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Toward optimal soil organic carbon sequestration with effects of agricultural management practices and climate change in Tai-Lake paddy soils of China

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ABSTRACT

Understanding the impacts of climate change and agricultural management practices on soil organic carbon (SOC) dynamics is critical for implementing optimal farming practices and maintaining agricultural productivity. This study examines the influence of climatic variables and agricultural management on carbon sequestration potentials in Tai-Lake Paddy soils of China using the DeNitrification-DeComposition (DNDC, version 9.1) model, with a high-resolution soil database (1:50,000). Model simulations considered the effects of no-tillage, the application rates of manure, N fertilization, and crop residue, water management, and changes in temperature and precipitation. We found that the carbon sequestration potential in the top soils (0–30 cm) for the 2.32 Mha paddy soils of the Tai-Lake region varied from 4.71 to 44.31 Tg C under the feasible management practices during the period of 2001–2019. The sequestration potential significantly increased with increasing application of N-fertilizer, manure, conservation tillage, and crop residues, with an annual average SOC changes ranged from 107 to 121 kg C ha^{-1} yr^{-1}, 159 to 326 kg C ha^{-1} yr^{-1}, 78 to 128 kg C ha^{-1} yr^{-1}, and 489 to 1005 kg C ha^{-1} yr^{-1}, respectively. Toward mitigating greenhouse emissions and N losses, no-tillage and increase of crop residue return to soils as well as manure application are recommended for agricultural practice in this region. Our analysis of climate impacts on SOC sequestration suggests that the rice paddies in this region will continue to be a carbon sink under future warming conditions. Specifically, with rising air temperature of 2.0 °C and 4 °C, the average annual SOC changes were 52 and 21 kg C ha^{-1} yr^{-1}, respectively.

1. Introduction

Soil organic carbon (SOC) is the largest carbon (C) pool in terrestrial ecosystems, with the storage of over 1550 Pg globally (Batjes, 1996), therefore, small changes in the SOC pool may have a significant impact on climate change. Agro-ecosystems, accounting for 10% of the total terrestrial area, are among the most vulnerable ecosystems to the global climate change due to their large carbon pool (Smit and Skinner, 2002). One-half to two-thirds of the original SOC pool have lost with a cumulative amount of 30–40 t C ha^{-1} in cultivated soils due to intensive farming (Lal, 2004a). Thus, adoption of a restorative management practices on agricultural soils is often required to improve the soil fertility and the environment (Lal, 2004b). In addition, climatic shifts in temperature and precipitation also significantly affect SOC change because the soil C sequestration is a function of both primary production and decomposition of organic matter in agricultural soils (Grace et al., 2006; Hutchinson et al., 2007).

However, the influences of management practices and climate factors on SOC change are often entangled, making it difficult to identify the major drivers at the regional scale (Liu et al., 2013). Process-based modeling combined with various experimental data provides opportunities to quantify the impacts of different management practices and future climate change on soil C dynamics (Gottschalk et al., 2012; Wang et al., 2014; Muñoz-Rojas et al., 2015). Among these modeling efforts, the DeNitrification–DeComposition (DNDC) model has been extensively used to investigate the C and N dynamics for various agro-ecosystems (Tang et al., 2006; Tonitto et al., 2007; Abdalla et al., 2011; Xu et al., 2012). In the international conference on global change in Asia-Pacific areas in 2000, the DNDC model was recommended as a primary tool for studying the carbon cycling in the Asia-Pacific region (Qiu et al., 2005).

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Rice is one of the most important agricultural food sources, feeding >50% of the world's population, covering ~155 Mha of the world's land surface (Kögel-Knabner et al., 2010). The total area of paddy soil in China is 45.7 Mha, accounting for 29% of the world's total rice areas while producing 38% of the world's rice yield (Wang et al., 1993; Liu et al., 2006; Xu et al., 2012). Paddy soils are characterized by high input of organic materials with relatively low decomposition rate under anaerobic conditions, which favors organic matter accumulation (Huang et al., 2015a). Previous studies have also demonstrated that the paddy soils in China may have had a positive effect on the terrestrial C sink over the last two decades (Pan et al., 2003, 2010; Huang and Sun, 2006; Xie et al., 2007; Sun et al., 2010; Yan et al., 2011; Qin et al., 2013). For example, Pan et al. (2003) estimated the SOC sequestration potential of paddy soils in China by using the data from 1979 to 1982 and from the nationwide arable soil monitoring system established since then, and the results showed that the current C sequestration rate of Chinese paddy soils is in the range of 0.13–2.2 t C ha^{-1} yr^{-1}. Sun et al. (2010) investigated the SOC density in Chinese croplands based on data sets extracted from 146 publications. They found that the SOC density of paddy soils in the topsoil to 30 cm depth increased by 2.75 Mg ha^{-1} between 1980 and 2000. Yan et al. (2011) collected national-wide 1, 394 cropland soil profiles in China and measured SOC contents in 2007–2008, and compared them with those of a previous national soil survey conducted in 1979–1982. Their results indicated that the SOC stock of paddy soils in China increased significantly over the last two decades. These above findings demonstrate the potentially important role in the mitigation of climate change of paddy soils in China. This may be attributed to an increase in net primary productivity, increased crop residue return, and the extension of good fertilization practice schemes discussed by Yu et al. (2012). Therefore, the implementation and extension of best agricultural management practices in China's paddy soils will further help to enhance the capacity of Chinese soils to mitigate China's increasing CO_2 emissions.

