. The influence of tillage-induced differences in surface moisture content on soil erosion. Soil Tillage Res. 32 (1), 41–50 (ISSN 0167-1987).

Boyer, J.S., Byrne, P., Cassman, K.G., Cooper, M., Delmer, D., Greene, T., Gruis, F., Habben, J., Hausmann, N., Kenny, N., Lafitte, R., Paszkiewicz, S., Porter, D., Schlegel, A., Schussler, J., Setter, T., Shanahan, J., Sharp, R.E., Vyn, T.J., Warner, D., Gaffney, J., 2013. The U.S. drought of 2012 in perspective: a call to action. Global Food Secur. 2, 139–143.

Brenner, J., Paustian, K., Bluhm, G., Cipra, J., Easter, M., Elliott, E.T., Kautza, T., Killian, K., Schuler, J., Williams, S., 2001. Quantifying the Change in Greenhouse Gas Emissions Due to Natural Resource Conservation Practice Application in Iowa. Final Report to the Iowa Conservation Partnership. Colorado State University Natural Resource Ecology Laboratory and USDA Natural Resources Conservation Service, Fort Collins, CO, USA.

CTIC, 2008. National Crop Residue Management Survey Data. Conservation Technology Information Center http://www.ctic.org/CRM/.

Causarano, H.J., Doraiswamy, P.C., McCarty, G.W., Hatfi eld, J.L., Milak, S., Stern, A.J., 2008. EPIC modelling of soil organic carbon sequestration in croplands of Iowa. J. Environ. Qual. 37, 8.

Ciais, P., Wattenbach, M., Vuichard, N., Smith, P., Piao, S.L., Don, A., Luyssaert, S., Janssens, I.A., Bondeau, A., Dechow, R., Leip, A., Smith, P.C., Beer, C., Van Der Werf, G.R., Gervois, S., Van Oost, K., Tomelleri, E., Freibauer, A., Schulze, E.D., Carboeurope Synthesis Team, 2010. The European carbon balance. part 2: croplands. Global Change Biol. 16, 1409–1428.

Eve, M.D., Sperow, M., Paustian, K., Follett, R.F., 2002. National-scale estimation of changes in soil carbon stocks on agricultural lands. Environ. Pollut. 116, 431–438.

Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. XVth ISTRO Conference on Tillage at the Threshold of the 21 st Century: Looking Ahead 61, 77–92.

Gervois, S., Ciais, P., de Noblet-Ducoudré, N., Brisson, N., Vuichard, N., Viovy, N., 2008. Carbon and water balance of European croplands throughout the 20th century. Global Biogeochem. Cycles 22, GB2022.

Hartman, M.D., Merchant, E.R., Parton, W.J., Gutmann, M.P., Lutz, S.M., Williams, S.A., 2011. Impact of historical land-use changes on greenhouse gas exchange in the U.S. Great Plains, 1883–2003. Ecol. Appl. 21, 1105–1119.

Hicke, J.A., Lobell, D.B., Asner, G.P., 2004. Cropland area and net primary production computed from 30 years of USDA agricultural harvest data. Earth Interact. 8, 1–20.

Johnson, J.M.-F., Allmaras, R.R., Reicosky, D.C., 2006. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. Agron. J. 98, 622–636.

Lal, R., Follett, R.F., Stewart, B.A., Kimble, J.M., 2007a. Soil carbon sequestration to mitigate climate change and advance food security. Soil Sci. 172.

Lal, R., Reicosky, D.C., Hanson, J.D., 2007b. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res. 93, 1–12.

Leys, A., Govers, G., Gillijns, K., Berckmoes, E., Takken, I., 2010. Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: the role of residue cover. J. Hydrol. 390 (3–4 (September)), 143–154, http://dx.doi.org/10.1016/j.jhydrol.2010.06.034.

Li, Z., Liu, S., Tan, Z., Bliss, N.B., Young, C.J., West, T.O., Ogle, S.M., 2014. Comparing cropland net primary production estimates from inventory, a satellite-based model, and a process-based model in the Midwest of the United States. Ecol. Modell. 277, 1–12.

