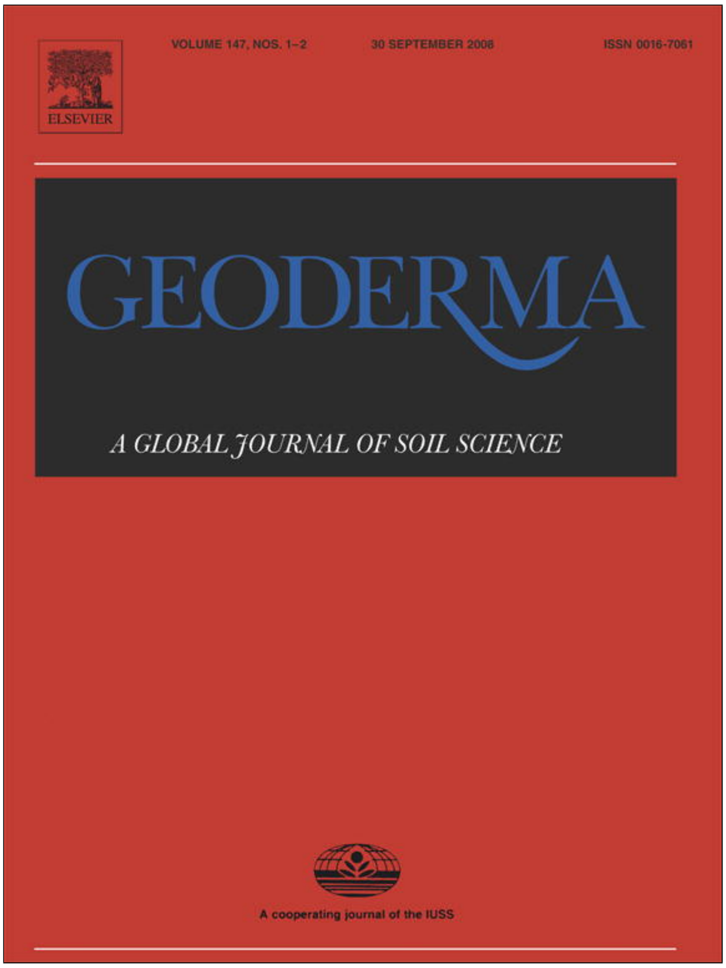
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Modelling soil organic carbon dynamics in the major agricultural regions of China

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ABSTRACT

This paper reports a modelling study on long-term (20 years) impacts of present and alternative farming management practices on (SOC) dynamics. A well documented, process-based model, DNDC, was employed, depending on the local climate, soil and management conditions in the six regions. Modelled results indicated that, under the present management conditions, the SOC status in the three northern sites (i.e., Qiqihar, Miyun and Pingliang) where upland crops dominated appeared more dynamic than that in the three southern sites (i.e., Zhijiang, Jiangning and Yantin) where paddy rice dominated. During the simulated 20 years, the northern sites were either losing or gaining SOC at relatively high rates from −1000 to 200 kg C/ha/yr; and the southern sites had relatively stable SOC contents with deviations ranging from −70 to 26 kg C/ha/yr. Increase in the fraction of above-ground crop residue incorporated in soil or application of manure effectively converted most of the tested sites into sinks of atmospheric carbon. Since crop residue and manure resources are available in most of the agricultural regions, adaptation of the management alternatives should be feasible in China.

1. Introduction

Soil organic carbon (SOC) is one of the most important terrestrial pools for C storage. It is estimated that the total SOC pool is about 1400–1500 PgC, which is approximately three times greater than the atmospheric pool (750 PgC) (Post et al., 1982; Schlesinger, 1997; Schuman et al., 2002). The SOC pool represents a carbon dynamic equilibrium of gains and losses. Even small changes of SOC may potentially add up to significant changes in large-scale carbon cycling (Fang et al., 2001). Furthermore, SOC is relatively dynamic and can be greatly influenced by agricultural practices. During the recent years, a great amount of studies paid more attention to carbon sequestration and to mitigate SOC loss by optimizing farming managements in many counties (West and Post,, 2002). Increase in SOC storage in cropland soils benefits soil productivity and environmental health, thus it is recognized as a "win–win strategy" (Hernanz and Lopèz, 2002; Lal, 2004; Li et al., 2005). In many countries, alternative farming management practices have been tested to identify their potentials for optimizing the carbon and nitrogen cycles in the agroecosystems (Yang, 2000; Lal, 2004).

Most of the croplands in China possess relatively low SOC contents due to the long cultivation history. Organic fertilizer including farmyard manure and compost used to be a major source of the soil nutrients in China before the 1950s. By that time, almost all of the organic resources such as animal waste, night soil, straw and lagoon slurry available in the agricultural areas were carefully collected and incorporated into the soils to maintain the soil fertility. However, along with the rapid growth of demand for food driven by the ever increasing population in the 1960s–90s, the organic fertilizers were gradually replaced by the more efficient synthetic fertilizers. In addition, the nationwide urbanizations attracted a great amount of man power from the countryside that also impeded the farmers' practices for collecting and processing the dispersed organic resources. By now organic farming is almost diminishing in China. Removal of the crop residue from field has long been a common practice in the country. The removed crop litter was used for fuel, forage or raw industrial materials (Wang et al., 2000; Li, 2003; Xie et al., 2004; Pan and Zhao, 2005). In many places, the farmers simply burned the crop residue in situ only because it interfered with the field practices for the next season planting. Since SOC storage is highly dynamic determined by the balance of gain and loss of organic matter, the litter removal and manure abandonment inherently led to lower SOC equilibriums. Several former studies have indicated the SOC decline at national scale in China (e.g., Cai, 1996; Li et al., 2003; Qiu et al., 2004; Tang et al., 2006). The study reported in this paper is a continuous effort to identify the SOC change trends in China and the alternative management practices for elevating SOC storages across the agricultural regions in China.