The Tai-Lake region is located in the middle and lower reaches of the Yangtze River paddy soil region of China (Xu et al., 1980). It is considered to be the most typical rice production area in China because of a long rice cultivation history (>7000 years) and intensified agricultural management (Xu et al., 1980; Chen et al., 2007). Recently, many studies have revealed that the paddy soils in the Tai-Lake region have high SOC sequestration potential. Liao et al. (2009) found that the average topsoil SOC content (0–20 cm) in the Tai-Lake plain increased from 14.04 ± 3.89 g kg^{-1} in 1982 to 15.30 ± 3.80 g kg^{-1} in 2004, based on 129, 540 and 3, 039 measured samples, respectively. Liu et al. (2013, 2014b) also found that the SOC content in the top layer (0–20 cm) increased by 1.09 g kg^{-1} from 1980 to 2000, based on 2157 soil samples in the paddy soils of this region. In addition, a lot of long-term experiments also indicated that the SOC content of paddy soils in this region has increased over the past three decades (Pan et al., 2009; Ma et al., 2011; Zhu et al., 2015). Physical entrapment of SOC in macroaggregates may account for SOC sequestration even in paddy soils with 2000-year history (Zou et al., 2015). More discussion of mechanism of SOC sequestration can be found in Zhou et al. (2009, 2010). In the past years, a new soil map for this region with improved spatial resolution of 1:50,000 scale was produced (Zhang et al., 2009). This new detailed soil map provided us an opportunity to optimize agricultural management practices from the perspectives of soil carbon sequestration and environmental protection through model simulations.

In previous studies, we have simulated the SOC dynamics in paddy soils of the Tai-Lake region during the period of 1982–2000 using the 1:50,000 soil database and DNDC model (Zhang et al., 2012). In order to quantify the impacts of climate change and agricultural management practices on SOC dynamics in the future, the most recent 19-year climate data (1982–2000) was repeatedly utilized for the 19 years of 2001–2019 (Xu et al., 2011). The specific objective of this study was to identify the best management practices by optimizing combination of the scenarios based on the local climatic and soil conditions.

2. Materials and methods

2.1. Study area

The Tai-Lake region (118°50′-121°54′E, 29°56′-32°16′N) encompasses parts of Jiangsu and Zhejiang provinces and the entire Shanghai City administrative area, covering 37 counties with a total area of 36,500 km^2 (Fig. 1) (Xu et al., 1980). The terrain is dominated by plains intersected by high density surface water networks. Northern subtropical monsoon climate prevails with annual sunshine of 1870 to 2225 h, precipitation of 1100 to 1400 mm, mean temperature of 16 °C and frost-free days of over 230 days (Xu et al., 1980). Approximately 66% of the total land area is covered with paddy soils (Zhang et al., 2012). Paddy soils in the region are derived mostly from alluvium, loess, and lacustrine deposits. The dominant cropping pattern is summer rice and winter wheat rotation.

2.2. DNDC model and regional simulations

The DNDC model is a process-based biogeochemistry model for carbon and nitrogen (N) dynamics in agroecosystems. The model consists of six interacting sub-models to represent the processes of soil climate, crop growth, decomposition, nitrification, denitrification and fermentation, respectively (Li, 2000; Li, 2007a). The DNDC model is also expanded to simulate biogeochemical processes in rice paddies, whereby the model has been modified by adding a series of anaerobic processes (Li et al., 2004). It has also been validated against data observed in rice paddy ecosystems worldwide (Cai et al., 2003; Giltrap et al., 2010; Xu et al., 2012). The verification indicated that the modeled results were well consistent with the observations.

For regional simulations using the DNDC model, counties are used as the basic spatial simulation unit that contains relatively coarse soil data with a resolution of about 0.5° × 0.5° (Li et al., 2004). As a result, the heterogeneity of soil properties within a county may bias model simulations (Pathak et al., 2005; Zhang et al., 2014). Instead, in this study, the basic spatial simulation units are polygons that representing specific soil types (Zhang et al., 2009), which accounts for the effects of spatial heterogeneity in soil characteristics. The SOC simulation was conducted for the top 30 cm of soils (Tang et al., 2006). Our model has been validated by measurements from 1033 paddy soil sampling sites acquired in 2000. The validation results indicated that the model estimates were encouragingly consistent with observations for the Tai-Lake region (Table 1). A detailed discussion on DNDC model validation can be referred to Zhang et al. (2012, 2014).

2.3. Data preparation

Spatial databases were constructed to store all the model input information including soil properties, cropping systems, climate, and agricultural management practices. Below we describe how data were organized for the DNDC simulations.

2.3.1. Soil and climate data

A polygon-based soil database at the scale of 1:50,000 was developed to drive the DNDC model, which currently is the most detailed soil database for the paddy region of China (Zhang et al., 2012). This soil database, consisting of 52,034 polygons produced from 1107 paddy soil profiles, is digitalized from the latest 1:50,000 national soil map which was collected during the Second Soil Survey of China from the 1980s to 1990s (Zhao et al., 2006). This database contains extensive soil information such as soil name, horizon thickness, clay content, organic carbon content, bulk density and pH value.

