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Modeling impacts of carbon sequestration on net greenhouse gas emissions from agricultural soils in China

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[1] Soil organic carbon (SOC) contents in many farmlands have been depleted because of the long-term history of intensive cultivation in China. Chinese farmers are encouraged to adopt alternative management practices on their farms to sequester SOC. On the basis of the availability of carbon (C) resources in the rural areas in China, the most promising practices are (1) incorporating more crop residue in the soils and (2) resuming traditional manure fertilizer. By implementing the alternative practices, increase in SOC content has been observed in some fields. This paper investigates how the C sequestration strategies could affect nitrous oxide (N_2O) and methane (CH_4) emissions from the agricultural soils in six selected sites across China. A process-based model, denitrification-decomposition or DNDC, which has been widely validated against data sets of SOC dynamics and N_2O and CH_4 fluxes observed in China, was adopted in the study to quantify the greenhouse gas impacts of enhanced crop residue incorporation and manure amendment under the diverse climate, soil, and crop rotation conditions across the six agroecosystems. Model results indicated that (1) when the alternative management practices were employed C sequestration rates increased, however, N_2O or CH_4 emissions were also increased for these practices; and (2) reducing the application rates of synthetic fertilizer in conjunction with the alternative practices could decrease N_2O emissions while at the same time maintaining existing crop yields and C sequestration rates. The modeling approach could help with development of spatially differentiated best management practices at large regional scales.

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1. Introduction

[2] Carbon (C) sequestration has been highlighted as an important approach for mitigating the greenhouse effect by converting the atmospheric carbon dioxide (CO_2) into biotic or abiotic C sequestered in terrestrial ecosystems and other sinks [*Lackner*, 2003]. As intensively managed systems, agroecosystems are being studied for their potential to sequester C in their soil organic pools through management alternatives. For example, replacing conventional tillage with no-till could result in net sequestration of soil organic carbon (SOC) at the soil top layers [*Lal*, 2003; *Robertson et al.*, 2000] although uncertainty exists for the entire soil profiles [*Blanco-Canqui and Lal*, 2008]. *Lackner* [2003] estimated global storage capacity of soil carbon at roughly 100 Gt C. Agricultural soils generally have capacity to store C, as their precultivation SOC reserves were depleted in the first few decades after cultivation [e.g., *Smith et al.*, 1997]. The increase in SOC storage in agricultural land has a dual benefit, which not only sequesters the atmospheric CO_2 but also elevates the soil fertility to optimize the crop production. The C sequestration issue is especially crucial for the regions such as China where the agricultural SOC has been depleted to a low level because of the long-term intensive cultivation.

[3] China possesses about 120 million hectares of croplands, most of which have been cultivated for hundreds of years. During the historical time period before the 1950s, the agricultural production in China was low, and the soil fertility was maintained mainly by relying on crop residue incorporation and manure application. However, since then, driven by the rapidly increased demands for food, fiber and energy, the traditional farming management practices have been gradually replaced by new technologies such as new crop cultivars, synthetic fertilizers, machinery etc. to elevate the crop yields. Without the incorporation of crop residue or manure amendments, which has been the major source of SOC for most Chinese farmlands, a continuous decline in SOC levels for a wide scope of Chinese agricultural soils has been observed. The end result of these changes was a series of environmental problems which included soil degradation, soil erosion and desertification across the country [*Fang et al.*, 1996; *Feng and Li*, 2000; *Fu et al.*, 2001; *Pan et al.*, 2005]. On the basis of the national soil survey data, the

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average SOC content in China is about 30% lower than the world average [*Xu*, 2002]. Since the soil degradation has started threatening the sustainability of Chinese agriculture, new policies have been launched during the past decade to encourage the farmers to return more organic matter including crop residues and various manure fertilizers back to the soils to maintain the soil fertility. On the basis of the latest reports from Chinese researchers, some of the agricultural fields have started gaining SOC, especially in the experimental stations [*Yan et al.*, 2007; *Huang and Sun*, 2006].

[4] Along with the improvement of the SOC status in millions of hectares of cropland in China, the issue of C trading is emerging, as a result of the proposed greenhouse gas mitigation credits initiated by the Kyoto Protocol (United Nations Framework Convention on Climate Change; see http://unfccc.int/resource/docs/convkp/kpeng.html). Since the biogeochemical cycles of C and nitrogen (N) are tightly coupled, any change in SOC storage could alter a series of C and N fluxes including emissions of CO_2, nitrous oxide (N_2O) and methane (CH_4) from the soils. From the view of global warming, it is crucial to assess the impacts of the C sequestration strategies on not only CO_2 but also N_2O and CH_4 emissions from the agricultural fields subject to the new farming management practices. For example, higher SOC can increase the concentrations of dissolved organic carbon (DOC) and inorganic N (e.g., ammonium and nitrate) by elevating decomposition rate in the soils; and the increased DOC and inorganic N can fuel nitrifiers and denitrifiers to produce more N_2O in upland soils or enhance methanogenesis to produce more CH_4 in wetland soils [*Li*, 2007]. Numerous field measurements indicate a positive correlation between N_2O flux and SOC content [*Sahrawat and Keeney*, 1986; *Federer and Klemedtsson*, 1988; *Ambus and Christenson*, 1994; *Christensen et al.*, 1990]. It has been observed that amendment of organic matter to soil can increase the soil N_2O emissions [e.g., *Flessa et al.*, 1996; *Khalil et al.*, 2002; *Bouwman et al.*, 2002; *Robertson et al.*, 2000; *Six et al.*, 2004]. Incubation experiments also identified SOC content as a key controller of N_2O production [e.g., *Leffelaar and Wessel*, 1998; *Federer and Klemedtsson*, 1988]. In paddy rice fields, CH_4 emission rates have been observed to be positively related to the available C content, which is regulated by SOC decomposition, root exudation or straw/manure amendment [*Shangguan et al.*, 1994; *Chen et al.*, 1992; *Cicerone et al.*, 1992; *Cai et al.*, 1995; *Rovira*, 1969; *Schütz et al.*, 1989; *Vermoessen et al.*, 1991; *Wassmann et al.*, 1993; *Sass et al.*, 1991]. The observations on the impacts of SOC on the trace gas emissions have been summarized by several former publications [e.g., *Li et al.*, 2005].

[5] Although measurements of soil CO_2, N_2O or CH_4 emissions have been carried out in China for decades, few sites have made measurements of the three gases simultaneously. To address this issue, a process-based model was adopted in the study to assess the impacts of the C sequestering strategies, i.e., crop residue incorporation and manure application, on CO_2, N_2O and CH_4 emissions from agricultural soils in the country. The denitrification-decomposition or DNDC model adopted in the study has been tested against observed CO_2, N_2O or CH_4 fluxes from a wide scope of agroecosystems across China. This paper reports how we utilized the model to assess the greenhouse gas impacts of the alternative farming practices for six selected crop fields across the major agricultural regions of China.

2. DNDC Model

[6] The DNDC model is a process-based biogeochemical model originally developed for predicting carbon sequestration and trace gas emissions from agroecosystems in the United States [*Li et al.*, 1992, 1994]. DNDC consists of six submodels for simulating soil climate, plant growth, decomposition, nitrification, denitrification and fermentation, respectively. DNDC predicts SOC dynamics mainly by quantifying the SOC input from crop litter incorporation and manure amendment as well as the SOC output through decomposition. DNDC simulates plant growth by tracking photosynthesis, respiration, water and N demand, C allocation, crop yield, and litter production. The modeled litter (roots and aboveground residue) production is one of the major factors controlling the C dynamics in soil. As soon as the modeled litter is incorporated in the simulated soil profile, DNDC will partition the litter into three soil litter pools, namely very labile litter, labile litter and resistant litter, on the basis of C/N ratio of the litter. Each of the litter pools has a specific decomposition rate though subject to temperature, moisture and N availability in the soil profile. During the decomposition of litter, part of the litter C is consumed as the energy source by the soil microbes and hence becomes CO_2; and part of the litter C is turned into the microbial biomass. After death of the microbes, the microbial remains will become humads to undergo further decomposition. During the decomposition processes, the N bound in the organic compounds is released into the soil in the form of ammonium. Ammonium can be oxidized into nitrate through nitrification. Ammonium or nitrate can be utilized by the soil nitrifiers or denitrifiers to produce N_2O through nitrification or denitrification, respectively. Under deeply anaerobic conditions, soil methanogens will be activated to produce CH_4 on the basis of the soil substrate (e.g., DOC or CO_2) concentrations. The above described processes have been embedded in DNDC to simulate decomposition, nitrification, denitrification and fermentation, which dominate CO_2, N_2O and CH_4 emissions from terrestrial soils. A complete set of farming management practices such as tillage, fertilization, manure amendment, irrigation, flooding, grazing etc. have also been parameterized in DNDC to regulate the soil environmental factors (e.g., temperature, moisture, pH, redox potential and substrate concentration gradients). Two classical equations, the Nernst equation and the Michaelis-Menton equation, were adopted in DNDC to integrate the ecological drivers (e.g., climate, soil, vegetation and anthropogenic activity), soil environmental factors and the biogeochemical reactions into a modeling framework. DNDC tracks the soil redox potential evolution and calculates productions and consumptions of CO_2, N_2O and CH_4 sequentially for both upland and wetland ecosystems (see details given by *Li et al.* [1992, 2004] and *Li* [2007]). In DNDC, DOC concentration is calculated on the basis of the SOC decomposition rate and controls N_2O or CH_4 production by fueling the relevant microbial activities in conjunction with other substrates