2. Materials and methods

2.1. The DNDC Model

The Denitrification–Decomposition (DNDC) model was originally developed for predicting carbon (C) and nitrogen (N) biogeochemical

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Table 1
Characteristics of the field sites selected for validation of DNDC model

Site	Region	Cropping system	Initial SOC g C/kg	Soil density g/cm^3	pH	Observed years
Qiqihar (47.2°N)	Northeast	Corn	25	1.2	6.8	1990–2001
Quzhou (36°N)	North	Winter wheat-corn	3.88	1.5	7.1	1984–2000
Hequ (39°N)	Northwest	millet-potato	2.75	1.2	8	1998–2000
Qiyang (26°N)	MidSouth	Winter heat-corn	6.67	1.65	5.7	1991–2000
Hangzhou (30.3°N)	Southeast	Barley-rice-rice	16.6	1.6	6.6	1990–2001
Chongqing (29.5°N)	Southwest	Winter wheat-rice	12.7	1.67	7.7	1991–2002

cycles in the U.S. agroecosystems (Li et al., 1992, 1994). The model consists of six sub-models, which simulate soil climate, plant growth, decomposition, nitrification, denitrification and fermentation, respectively. DNDC simulates plant growth by tracking photosynthesis, respiration, water and N demand, C allocation, crop yield, and litter production. The modeled litter (root and above-ground residue) production is one of the major processes controlling the soil C dynamics. In the DNDC model, SOC resides in four major pools: plant residues or litter, microbial biomass, humads, and active humus. Each pool consists of one or more subpools with different properties. The daily decomposition rate for each sub-pool is regulated by pool size. As soon as the litter is incorporated in the soil, DNDC will partition the litter into the very labile, labile and resistant soil litter pools based on C/N ratio of the litter. Each of the litter pool has a specific decomposition rate though subject to temperature, moisture and free N availability in the soil profile. During the simulated decomposition of litter, part of the litter C is consumed as the energy source by the soil microbes and hence becomes carbon dioxide (CO_2) that is finally emitted into the atmosphere; part of the litter C is turned into the microbial biomass. After death of the microbes, the humads from the microbial remains will further decompose and become passive humus. Emission of CO_2 from decomposition is one of the major processes leading to loss of SOC.

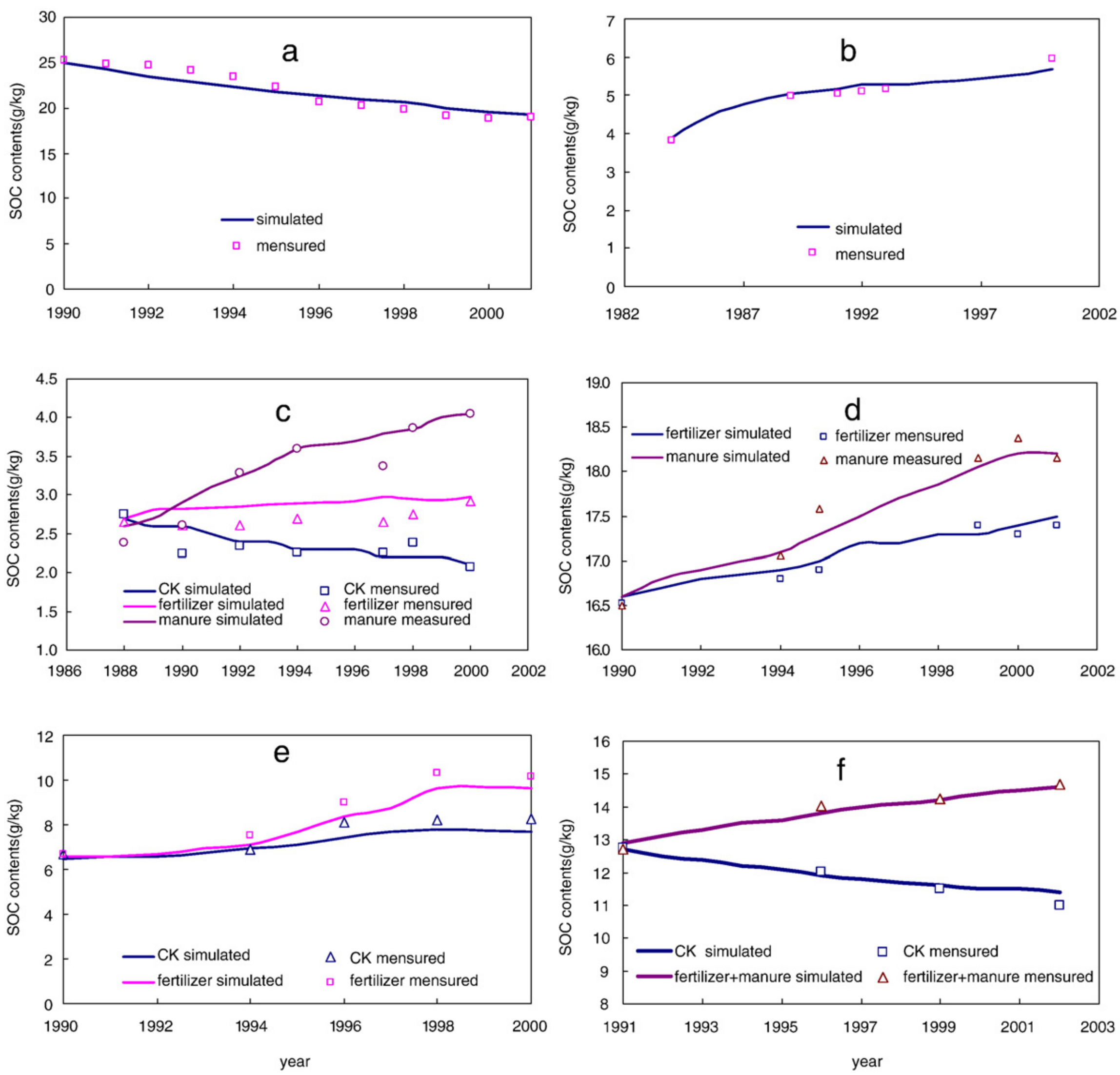

Fig. 1. The validation of the DNDC model by comparison with long term observed and modeled SOC dynamics in China. a — Qiqihar (Northeast Region),b — Quzhou (North Region), c — Hequ (Northwest Region), d — Hangzhou (South Region), e — Qiyang (East Region) and f — Chongqing (South west Region).

Since crop litter production is a major factor affecting the SOC dynamics, the physiological and phenology parameters for the major crops widely planted in China have been calibrated and stored as library data in DNDC. In addition, the farming management practices specific for China, such as midseason drainage for paddy rice, application of ammonium bicarbonate as a common fertilizer for almost all crops etc, have been parameterized in DNDC to make the model more suitable for the Chinese agroecosystems (Li et al., 2006). The modified DNDC has been utilized in several studies for estimating soil carbon sequestration in or greenhouse gas emissions from the agricultural lands in China (Xu et al., 1999; Wang and Ouyang, 2001; Li et al., 2001, 2002, 2003; Qiu et al., 2003; Cai et al., 2003; Tang et al., 2006; Zhang et al., 2006; Li et al., 2007). Through the studies, DNDC has been validated against a wide range of observations obtained for various cropping systems in China. For example, in Zhang et al. (2006), five datasets of long-term (10–100 years) changes in SOC storage observed across the major agricultural regions have been utilized to test DNDC with encouraging results. DNDC-modeled daily CO_2 fluxes from corn, wheat and cotton fields in the North China Plain during the crop seasons were also in agreement with observations (Li et al., 2007). Further validation tests were conducted in the study.