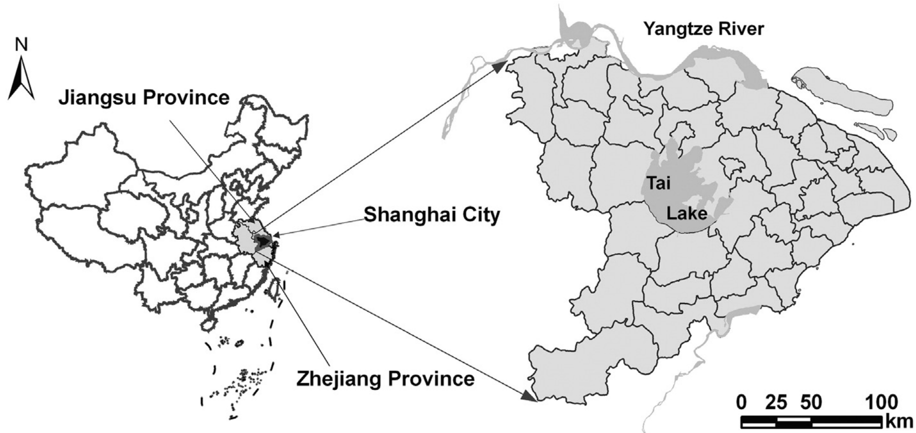

Fig. 1. Geographical location of the study area in China.

Meteorological data for 1982–2000 from 13 weather stations in the study area were collected from the China Meteorological Administration (China Meteorological Administration, 2011), including daily maximum and minimum air temperatures and precipitation. The climate data from the nearest weather station of each county were used in model simulations.

2.3.2. Crop and farming management data

Rice-wheat rotation scheme was assigned for each county according to the agricultural census data (Zhang et al., 2012; Xu et al., 2012). The basic crop physiological parameters and the agricultural management data were collected (Li, 2007b; Gou et al. 1999; Xu et al. 2012). The main measures of conventional management in the study area are detailed below. First, during the growing period, summer rice was planted in June and harvested in October and then winter wheat was planted in November and harvested in May of the next year (Xu et al., 1980). Second, for tillage management, conventional tillage with a depth 20 cm was applied for rice once on the planting dates and no-till for wheat (Zhang et al., 2012). Third, for crop residue management, 15% of non-grain post-harvest crop biomass was returned to soil annually (Tang et al., 2006). Fourth, for water management, midseason drainage and shallow flooding was applied to rice cultivation (Gou et al., 1999). Fifth, in fertilizer application, 20% livestock and 10% human manure were added to soil as base fertilizer at the rates calculated based on the local livestock numbers (866, 95, 44, and 23 kg C head^{-1} yr^{-1} for cattle, swine, sheep and human manure, respectively) (Lu and Shi, 1982; Tang et al., 2006). Nitrogen synthetic fertilizer was applied three times in the basal, tillering and heading stages for rice and three times in the basal, jointing and heading stages for wheat (Zhang et al., 2014).

2.4. Baseline and scenarios of alternative management practices

The model was calibrated based on the above-mentioned conventional management methods. Alternative scenarios were constructed by varying management practices or natural factors in prescribed ranges, which were commonly observed in the local farming practices. The details of the baseline and alternative scenarios are listed in Table 2.

In the baseline scenario, the management practices in 2000 were assumed to be continuously used until 2019, including crop residue return, application rates of N-fertilizer and manure, tillage and water management. To estimate the SOC dynamics during 2001–2019, the recent 19-year climate data (1982–2000) were used for all scenarios (Xu et al., 2011).

Table 1
Validation results of modeled SOC for the Tai-Lake region, China.

Study area	Sample number	Correlation coefficient	Relative error	Mean absolute error	Root mean square error
Tai-Lake region	1033	0.5**	6.4%	4.0 g kg^{-1}	5.0 g kg^{-1}

** Significant at the 0.01 levels.

2.5. Data analysis

Total SOC change (TSC, Tg C) and average annual SOC change (AASC, kg C ha^{-1} yr^{-1}) of different scenarios were calculated as follows:

$$\mathrm{AMSC}_i = \sum_{f=1}^{h} \mathrm{ASC}_f \tag{1}$$

$$\mathrm{TSC} = \sum_{i=1}^{n} (\mathrm{APS}_i \times \mathrm{AMSC}_i) \tag{2}$$

$$\mathrm{APS} = \sum_{i=1}^{n} \mathrm{APS}_i \tag{3}$$

$$\mathrm{AASC} = \mathrm{TSC}/\mathrm{APS}/19 \tag{4}$$

Table 2
Baseline and alternative scenarios in the Tai-Lake region.

Scenario	Conditions or variations
Baseline (conventional management, CT)	Rice-winter rotation (R-WW), 1 time of midseason (MD1), 15% of above-ground crop residue incorporated in soil after harvest (0.15R), 20 cm tilling depth for rice of conventional tillage (CVT), manure of 20% of livestock wastes and 10% of human wastes (MCT), N concentration in rainfall 2.07 ppm, and CO_2 concentration in the atmosphere was stabilized at 379 ppm.
Management alternatives	
Fertilizing amount	no fertilizer (NFL), 0.5, 1.5 and 2.0 times of conventional management (0.5FL, 1.5FL and 2.0 FL, respectively)
Percent of residue incorporated	10%, 50% and 90% of above-ground crop residue incorporation (0.1R, 0.5R and 0.9R, respectively)
Tillage	no-till (NT)
Midseason drainage	0 and 2 times of midseason draining (MD and MD2, respectively)
Manure	2.0, 3.0 and 4.0 times of conventional management (2.0M, 3.0M and 4.0M, respectively)
Climatic factors	
Air temperature	increase by 2 °C and 4 °C (IT2 and IT4, respectively)
Precipitation	decrease by 20% (DP) and increase by 20% (IP)

where ASC_f (kg C ha^{-1} yr^{-1}) is the annual SOC change in a specific polygon; $AMSC_i$ (kg C ha^{-1} yr^{-1}) is the accumulated annual SOC change in a specific polygon from 2001 to 2019. APS_i is the area of i-th polygon of paddy soil. APS is the total area of a specific paddy soil subgroup (or the entire Tai-Lake region). n is the polygon number. h is the order of simulation year from 2001 to 2019 ($h = 1, 2, 3......19$).