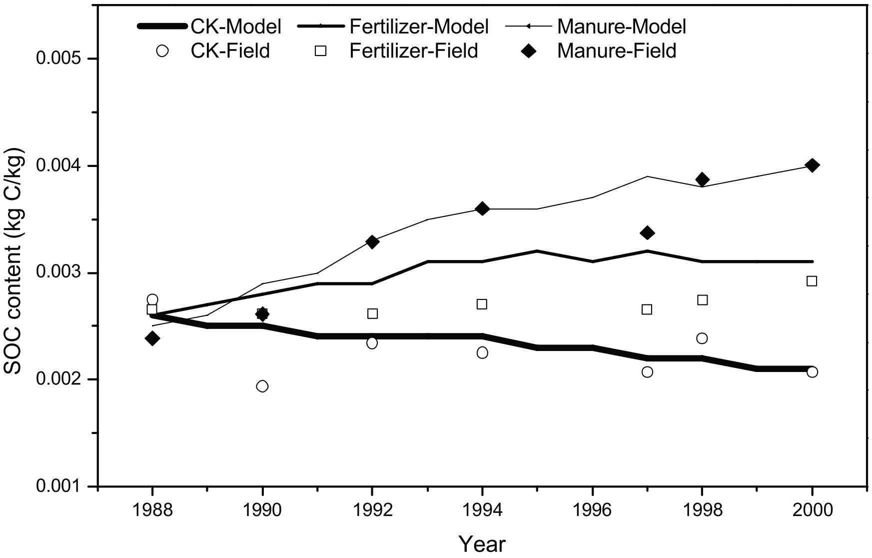


Figure 1. Observed and DNDC-modeled 13-year SOC dynamics at a potato field with three treatments (i.e., CK, control treatment; Fertilizer, synthetic fertilizer; Manure, manure amendment) in Hequ county, Shanxi Province, China from 1988 to 2000 [*Zhang et al.*, 2006].

(e.g., ammonium, nitrate, hydrogen). By precisely simulating the soil microbial activities, DNDC links C sequestration to N_2O or CH_4 emissions.

[7] During the past decade, DNDC has been tested by many researchers worldwide with promising results [*Brown*, 1995; *Smith et al.*, 1997; *Plant et al.*, 1998; *Butterbach-Bahl et al.*, 2001; *Saggar et al.*, 2003; *Grant et al.*, 2004; *Kiese et al.*, 2005; *Pathak et al.*, 2005; *Kesik et al.*, 2005; *Jagadeesh Babu et al.*, 2006; *Beheydt et al.*, 2007; *Smith et al.*, 2008]. The model is currently applied for greenhouse gas inventory or mitigation in North America, Europe, Asia, and Oceania. In the International Workshop on Global Change for Asia Pacific Region in 2000, DNDC was designated as one of the biogeochemical models applicable for the Asia Pacific regions [*Lal*, 2002]. In China, a number of researchers have been involved in the DNDC development by calibrating and validating the model against the data sets observed across a wide range of agroecosystems in the country. For example, *Xu et al.* [1999], *Xu-Ri et al.* [2003] and *Cai et al.* [2003] tested DNDC for N_2O emissions from Chinese agricultural soils; *Cai et al.* [2003] tested DNDC with 17 data sets of CH_4 fluxes measured in eight provinces in China; *Qiu et al.* [2003, 2004], *Shi and Liu* [2002], *Sun and Zhu* [2003], *Wang et al.* [2004], *Zhang et al.* [2006], and *Li* [2007] tested DNDC for long-term SOC dynamics or CO_2 emissions at multiple sites across China. The test results indicate that DNDC is capable of quantifying SOC dynamics in and N_2O and CH_4 emissions from the major agroecosystems including upland and wetland cropping systems in China. For example, DNDC was tested by *Zhang et al.* [2006] against a long-term (13 years) SOC data set measured at an experimental field in Hequ County, Shanxi Province in North China from 1988 to 2000. The site was planted with potatoes under three different treatments (i.e., manure amendment, synthetic fertilizer application and control) during the experimental period. Field observations indicated that the three treatments had different impacts on the SOC dynamics during the 13 years. DNDC was applied to simulate the impacts of the three management scenarios on the SOC dynamics for the field. The modeled results captured the trends of SOC dynamics observed at the three plots (Figure 1). Another example showed how DNDC worked for wetland crops. DNDC was applied for a paddy rice field in Wu County, Jiangsu Province in South China, where both CH_4 and N_2O fluxes were measured during the rice growing season [*Zheng et al.*, 1997]. The DNDC-modeled results demonstrates a fair agreement between observed and modeled CH_4 and N_2O fluxes regarding their patterns and magnitudes for the rice field applied with midseason drainage (Figure 2). The DNDC model captured the episodes of CH_4 emission depressions and N_2O emission increases during the soil drying periods by tracking the soil Eh dynamics, CH_4 oxidation, labile organic matter decomposition, and stimulated nitrification and denitrification fueled by the increased ammonium and nitrate production due to the conversions of soil anaerobic to aerobic conditions driven by the midseason drainage. With the support of many validations, DNDC was employed in the study to assess the impacts of the nationwide C sequestration strategies, i.e., crop residue incorporation and manure application, on net greenhouse gas emissions across the agricultural regions in China.

3. Site Selection

[8] To facilitate the administrative management of the entire 120 million hectares of cropland in China, the national farmlands are divided into six agricultural regions, based mainly on their agrometeorological and cropping management conditions. These regions are northeast, northwest, mid-north, mid-south, southeast, and southwest regions (Figure 3). The northeast region possesses cool but humid weather with relatively fertile soils (SOC content 0.01–0.04 kg C kg^{-1}).

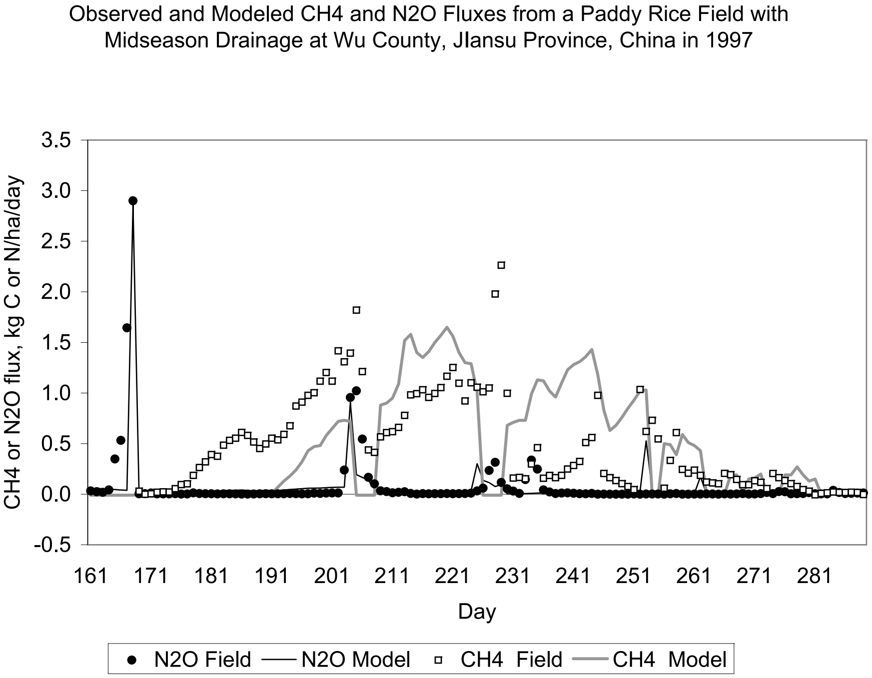


Figure 2. Comparison between observed and DNDC−modeled CH_4 and N_2O fluxes from a paddy rice field applied with midseason drainage in Wu County, Jiangsu Province, China, in 1995 (field data from *Zheng et al.* [1997]).