2.2. Validation of the DNDC model

In this study, six long-term (10–20 years) SOC datasets from Northeast China, North China, Northwest China, Central South China, East China and Southwest China were collected for validation tests. The measured SOC values with other relevant data (e.g., climate, soil properties, crop type and rotation, cropping practices etc.) from the sites were utilized for DNDC validations. The detailed information about the six sites is listed in Table 1.

2.2.1. Case 1: a corn field in Qiqihaer, Heilongjiang Province

Qiqihaer is located in Northeast China with the typical black soils, which contain high SOC contents. The experimental field was cultivated with continuous corn for 12 years, receiving 140 kg urea–N/ha and 80 kg diammonium phosphate–N/ha annualy. Field observations indicated that SOC contents in the soil decreased fast during the 12 years. The DNDC-modeled results for the site recreated the decreasing trend of SOC that is in agreement with observations (Fig. 1a). The modeled results are also consistent with the long-term observations reported by Qiu et al. (2004) for the same area.

2.2.2. Case 2: a winter wheat-corn field Quzhou County, Hebei Province

Quzhou is located in the North China region where wheat and maize are the dominant crops. The experimental field was planted with winter wheat-corn rotation receiving fertilizer of 270 kg N/ha and 500 kg of farmyard manure annually from 1983–2003 (Wang and Qiu, 2003). Model results indicated application of chemical fertilizer increased SOC through elevating the crop litter production as well directly adding organic matter into the soil. In terms of DNDC-simulated results, the SOC content increased rapidly during 1983–1990, whereas the increase rate slowed down after 1990 that was consistent with observations (Fig. 1b).

2.2.3. Case 3: a potato field in Hequ County, Shanxi Province

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 experimental field was planted with millet-potato rotation under three different treatments (i.e., manure amendment at 22,500 kg/ha containing 9.9% organic matter and 0.4% nitrogen, synthetic fertilizer application 120 kg/ha containing 46% nitrogen, and control). The modeled results captured the trends of SOC dynamics observed at the three treatments (Fig. 1c). The simulated results indicated that the SOC content at the control plot decreased while the SOC content at the manure amendment site substantially increased during the 13-year simulations. The results were in agreement with the measured data reported by Zhang et al. (2006).

2.2.4. Case 4: a double rice field in Hangzhou, Zhejiang Province

The experimental field is located in the agricultural research station of Zhejiang Academy of Agricultural Sciences in Hangzhou, Zhejiang Province in Southeast China where paddy rice is the dominant crop. The experimental field was planted with rice for a long period under two different treatments (i.e., manure amendment and synthetic fertilizer application). The manure-treated plot received 22,500 kg of farmyard manure ha^{-1}, and the fertilizer-treated plot received fertilizers containing 315 kg N/ha, 157.5 kg P/ha and 157.5 kg K/ha annually from 1990–2000. The simulated results for the two plots were consistent with the measured values reported by Wang (1999) (Fig. 1d). Both the measured and simulated values showed increase in the SOC contents for the two plots from 1990–2000.

2.2.5. Case 5: a winter wheat-corn field Qiyang County, Hunan Province

Ten-year measurements were conducted at an experimental station of Chinese Academy of Agricultural Sciences in Qiyang County, Hunan Province in South China with a focus on long-term variation in the red soil fertility and fertilizer efficiency (Wang et al., 2002). The arable soil has an organic carbon content of 6.6 g/kg. The tested field had a double-cropping system with winter wheat-corn rotated . Treatments included the control (CK) and the chemical fertilizer application with 300 kg N/ha, 120 kg P/ha and 120 kg K/ha applied annually. DNDC basically captured the magnitudes and patterns of the SOC dynamics observed at the site (Fig. 1e).

2.2.6. Case 6: a winter wheat-rice field at Chongqing municipality

The tested site is located in the suburbs of Chongqing, Sichuan Province in Southwest China where the purple soil is widely distributed. Thirteen-year measurements was conducted at the station of Southwest Agricultural University in Chongqing from 1991–2003. The experimental field was planted with wheat-rice rotation under two treatments (the control and the combined fertilizer and manure application). The annual fertilizer application rates were 150 kg N/ha, 75 kg P/ha and 75 kg K/ha. 60% of the N fertilizer and 100% of the P and K fertilizers were applied for the wheat season as base fertilizers and 40% of N fertilizer was amended in the 3–4 leaf period. A similar method was allied for the rice season. Farmyard manure of 22,500 kg/ha was applied before the seeding date of wheat

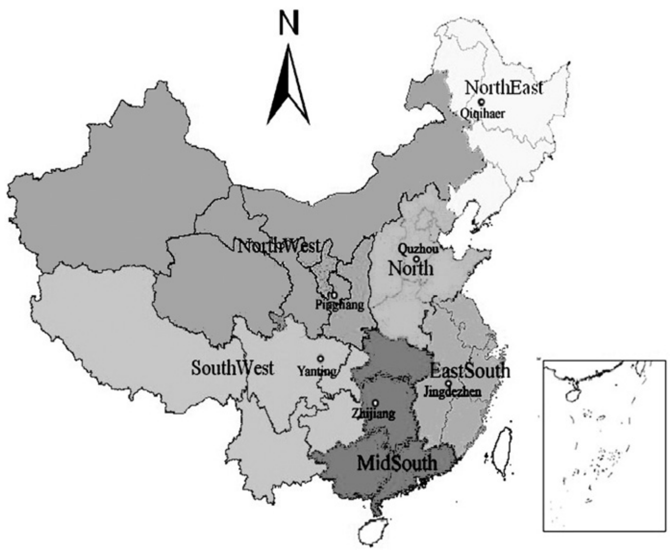

Fig. 2. Regionalization of Chinese agriculture.

in autumn (Wang et al., 2005). The modeled trends of SOC dynamics were in agreement with observations (Fig. 1f). Modeled results indicated application of manure increased the SOC content through directly adding organic matter into the soil, and the decrease in SOC at the control plot was mainly due to low input during the experimental period.