The SOC increase (or decrease) rate (y) of alternative scenarios was calculated as (Cai et al., 2003):

$$y = (x_s - x_0)/x_0 \times 100 \quad (5)$$

where x_0 is the AASC of conventional management for the baseline and x_s is the AASC of alternative scenarios.

The sensitivity tests of the DNDC model indicated that soil properties are major sources of uncertainty for simulated SOC changes at regional scale (Li et al., 2004). To evaluate the most sensitive soil properties in SOC changes, the correlation of soil properties and average annual SOC change was examined by using Pearson's test and multiple stepwise regression analysis (Saint-Laurent et al., 2014). This was performed using the Statistical Package for Social Sciences (SPSS) statistical software (Leech et al., 2008).

3. Results and discussion

3.1. Changes in SOC in the Tai-Lake region

3.1.1. Conventional management

Average annual SOC changes exhibited different responses to various climate change and management practice scenarios (Figs. 2 and 3). Under the baseline scenario (CT), 2.32 Mha paddy soils in the Tai-Lake region increased 3.44 Tg C from 2001 to 2019, with the annual SOC change of 78 kg C ha^{-1} yr^{-1} (Figs. 4a and 5a). This is mainly associated with the average chemical fertilizer application and farmyard manure incorporation rate of as high as 335 kg N ha^{-1} yr^{-1} and 270 kg C ha^{-1} yr^{-1}, respectively. Applications of nutrients through fertilizers or organic manure increased crop yield and residue accumulation, and thus large amount of organic matter is returned to the soil (Singh and Lal, 2005). In addition, SOC decomposition has been reduced in this region by utilizing no-tillage practices in wheat planting, which reduces the physical disturbance and increases the crop residues-covered area of the soil surface (Farahbakhshazad et al., 2008).

The modeled results are generally consistent with the results of Yu et al. (2013), which found that China's croplands will maintain their capacity of carbon sequestration over the next 40 years, even if