Single-cropping (i.e., only one crop is planted per year) systems dominate in the region with corn, soybeans, potatoes, winter wheat and rice as major crops. The northwest region is located in the semiarid and arid zones with low precipitation and poor soils (SOC< 0.01 kg C kg^{-1}). The farmlands are managed with single-cropping and double-cropping (i.e., two crops are planted consecutively per year) systems with corn, wheat and potatoes as major crops. The mid-north Region is located in the North China Plains with warm but dry weather. Relying on well-established irrigation

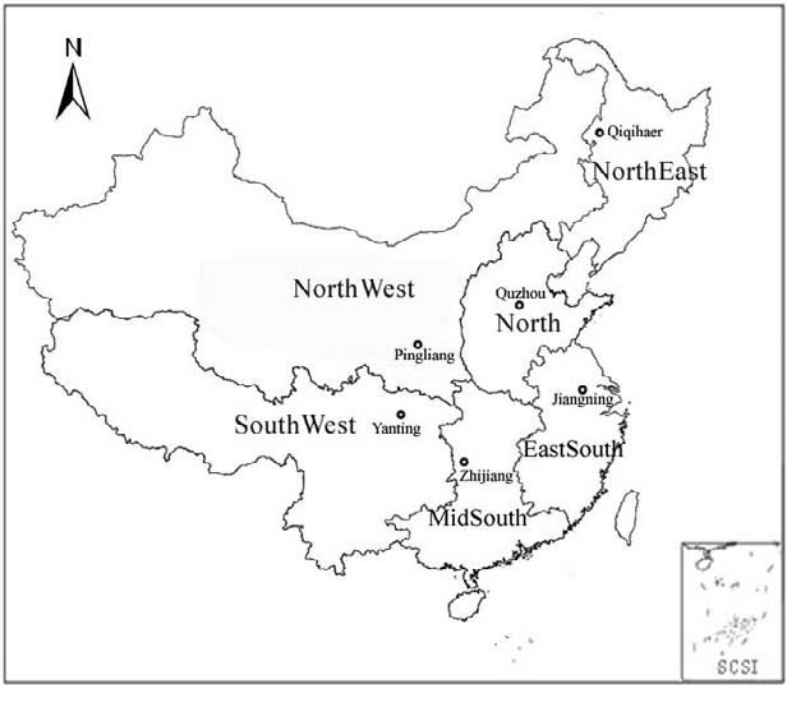


Figure 3. Locations of six selected farm fields and major agricultural regions of China.

Table 1. Characteristics of Six Selected Cropping Systems Across the Agricultural Regions in China

Agricultural Region	Cropping System	Location (County, Province)	Latitude	Average Temperature (°C)	Average Precipitation (mm)	SOC ($kg\ C\ kg^{-1}$)	Bulk Density ($g\ cm^{-3}$)	Clay Fraction	pH
Northeast	Single corn	Qiqihaer (QQ), Heilongjiang	47.2°N	4.59	346	0.04	1.2	0.19	6.8
Mid-north	Wheat-corn	Quzhou (QZ), Hebei	36°N	14.91	799	0.0097	1.5	0.19	7.2
Northwest	Corn-wheat	Pingliang (PL), Gansu	37°N	10.32	364	0.004	1.4	0.14	8.0
Mid-south	Single rice	Zhijiang (ZJ), Hunan	25°N	17.19	1384	0.011	1.26	0.27	6.3
Southeast	Rice-wheat	Jiangning (JN), Jiangsu	29.3°N	17.27	971	0.006	1.35	0.41	6.0
Southwest	Rice-wheat	Yanting (YT), Sichuan	30°N	15.09	975	0.016	1.12	0.20	8.6

systems as well as intensive management, the agriculture in the region has been being prosperous for hundreds of years. The farming systems are dominated by double-cropping practices with winter wheat, corn, rice, cotton and rapeseeds rotated. The SOC contents in the region are now approaching equilibrium after having experienced decades of decreasing SOC levels. The mid-south, southeast, and southwest regions are influenced by the monsoon climate and hence possess warm or subtropical weather with relatively abundant precipitation. The agricultures in the three southern regions are dominated by double-cropping systems mostly with paddy rice rotated with an upland crop (e.g., winter wheat, rapeseeds, corn etc.). Because of the relatively stable thermo-hydrological conditions, the paddy soils contain a narrow range of SOC contents (0.01–0.02 kg C kg^{-1}) across the three southern regions. However, the three regions differ in topography. The southeast and mid-south regions possess flatter landscapes with alluvial soils. The southwest region contains a lot of mountainous or hilly areas with highly weathered soils [*Yu et al.*, 2003; *Xu et al.*, 2004; *Huang and Sun*, 2006; *Liu*, 2005; *Wang et al.*, 2006; *Li et al.*, 2006]. The diverse natural and management conditions across the six agricultural regions in China would inherently affect the effectiveness of the C sequestration strategies as well their impact on greenhouse gas emissions. In the study a typical site was selected from each of the six agricultural regions to serve the modeling predictions for China.

[9] A total of six farm fields were selected respectively at Qiqihaer (QQ) in Heilongjinag Province, Quzhou (QZ) in Hebei Province, Pingliang (PL) in Gansu Province, Jiangning (JN) in Jiangsu Province, Zhijiang (ZJ) in Hunan Province and Yanting (YT) in Sichuan Province to represent the dominant cropping systems in the northeast, mid-north, northwest, mid-south, southeast, and southwest regions, respectively. The selected sites possess climate and soil conditions which are roughly representative for the agricultural regions where the sites are located. The locations of the selected sites are shown in Figure 3, and the detailed information of climate, soil and current farming practices for the sites are listed in Table 1.

4. Farming Management Scenarios

[10] Farming management practices such as crop type and rotation, tillage, fertilization, manure amendment and irrigation play an important role in controlling SOC dynamics as well as N_2O and CH_4 emissions in agroecosystems. Any change in the practices can mostly alter either the quantity and/or quality of the incorporated crop litter or the SOC decomposition rate that eventually redefines the soil C and N balances in conjunction with the local climate and soil conditions. To simulate the greenhouse gas impacts of alternative farming practices we compiled three management scenarios, baseline (BASE), alternative 1 (ALTER-1) and alternative 2 (ALTER-2), for each of the six selected sites. The BASE scenario was compiled for each site on the basis of the information collected from the local investigations at the specific site. In the BASE scenarios, conventional tillage was adopted, no manure was applied, and 15% of aboveground crop residue (leaves + stems) was incorporated after harvest for all the sites; irrigation was adequately applied for all the three southern cropping systems in JN, ZJ and YT where paddy rice was planted. Synthetic fertilizer application rates varied among the crop types as well as the sites from the lowest 65 kg N ha^{-1} for the corn or winter wheat season in PL in the northwest region to the highest 266 kg N ha^{-1} for the rice season in JN in the southeastern region. Annual fertilizer application rate for each site is the sum of the rates applied for all the crops consecutively planted in the site during the same year. The annual fertilizer application rates were 160, 300, 130, 106, 402 and 300 kg N ha^{-1} a^{-1} for QQ, QZ, PL, ZJ, JN and YT, respectively (see detailed information of fertilizer application rates and dates for each crop at each site in Table 2). The first alternative management scenario (ALTER-1) was designed to represent the C sequestration strategies. ALTER-1 was compiled by adopting the baseline scenario but with two alterations: elevating the rate of aboveground crop residue incorporation from 15% to 50% and amending 1000 kg C ha^{-1} a^{-1} of farmyard manure for each of the six sites. The 1000 kg C of farmyard manure for amendment is a conservative number as the actual amount could be as high as 2000–4000 kg C ha^{-1} a^{-1} in the agricultural areas in China. Since fertilizer overuse is a common issue in China, the second alternative management scenario (ALTER-2) was designed to test impacts of the C sequestration strategies plus reduced synthetic fertilizer rates. ALTER-2 was compiled by adopting ALTER-1 but with an adjusted synthetic fertilizer application rate reduced by 50 kg N a^{-1}, which is equivalent to the organic N added from the manure amendment, for each site.