In summary, the above-described six validations tests support the conclusions reported by other researchers in China that DNDC is capable of quantifying SOC dynamics in the agroecosystems across China. In this study, we utilized the well tested model to estimate the impacts of farming management alternatives on SOC dynamics across the major agricultural regions in the country.

3. Regionalization of Chinese agriculture

China has about 120 million hectares of cropland distributed in a large geographic domain across different climatic zones, soil types and cropping management regimes. To facilitate the agricultural management for such a large domain, the entire Chinese croplands are grouped into six regions, i.e., the Northeast, North, Northwest, MidSouth, Southeast and Southwest Regions, based on their climatic characteristics as well dominant cropping systems (Fig. 2 and Table 2.)

Decades-long field investigations showed that the six agricultural regions differ in SOC dynamics driven by the spatially differentiated climate, soil and farming management conditions,. The Northeast Region possesses the youngest croplands of China. The cultivation history in the region, which includes Heilongjinag, Jilin, Liaoning Provinces and eastern part of Inner Mongolia, started about 200 years ago (Meng and Zhang, 2001), by converting the local forests, prairies or wetlands into croplands. The soils in the region contain the highest SOC contents (0.02–0.03 kg C/kg) in China although the SOC contents have been dramatically decreased from 0.06 kg C/kg or higher during the short cultivation period (Yu et al., 2003). The major crops in the region are corn, soybeans, rice, potato and other single-season crops. The North Region includes Beijing, Tianjin, Hebei, Henan, Shandong, Shanxi Provinces, which constitute a major base of agricultural production in China. The region has a long-term cultivation history (>1000 years) with intensively managed farm lands, and the crop yields have been well maintained optimized. The SOC contents range from 0.008–0.01 kg C/kg in the region (Xu et al., 2004; Huang and Sun, 2006). The dominant crops are corn, winter wheat, cotton, soybeans and vegetables. The Northwest Region is located in the semiarid and arid zones with unstable crop yields. The crop production is vulnerable to water stress. The SOC contents in the region are usually lower than 0.01 kg C/kg (Liu, 2005). The major crops are wheat, corn, cotton, potato and soybeans. The MidSouth Region is one of the major bases producing grains in China. With the warm weather and abundant precipitation, double- or triple-cropping systems are prevailing. The SOC contents range from 0.01–0.02 kg C/kg. The soil textures are relatively heavy (Wang et al., 2006). Major crops are paddy rice, wheat, corn, cotton and rapeseeds. The Southeast Region possesses flat landscape with the alluvial soils, which contain relatively high SOC contents (Li et al., 2006). Paddy rice is dominant in the region. The Southwest Region has long-term cultivation history with almost equal areas of upland and wetland croplands (Li and Wu, 2006). The upland crops are mainly distributed on the slopes in the mountain or hilly areas. The purple soils were developed from the highly weathered parent materials (Xu et al., 2006). The major crops are paddy rice, wheat, corn, rapeseeds, beans and potatoes. The six agricultural regions were adopted in the study as geographic domains to test their responses to the farming management alternatives. To test the impacts of alternative management scenarios on SOC for the six agricultural regions, we selected a typical site for each of the six regions for model simulations. The characteristics for the selected six sites are shown in Table 3.

Table 3
Locations and characteristics of climate, soil and cropping system of selected six sites representing the agricultural regions in China

Site	Location	Temperature (°C)/ precipitation (mm)	Cropping system	SOC kg C/kg	Soil density g/cm^3	pH
Qiqihar (47.23°N)	Heilongjiang Province, Northeast Region	5.16/294	Corn	0.04	1.2	6.8
Miyun (36°N)	Beijing, North Region	13.88/583	Winter wheat-corn	0.019	1.5	7.2
Pingliang (37°N)	Gansu Province, Northwest Region	10.73/410	Winter wheat-corn	0.004	1.4	8.0
Zhijiang (25°N)	Hunan Province, MidSouth Region	18/1516	Rice	0.0114	1.26	6.3
Jiangning (29.3°N)	Jiangsu Province, Southeast Region	17.49/975	Rice-winter wheat	0.018	1.14	6.2
Yanting (30°N)	Sichuan Province, Southwest Region	17.16/1021	Rice-winter wheat	0.0155	1.12	8.56

4. Farming management scenarios

In China, agricultural management practices have been undergoing significant changes during the past decades. For example, farmyard manure or compost used to be the major sources of soil nutrients before the 1960s. However, since then, the organic fertilizers were gradually replaced by synthetic fertilizers along with the increase in their availability for the Chinese farmers. The evolution has led to higher agricultural productivities but induced new environmental problems.

Table 2
Climate, soil and dominant crop types for six agricultural regions in China

Region	Provinces	Climate	Soil	Dominant crops
Northeast	Heilongjiang, Jilin, Liaoning, eastern part of Inner Mongolia	Warm-cool, semi-humid	Black soil with high SOC contents with relatively short cultivation history	Single-season corn, soybeans, rice, other cereals
North	Beijing, Tianjin, Heibei, Heinan, Shandong, Shanxi	Warm, semi-humid	Long-term cultivated loam soils with low SOC and high silt	Corn-winter wheat rotation, cotton, soybeans
Northwest	Shanxi, Gansu, Ningxia, Qinghai, Xinjiang, midwest part of Inner Mongolia	Warm-cool, semi-arid	Long-term cultivated soils with low SOC and high sand, fertility is limited by water availability	Single-season wheat, corn, cotton, potatoes
Midsouth	Hubei, Hunan, Guangdong, Guangxi, Hainan	Warm, humid	Highly weathered red soils with high clay and moderate SOC, with good irrigation facilities	Double-season paddy rice, wheat, corn, rapeseeds, cotton
Southeast	Shanghai, Anhui , Jiangsu, Jiangxi, Zhejiang, Fujian	Warm, humid	Paddy soils with moderate SOC and high clay, well irrigated	Double-season paddy rice, corn, rapeseeds, wheat
Southwest	Chongqing, Sichuang, Yunnan, Guizhou, Xizang	Warm, humid	Highly weathered purple soils with high clay and moderate SOC	Single or double-season paddy rice, corn, rapeseeds, wheat, potatoes

Currently, overuse of synthetic fertilizer or mismanagement of animal waste or crop residue is becoming a notable social problem for most the agricultural regions in China (Zhang et al., 2004). Eutrophication has been observed in a big portion of the rivers, lakes and reservoirs in the entire eastern part of China (Yu et al., 2003). Soil degradation and desertification were widely reported across the northern parts of the country (Huang and Sun, 2006). All the negative environmental issues are directly or indirectly related to losses of SOC from the agricultural lands. In this study, we focused our modeling tests on the SOC dynamics affected by different farming management practices across China. A baseline scenario was composed for each of the six sites based on the actual farming management practices (i.e., crop rotation, fertilization, crop residue incorporation, manure use and irrigation) that commonly adopted by the local farmers in the corresponding region. The details of the baseline practices for the six sites were obtained from the local investigations and are listed in Table 4.