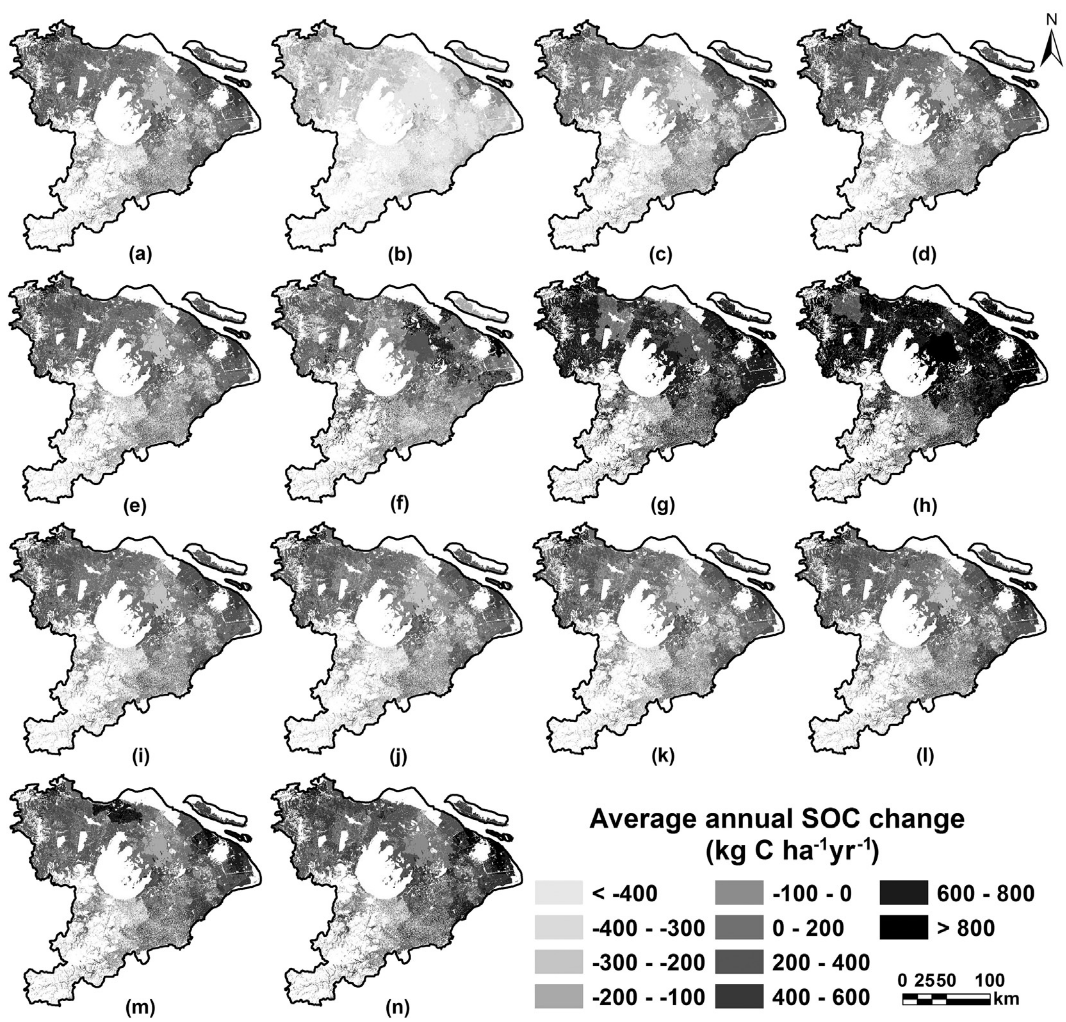

Fig. 2. Spatial distribution of average annual SOC change under different management practice scenarios in the Tai-Lake region, China: (a) conventional management (Baseline); (b) no fertilizer (NFL); (c) 0.5 time of fertilizing amount under the conventional management (0.5FL); (d) 1.5 times of fertilizing amount under the conventional management (1.5FL); (e) 2.0 times of fertilizing amount under the conventional management (2.0FL); (f) 10% of above-ground crop residue incorporation (0.1R); (g) 50% of above-ground crop residue incorporation (0.5R); (h) 90% of above-ground crop residue incorporation (0.9R); (i) No-till (NT); (j) no midseason draining (MD); (k) 2 times of midseason draining (MD2); (l) 2.0 times of manure amount under the conventional management (2.0M); (m) 3.0 times of manure amount under the conventional management (3.0M); (n) 4.0 times of manure amount under the conventional management (4.0M).

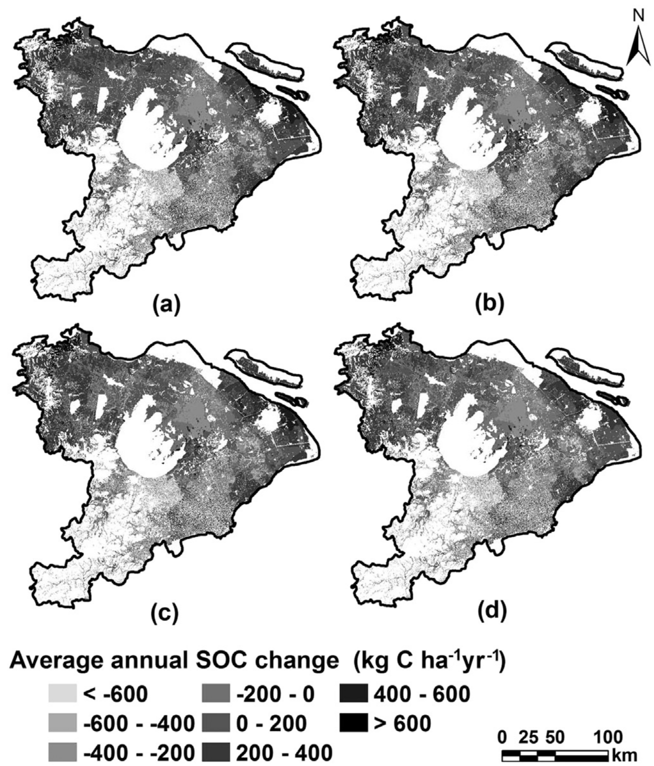

Fig. 3. Spatial distribution of average annual SOC change under different climatic scenarios in the Tai-Lake region, China: (a) decreasing precipitation by 20% (DP); (b) increasing precipitation by 20% (IP); (c) increasing air temperature by 2 °C (IT2); (d) Increasing air temperature by 4 °C (IT4).

crop yields and agricultural management maintain at current levels. Therefore, our findings suggest that the SOC storage in paddy soils of the Tai-Lake region is likely to help mitigate climate change under current agricultural practices.

3.1.2. N-fertilizer and manure application

Increasing the rate of fertilizer application could increase SOC levels linearly by enhancing residue accumulation (Singh and Lal, 2005). As can be seen from the Fig. 5a, when fertilizer N application rates are 1.5 (1.5FL) and 2.0 (2.0FL) times of the baseline level, the average annual SOC changes are 1.37 and 1.55 times that of the baseline level, respectively (Fig. 6). In contrast, reduced N-fertilizer (0.5FL) and no N-fertilizer (NFL) application would significantly reduce the SOC in the region. The average annual SOC changes were −33 and −330 kg C ha^{-1} yr^{-1} for the 0.5FL and NFL scenarios, respectively (Fig. 5a), and the corresponding SOC changes are 142% and 522% lower than the baseline scenario (Fig. 6). Our simulations are consistent with previous studies (Singh and Lal, 2005; Kong et al., 2006), in which positive effects on SOC sequestration was demonstrated by increasing fertilizers and manures input.

The SOC content has increased because of increased chemical fertilizers over the past 20 years (Liu et al., 2013). However, increased mineral N fertilizer rate that increases C sequestration often has adverse effects on emissions of greenhouse gases (e.g., N_2O) (Desjardins et al., 2001). Additionally, N leaching from the first soil layer linearly increased with the increase of N-fertilizer application rate (Peinetti et al., 2008). N losses from paddy soils in the Tai-Lake region have been reported (Wang et al., 2007). It is urgent to choose an optimal N-fertilizer application rate from the perspectives of carbon sequestration management and environmental protection.

