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Modeling impacts of management alternatives on soil carbon storage of farmland in Northwest China

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Abstract

Long-term losses of soil organic carbon (SOC) have been observed in many agriculture lands in Northwest China, one of the regions with the longest cultivation history in the world. The decline of SOC contents not only impaired the soil fertility but also increased the amount of carbon dioxide (CO₂) emitted from terrestrial ecosystems into the atmosphere. However, quantifying the SOC losses at regional scale has long been remaining unsolved. A process-based model, **Denitrification-Decomposition** or DNDC, was adopted in the study to quantify impacts of farming management practices on SOC dynamics for a selected region, Shaanxi Province. The selected domain, with 3 million hectares of cropland across different climatic and farming management regimes, is representative for the major agricultural areas in Northwest China. The DNDC model was tested against long-term SOC dynamics observed at five agricultural sites in China. The agreement between the observed and modeled results indicate that DNDC was capable of capturing patterns and magnitudes of SOC changes across the climate zones, soil types, and management regimes in China. To quantify SOC dynamics for Shaanxi, we constructed a GIS database to hold all of the DNDC-required input information (e.g., weather, soil properties, crop acreage, and farming practices) for all the farmland in the studied domain. Sensitivity tests indicated the spatial heterogeneity of soil properties, especially initial SOC content, was the major source of uncertainty for the modeled SOC dynamics at regional scale. The Most Sensitive Factor (MSF) method was employed in the study to quantify the uncertainties produced from the up-scaling process. The results from the regional simulations for Shaanxi indicated that (1) the overall 3 million hectares of farmland in the province was a source of atmospheric CO₂ with 0.5 Tg C yr⁻¹ lost in 2000 under the current farming management conditions, (2) an increase in the rate of crop residue incorporation from 15% to 50% or 90% converted the farmland from the C source to a C sink with 0.7 or 2.1 Tg C yr⁻¹ sequestered, respectively, and (3) applying farmyard manure at a rate of 500 kg C ha⁻¹ also converted the cropland into a weak C sink with 0.18 Tg C sequestered in the farm-

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land in Shaanxi. In the studied domain, crop residue and farmyard manure used to be the major sources of soil nutrients during the centuries-long cultivation history but were gradually abandoned since 1950s when synthetic fertilizers became available. The results from this modeling study suggest that recovery of the traditional farming practices (i.e., residue incorporation and manure amendment) be a feasible approach to substantially improve the soil C status in the farmland of Shaanxi. The values of C gain or loss from this study for Shaanxi could vary if the modeled domain shifts to other provinces in Northwest China although the general conclusion may remain.

1 Introduction

Since the Industrial Revolution humankind came to realize the great impact of anthropogenic activities on earth systems. Driven by fossil fuel combustion, agricultural cultivation, deforestation and other human's activities, carbon (C) release from terrestrial ecosystems to the atmosphere has exceeded the range earth systems can adjust (Sun et al., 2001). It is estimated that the total terrestrial biosphere C pool is 2000 Gt C, which is approximately three times greater than the total amount of carbon dioxide (CO₂) in the atmosphere. The sum of carbon in dead biomass and soil organic carbon (SOC) pool is up to 1200 Gt C (Falkowski et al., 2000). Soil organic carbon is one of the most important terrestrial pools for C storage, which affect atmospheric CO₂ through C exchange at the soil-atmospheric interface (Cardon et al., 2001; Follett, 2001). Agro-ecosystem, accounting for 10% of the total terrestrial area, is one of the most sensitive terrestrial ecosystems suffering from heavy human disturbances. It has been widely observed that long term farming cultivation caused severe losses of soil carbon (Follett, 2001; Janzen et al., 1998; Sherrod et al., 2003; Wairiu and Lal, 2003; Wu et al., 2003). Conversion of natural prairies or forests to cultivated systems usually causes rapid depletion of the soil organic matter (Buyanovsky and Wagner, 1998). For example, field observations indicated about 40%–50% of soil carbon lost due to the transition from grassland to cultivated cropland at an agro-ecosystem in Australia (Grace, 1996).

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The emissions of CO₂, methane and nitrous oxide from agriculture account for approximately one-fifth of the annual increment of radiative forcing globally (Cole et al., 1997). When changes induced by agriculture-related land-use involving biomass burning and soil degradation are included, the overall radiative forcing amounts to one-third of the anthropogenic impact. In addition, decrease in SOC storage leads to decline of soil fertility and hence threaten agro-ecosystem sustainability.

During the past two decades, a great amount of field and modeling studies have been conducted to demonstrate how to mitigate soil carbon loss by improving farming management practices such as tillage, residue incorporation, manure amendment etc. (Huggins et al., 1998; Janzen et al., 1998; Li, 1995; Li et al., 1994; Paustian et al., 2000; Sherrod et al., 2003). In fact, searching farming management alternatives for optimizing C biogeochemical cycle is becoming a main stream in agricultural studies in many countries (Buyanovsky and Wagner, 1998; Paustian et al., 2001; Post and Kwon, 2000). China possesses about 20% of world population but with only about 10% of world arable land (Chinese environmental status bulletin, 2003). Due to the intensive cultivations in history, 57% of the cultivated soil subgroups or 31% of the total soil area in China have experienced significant carbon losses (Wu et al., 2003). Field observations of agricultural SOC depletion were reported for many locations in China (Li and Pan, 1999; Pan et al., 2003; Qiu et al., 2004; Wang et al., 2003). However, most of the reports stated the losses of SOC observed in individual fields with few estimates for regional or national scale. The soil degradation along with other problems such as decrease in total arable land, erosion, desertification etc., has brought an unprecedented tension to the Chinese agriculture (Pan and Zhao, 2005).

Field observations provide direct information about SOC pools and fluxes at specific sites. However, since SOC is highly dynamic in space and time driven by complex combinations of climate, soil and management conditions, quantifying SOC dynamics at regional or national scale through field measurements is inherently infeasible. Models were developed to try extrapolating the understandings gained at site scale to regional scale (Coleman et al., 1997; Peng et al., 1998; Schimel et al., 2000; Sellers

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et al., 1997). This kind of models, such as DNDC, Roth-C, TEM, Century, CASA etc., have been widely applied for SOC inventory or sequestration in many regions (Smith et al., 1997). Basic processes of physics, chemistry and biology have been embedded in the models to enable them to simulate SOC accumulation and turnover across climate zones, soil types and management regimes. For this study on regional SOC dynamics for China, we selected the **Denitrification-Decomposition** (DNDC) model due to its limited requirement for input parameters as well as its successful applications in other countries (e.g., Pathak et al., 2005; Brown et al., 2002; Butterbach-Bahl et al., 2001). This paper reports how we tested and applied the model for quantifying impacts of farming management alternatives on SOC dynamics in a selected agricultural domain in Northwest China, which possesses the longest cultivation history in the world and is currently faced by SOC depletion.