Liu, S., Bliss, N., Sundquist, E., Huntington, T.G., 2003. Modeling carbon dynamics in vegetation and soil under the impact of soil erosion and deposition. Global Biogeochem. Cycles 17 (1074) (1010.1029/2002GB002010).

Liu, S., Loveland, T.R., Kurtz, R., 2004. Contemporary carbon dynamics in terrestrial ecosystems in the southeastern plains of the United States. Environ. Manage. 33, S442–S456.

Liu, S., Tan, Z., Li, Z., Zhao, S., Yuan, W., 2011. Are soils of Iowa USA currently a carbon sink or source? Simulated changes in SOC stock from 1972 to 2007. Agriculture. Ecosyst. Environ. 140, 106–112.

Liu, S., 2012. Quantifying the spatial details of carbon sequestration potential and performance. In: McPherson, B., Sundquist, E. (Eds.), Carbon Sequestration and Its Role in the Global Carbon Cycle. American Geophysical Union, Washington DC, pp. 117–128.

Lokupitiya, E., Paustian, K., Easter, M., Williams, S., Andrén, O., Kätterer, T., 2012. Carbon balances in US croplands during the last two decades of the twentieth century. Biogeochemistry 107, 207–225.

Michalak, A.M., Jackson, R.B., Marland, G., Sabine, C.L., Carbon Cycle Science Working Group, 2011. A U.S. Carbon Cycle Science Plan.

Ogle, S.M., Jay Breidt, F., Eve, M.D., Paustian, K., 2003. Uncertainty in estimating land use and management impacts on soil organic carbon storage for US agricultural lands between 1982 and 1997. Global Change Biol. 9 (11), 1521–1542.

Ogle, S.M., Breidt, F.J., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72 (1), 87–121.

Ogle, S.M., Breidt, F.J., Easter, M., Williams, S., Paustian, K., 2007. An empirically based approach for estimating uncertainty associated with modelling carbon sequestration in soils. Ecol. Modell. 205 (3), 453–463.

Ogle, S.M., Breidt, F.J., Easter, M., Williams, S., Killian, K., Paustian, K., 2009. Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model. Global Change Biol. 16, 810–822.

Ogle, S.M., Swan, A., Paustian, K., 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agriculture. Ecosyst. Environ. 149, 37–49.

Parton, W.J., Gutmann, M.P., Ojima, D., 2007. Long-term trends in population, farm income, and crop production in the great plains. Bioscience 57, 737–747.

Potter, S.R., Atwood, J.D., Lemunyon, J., Kellogg, R.L., 2009. A national assessment of soil carbon sequestration on cropland: a microsimulation modeling approach. In: Soil Carbon Sequestration and the Greenhouse Effect, (Soilcarbonseque)., pp. 1–11.

Prince, S.D., Haskett, J., Steininger, M., Strand, H., Wright, R., 2001. Net primary production of U.S. Midwest croplands from agricultural harvest yield data. Ecol. Appl. 11, 1194–1205.

Schmidt, Gail, Liu, Shuguang, Oeding, Jennifer, 2011. Derived Crop Management Data for the LandCarbon Project: U.S. Geological Survey Open-File Report, 2011–1303 (15 p.).

Smith, J.O., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I., Ewert, F., 2005. Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. Global Change Biol. 11, 2141–2152.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. Phil. Trans. R. Soc. B : Biol. Sci. 363, 789.

Sohl, T.L., Sayler, K.L., Drummond, M.A., Loveland, T.R., 2007. The FORE-SCE model: a practical approach for projecting land cover change using scenario-based modelling. J. Land Use Sci. 2, 103–126.

Sohl, T., Loveland, T., Sleeter, B., Sayler, K., Barnes, C., 2010. Addressing foundational elements of regional land-use change forecasting. Landscape Ecol. 25, 233–247.

Sohl, T.L., Sleeter, B.M., Sayler, K.L., Bouchard, M.A., Reker, R.R., Bennett, S.L., Sleeter, R.R., Kanengieter, R.L., Zhu, Z., 2012. Spatially explicit land-use and land-cover scenarios for the Great Plains of the United States. Agric. Ecosyst. Environ. 153, 1–15.