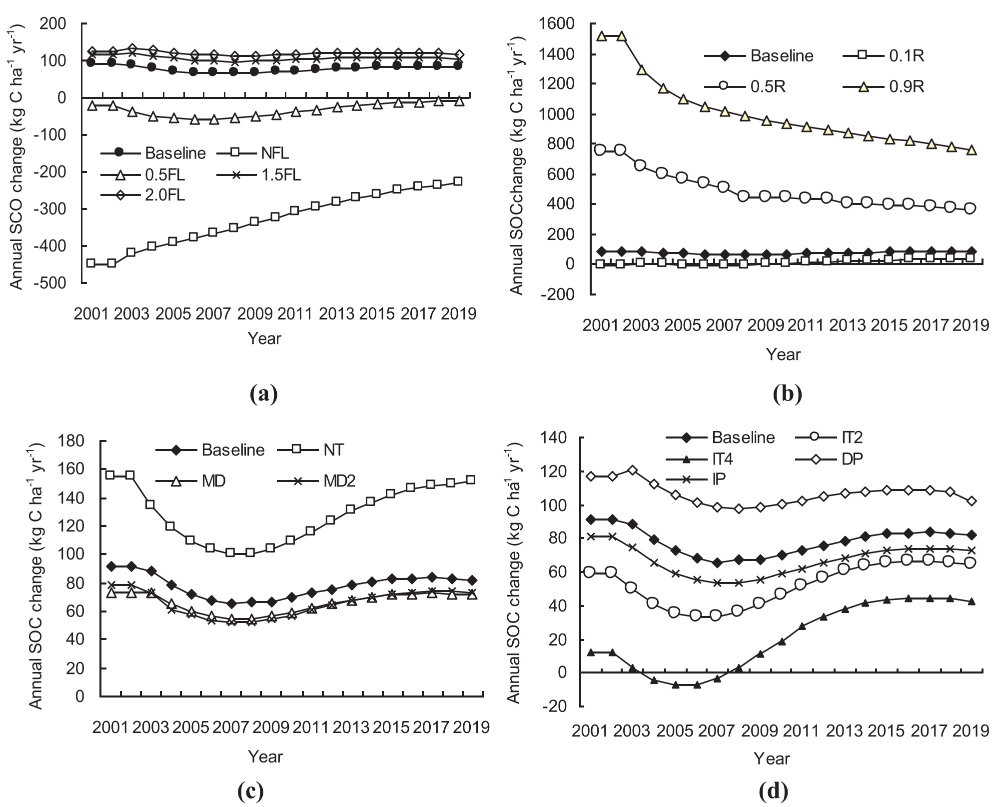

Fig. 4. Annual SOC change from 2001 to 2019 under different management practices and climatic factor scenarios in the Tai-Lake region, China: (a) Baseline–Conventional management; NFL–No fertilizer; 0.5FL, 1.5FL and 2.0FL–0.5, 1.5 and 2.0 times of fertilizing amount under the conventional management, respectively; (b) 0.1R, 0.5R and 0.9R–10%, 50% and 90% of aboveground crop residue incorporation, respectively; (c) NT–No-till; MD and MD2–0 and 2 times of midseason draining, respectively; (d) IT2 and IT4–Increasing air temperature by 2 °C and 4 °C, respectively; DP and IP–Decreasing and increasing precipitation by 20%, respectively.