2 Materials and methods

The C stored in soils is mainly in form of organic matter. SOC content is highly dynamic affected by ecological drivers (e.g., climate, vegetation, and anthropogenic activity), soil environmental factors (e.g., temperature, moisture, pH, redox potential, and substrate concentration gradients), and biochemical or geochemical reactions (e.g., decomposition, assimilation, leaching etc.) (Li, 2000, 2001; Li et al., 2004). Process-based models are used to quantify SOC accumulation or turnover driven by the local climate, soil, vegetation and management conditions at the site scale. Geographic Information System (GIS) databases provide spatially differentiated information of climate, soil, vegetation, and management to drive the model runs across the region. To quantify the impacts of farming management alternatives on C sequestration from the 3 million hectares of cropland in the studied domain, we integrated a process-based model, DNDC, with a GIS database of cropland area, soil properties, cropping management (crop rotation, fertilizer use, irrigation, crop residue management, planting and harvest dates), and daily weather data.

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2.1 DNDC model validation

DNDC is a process-based model of carbon (C) and nitrogen (N) biogeochemistry in agricultural ecosystems. DNDC was originally developed for predicting C sequestration in and trace gas emissions from agricultural lands for the United States (Li et al., 1992, 1994, 1996; Li, 1995). During the past decade, along with more international researchers involved in the modeling effort, DNDC has been substantially enhanced and become a generic agro-ecosystem model for predicting crop growth, C sequestration, greenhouse gas emissions, nitrate leaching, and water use efficiency for both upland and wetland crops. DNDC consists of six sub-models, which simulate soil climate, plant growth, decomposition, nitrification, denitrification and fermentation, respectively. The soil climate submodel calculates soil temperature and moisture profiles based on soil physical properties, daily weather and plant water use. The plant growth submodel tracks crop growth and partitioning of the biomass into grain, stalk and roots. The decomposition submodel simulates decomposition of soil organic matter driven by the soil microbial respiration. The nitrification submodel calculates growth of nitrifiers and oxidation of ammonium to nitrate. The denitrification submodel operates at an hourly time step to simulate denitrification and the production of nitric oxide, nitrous oxide, and dinitrogen. The fermentation submodel simulates methane production and oxidation under anaerobic conditions. The six sub-models interact to enable DNDC to simulate a relatively complete suite of biochemical and geochemical processes occurring under both aerobic and anaerobic conditions. DNDC simulates SOC dynamics by tracking the turnover of four SOC pools, namely plant residue (or litter), microbial biomass, humads (or active humus), and passive humus. Each pool consists of two or three sub-pools with specific decomposition rates subject to temperature, moisture, redox potential and N availability in the soil (Li, 2000; Li et al., 1992, 1994, 2004). The DNDC model has been independently tested and applied for soil C and N studies in North America, Europe, Asia and Oceania during the past about 15 years. The tests demonstrate that DNDC is capable of capturing the basic patterns and magnitudes of SOC variations or

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trace gas emissions across climatic zones, soil types and management regimes (Brown et al., 2002; Butterbach-Bahl et al., 2001; Cai et al., 2003; Grant et al., 2004; Kiese et al., 2004; Li et al., 1994; Pathak et al., 2005; Saggarr et al. 2003; Smith et al., 1997, 2004; Xu-Ri et al., 2003).

5 DNDC has been tested against a number of datasets of long-term SOC dynamics observed in the U.S., the UK, Germany, Canada and Australia (Li et al., 1994; Smith et al., 1997) although few validations were reported for China. In this study, five long-term (10–100 years) SOC datasets were collected across typical agricultural ecosystems in China (Fig. 1a). The measured SOC values with other relevant data (e.g., climate, soil
10 properties, crop type and rotation, cropping practices etc.) from the sites were utilized for DNDC validations. The detailed information about the five sites is listed in Table 1.

Case 1: A potato field in Hequ County, Shanxi Province

15 Long-term (13 years) measurements on SOC were conducted at an experimental field in Hequ County, Shanxi Province in North China from 1988–2000. The site possessed typical continental climate with annual precipitation ranging from 220–520 mm. The local environmental conditions with frequent droughts and lack of irrigation water severely limited the crop yield as well the litter production. The experimental field
20 was planted with potatoes under three different treatments (i.e., manure amendment, synthetic fertilizer application and control) during the experimental period (Duan et al., 2001). Field observations indicated that the three treatments had different impacts on the SOC dynamics during the 13 years. At the control plot where neither fertilizer nor manure was applied, the SOC content at the top soil (0–20 cm) decreased gradually
25 from 0.0028 kg C/kg to 0.0021 kg C/kg in 1988–2000. At the plot with only synthetic fertilizer (120 kg urea-N/ha) applied, SOC slightly increased from 0.0027 to 0.0029 kg C/kg during the 13 years. At the plot amended with farmyard manure (22 500 kg/ha), SOC increased from 0.0024 to 0.0040 kg C/kg during the same period. Model simulations were conducted with the three management scenarios for the field. The modeled

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results captured the trends of SOC dynamics observed at the three plots (Fig. 2). The simulated results indicated that (1) the decrease in SOC at the control plot was mainly due to low input of the crop residue during the experimental period, (2) synthetic fertilizer application improved the crop biomass production and hence increased the litter incorporated into the soil, and (3) manure amendment substantially elevated SOC content through not only directly adding organic matter into the soil but also increasing litter production and incorporation. The observed and modeled results for the Hequ site are consistent with the long-term observations reported for a wheat field in the Rothemsted Agricultural Station in the UK (Jenkinson, 1991) although the climate and soil conditions were quite different between the two sites.

Case 2: A corn field in Qujing County, Yunnan Province

A 13-year (1978–1990) experiment was conducted at a corn field in Qujing County, Yunnan Province in southwestern China with typical subtropical climate conditions (average annual precipitation 980 mm). The field was divided into two plots with different treatments: farmyard manure (30 000 kg/ha) amendment and control (only 30 kg urea/ha used). There were significant inter-annual variations in the crop yields driven by precipitation. The field observations indicated that application of farmyard manure increased both the crop yield and SOC content. At the manure-treated plot, SOC contents increased from 0.0093 to 0.016 kg C/kg during the 13 years. In contrast, the SOC contents at the control plot only fluctuated between 0.0072 to 0.0094 kg C/kg during the same period of time (Dai et al., 1994). Simulations were conducted with DNDC for the two plots with local climate data and soil conditions. The modeled trends of SOC dynamics are in agreement with observations (Fig. 3). Modeled results indicated application of manure increased SOC through elevating crop litter production as well directly adding organic matter into the soil.

Case 3: A triple-cropping system in Jingqu County, Zhejiang Province

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The Jingqu site possesses rice fields with different lengths of cultivation histories. Some of the fields have been used for rice production for about a century, and some were converted from upland crops only a couple of years ago. Before the conversion, most of the fields shared similar properties with relatively low SOC contents (about 0.007 kg C/kg). Sixty-six fields converted from upland crops to paddy rice 2–100 years ago were selected for observing impact of the land-use change on SOC storage across the fields. The observations indicated that (1) the SOC in the paddy soils were unexceptionally higher than that in the upland soils, and (2) the SOC contents in the paddy soils increased along with increase in the years of rice cultivation (Zhang and He, 2004). A 100-year scenario was designed to represent the typical farming practices for rice cultivation in the area, including the triple-planting system (i.e., annual rice-rice-rapeseed rotation), 25% of crop residue incorporated, and farmyard manure amended in the early years of the rice cultivation. The modeled SOC content increasing along with the increase in the years of rice cultivation was in agreement with the observed results that SOC increased with the length of rice planting history (Fig. 4).