[11] For each site, DNDC was run first with the BASE scenario for 20 years; and in year 21 DNDC was continuously run with the BASE, ALTER-1 and ALTER-2 scenarios in parallel for 50 years. The reason for implementing the first 20-year presimulation was to eliminate the possible uncertainties that could be induced from the initial settings of some input parameters such as SOC partitioning. The simulated results from the last 50 years were selected for analyses serving this study. The weather data (i.e., daily maximum, minimum air temperatures and precipitation) of 1990–1999

Table 2. Baseline Farming Management Practices for Selected Six Cropping Systems in China

Location	Cropping System	Planting Date (Day/Month)	Harvest Date (Day/Month)	Tillage Date (Day/Month)	N Fertilizer Rate (kg N ha^{-1} Per Application)	N Fertilizer Application Date (Day/Month)	Manure Application	Residue Returned
QQ	Single corn	10/5	27/9	1/5, 1/10	100, 60	1/5, 2/7	no	15%
QZ	Corn/winter wheat	10/6, 1/10	25/9, 5/6	6/6, 1/10	80, 80, 70, 70	5/7, 1/10, 20/3, 20/8	no	15%
PL	Corn/winter wheat	25/5, 10/10	1/10, 15/5	20/5, 1/10	65, 65	25/5, 10/10	no	15%
ZJ	Single rice	21/04	26/9	20/4, 27/9	53, 53	26/4, 23/5	no	15%
JN	Rice/winter wheat	15/5, 25/10	20/10, 10/5	11/5, 12/10	50, 50, 166, 50, 86	1/3, 21/6, 5/8, 30/8, 1/11,	no	15%
YT	Rice/winter wheat	23/5 10/9	7/9 20/5	20/5, 10/9	150, 150	23/5, 26/10	no	15%

were obtained from the China Meteorological Data Sharing Service System for the six sites. The 10-year weather data were repeatedly utilized for the simulated 70 years. The soil data (i.e., bulk density, SOC content, texture and pH) for the selected sites were extracted from the soil maps published by the *National Soil Survey Office* [1986]. The modeled results including annual change in SOC storage (dSOC) in the topsoil (0–30 cm) and annual N_2O and CH_4 fluxes were recorded for the last simulated 50 years for each site. A 50-year average annual flux of dSOC, N_2O or CH_4 was calculated for each scenario at each site to serve cross-management scenario and cross-site comparisons (Table 3). Along with the three main greenhouse gases, other estimates of crop yield, litter production, nitrate leaching, total denitrifcation flux etc., were also recorded because of their influence on C and N dynamics.

5. Impact of Alternative Farming Management Practices on Soil C Dynamics

[12] Results from the simulations with the BASE management scenarios indicated that the SOC contents at the tested six sites decreased during the simulated 50 years although the decreasing rates were low ranging from −15 to −95 kg C ha^{-1} a^{-1} across the six sites. This implied that the SOC contents in the fields were approaching equilibrium after years of intensive cultivation. When the management scenario shifted from BASE to ALTER-1, all the tested sites turned from sources to sinks of atmospheric CO_2 (Table 2 and Figures 4). However, the C sequestration rates varied among the six sites. The two double-cropping systems at JN and YT gained the most SOC because of the high litter productions from the rice-involved agroecosystems in the southern region of China where the paddy soils well protected the fresh litter from rapid decomposition. The upland field in QZ in the mid-north region gained the least SOC. The modeled data indicated that the crops growing at the site suffered frequent drafts that led to low yields as well as low litter production. In contrast to QZ, the upland field in QQ in the northeastern region gained much more SOC. The modeled data indicated that the corn growing at the site received adequate precipitation and the cool weather decreased the SOC decomposition rate. In general, by adopting the alternative management practices (i.e., increased crop residue incorporation and manure application), the soils at all the tested six sites effectively became sinks of atmospheric C although the magnitudes of C sequestration were subject to the local climate and soil conditions. Running DNDC with the ALTER-2 scenario, we observed the impact of reduced synthetic fertilizer application rate (50 kg N ha^{-1} a^{-1} less than that in the baseline scenario) in combination with the C sequestration strategies on the SOC dynamics for each site. The results indicated that the C sequestration rates basically remained without decrease (for QQ, QZ, JN and YT) or with a little decrease (for PL and ZJ) (Table 3). The modeled SOC dynamics are shown in Figures 4–9, which were set with same scale in purpose to facilitate the comparisons across the six sites.

[13] Dynamics of SOC storage is controlled by the balance between the C input mainly through crop litter incorporation and the C output mainly through SOC decomposition. During the model simulations, annual crop yields and litter productions were recorded to track impacts of the alternative management practices on the soil C input. The results indicated that the crop productions maintained almost constant across the BASE, ALTER-1 and ALTER-2 scenarios for QQ, QZ, JN and YT. It implied that those sites had received so much synthetic fertilizer already under the BASE scenarios that changing the synthetic fertilizer application rates through ALTER-1 or ALTER-2 had little effect on the crop growth. However, the alternative management practices

Table 3. Modeled 50-Year Average Annual SOC Changes, N_2O and CH_4 Fluxes, and Global Warming Potentials for the Tested Six Croplands in China

Cropping System Scenario[a]	SOC Change (kg C ha^{-1} a^{-1})			N_2O Flux (kg N ha^{-1} a^{-1})			CH_4 Flux (kg C ha^{-1} a^{-1})			GWP (kg CO_2 Equivalent ha^{-1} a^{-1})		
	BASE	ALTER-1	ALTER-2	BASE	ALTER-1	ALTER-2	BASE	ALTER-1	ALTER-2	BASE	ALTER-1	ALTER-2
QQ	−20	269	268	21.3	40.2	22.5	−1.2	−1.2	−1.2	10416	18563	9944
QZ	−39	8	8	14.2	20.3	18.5	−0.4	−0.5	−0.5	7049	9846	8969
PL	−15	176	161	0.1	0.7	0.4	0.0	0.0	0.0	104	−304	−395
JN	−28	370	370	3.0	3.7	3.0	274	362	362	9236	10582	10241
ZJ	−40	229	207	0.1	0.3	0.3	679	859	783	19207	23358	21311
YT	−95	297	298	5.4	8.8	5.8	1928	2155	2155	56963	63538	62073

[a] Farming management scenarios: BASE, Baseline management scenario with current farming practices as described in the paper; ALTER-1, Alternative management scenario 1 with increased crop residue incorporation and manure application; ALTER-2, Alternative management scenario 2 with increased crop residue incorporation and manure application but reduced synthetic fertilizer application rate.

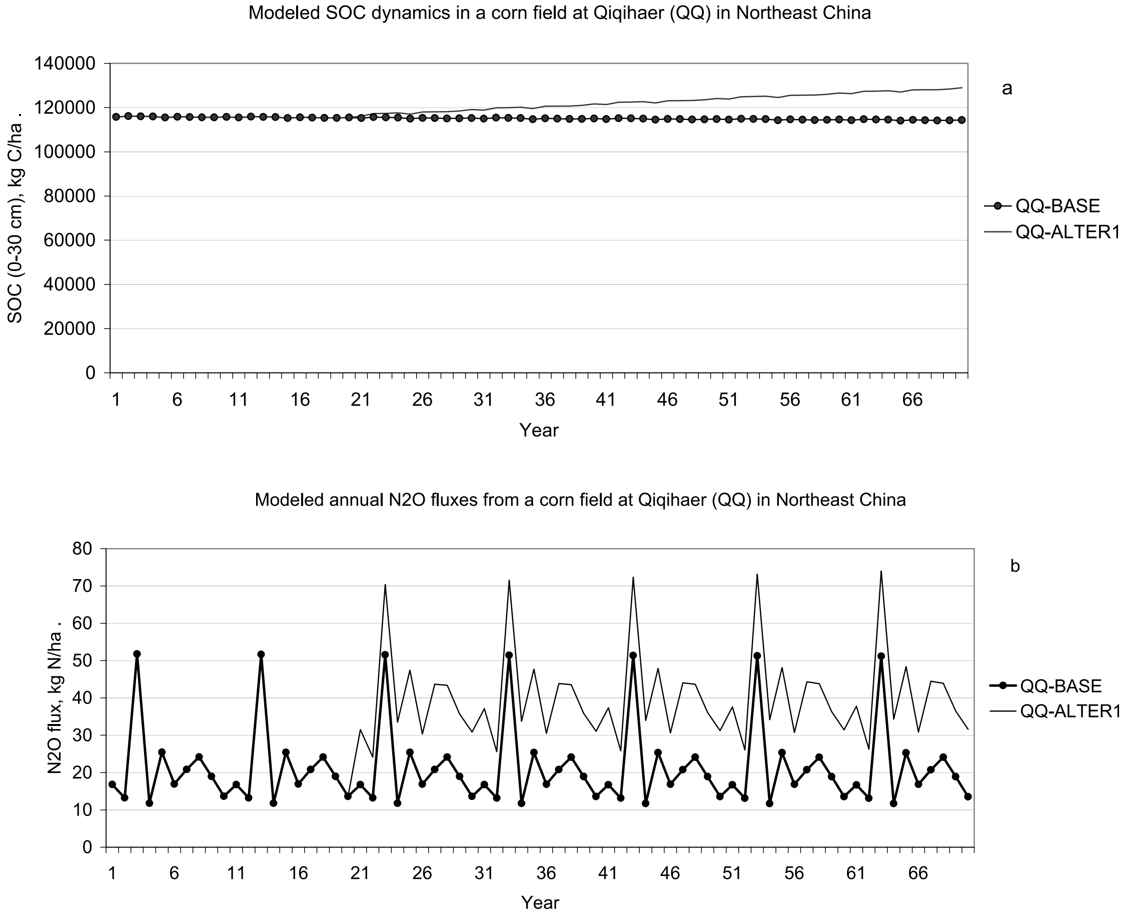
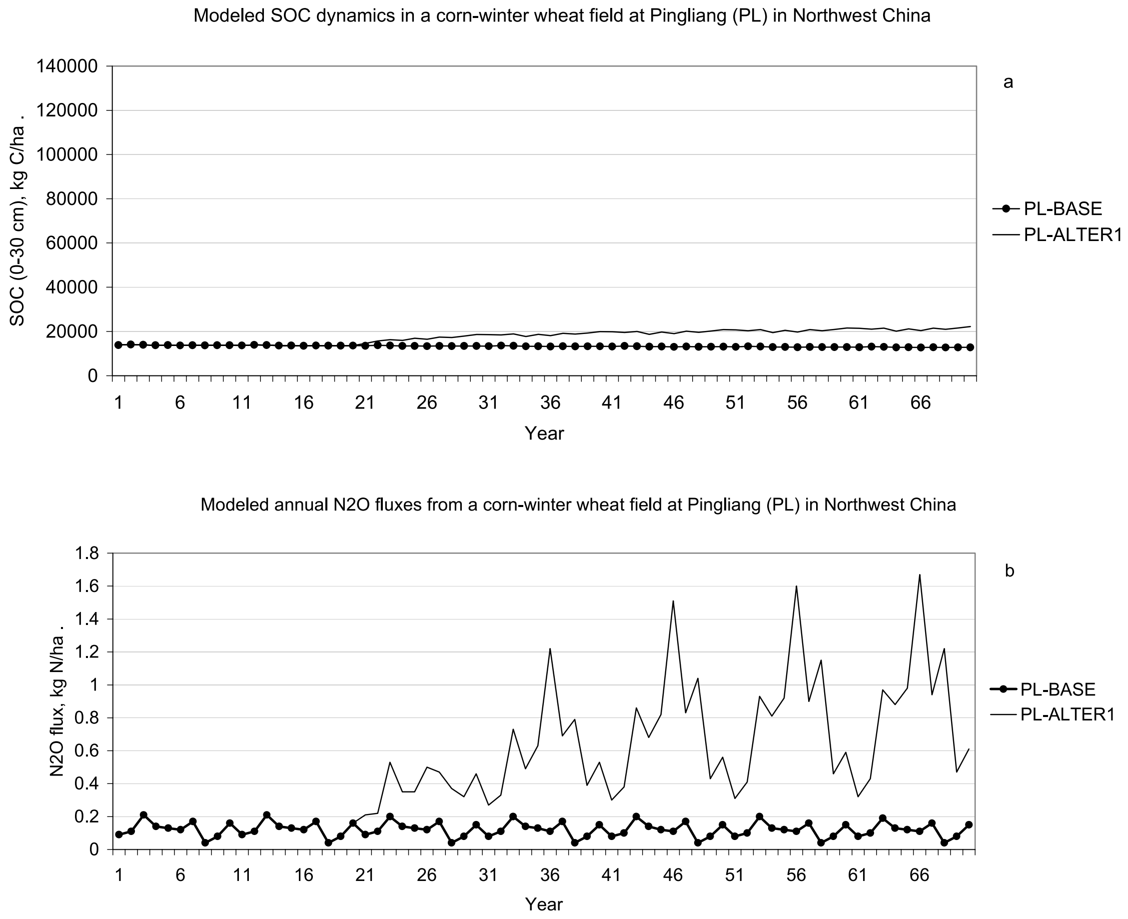