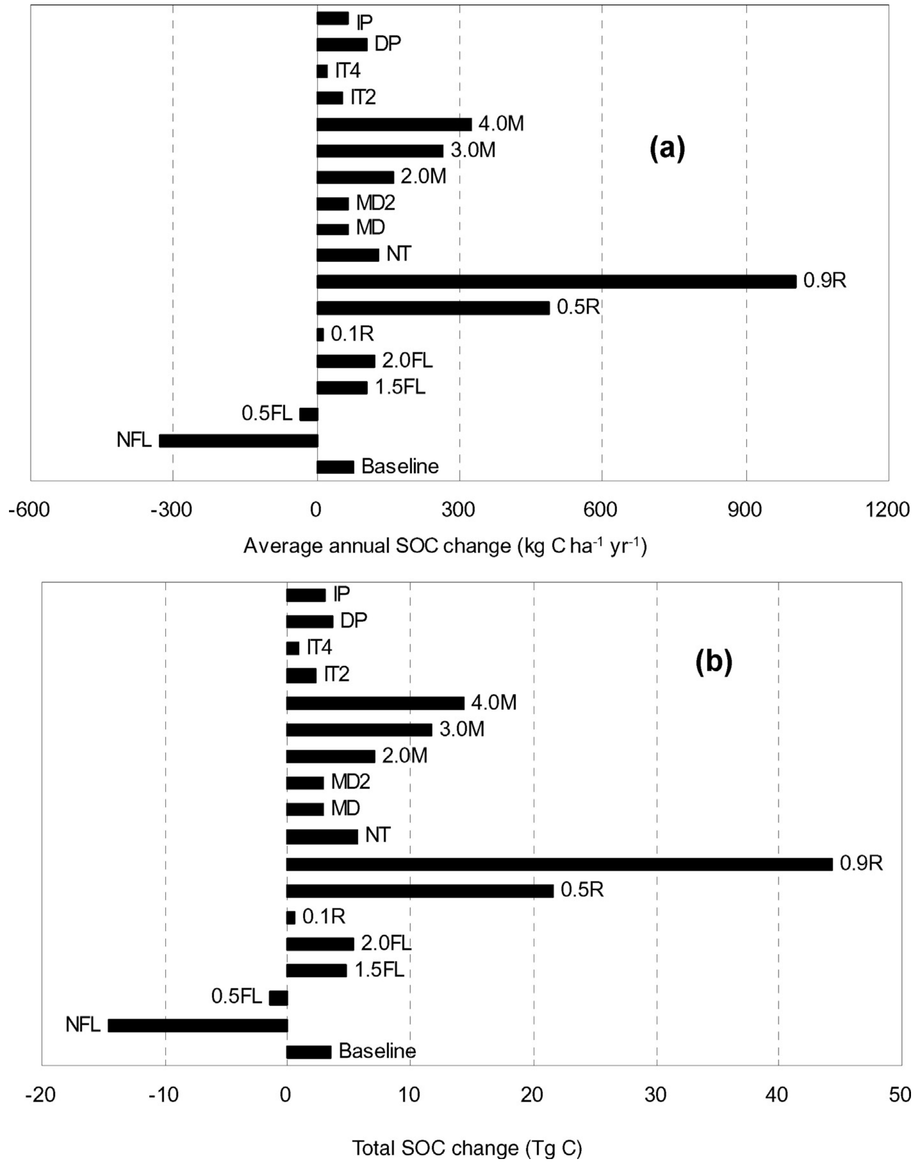

Fig. 5. (a and b) Comparison of average annual-, total SOC change under different management practices and climatic factor scenarios in the Tai-Lake region during the period of 2001–2019, China: Baseline–Conventional management; NFL–No fertilizer; 0.5FL, 1.5FL and 2.0FL–0.5, 1.5 and 2.0 times of fertilizing amount under the conventional management, respectively; 0.1R, 0.5R and 0.9R–10%, 50% and 90% of above-ground crop residue incorporation, respectively; NT–No-till; MD and MD2–0 and 2 times of midseason draining, respectively; 2.0M, 3.0M and 4.0M–2.0, 3.0 and 4.0 times of manure amount under the conventional management, respectively; IT2 and IT4–Increasing air temperature by 2 °C and 4 °C, respectively; DP and IP–Decreasing and increasing precipitation by 20%, respectively.

As organic fertilizer, manure can be applied to increase SOC (Fig. 5). When the application rates of manure increases at 2.0, 3.0, and 4.0 times the baseline scenario (2.0M, 3.0M and 4.0M, respectively), the average annual SOC changes were 159, 264, and 356 kg C ha^{-1} yr^{-1}, respectively (Fig. 5a), which are 104%, 238% and 317% higher than the baseline simulation. The modeled results are comparable to the findings of Buysse et al. (2013), who found manure caused significant SOC increases (100 $\pm$ 50 kg C ha^{-1} yr^{-1}) from a long-term experiment initiated in 1959 at a site in the Hesbaye region of Belgium.

Traditionally, farmers of the Tai-Lake region returned farmyard manure back to fields as much as possible to maintain or increase SOC content. However, with the rapid economy development, the farmyard manures were gradually replaced by synthetic fertilizers to gain short-term profits (Xu et al., 2011). Only 10%–20% of manure was returned to the fields through conventional management (Tang et al., 2006).

3.1.3. Crop residue

Increasing crop residue return was associated with higher rates of C sequestration when compared to an increasing of N-fertilizer or manure (Fig. 4a and b). When the rate of crop residue incorporation was increased from 15% (Baseline) to 50% (0.5R) and 90% (0.9R), the average annual SOC changes increased from 78 to 489 and 1005 kg C ha^{-1} yr^{-1}, respectively (Fig. 5a). In contrast, when the rate of crop residue incorporation was decreased from 15% (Baseline) to 10% (0.1R), the average annual SOC change decreased from 78 to 13 kg C ha^{-1} yr^{-1} (Fig. 5a). Our study indicates that increasing crop residue return is the most effective approach to enhance soil C stocks (Fig. 5b). Keeping crop residue on the soil surface not only controls soils erosion but also reduces CO_2 release and possibly the biological oxidation of SOC (Singh and Lal, 2005).

Paddy soils in this region have relatively low C content (15.4 g kg^{-1}) (Table 3), which may due to the injudicious management of a large amount of crop residues for a long time (Xu et al., 2011). According to the report of agricultural sector, before the 1980s, most crop residue