Case 4: A double-rice field in Xinyi County, Guangdong Province

Xinyi County is located at south of China with typical monsoon climate. Long-term field measurements of SOC were conducted at a site with double-rice system in the county from 1992–2001 (Tang, 2003). Field data indicated the SOC content increased from 0.013 to 0.016 kg C/kg under the local farming management conditions with both synthetic fertilizer and manure applied during the 10-year period. We run DNDC with the local climate, soil and management conditions for the site. The modeled results are in agreement with observations (Fig. 5).

Case 5: An upland crops-rice rotated field in Taojiang County, Hunan Province

Fifteen-year (1987–2001) measurements were conducted at an experimental station

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in Taojiang County, Hunan Province with a focus on long-term variation in the soil fertility. The field was planted with rice rotated with corn, barley and vegetables in years 1988–1991, 1992–1997 and 1998–2001, respectively. The field received 160 kg fertilizer-N/ha and 5000 kg manure-C/ha annually. The SOC content at the site increased rapidly from 0.0015 to 0.0028 kg C/kg during the experimental period (Fu et al., 2003). Driven by the local climate, soil and management conditions, DNDC captured the magnitude and pattern of the SOC dynamics observed at the site (Fig. 6).

The above-described five cases represented a wide range of agroecosystems in China. The validation tests against the observations proved applicability of DNDC for predicting SOC dynamics across climate zones, soil types, and management regimes for China.

2.2 Sensitivity tests

A series of sensitivity tests were conducted to demonstrate how the DNDC-predicted SOC dynamics respond to variations in the input parameters related to climate, soil and management. A typical corn field in Changwu County, Shaanxi Province was selected for constructing a baseline scenario for the tests. A 10-year baseline scenario was composed based on the local 1988–1997 weather data as well as the local soil and management conditions in the county (see details in Table 2). The 10-year average annual precipitation was 496.6 mm with the maximum (720.7 mm) in 1996 and the minimum (313.6 mm) in 1997. Alternative scenarios were designed by varying each of the climate, soil or management factors in their ranges commonly observed in Northwest China (Table 2).

Ten-year simulations were conducted with the baseline and alternative scenarios. A mean annual change in SOC content was calculated for each simulation. Based on the difference in the mean annual SOC changes between the baseline and alternative scenarios, we quantitatively determined the impact of a variation in a single environmental or management factor on the mean annual change in SOC content. The results from the sensitivity tests indicate that (1) among the environmental factors, initial SOC con-

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5 tent is the most sensitive factor for regulating SOC sequestration rate, and (2) among the management factors, crop residue incorporation and manure amendment are the most sensitive factors affecting the SOC dynamics (Fig. 7). The results are in agreement with the general understanding of SOC dynamics in agroecosystems where SOC storage is basically controlled by the balance between the SOC gain through crop residue or manure incorporation and the SOC loss through decomposition, the rate of which is fundamentally determined by the initial size of SOC pool (Li et al., 1994; Smith et al., 1997).

10 Results from the sensitivity tests have a dual implication, which indicate that (1) there are potentials for enhancing SOC sequestration through alternative management practices and (2) SOC dynamics is sensitive to some input factors (e.g., initial SOC content, crop residue incorporation, manure amendment) more than others. The latter should have brought us a clear message that the most sensitive factors for modeling SOC dynamics should be given a high priority during the input data acquisition as they could make more contributions to the uncertainties produced during the upscaling process. In fact, we have applied this conclusion for our database construction as described in the next section.

2.3 Database construction in consideration of uncertainty analysis

20 Shaanxi Province was selected as a modeled domain for this study due to its typical climate, soil and agricultural management conditions for Northwest China. Shaanxi Province is located in the eastern edge of Northwest China with complex landforms and continental climates. The province consists of three major agricultural zones distinguished with different climate conditions as well as farming management regimes. The northern zone (N 34°15'~39°25') is base on the Loess Plateau with typical continental climate. Only upland crops are planted in the zone. Droughts are the main factor limiting the crop yields due to the limited precipitation as well the lack of water resources for irrigation. The middle zone (N 33°51'~35°37') is located on the alluvial plain along the Wei River where there are well-developed irrigation systems to provide adequate

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water from either the river or groundwater to support the prosperous agriculture in the zone. The southern zone (N 31°43'~34°23') consists of scattered farmlands spread on the southern slope of the Qin-Ling Mountains where the monsoonal climate provides relatively warm weather and abundant rainfalls to the crops. Upland crops such as winter wheat, corn, rapeseeds etc. are dominant in the northern and middle zones while paddy rice is a popular crop for the southern zone. However, under the demands of the ever increasing population as well as the rapid development of local economy, all of the farmlands in the three zones have been experienced intensive cultivations during the past 5 or 6 decades. A lot of traditional farming practices, such as incorporation of crop residue or manure amendment, which had maintained the soil fertility for centuries, were gradually abandoned since 1950s when synthetic fertilizers became available. For example, burning crop redidue in site after harvest is a common practice across the entire Northwest China that substantially diminished the litter incorporation in the soils. In addition, under the new social-economic conditions amendment of farmyard manure, which requires more labor work, is almost totally abandoned. These changes in farming management, which have inherently accelerated SOC losses from the local farmland, were included in our database to support the model simulations.

To support the DNDC runs at regional scale for the selected domain, a Geographic Information System (GIS) database was constructed to hold the spatially differentiated information of climate, soil and farming management for all of the croplands in Shaanxi. Year 2000 was selected as the baseline year for the study. Since the data of crop census were provided at a county scale, county was selected as the basic simulated unit to maintain the accuracy of the original acreage information.

2.3.1 Crop data

In 2000, Shaanxi had 3 million hectares of cropland mainly planted with corn, winter wheat, rice, soybeans, oats, cotton, potatoes, and millet. Forty-five cropping systems including 19 single-, 24 double- and 2 triple-cropping systems were practiced for the croplands across 107 counties in Shaanxi (Shaanxi Technology Press, 1987; Yang,

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2001). Farming management information was collected from various sources reporting tillage, fertilization, irrigation and other practices for Northwest China (e.g., Shan and Chen, 1993; Peng, 2001).

2.3.2 Climate data

5 Weather data (daily maximum and minimum temperature, and daily precipitation) of year 2000 from 19 climatic stations within the Shaanxi province were collected from National Meteorological Agency of China and <http://www.ntsg.umd.edu/personnel/mattj/bgc.extract.htm> the climatic stations was assigned to a cluster of counties based on their geographic locations (Fig. 1b). Figure 8 shows the mean annual temperatures and annual precipitations for Shaanxi in 2000. Both temperature and precipitation decreased from the south to the north of the province. Mean annual temperature is between 6–12°C for Northern Shaanxi, and 12–17°C for Southern Shaanxi. Most of the areas in the north have mean annual precipitations less than 400 mm. The precipitation in the middle and southern zones varies from 400 to 1130 mm per year.

15 2.3.3 Soil data

DNDC requires four soil properties (i.e., bulk density, SOC content, texture and pH) as input parameters to drive the model simulations. The soil data adopted in our databases were collected from the National Soil Atlas of China (1:14 000 000, Institute of Soil Science, 1986) and calibrated with other sources (e.g., National Soil Survey Office of China 1993–1997).