Nine alternative scenarios were designed by varying one of three selected farming practices, namely fertilizer application rate, manure application rate and crop residue incorporation rate. Specifically, the alternative fertilizer application rate was 40%, 50%, 80% or 120% of the baseline fertilizer application rate for each site; the alternative crop residue incorporation rate was 30%, 50% or 80% of above-ground crop residue (the baseline rate was 15%); and the alternative manure application rate was 500 or 1000 kg C/ha. In addition, two alternative scenarios were composed by combining a lower fertilizer application rate (reduced to 50% of baseline rate) with an increased crop residue incorporation rate (50%) or with an increased manure amendment rate (1000 kg C/ha). Table 5 summarizes all the tested optional management practices. DNDC was run with the baseline scenario and all the alternative scenarios for 20 years to observe their long-term impacts on the SOC dynamics at the six sites.

Table 4
Baseline farming management practices for the six sites representing the agricultural regions in China

Site (region)	Current farming management practices
Qiqihar (Northeast)	Single-cropping system with corn (May 10–September 27); tilled twice on June 14 and October 1; urea applied at 80 and 60 kg N/ha on May 1 and July 2, respectively; ammonium phosphate applied at 80 kg N/ha on May 1; 15% of above-ground crop residue incorporated; no irrigation.
Miyun (North)	Double-cropping system with corn (June 16–September 25) and winter wheat (September 30–June 15); tilled once on September 29; urea applied at 110 kg N/ha on April 13 and September 30; ammonium phosphate applied at 54 kg N/ha on September 30; 15% and 10% of above-ground crop residue incorporated following corn and winter wheat harvest, respectively; irrigated twice on April 15 and November 20.
Pingliang (Northwest)	Double-cropping system with corn (May 20–October 1) and winter wheat (October 10–May 15); tilled twice on May 20 and October 2; urea applied at 45 kg N/ha on May 20 and October 10; 1350 kg C of farmyard manure applied on May 1; 15% of above-ground crop residue incorporated following corn and winter wheat harvest; irrigated twice on April 15 and November 20.
Zhijiang (South)	Single-cropping system with paddy rice (April 21–September 26); tilled twice on April 20 and September 27; 26 kg N of urea and 27 kg N of ammonium bicarbonate applied on April 26 and May 23; flooded from April 30–September 15; no manure used; 20% of above-ground crop residue incorporated.
Jiangning (East)	Double-cropping system with paddy rice (May 15–October 20) and winter wheat (October 25–May 10); tilled twice on May 11 and October 22; urea applied at 50 kg N on March 1, August 30 and November 1, at 166 kg N/ha on June 21, and at 86 kg N/ha on August 5; flooded from April 18–July 20 and July 30–October 13; no manure used; 20% of above-ground rice residue and 80% of above-ground wheat residue incorporated.
Yanting (Southwest)	Double-cropping system with paddy rice (May 23–September 7) and winter wheat; tilled twice on May 20 and October 20; urea applied at 150 kg N on May 23 and October 26; flooded from May 20–August 20; no manure used; 10% of above-ground rice residue and 5% of wheat above-ground residue incorporated.

Table 5
Farm management scenarios used for the modeling

Management	Alternative scenarios
Chemical fertilizer (% of baseline rate)	50, 80, 120
Manure (kg C/ha)	+1000
Residue returned rate (%)	50, 80

Except the management information, climate and soil data were also collected to support the model simulations. Daily weather data (daily maximum and minimum temperature, and daily precipitation) of 1984–2003 for the six sites were obtained from the National Meteorological Bureau of China and utilized for the 20-year simulations. Soil properties for the sites were obtained from “Atlas of Chinese Soils”. Farming management information was collected from the field experimental observations or local investigations.

5. Modeled results

For each of the six tested sites, DNDC was run for 20 years with the baseline and all the alternative management scenarios. The climate data of 1984–2004 were used for the 20-year simulations. The modeled results included annual crop yields, changes in SOC storage, N leaching losses, and emissions of trace gases (e.g., nitrous oxide, nitric oxide, methane etc.). In this paper, our discussions mainly focus on SOC dynamics. 20-year average annual changes in SOC were calculated for each scenario at each site to serve comparisons across the scenarios or sites.

5.1. SOC dynamics under baseline management conditions

Under the baseline management conditions, modeled SOC dynamics showed different trends across the tested six sites that represent the six agricultural regions in China. The SOC contents in the upland crop fields at Qiqihar representing the Northeast Region and Miyun representing the North Region continuously decreased during the simulated 20 years although the decreasing rate at Qiqihar was much higher than that at Miyun. The soil in the corn-winter wheat rotated field at Pingliang representing the Northwest Region consistently gained SOC during the simulated years. The modeled data shown in Table 6 explain why the SOC dynamic trends differ among the sites. Among the six sites, the soil at Qiqihar lost the most organic carbon mainly due to its high initial SOC content (0.04 kg C/kg), which led to high soil heterotrophic respiration rates (20-year average rate is 4800 kg C/ha/yr) that overwhelmed the SOC input rate (3800 kg C/ha/

Table 6
DNDC-modeled 20-year average annual crop litter incorporation rates, soil decomposition rates and changes in SOC storage for simulated six sites

Site (region)	Organic matter incorporation rate, kg C/ha/yr	Soil decomposition rate, kg C/ha/yr	Change in SOC, kg C/ha/yr	Crop yield, kg C/ha/yr
Qiqihar (Northeast)	3783	4796	−1013	3168
Miyun (North)	1417	1852	−435	1924
Pingliang (Northwest)	3162	2926	200	1538
Zhijiang (South)	1127	1197	−70	2584
Jiangning (East)	2196	2170	26	3905
Yanting (Southwest)	1375	1443	−68	3816

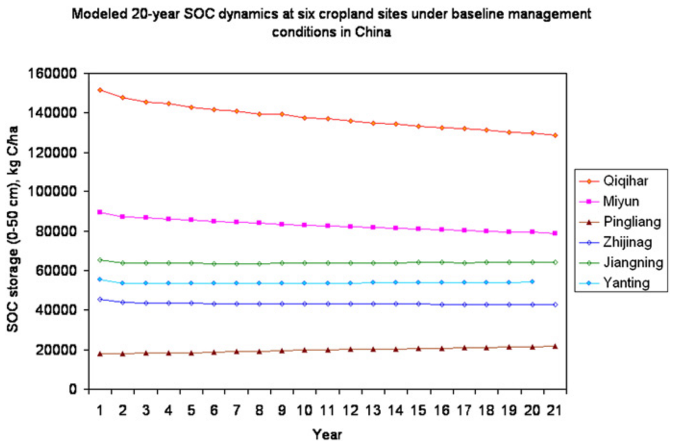

Fig. 3. Modeled 20-year SOC dynamics at the six sites Qiqihar (Northeast Region), Miyun (North Region), Pingliang (Northwest Region), Zhijinag (South Region), Jiangning (East Region) and Yanting (South west Region) under their baseline management conditions.