Figure 4. Modeled 70-year dynamics of SOC storages (0–30 cm) (a) in and N_2O fluxes (b) from a corn field with baseline management scenario (QQ-BASE, from year 1 to 70) and alternative scenario (QQ-ALTER1, from year 21 to 70) at Qiqihar (QQ), Heilongjiang Province in the northeast agricultural region of China.


Modeled SOC dynamics in a corn-winter wheat field at Pingliang (PL) in Northwest China

Modeled annual N2O fluxes from a corn-winter wheat field at Pingliang (PL) in Northwest China

Figure 5. Modeled 70-year dynamics of SOC storages (0–30 cm) (a) and N_2O fluxes (b) in a corn–winter wheat rotated field with baseline management scenario (PL-BASE, from year 1 to 70) and alternative scenario (PL-ALTER1, from year 21 to 70) at Pingliang (PL), Gansu Province in the northwest agricultural region of China.

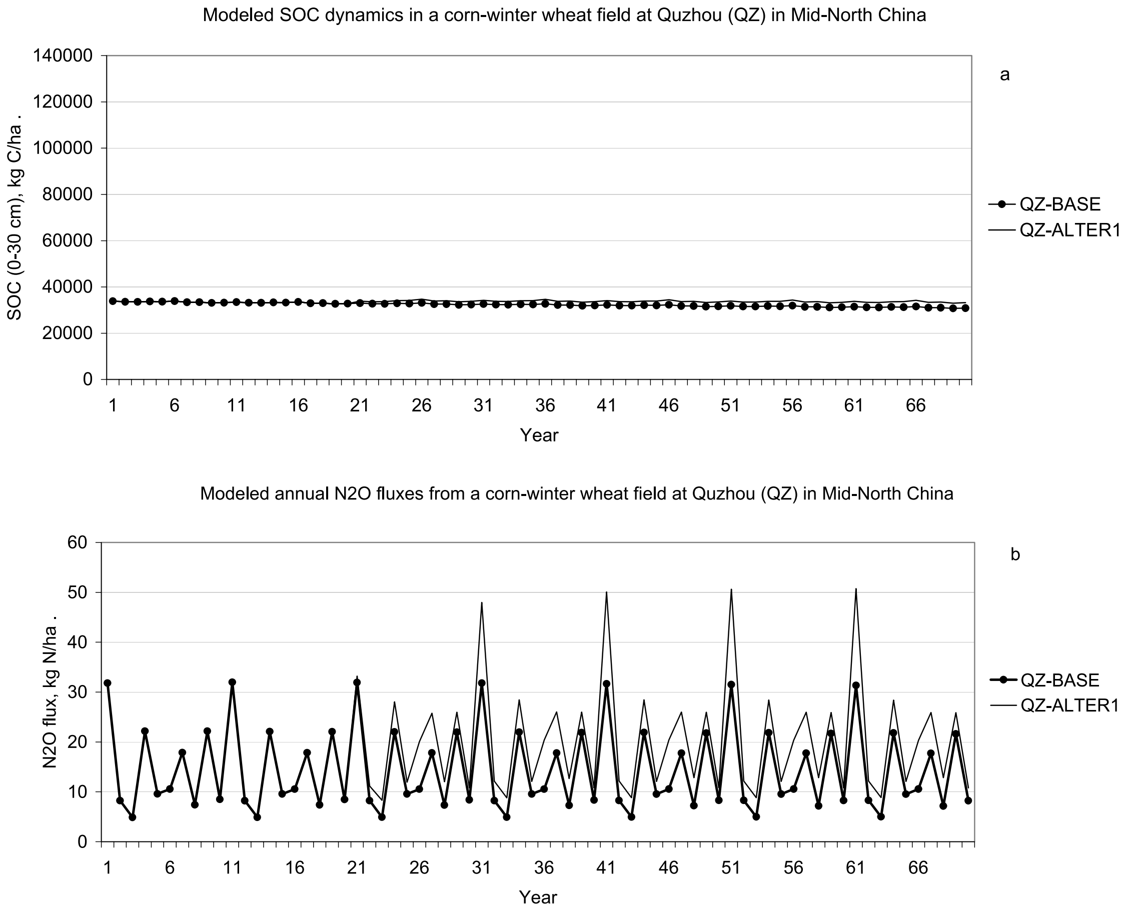


Figure 6. Modeled 70-year dynamics of SOC storages (0–30 cm) (a) and N_2O fluxes (b) in a corn–winter wheat rotated field with baseline management scenario (QZ-BASE, from year 1 to 70) and alternative scenario (QZ-ALTER1, from year 21 to 70) at Quzhou (QZ), Hebei Province in the mid-north Agricultural Region of China.