20 The soil data were relatively coarse that would constitute a major source of uncertainty for the regional estimation. Following a routine adopted by most regional modeling studies, our domain, Shaanxi, was divided into many polygons or grid cells with an assumption that each grid cell is uniform in all its properties. This assumption is against the fact that soil properties usually vary even within small scales such as a county or
25 a farm. Averaging the variations of soil properties may not resolve the problem as

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the correlation between SOC dynamics and any of the soil properties is nonlinear. To accommodate the challenge induced from the soil heterogeneity, we adopted the Most Sensitive Factor (MSF) method developed by Li and his colleagues (Li et al., 1996, 2001, 2004). As indicated by the above-described sensitivity tests, some soil properties, especially initial SOC content, are the most sensitive factors for estimating SOC dynamics. Based on MSF method, we assigned each soil factor (i.e., bulk density, texture, SOC contents or pH) for each grid cell (i.e., each county for this study) with two values, the maximum and minimum values observed within the county for the soil factor. During the model simulations, DNDC ran twice for each cropping system in each county with the two extreme values of the most sensitive factor (i.e., initial SOC content for this study). The two runs produced two fluxes (i.e., annual SOC change) to form a range, which was assumed to be wide enough to include the “real” flux with a high probability. This methodology has been verified against the Monte Carlo method, a classical tool for sensitivity test. The results indicated more than 90% of the SOC changes predicted with the Monte Carlo method were located within the range produced by the MSF method (Li et al., 2004). By constructing our GIS database with the maximum and minimum values for soil texture, SOC content, bulk density and pH, we brought the uncertainties induced by soil heterogeneity under control.

Maps of soil properties (e.g., mean values for clay fraction, soil pH, SOC content and bulk density) for Shaanxi are shown in Fig. 9. Clay fraction varied from 3% to 30% across the province with higher values for the southern zone. The soils in the cropland of Shaanxi are basically neutral with a little alkaline for the northern zone and a little acidic for the southern zone. The geographic distribution of SOC contents in Shaanxi was highly uneven. Contents of SOC varied from 0.003–0.02 kg C/kg within the provincial scope. The soils relatively rich in SOC (0.01–0.02 kg C/kg) were mainly distributed in the southern zone, especially along the southern slope of the Qin-Ling Mountains with the relatively warm and humid climates. The soils with the lowest SOC (<0.004 kg C/kg) were mostly located in the northern counties with typical arid or semi-arid climates.

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2.4 Upscaling

We conducted county-scale simulations with DNDC for all cropping systems in all counties in Shaanxi Province. During the simulations, input parameters including daily weather data, soil properties, crop acreage, crop types and rotations, and farming practices (e.g., tillage, fertilization, manure amendment, and irrigation) for each county were read out from the GIS database; and the simulated daily and annual changes in SOC content were recorded for each cropping system in each county. Each cropping system was simulated twice with the maximum and minimum values of initial SOC content for each county to produce a pair annual changes in SOC for the cropping system in the county. Total change in SOC for a county was calculated by summing up the SOC changes for all of the cropping systems in the county. The provincial change in SOC is the sum of the SOC changes in all the counties. The DNDC model did not estimate SOC loss due to physical erosion, so the modeled results represent a conservative estimate of SOC losses in the domain.

A baseline and three alternative scenarios were designed to represent the current and altered cropping management practices for the regional predictions. The baseline scenario was composed based on the actual cropping management practices commonly applied in Northwest China. In the baseline scenario, the cropland was conventionally tilled with 15% of aboveground crop residue incorporated in the soils. Based on the reported county-scale data for Shaanxi in 2000, N-fertilizer application rates varied greatly (30–250 kg N/ha) from county to county due to the uneven accessibilities of the farmers to fertilizer. The spatially differentiated fertilizer application rates were recorded in the GIS database for all the counties. There was no manure used for the baseline scenario. An irrigation index was calculated based on the irrigated fraction of total farmland in the county. Three alternative management scenarios were designed to test the impacts of increases in crop residue incorporation rate and application of manure. Crop residue as well farmyard manure used to be the major sources of nutrients for agricultural soils in China before 1950s. Since then synthetic fertilizer became

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available in China that made manure use substantially decreased. Based on the official report of China, only 15% of above-ground crop residue was incorporated in the soils after harvest (Ministry of Agriculture, 1997). Most of the residue was burned or moved from the fields. We designed two alternative scenarios, CR1 and CR2, to represent the increases in crop residue incorporation rates to 50% and 90%, respectively. Another alternative scenario was designed to represent application of farmyard manure. In 2000, there were 1.5, 6.3 and 8.8 million heads of cattle, sheep and pigs, respectively, in Shaanxi, which produced about 5.1 million tons of dry matter of manure per year. By assuming about half of the manure could be finally used for land application, each hectare of cropland in Shaanxi would receive 850 kg manure (equivalent to 500 kg manure C). We composed scenario MN to represent manure amendment at a rate of 500 kg C/ha per year for all the cropping systems in the modeled domain.

By comparing the modeled annual changes in SOC between the baseline and the three alternative scenarios, we quantified the impacts of the farming management alternatives on SOC dynamics at the regional scale.

3 Results

The simulations with DNDC for 3 million hectares of farmland with 45 cropping systems in Shaanxi produced spatially differentiated SOC storage as well annual SOC changes for 107 counties in the domain. Total SOC storage and its variations under either the baseline or the alternative management conditions were calculated to quantify the role of the entire farmland of Shaanxi in atmospheric CO₂ sequestration.

3.1 Storage of SOC

Modeled results indicated that total SOC content (0–50 cm) in all cropland of Shaanxi was 55–150 Tg C with a mean 103 Tg C for 2000. The modeled results indicated that the sharp contrast on SOC contents between the southern and northern counties

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attribute to not only the climatic conditions but also farming management practices (Fig. 9). In the southern counties, double-cropping systems were prevailing that produced more crop residue to sustain the relatively high SOC levels. In addition, paddy rice was a popular crop in the southern counties that was favorable for sustaining the high SOC levels under the season-long anaerobic conditions in the soils. In the northern counties, low precipitation and insufficient irrigation facilities limited the crop yields as well litter production that lowered the SOC equilibrium. The modeled results indicated that the geographic distribution of SOC at present resulted from the collective effects of climate, land-use history and current farming management practices.

3.2 Impacts of management alternatives

Annual changes in SOC contents simulated with the baseline and alternative management scenarios were calculated for each county as well for the entire province. The differences in the annual SOC changes between the baseline and alternative scenarios were utilized to represent the impacts of the farming management alternatives on SOC dynamics at the county or provincial scale. The results indicated that all the three alternative scenarios (i.e., increase in crop residue incorporation rate from 15% to 50% and 90%, and manure application at rate of 500 kg C/ha) converted the Shaanxi farmland as a whole from a source to a sink of atmospheric CO₂ by increasing C sequestration rates in the soils.