Tan, Z., Liu, S., 2013. Baseline-Dependent responses of soil organic carbon dynamics to climate and land disturbances. Appl. Environ. Soil Sci. 2013, 7.

United States Environmental Protection Agency (US-EPA), 1999. Level III ecoregions of the continental United States. In: Karl, T.R., Melillo, J.M., Peterson, T.C. (Eds.), National Health and Environmental Effects Research Laboratory, Scale 1:7,500,000. U.S. Environmental Protection Agency, Corvallis, Oregon.

United States Environmental Protection Agency (US-EPA), 2012. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010.

United States Department of Agriculture (USDA), 2006. Major Land Resource Regions Custom Report (USDA Agriculture Handbook 296). USDA.

United States Department of Agriculture, (Available online at Accessed 2009) http://websoilsurvey.nrcs.usda.gov/.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation. Soil Sci. Soc. Am. J. 66, 1930–1946.

West, T.O., Brandt, C.C., Marland, G., De La Torre Ugarte, D.G., Larson, J., Hellwinckel, C.M., Wilson, B., Tyler, D.G., Nelson, R.G., 2008. Estimating regional changes in soil carbon with high spatial resolution. Soil Sci. Soc. Am. J. 72, 285–294.

West, T.O., Brandt, C.C., Baskaran, L.M., Hellwinckel, C.M., Mueller, R., Bernacchi, C.J., Bandaru, V., Yang, B., Wilson, B.S., Marland, G., Nelson, R.G., Ugarte, D.G.D.L.T., Post, W.M., 2010. Cropland carbon fluxes in the United States: increasing geospatial resolution of inventory-based carbon accounting. Ecol. Appl. 20, 1074–1086.

Wilts, A.R., Reicosky, D.C., Allmaras, R.R., Clapp, C.E., 2004. Long-term corn residue effects. Soil Sci. Soc. Am. J. 68, 1342–1351.

Wu, Y., Liu, S., Li, Z., Dahal, D., Young, C.J., Schmidt, G.L., Liu, J., Davis, B., Sohl, T.L., Werner, J.M., Oeding, J., 2014. Development of a generic auto-calibration package for regional ecological modeling and application in the Central Plains of the United States. Ecol. Inf. 19, 35–46.

Zhang, X., Izaurralde, R.C., Manowitz, D.H., Sahajpal, R., West, T.O., Thomson, A.M., Xu, M., Zhao, K., LeDuc, S.D., Williams, J.R., 2015. Regional scale cropland carbon budgets: evaluating a geospatial agricultural modeling system using inventory data. Environ. Modell. Software 63, 199–216.

Bergamaschi, B., Bernknopf, R., Clow, D., Dye, D., Faulkner, S., Forney, W., Gleason, R., Hawbaker, T., Liu, J., Liu, S., Prisley, S., Reed, B., Reeves, M., Rollins, M., Sleeter, B., Sohl, T., Stackpoole, S., Stehman, S., Striegl, R., Wein, A., Zhu, Z., 2010. In: Zhu, Z. (Ed.), A Method for Assessing Carbon Stocks, Carbon Sequestration, and Greenhouse-gas Fluxes in Ecosystems of the United States Under Present Conditions and Future Scenarios: U.S. Geological Survey Scientific Investigations Report 2010–5233. (188 p. Also available at) http://pubs.usgs.gov/sir/2010/5233/.

Bouchard, M., Butman, D., Hawbaker, T., Li, Z., Liu, J., Liu, S., McDonald, C., Reker, R., Sayler, K., Sleeter, B., Sohl, T., Stackpoole, S., Wein, A., Zhu, Z., 2011. In: Zhu, Z. (Ed.), Baseline and Projected Future Carbon Storage and Greenhouse-gas Fluxes in the Great Plains Region of the United States: U.S. Geological Survey Professional Paper 1787. (28 p. Also available at) http://pubs.usgs.gov/pp/1787/.