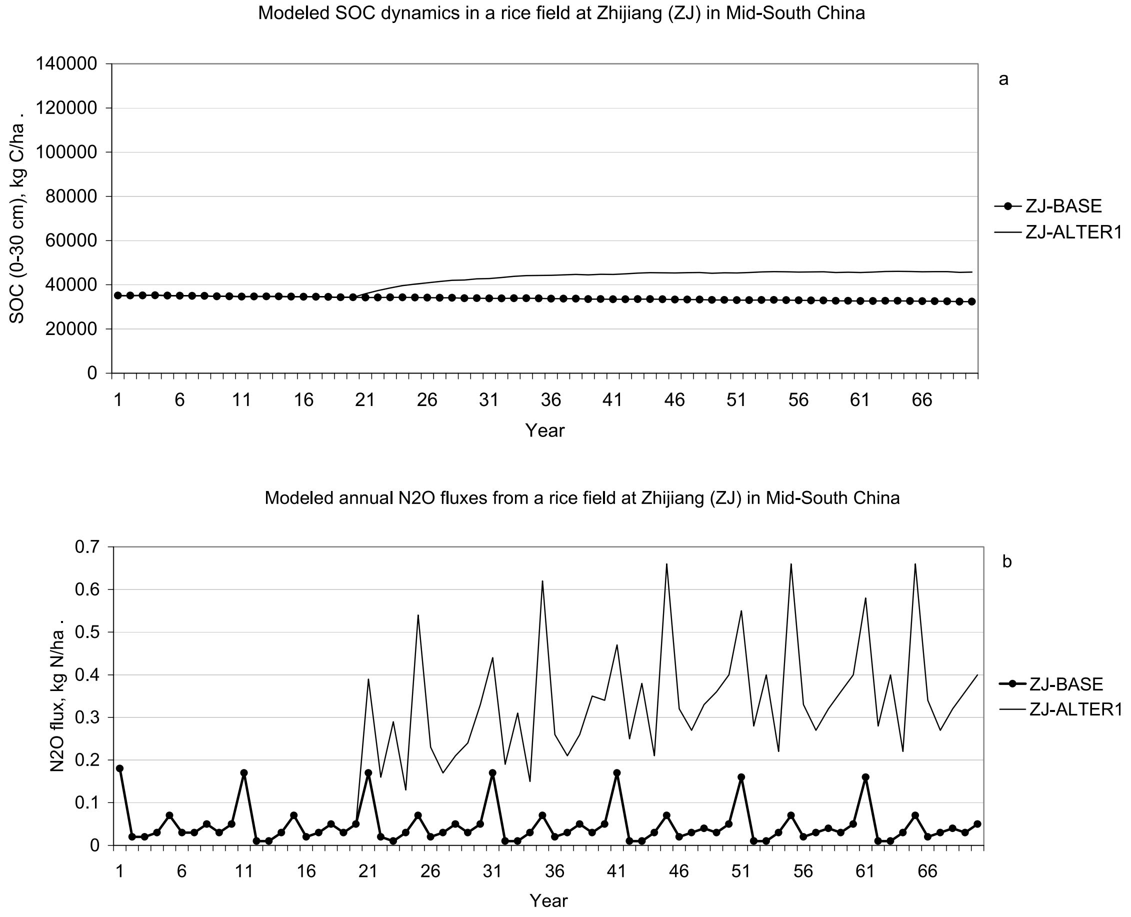


Figure 7. Modeled 70-year dynamics of SOC storages (0–30 cm) (a) and N_2O fluxes (b) in a rice field with baseline management scenario (ZJ-BASE, from year 1 to 70) and alternative scenario (ZJ-ALTER1, from year 21 to 70) at Zhijiang (ZJ), Hunan Province in the mid-south Agricultural Region of China.

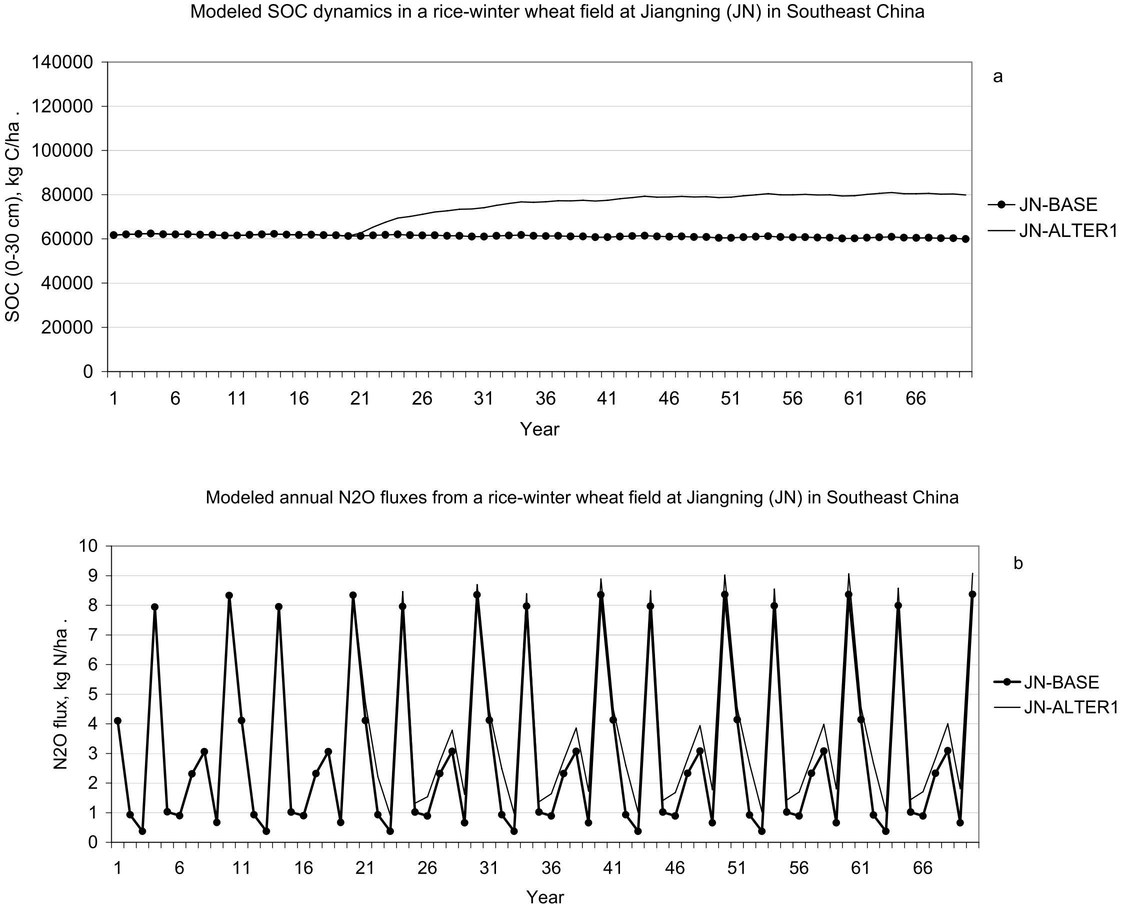


Figure 8. Modeled 70-year dynamics of SOC storages (0–30 cm) (a) and N_2O fluxes (b) in a rice–winter wheat rotated field with baseline management scenario (JN-BASE, from year 1 to 70) and alternative scenario (JN-ALTER1, from year 21 to 70) at Jiangning (JN), Jiangsu Province in the southeast agricultural region of China.

substantially increased the crop productions for PL and ZJ where the baseline scenarios provided relatively low fertilizer rates (130 and 106 kg N ha^{-1} a^{-1}, respectively). The simulated results indicated that the mechanisms for the C sequestration could come from two sources including (1) the direct organic C addition through the increased crop residue incorporation and manure amendment and (2) the indirect C addition by elevating the crop (as well as the crop litter) production. Consistent with the model predictions, the observations reported for the agricultural regions where more crop residue has started being incorporated in the local soils also indicated the SOC increases [*Huang and Sun*, 2006; *Li and Wu*, 2006].

6. Impact of Alternative Farming Management Practices on Soil N_2O Emissions

[14] In the 50-year simulations, DNDC calculated the soil N_2O and CH_4 fluxes in parallel with the SOC changes at daily and annual time steps. The simulated annual N_2O flux rates showed high interannual variations. For example, the annual N_2O fluxes at QQ where the soil was in rich of SOC varied from 12 to 52 kg N ha^{-1} a^{-1}. The modeled data indicated that the high interannual variations were caused by combination of the rainfall events and the accumulation of residue nitrate in the soil profile. However, in spite of the interannual variations, the long-term trends of N_2O emissions during the 50-year span were relatively constant under the BASE management scenario conditions for all the six sites (Figures 4–9). The shift of the management practices from BASE to ALTER-1 increased N_2O emissions at all the tested six sites. The amounts of increase in the 50-year average annual N_2O emissions were 18.9, 6.1, 0.6, 0.7, 0.2 and 3.4 kg N ha^{-1} a^{-1} for QQ, QZ, PL, JN, ZJ and YT, respectively (Table 3). The magnitudes of N_2O increase induced by ALTER-1 were determined by the local climate, soil properties and baseline fertilizer application rate. For example, the QQ site possessed high SOC content (4%), which produced high contents of dissolved organic carbon (DOC) as well as ammonium and nitrate through the SOC decomposition; and the accumulated DOC and available N in the soil profile stimulated both nitrifiers and denitrifiers during the rainfall events or the soil freezing/thawing processes. In contrast with QQ, site PL had very low N_2O emissions under the BASE scenario conditions. The simulated data showed the extremely low SOC content with the semiarid climate at PL limited the micro-