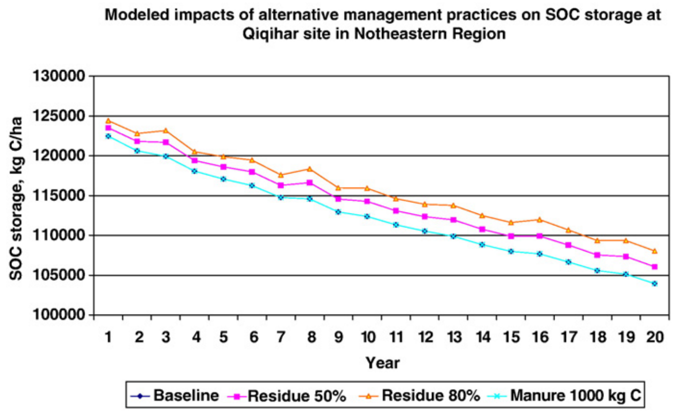

Fig. 4. The SOC storage at Qiqihar will continuously decrease with all the tested alternative management scenarios although increase in litter or manure incorporation rates will moderate the C decrease rates.

yr) from the crop litter incorporation. The soil at Pingliang had the lowest initial SOC content (0.004 kg C/kg) among the six sites and was amended with 1350 kg C of farmyard manure every year. The low decomposition rate with the direct addition of organic carbon from the manure at the site turned its soil into a sink of atmospheric C.

In contrast to the three upland crop sites in the northern regions in China, the three rice-involved sites in the MidSouth, Southeast and Southwest Regions showed relatively moderate changes in their SOC contents. The annual variations in SOC storages at the three rice sites were lower than 100 kg C/ha/yr. Jiangning representing the East Region gained a little of SOC while Zhijinag representing the South Region and Yantin representing the Southwest Region lost SOC at relatively low rates during the simulated 20 years (Fig. 3). The near-equilibrium status for the three southern sites was induced by two reasons: (1) the special water management practice (i.e., flooding) for paddy soils reduced SOC decomposition rate, and (2) the relatively high crop productivities introduced more litter into the soils.

5.2. Effects of alternative crop residue or manure management practices on SOC dynamics

In this study, three farming management practices (i.e., fertilization, manure application and crop residue incorporation) were tested by varying one or more of the practices (Table 5). DNDC was run with each of the scenarios to quantify its impacts on SOC storage and other relevant C and N fluxes for the tested sites. By comparing the modeled impacts between the alternative scenarios and the baseline scenarios, we were able to quantify the contributions of the management alternatives to SOC dynamics or other environmental issues. The simulated results indicated that a same management alternative, such as manure application or increase in above-ground crop residue incorporation, could have different impacts on SOC dynamics across the six sites. The modeled impacts are summarized for each site as follows.

5.2.1. Site Qiqihar in the Northeast Region

The SOC storage at the site continuously decreased during the simulated 20 years no matter which of the farming management alternative was applied. The high SOC decomposition rates (about 5000 kg C/ha/yr) in the black, carbon-rich soil overwhelmed the C input from either the crop residue incorporation or the manure amendment. However, increase in crop residue incorporation or manure application rate moderated the SOC loss rates (Table 7 and Fig. 4).

5.2.2. Site Miyun in the North Region

The North Region is one of the main grain producing regions in China. The long-term cultivation history (>1500 years) has depleted the soil fertility and led to a low equilibrium of SOC in the region. The modeled SOC dynamics at the site was relatively sensitive to the alternative management practices. The increase in crop residue incorporation or manure application rate effectively reduced SOC losses at the site. When the above-ground crop residue incorporation rate increased to 80% or manure application rate increased to 2500 kg C/ha/yr, the site turned from a source to a sink of atmospheric C (Table 7 and Fig. 5).

Table 7
DNDC-modeled 20-year average annual SOC changes under baseline and alternative management conditions for simulated six sites

Scenario	Qiqihar (Northeast)	Miyun (North)	Pingliang (Northwest)	Zhijiang (South)	Jiangning (East)	Yanting (Southwest)
Baseline	−1013	−435	200	−70	26	−68
Manure 1000	−1013	−307	333	74	544	56
Residue 50%	−967	−152	265	−18	37	271
Residue 80%	−918	54	317	64	522	514

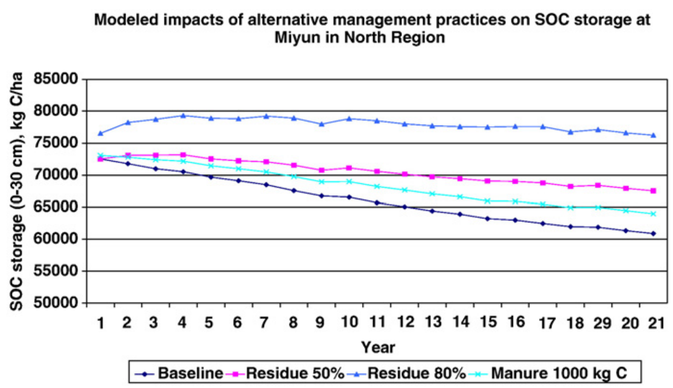

Fig. 5. The SOC storage at Miyun decreases under the baseline management conditions although the decrease rate can be moderated by applying more crop residue or manure in the soil. With the scenario of 80% of above-ground crop residue incorporation, the soil will be turned to a weak sink of atmospheric C.