With the present farming practice defined in the baseline scenario, the annual changes in SOC storage in the Shaanxi farmlands ranged from -2.1 to 1.0 Tg C yr⁻¹ with a mean -0.5 Tg C yr⁻¹. High rates (>1400 kg C/ha) of SOC losses occurred in the southern counties, which possessed relatively high initial contents of SOC. In contrast, the soils in most northern counties slightly gained SOC where the initial SOC contents were relatively low. In the modeled domain, there were 32 counties gaining SOC and 75 counties losing SOC under the baseline management conditions (Fig. 10). In general, the overall farmlands in Shaanxi was a weak source of atmospheric CO₂ in 2000. By elevating the rate of crop residue incorporation to 50%, the annual change in SOC

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storage in all the farmland increased to -0.8 – 2.2 Tg C yr⁻¹ with a mean 0.7 Tg C yr⁻¹. Elevating the residue incorporation rate to 90% increased the annual SOC change to 0.6 – 3.5 Tg C yr⁻¹ with a mean 2.1 Tg C yr⁻¹. The results implied that increases in crop residue incorporation converted the farmlands from a source to a sink of atmospheric CO₂ by substantially altered the SOC dynamics in the agroecosystems. With the 90% residue incorporation scenario, there were 86 counties gaining SOC and only 21 counties losing SOC in Shaanxi (Fig. 11). The magnitudes of the SOC increases driven by elevated residue incorporation rates were uneven across the domain. By comparison of the baseline scenario with the 90% residue incorporation scenario, the farmlands gaining the most SOC were located in the southern counties where the double-cropping systems (e.g., rice-winter wheat, corn-winter wheat etc.) provided more crop residue at an annual basis (Fig. 12).

Application of manure at rate of 500 kg C/ha also converted the Shaanxi farmland to a weak sink of atmospheric CO₂. With this scenario, the changes in annual SOC storage ranged from -1.3 to 1.7 Tg C yr⁻¹ with a mean 0.2 Tg C yr⁻¹. The croplands most benefited with this approach were located in the northern and middle zones where the climate was relatively dry and cool that sustain the soil organic matter (Fig. 13). The spatial difference in the SOC dynamics is in agreement with the results from the sensitivity tests reported in this paper.

4 Discussions

China possesses 1.3 million km² of farmland mostly with long-term cultivation histories. For example, agricultural activities in Shaanxi Province, the domain selected for this modeling study, started as early as in the Qin Dynasty in 200 B. C. The survival of Chinese civilization from the millenniums mainly relied on its agriculture for food, fiber and energy. Traditionally, the Chinese farmers returned crop residue and manure from either animal's or human's wastes as much as possible back to the fields. It is the practices that sustained the soil fertility through the thousands-year cultivation. In

1950s, the traditional farming practices were challenged by the rapid changes in the socio-economic conditions in the country. The concerns about the long-term soil fertility were gradually replaced by the short-term profits gained from the land use. Especially, the significant improvement in availability and accessibility of synthetic fertilizers during the past several decades has gradually made the traditional practices abandoned in China. Based on the reports from many researchers (e.g., Leemans, 1999; Matson et al., 1997), this kind of changes in the farming management is, at least partially, responsible for the long-term decline in SOC in the agro-ecosystems. A former study for China also reported the negative SOC balances for most upland agroecosystems in the country (Li, 2000). The losses of SOC not only diminish the soil sustainability but also elevate CO₂ emissions from terrestrial ecosystems to the atmosphere. New regulations were recently issued by the Chinese authorities to encourage the farmers to resume the traditional farming practices (e.g., crop residue incorporation and farmyard manure amendment). It is apparently becoming an urgent, scientific issue for China to quantify the current SOC dynamics as well to optimize mitigation approaches for C sequestration at regional or national scale. This paper reports a modeling study on quantifying the impacts of increase in crop residue incorporation and manure application on C sequestration in a region with long-term cultivation history. The modeled results indicated that the alternative practices effectively converted the farmlands in the domain from a C source to a C sink. Since the modeled crop residue or farmyard manure is actually available in the region, implementation of the two management alternatives should be feasible. The magnitude of C sequestration induced by the alternative management may vary when the modeled domain shifted from Shaanxi to other provinces in Northwest China, but the general trends should remain.

Acknowledgements. We would like to thank academician Zhisheng An and Zhengtang Guo for helpful advice. Climate data used for this work were provided by the National Meteorological Agency of China. This research was supported by the National Basic Research Program of China (2004CB720200), and National Natural Sciences Foundation (No. 40599422, 40121303), and NASA's Terrestrial Ecology Project (NNG05GH80G).

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Table 1. Characteristics of the filed sites used for validation of DNDC.

County, Province	Coordinate	Average Annual Temperature °C	Average Annual Precipitation cm	Crop System	Soil Texture	Soil Density g.cm ⁻³	pH	SOC g.kg ⁻¹
Hequ, Shanxi	111°16'E 39°12'N	3003.35	38.01	millet-potato	silty loam	1.2	8	2.75
Taojiang, Hunan	111°57'E 28°27'N	6322.89	142.39	rice-rice, corn-rice	clay loam	1.34	7.5	17.2
Jinqu, Zhejiang	119°55'E 29°18'N	6449.6	114.38	rice-rice-rapeseed	clay loam	1.4	6.8	6.34
Xinyi, Guangdong	110°56'E 22°21'N	8301.86	185.74	rice-rice	clay loam	1.7	5	15
Qujing, Yunnan	103°47'E 25°30'N	5278.33	97.99	corn	clay	1.07	5.6	10

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Table 2. Baseline and alternative scenarios for sensitivity tests.

Scenario	Conditions or Variations
Baseline	Climate: 1988–1997 daily temperature and precipitation data with mean annual temperature 11.2°C and precipitation 496.6 mm Soil: clay loam, SOC 1%, pH 8.2, bulk density 1.4. Crop: corn, planted on 1 May and harvest on 1 October Residue incorporation: 15% Tillage: conventional tillage (tilling twice to depth 10 cm) Fertilization: 120 kg urea-N/ha per year, no manure applied Irrigation: none (irrigation index=irrigated fraction of land)
Change in temperature	Decrease (DT) by 3°C and 6°C and increase (IT) by 3°C and 6°
Change in precipitation	Decrease (DP) by 10% and 20% and increase (IP) by 10% and 20%
Change in soil texture	silt loam (SiL), loam (L), sandy clay loam (SCL), Silty clay loam (SiCL), sandy clay (SC), silty clay (SiC), clay (C)
Change in initial SOC content	0.005, 0.015, 0.02, 0.025 kg C/kg
Change in crop residue incorporation	10%, 50%, 80%
Change in fertilizer application rate	60, 90, 150, 180 kg N/ha
Change in manure application rate	500, 1000, 1500 kg C/ha
Change in irrigation index	0.2, 0.4, 0.6, 0.8, 1.0

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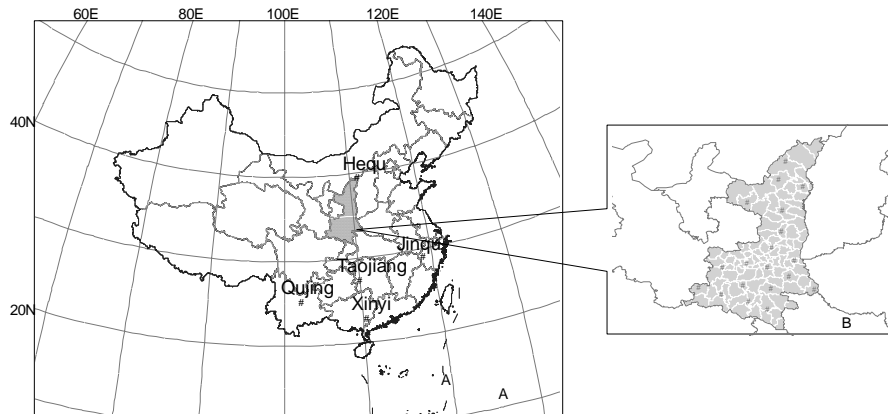


Fig. 1. Location of cropland sites for validation tests in China **(A)**. The shadow part represents our research region, Shaanxi Province. Panel **(B)** shows the distribution of the 19 climate stations of Shaanxi.