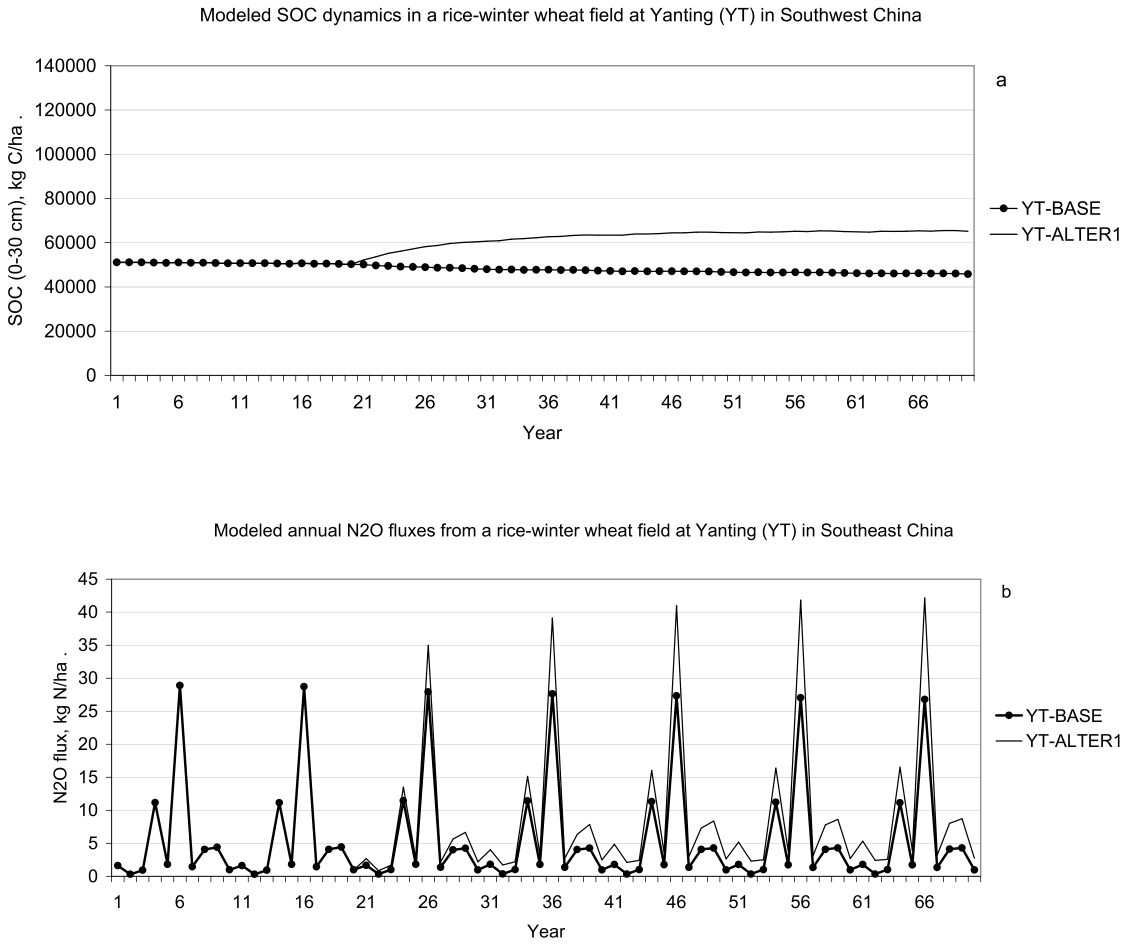


Figure 9. Modeled 70-year dynamics of SOC storages (0–30 cm) (a) and N_2O fluxes (b) in a rice–winter wheat rotated field with baseline management scenario (YT-BASE, from year 1 to 70) and alternative scenario (YT-ALTER1, from year 21 to 70) at Yanting (YT), Sichuan Province in the southwest agricultural region of China.

bial activities including decomposition, nitrification and denitrification at the site. By applying manure and increasing crop residue incorporation, the SOC status was improved and hence elevated N_2O emissions at PL.

[15] The modeled results also indicated that along with the SOC increase driven by the ALTER-1 scenario, an interannual increase trend in N_2O emissions showed up for all the six sites (Figures 4–9). This modeled result is consistent with many observations described in the Introduction of this paper. In comparison with the three upland cropping systems at QQ, QZ and PL where ALTER-1 caused drastic increases in N_2O emissions, the three wetland cropping systems at JN, ZJ and YT showed relatively low impacts of ALTER-1 on N_2O emissions (Figures 7–9). The modeled data indicated that the seasonal flooding for the paddy soils was favorable to convert the soil available N into dinitrogen (N_2) instead of N_2O. Replacing ALTER-1 with ALTER-2 decreased N_2O emissions by 44%, 8%, 43%, 19%, 0% and 35% from the soils in QQ, QZ, PL, JN, ZJ and YT, respectively (Table 3). The results implied that the fertilizer application rate was one of the most sensitive factors affecting N_2O emissions from the Chinese agricultural soils. Since the postharvest residue N was observed in model results for nearly all of the tested sites, optimizing fertilizer application rate should be a priority alternative to reduce the agricultural N_2O emissions in China.

7. Impact of Alternative Farming Management Practices on Soil CH_4 Emissions

[16] Methane production and oxidation are controlled by redox potential (i.e., Eh) and C sources in the soil. The two factors are further affected by a series of environmental factors including plant root activity and soil temperature, moisture, pH, texture and substrate concentration [*Li*, 2007]. In the study, the modeled results indicated that the three wetland cropping systems emitted CH_4 while the three upland systems consumed CH_4. The 50-year average annual CH_4 emission rates were −1.2, −0.4, 0.0, 274, 679 and 1928 kg C $ha^{-1}yr^{-1}$ for QQ, QZ, PL, JN, ZJ and YT, respectively (Table 3). The difference in CH_4 emissions among the three paddy soils was determined by the soil texture and climate conditions. Replacing BASE with ALTER-1 or ALTER-2 elevated the SOC contents and hence increased DOC concentration in the soils that stimulated the activity of methanogens during the flooding seasons at JN, ZJ and YT. Under the ALTER-1 conditions, the annual CH_4 emission rates

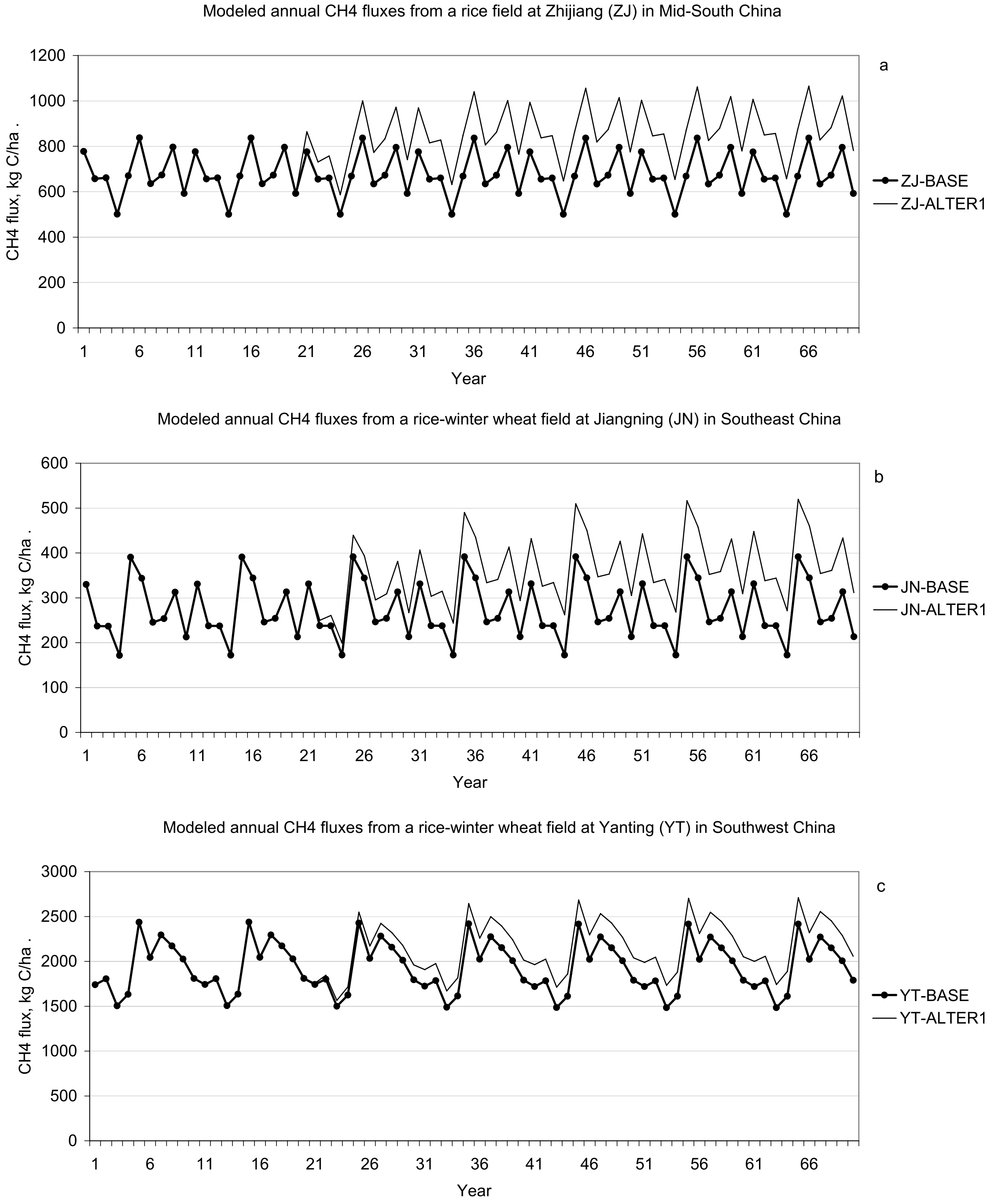


Figure 10. Modeled 70-year annual CH_4 fluxes from three rice-planted cropping systems with baseline management scenario (BASE, from year 1 to 70) and alternative scenario (ALTER1, from year 21 to 70) at Zhijiang (ZJ), Jiangning (JN) and Yanting (YT) in the mid-south, southeastern and southwest agricultural regions of China.

increased by 1.1–1.3 times for the three wetland systems (Figure 10). The impacts of the alternative practices on CH_4 oxidation at the upland systems were negligible (Table 3).