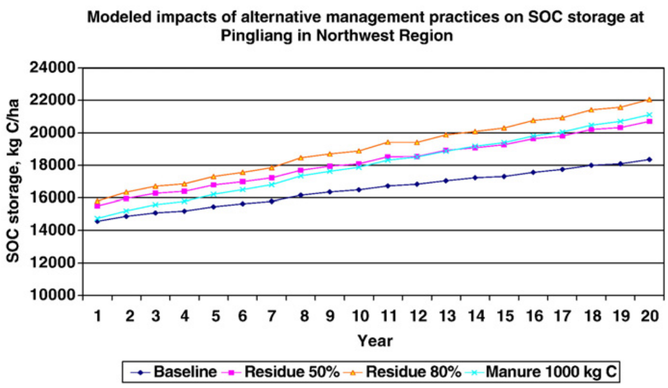

Fig. 6. The SOC storage at Pingliang increased under the baseline management conditions. Applying more crop residue or manure in the soil increased the C sequestration rates in the soil.

5.2.3. Site Pingliang in the Northwest Region

Among the tested sites, this site was the only one receiving manure fertilizer in its baseline scenario. Due to the low initial SOC content (0.004 kg C/kg) as well the manure amendment, the SOC storage at the site gradually increased during the simulated 20 years (Fig. 6). Increasing manure amendment or crop residue incorporation greatly elevated the soil capacity for SOC sequestration.

5.2.4. Site Zhijiang in the South Region

With a single-season paddy rice planted, the soil at the site received a limited amount of crop residue that led to a slight decrease in SOC storage during the simulated 20 years. However, increase in fraction of the above-ground crop residue incorporated in the soil after harvest from 15% (MOA, 2004) to 50% brought the cropping system to an equilibrium status regarding the SOC dynamics. Further increase in crop residue incorporation or manure application significantly increased the SOC storage (Fig. 7).

5.2.5. Site Jiangning in the East Region

Driven by the double-cropping paddy rice system, the site had high litter production rates and hence received more crop residue incorporated into the soil that led to increases in the SOC storage during the simulated 20 years. Increase in the crop residue incorporation fraction to 80% or increase in the manure application rate to 1000 kg C/ha significantly elevated the SOC storage (Fig. 8).

5.2.6. Site Yanting in the Southwest Region

The SOC storage in this double-season cropping system with paddy rice and winter wheat rotated was in a well established equilibrium status. Any increase in the input of organic matter from crop residue incorporation or manure application promptly increased the SOC content (Fig. 9).

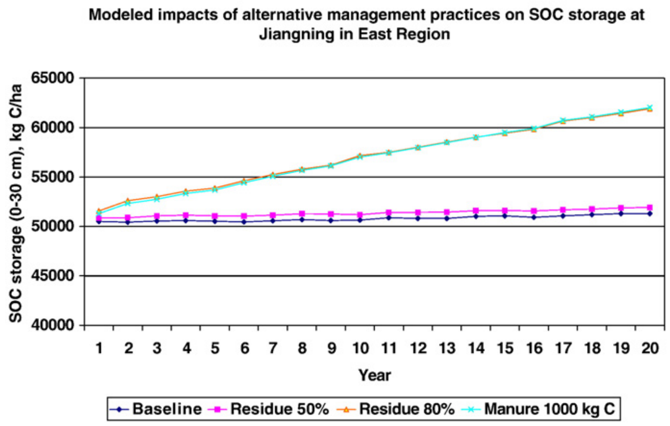

Fig. 8. The SOC storage at Jiangning is in equilibrium under the baseline conditions and can become a strong sink with 80% of above-ground crop residue incorporation or 1000 kg C/ha of manure amendment.

5.3. Effects of alternative fertilizer application rates on SOC dynamics

Fertilizer application rates used to vary greatly in China due to not only the demands of different cropping systems but also the accessibility to the fertilizers. However, along with the rapid development of the rural economics in a large portion of the country, the fertilizer accessibility for most the farmers has been substantially improved, and overuse of fertilizer is becoming a new issue. The baseline fertilizer application rates adopted in this study were set conservatively based on official recommendations. By varying the fertilization rates, we tested the impacts of increase or decrease in fertilizer application rate on not only SOC dynamics but also crop yield, nitrate leaching loss and nitrous oxide (N_2O) emission for the six sites. The modeled results are summarized in Tables 8, 9, 10 and 11. The modeled data indicated that increase in fertilizer application rate by 20% had little effect on the SOC dynamics for all the tested sites except Jiangning (Table 8). The reason is demonstrated in Table 9, in which the crop yields didn't increase very much with the increased fertilization rates. The results imply that the fertilizer application rates adopted in the baseline scenarios have reached the maximum levels already, and hence any further increase in the fertilization rates

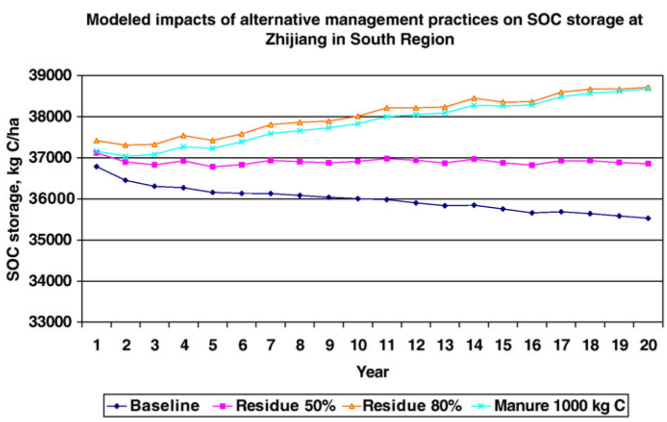

Fig. 7. The SOC storage at Zhijiang slowly decreased under the baseline scenario conditions but could be easily turned into a sink of atmospheric C with any of the alternative residue or manure management practices.

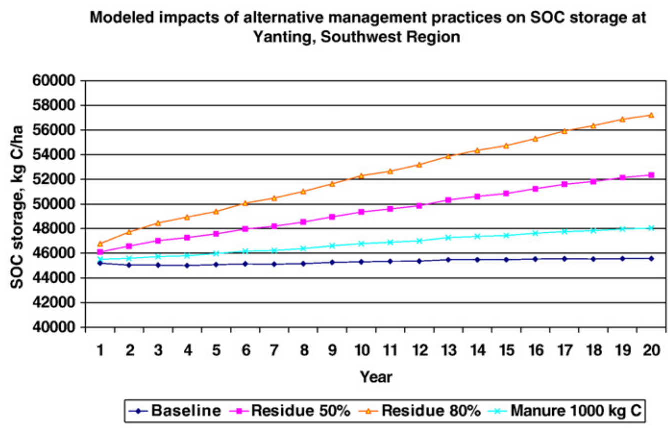

Fig. 9. The SOC storage at Yanting is near equilibrium under the baseline conditions and can significantly increase with more above-ground crop residue incorporated or manure amended in the soil.