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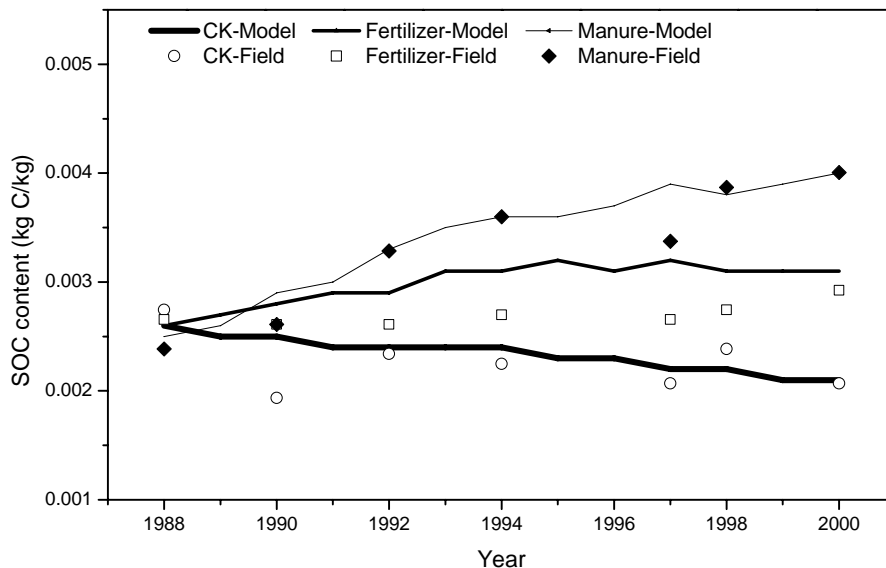


Fig. 2. Observed and modeled SOC dynamics at a potato field with three treatments (i.e., CK, control treatment; Fertilizer, synthetic fertilizer; Manure, manure amendment) in Hequ county, Shanxi Province, China from 1988–2000.(i.e., Manure, manure amendment; CK, control treatment) in Qujing county, Yunnan Province, China from 1978–1990.

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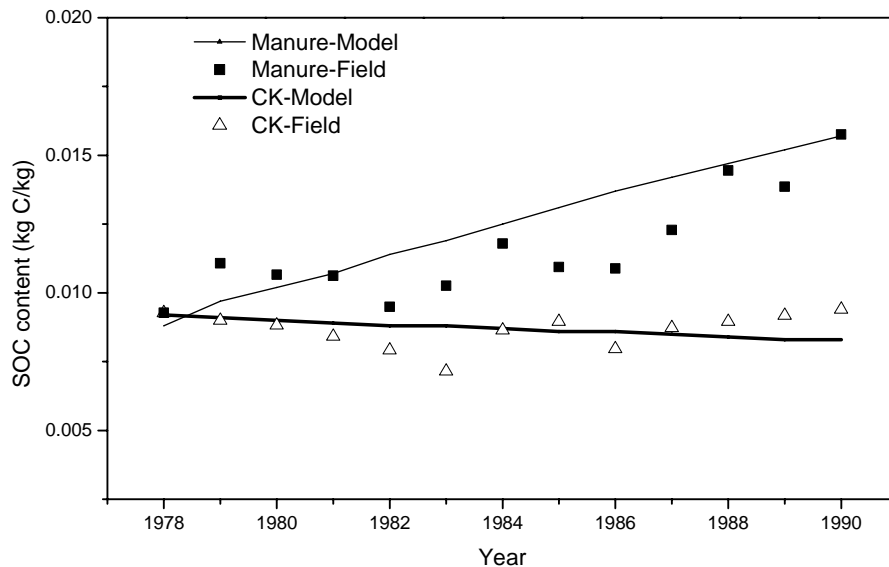


Fig. 3. Observed and modeled SOC dynamics at a corn field with two treatments.

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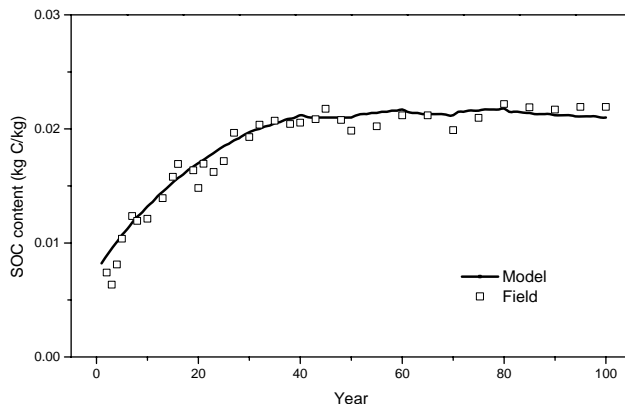


Fig. 4. A 100-year scenario representing 66 fields with the different time periods of rice cultivation was simulated with DNDC for Jingqu County, Zhejiang Province. The results indicated a rapid increase in SOC contents in the early stage of the conversion of upland crops to rice paddies in 1900–2000.

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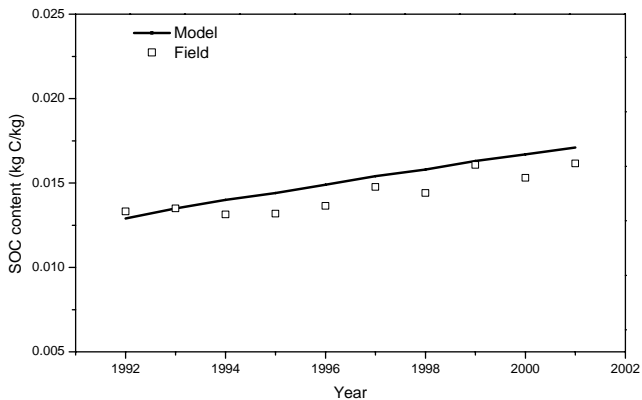


Fig. 5. Observed and modeled SOC dynamics at a double-rice field with synthetic fertilizers and manure applied in Xinyi County, Guangdong Province in 1992–2001.