8. Net Greenhouse Gas Emissions

[17] Different greenhouse gases can be compared on a common basis by converting the fluxes of the non-CO_2 greenhouse gases (i.e., CH_4 and N_2O) into CO_2 equivalents via their radiative forcings [*IPCC*, 2001; *Ramaswamy et al.*, 2001]. The radiative forcing of each gas was determined on the basis of its heat trapping capacity as well its life time in the atmosphere. According to the IPCC's Second Assessment Report [*IPCC*, 1996], the radiative forcings of CH_4 and N_2O are 21 and 310 times, respectively, higher than that of CO_2 per unit of weight on a basis of 100-year horizon. In the study,

the modeled annual decrease in SOC storage (dSOC) was regarded as annual net CO_2 emission from the soil; and the modeled annual N_2O and CH_4 fluxes were converted to CO_2 equivalents on the basis of their radiative forcings. Since each management scenario at each site had a specific group of modeled CO_2, CH_4 and N_2O fluxes, the global warming potential (GWP) of the scenario can be calculated by summing up the CO_2 equivalents of all the three greenhouse gases. The GWP value for each scenario at each site was calculated as follows:

$$\begin{aligned}
&\mathrm{GWP_i} = \mathrm{CO_{2i}} + \mathrm{N_2O_i} \times 310 + \mathrm{CH_{4i}} \times 21;\\
&\text{with } \mathrm{CO_{2i}} = \mathrm{CO_2\text{-}C_i} \times (44/12)\\
&\mathrm{N_2O_i} = \mathrm{N_i} \times (44/28)\\
&\mathrm{CH_{4i}} = \mathrm{CH_4\text{-}C_i} \times (16/12)
\end{aligned}$$

where GWP_i (kg CO_2 equivalent ha^{-1} a^{-1}) is the GWP induced by scenario i; CO_{2i}, N_2O_i and CH_{4i} are CO_2 flux (kg CO_2 ha^{-1} a^{-1}), N_2O flux (kg N_2O ha^{-1} a^{-1}) and CH_4 flux (kg CH_4 ha^{-1} a^{-1}), and CO_2-C_i, CH_4-C_i and N_i are CO_2, CH_4 and N_2O fluxes in carbon and nitrogen units respectively (kg C ha^{-1} a^{-1} and kg N ha^{-1} a^{-1}), induced by scenario i.

[18] The calculated results indicated that the BASE scenarios for all the six sites had positive GWP values that indicated all the sites increased the global warming trend although their contributions varied from site to site. Sites QQ, QZ, PL, JN, ZJ and YT with their BASE management scenarios contributed 10, 7, 0, 9, 19 and 57 ton CO_2 equivalent ha^{-1} a^{-1}, respectively (Table 3). Shifting the management scenarios from BASE to ALTER-1 increased the GWP values for most of the sites. For QQ, QZ, JN, ZJ and YT, ALTER-1 converted the sites from sources to sinks of atmospheric C, but the increased N_2O and/or CH_4 emissions offset the benefits gained by the C sequestered in the soils. Only YT was an exception. YT was an upland field with very low SOC content (0.4%) and semiarid climate. The ALTER-1 management practices apparently increased the C sequestration rate but only slightly elevated the N_2O emissions by 0.6 kg N ha^{-1} a^{-1} that led to a negative GWP value of ALTER-1 for YT (Table 3). With ALTER-2, the decrease in fertilizer rates significantly reduced the GWP values almost by half for QQ, and slightly decreased the GWP values for all other sites. In general, the modeled results indicated that the increases in N_2O and CH_4 emissions induced by the alternative management practices overwhelmed the C sequestration gained by the same practices regarding their contributions to global warming.

9. Discussions

[19] In China, as a nation with a long-term cultivation history, the farming management practices have undergone a lot of changes, especially during the past century. Traditionally, Chinese farmers fully utilized farmyard manure or crop residue to maintain the soil organic matter and hence sustained the soil fertility. However, driven by the rapid development of the rural social-economic conditions during the last decades, Chinese farmers gradually replaced the organic fertilizers with synthetic fertilizers to pursue higher yields with lower man power. The abandoned crop residue was either moved from the fields for other uses (e.g., fuel, feed or building materials) or simply burned in situ; and a lot of animal wastes were randomly disposed that caused environmental pollution. The lack of organic matter incorporated into the soils caused the decrease in SOC contents in the agricultural lands nationwide. Soil degradation has been reported as a widespread environmental problem in China. Recovering SOC contents in the agricultural lands has become an urgent task in the country. The new policies encouraged the Chinese farmers to incorporate more crop residue into the soils, meanwhile, to resume manure applications. On the basis of observations at several experimental stations, the alternative management practices effectively elevated the SOC contents especially for the C-depleted soils in the country. Since increase in SOC storage will provide multibenefit for agroecosystems by improving the soil structure and fertility, the C sequestration-oriented policies are and will be crucial for sustaining the Chinese agriculture. However, the study reported in this paper indicated that there would be an uncertainty to credit greenhouse gas mitigation to the management alternatives. On the basis of the modeled results from the study, simply adding more organic C into the soils could increase N_2O and/or CH_4 emissions from the agroecosystems that would in a large degree offset the C benefit. As a solution for the dilemma, best management practices should be developed to cope with the conflict among crop production, C sequestration and non-CO_2 greenhouse gas mitigation. The results from this study suggest that optimization of the synthetic fertilizer application rates could be the top priority for compiling the best management practices for Chinese agriculture. The modeled data indicated that when the management scenario shifted from ALTER-1 to ALTER-2, that reduced synthetic fertilizer application rates by 50 kg N ha^{-1} a^{-1} for all the tested sites, the crop yields remained the same for QQ, QZ, JN and YT but decreased at PL and ZJ (Table 4). The results implied that reducing fertilizer application rates was feasible for the majority of the tested sites, where fertilizer was already overused. The modeled data further indicated that reducing fertilizer application rates could not only decrease N_2O emissions, but also benefit more environmental issues. For example, shifting ALTER-1 to ALTER-2 reduced the N loss through nitrate leaching by 25–50% (Table 4) that would apparently benefit the water eutrophication issues in China. In addition, the reduction in fertilizer use will also save the energy and reduce the CO_2 emissions related to fertilizer manufacture.

[20] By testing the impacts of farming management alternatives for six agroecosystems selected across the major agricultural regions in China, we realized efficacy of the alternative practices is highly spatially differentiated depending on the local climate, soil and management conditions. A process-based model, DNDC, was employed in the study to cope with the intricate relationship among climate, soil and farming management practices, by identifying their contributions to crop yield, C sequestration, non-CO_2 greenhouse gas emissions, nitrate leaching and other environmental objectives. The methodology of this kind would be helpful for assessing any future policies or management strategies that

Table 4. Modeled 50-Year Average Annual Crop Yields and Nitrate Leaching for the Tested Six Croplands in China

	Crop Yield (kg C ha^{-1} a^{-1})			Leached Nitrate (kg N ha^{-1} a^{-1})		
Cropping System Scenario[a]	BASE	ALTER-1	ALTER-2	BASE	ALTER-1	ALTER-2
QQ	2102	2102	2100	5.7	10.2	6.9
QZ	2347	2347	2347	158.5	205.0	177.0
PL	1643	2614	2480	1.3	3.3	2.7
JN	5679	5679	5678	113.1	183.1	128.4
ZJ	1866	2508	2120	10.5	41.2	21.2
YT	3416	3416	3416	130.8	202.8	158.0

[a] As in Table 3.

require more than a single objective. This study again demonstrated that the process-based models such as DNDC could make unique contributions to the new era of agricultural management.

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