Table 8
DNDC-modeled 20-year average annual SOC changes (kg C/ha/yr) with baseline and alternative fertilizer application rates for simulated six sites

Scenario	Qiqihar (Northeast)	Miyun (North)	Pingliang (Northwest)	Zhijiang (South)	Jiangning (East)	Yanting (Southwest)
Baseline	−1013	−435	200	−70	26	−68
Fertilizer 50%	−998	−311	188	−72	5	−89
Fertilizer 80%	−1007	−291	195	−71	17	−71
Fertilizer 120%	−1013	−423	204	−69	29	−67

Table 9
DNDC-modeled 20-year average annual crop yield (kg C/ha/yr) with baseline and alternative fertilizer application rates for simulated six sites

Scenario	Qiqihar (Northeast)	Miyun (North)	Pingliang (Northwest)	Zhijiang (South)	Jiangning (East)	Yanting (Southwest)
Baseline	3168	1924	1538	2584	3905	3816
Fertilizer 50%	2618	1520	1396	2463	3763	3509
Fertilizer 80%	2973	1745	1487	2506	3854	3761
Fertilizer 120%	3168	2060	1580	2618	4365	3820

won't effectively elevate the crop yields anymore. However, the increase in fertilization rates did increase nitrate leaching losses and N_2O emissions from all of the sites (Tables 10 and 11) that should contribute to the local water eutrophication or global climate change. In another direction, decrease in the fertilizer application rate by 20% or 50% decreased the crop yield as well SOC storage although the correlations are non-linear. For example, decrease in fertilization rate by 50% decreased the crop yields by 17%, 21%, 9%, 4%, 4% and 8% and decreased the annual SOC sequestration rates by 1%, 29%, 6%, 3%, 81% and 30% for Qiqihar, Miyun, Pingliang, Zhijiang, Jiangning and Yanting, respectively. However, the decrease in fertilizer application rates reduced nitrate leaching losses as well N_2O emissions. The calculation for the net benefit of the alternative practices would rely on the future, new policies that count both crop yields and environmental consequences in China.

6. Discussion

Chinese agriculture has survived from a millennia history and still supports one fifth of the population on the planet. However, driven by the rapid development of economy in the country, the Chinese agriculture is faced by a series of environmental stresses from soil degradation, water contamination to air pollution. SOC is one of the central issues related to not only soil fertility but also environmental safety. Assessing SOC dynamics has long been a challenge in China due to the lack of proper methodologies. Soil survey has been conducted for two times in China during the past decades. The surveys resulted in valuable data sets describing the soil distribution and properties nationwide. However, comparison between the survey data collected from different time periods were not very straightforward mainly due to the lack of detailed documents recording the specific sampling locations or analysis methods utilized in the surveys. As an alternative approach for studying SOC dynamics, process-based models were adopted to meet the gaps. An internationally recognized biogeochemical model, DNDC, was validated and then employed in this study to try understanding the possible trends of SOC dynamics across the major agricultural regions of China.

Based on the simulations for the selected six sites, which represent the six agricultural regions in China, we learnt that the SOC status between the northern agricultural regions represented by the sites at Qiqihar, Miyun and Pingliang and the southern regions represented by Zhijiang, Jiangning and Yantin were apparently different. Under the current (or baseline) management conditions, the SOC status in the northern regions appeared more dynamic than that in the southern regions. The tested three northern sites were either losing or gaining SOC at relatively high rates (−1000, −400 and 200 kg C/ha/yr for Qiqihar, Miyun and Pinagliang, respectively). In contrast, the SOC contents in the southern sites were basically in equilibrium with deviations ranging from −70 to 26 kg C/ha/yr. The modeled results indicated that the difference between the northern and southern cropping systems resulted mainly from two processes, i.e., SOC decomposition and organic matter addition through crop residue incorporation and/or manure amendment. Both the processes were further regulated by the primary drivers, i.e., climate, soil properties, crop type, and farming practices. Any change in the primary drivers would alter the SOC balance by simultaneously changing the litter incorporation and SOC decomposition. The DNDC-modeled results revealed that increase in the fraction of above-ground crop residue incorporation or application of manure fertilizer could effectively elevate the SOC storage with least negative effects on the crop yields across the major agricultural regions in China. This conclusion is consistent with the results from many researchers (Franzluebbers et al., 1994; Hernanz and Lopèz, 2002; Wang et al., 2004; Meng et al., 2005; Ma and Chen, 2006). China had 150 million heads of large livestock (e.g., cattle, horse, buffalo, mule etc.), 466 million heads of pigs, 339 million heads of sheep and goats, and 5058 million fowls in 2003 with about 2600 million tons of manure produced annually (MOA, 2004). If 50% of the manure can be finally applied to the cropland in China, each hectare would receive 10 tons of manure fertilizer. In addition, only about 10%–20% of above-ground crop residue is currently returned to the field in China (Han et al., 2002; Sun and Sun, 2006). So the farming management alternatives by utilizing crop residue and animal manure are feasible for improving the SOC status in China.

Table 10
DNDC-modeled 20-year average annual nitrate leaching losses (kg N/ha/yr) with baseline and alternative fertilizer application rates for simulated six sites

Scenario	Qiqihar (Northeast)	Miyun (North)	Pingliang (Northwest)	Zhijiang (South)	Jiangning (East)	Yanting (Southwest)
Baseline	9.30	2.53	2.26	2.61	7.63	2.94
Fertilizer 50%	9.33	0.65	1.38	0.61	3.66	0.28
Fertilizer 80%	9.33	1.05	1.90	1.62	4.97	1.18
Fertilizer 120%	10.82	3.38	2.64	3.87	14.93	5.24

Table 11
DNDC-modeled 20-year average annual N_2O emissions (kg N/ha/yr) with baseline and alternative fertilizer application rates for simulated six sites

Scenario	Qiqihar (Northeast)	Miyun (North)	Pingliang (Northwest)	Zhijiang (South)	Jiangning (East)	Yanting (Southwest)
Baseline	25.9	5.65	4.03	7.45	13.96	3.56
Fertilizer 50%	25.3	3.54	3.01	2.61	8.21	0.94
Fertilizer 80%	25.5	3.67	3.65	5.91	11.93	1.30
Fertilizer 120%	27.6	6.11	4.38	8.32	20.21	4.05

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