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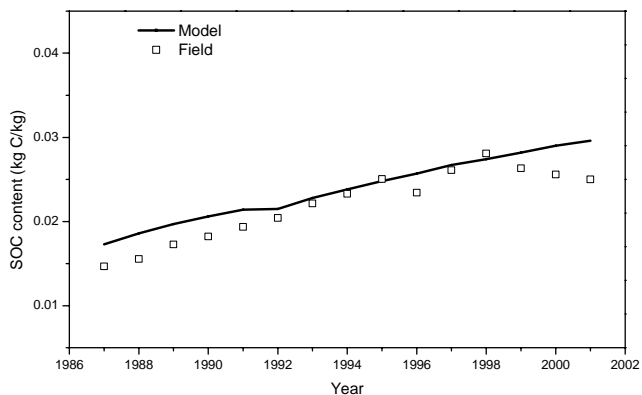


Fig. 6. Observed and modeled SOC dynamics at a rice-upland crops rotated field with synthetic fertilizers and manure applied in Taojiang County, Hunan Province in 1987–2001.

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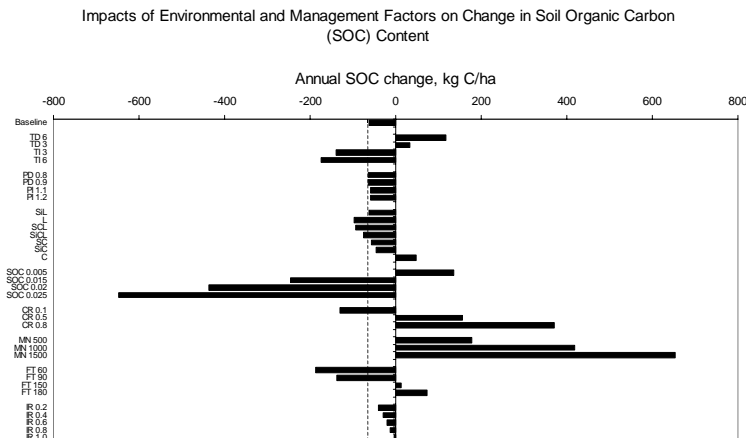


Fig. 7. Results from sensitivity tests by varying each single environmental or management factor in its range commonly observed in agricultural areas in Northwest China. Among the environmental factors, initial SOC content is the most sensitive factor determining the SOC sequestration or loss rate. Among the management factors, crop residue incorporation and manure amendment can significantly affect the SOC dynamics. The dot line indicates the annual SOC change (−63 kg C/ha) under the baseline conditions. (abbreviation: TD, decrease temperature by 3°C and 6°C; TI, increase temperature by 3°C and 6°C; PD, decrease precipitation to 80% and 90%; PI, increase precipitation to 110% and 120%; SOC, initial SOC content; CR, crop residue application; MN, manure amendment; FT, synthetic fertilizer application; IR, irrigation index).

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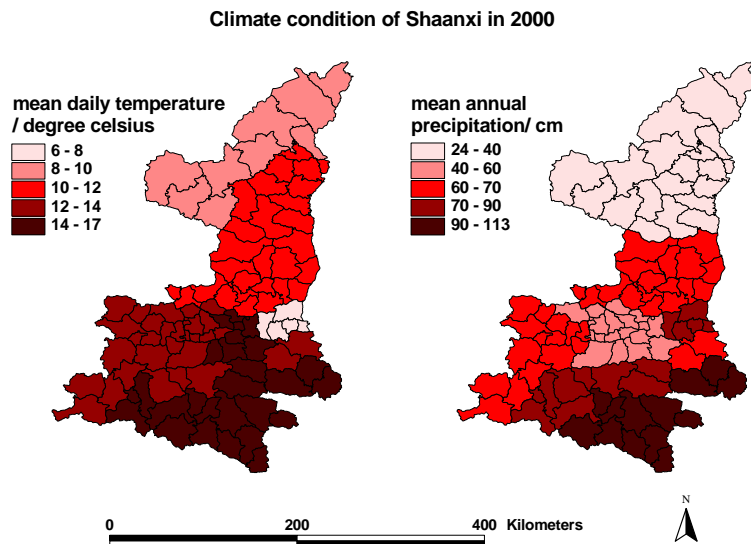


Fig. 8. Distribution of annual temperature and annual precipitation across Shaanxi in year 2000. Annual temperature was showed as mean value. Data were provided by National Meteorological Agency of China.

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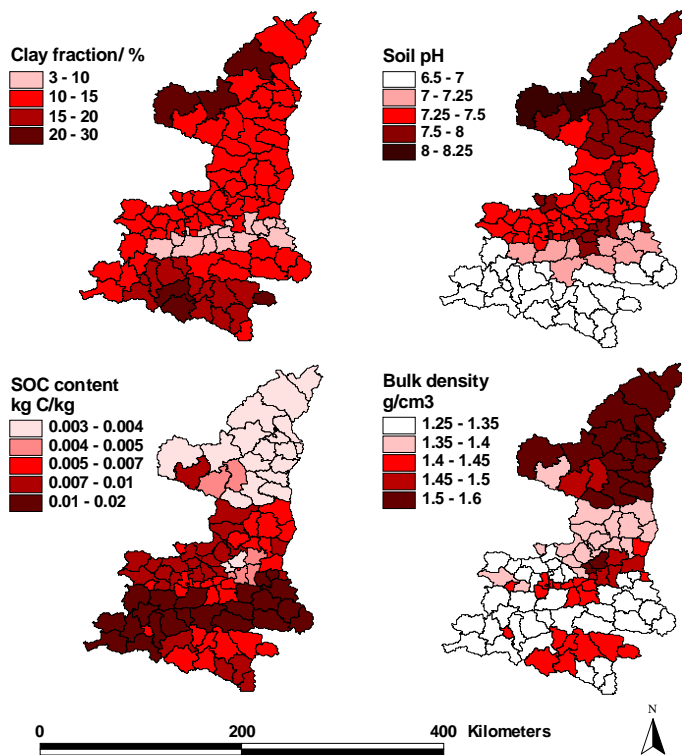


Fig. 9. Distribution of four main soil properties (clay fraction, soil pH, bulk density and initial SOC content) of cropland across Shaanxi in year 2000. All the contents of the soil properties show gradient change trend.

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Baseline scenario

annual change in
SOC, kg C/ha

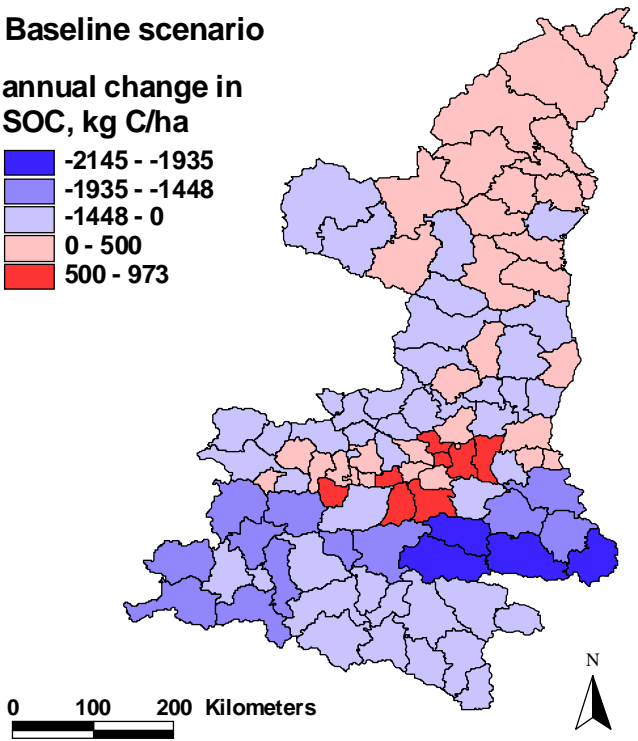
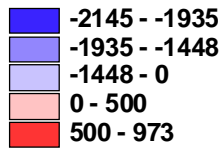


Fig. 10. Annual change values in SOC of baseline scenario (in kg C/ha). Most of the region showed decrease in SOC storage under current farm management.

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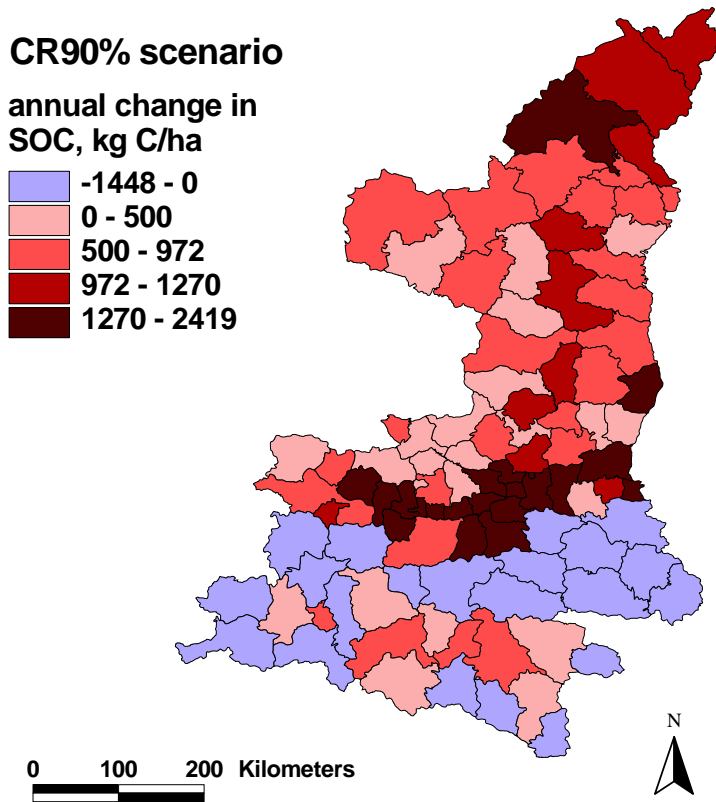


Fig. 11. Annual change values in SOC of crop residue 2 scenario (90% crop residue application, shows in kg C/ha). Farmland soil in Shaanxi increased SOC content distinctly with 90% crop residue incorporation. The north region with lower initial SOC content has great potential in carbon sequestration than south area and sequestered more carbon.

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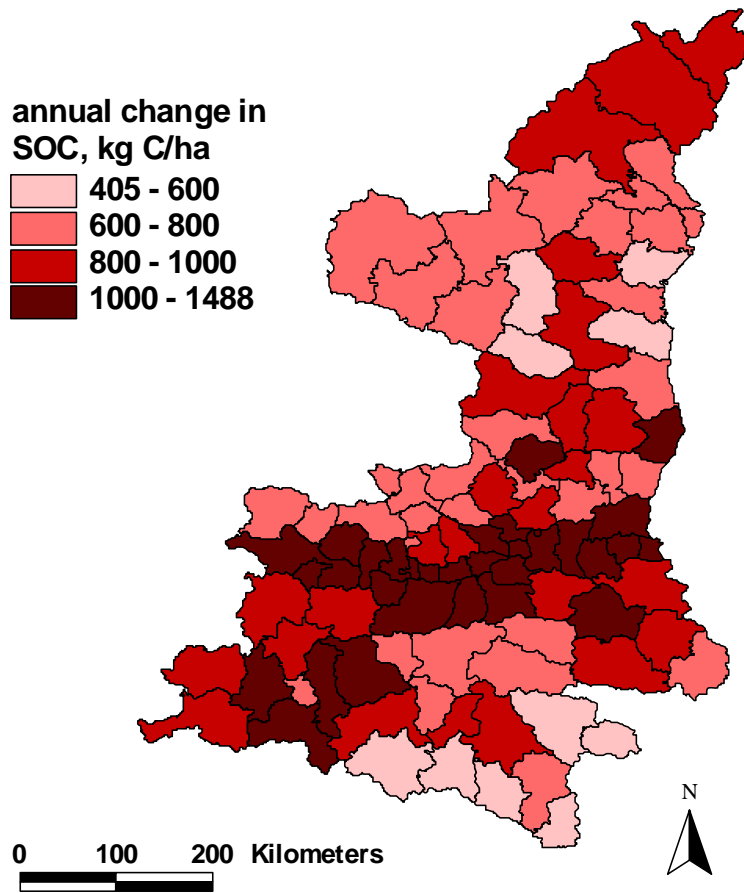


Fig. 12. Relative change in annual SOC change between crop residue 2 and baseline scenario (in kg C/ha). Increase crop residue incorporation from 15% to 90% changed the SOC dynamics and enhanced SOC storage.

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Manure scenario

annual change in
SOC, kg C/ha

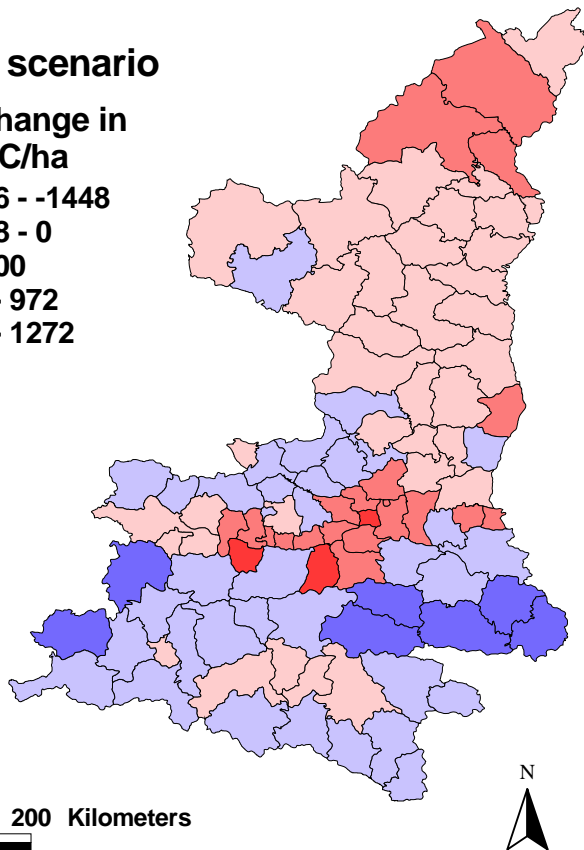
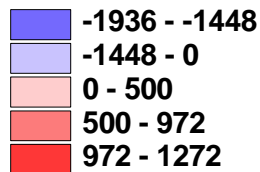


Fig. 13. Annual change values in SOC of manure scenario (in kg C/ha). Soil carbon input increasing through manure amendment improved soil properties and increased SOC content.

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