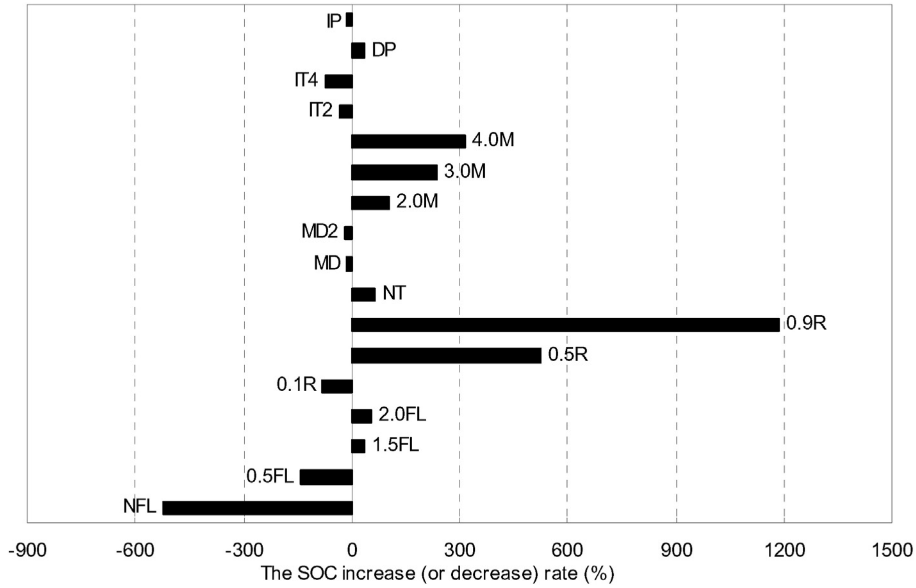

Fig. 6. The SOC increase (or decrease) rates under alternative management practices or climatic change scenarios relative to conventional management as the baseline in the Tai-Lake region: NFL–No fertilizer; 0.5FL, 1.5FL and 2.0FL–0.5, 1.5 and 2.0 times of fertilizing amount under the conventional management, respectively; 0.1R, 0.5R and 0.9R–10%, 50% and 90% of above-ground crop residue incorporation, respectively; NT–No-till; MD and MD2–0 and 2 times of midseason draining, respectively; 2.0M, 3.0M and 4.0M–2.0, 3.0 and 4.0 times of manure amount under the conventional management, respectively; IT2 and IT4–Increasing air temperature by 2 °C and 4 °C, respectively; DP and IP–Decreasing and increasing precipitation by 20%, respectively.

was removed from the field and used as fuel and animal feed in rural areas; whereas after the 1980s, most crop residue was burned in the field since farmers ceased taking crop straw as fuel due to improved living conditions (Yan et al., 2007).

3.1.4. No-till management

Adopting no-tillage in agro-ecosystems has been widely recommended as a means of enhancing C sequestration in soils. However, literature is inconsistent in the effects of no-tillage on SOC changes–varying from significant positive to significant negative across different sites, depending on multiple factors such as site-specific land use change history, on-farm practices, soil properties, soil layer depths, topography, microclimate and large-scale climate change (Six et al., 2002; Luo et al., 2010a; Dimassi et al., 2014). In this study, no-till management has been revealed to be one of the most efficient practices for C sequestration (Fig. 5). Comparing to conventional tillage practice, no tillage practice showed a significant increase of 128 kg C ha^{-1} yr^{-1} for average annual SOC in the top 30 cm soils during 2001–2019 (Figs. 4c and 5a). This is likely attributed to the effects of crop frequency and crop diversity in this region. Winter wheat-rice rotation is one of the most popular cropping systems in this region, and it has a feature of high crop frequency, and this feature may be favorable for C sequestration in agro-ecosystems (Luo et al., 2010a). Additionally, although no-tillage has no significant effect on rice yield across a wide range of environmental and management conditions in China, it still increases grain yield in rice–upland cropping systems such as winter wheat-rice rotation (Huang et al., 2015b). Further, increasing grain yield tends to be beneficial for C sequestration in this region (Qiu et al., 2009; Liu et al., 2013).Thus, due to the specific characteristics of crop frequency and crop diversity; no-tillage tends to be a beneficial on-farm practice for C sequestration in the top 30 cm soils.

Our findings in this work are consistent with many previous studies which indicated the positive effects of no-tillage on SOC changes (Lu et al., 2009; Wang et al., 2009; Sombrero and de Benito, 2010; Xu et al., 2011; Zhao et al., 2013; Zhang et al., 2013; Liu et al., 2014a; Xue et al., 2014; Chen et al., 2015a, b). For example, Lu et al. (2009) reviewed the relationship between soil carbon sequestration and no-tillage practices by using the available results of the field experiments in China, showing that the current C sequestration rate of no-tillage in China's cropland reached to 0.8 Tg C yr^{-1}. Based on the topsoil SOC data in long term field experiments of China from publications available from 1979 to 2008, Wang et al. (2009) summarized and analyzed the dynamics of SOC under conservation tillage. They found that the average increase rate of SOC with conservation tillage was estimated to be 0.21 g kg^{-1} yr^{-1} for dry cropland soils, and 0.51 g kg^{-1} yr^{-1} for rice paddy soils. Sombrero and de Benito (2010) investigated the effect of

Table 3
Soil properties, climatic factors and fertilizer amount used as input for DNDC model under conventional management (CT) scenario in the Tai-Lake region.

	Areas 10^4 ha	Soil properties				Climatic factors		Fertilizer amount	
		Initial SOC (g kg^{-1})	Clay (%)	pH	Bulk density (g cm^{-3})	Annual mean rainfall (mm)	Mean annual temperature (°C)	Fertilizer (kg N ha^{-1} yr^{-1})	Manure (kg C ha^{-1} yr^{-1})
Whole Tai-Lake region									
Tai-Lake region	232.02	15.4	26	6.7	1.18	1216	16.4	335	270
Soil subgroups									
Bleached	20.22	10.4	16	6.1	1.20	1153	16.4	302	188
Gleyed	10.17	24.8	35	7.1	1.00	1209	16.6	363	223
Percogenic	37.16	11.5	22	6.9	1.22	1147	16.3	369	237
Degleyed	40.96	19.3	30	6.5	1.20	1256	16.7	351	308
Submergenic	0.73	10.4	15	6.8	1.10	1179	15.2	281	164
Hydromorphic	122.56	15.4	28	6.7	1.17	1234	16.4	323	187

The value of all factors is weighted average by the area of each polygon.

tillage systems and cropping sequences on SOC patterns after 10 years of soil management, showing that carbon sequestration in the top 30 cm layer can be improved if minimum or no-tillage is used instead of conventional practice. Xu et al. (2011) found that shifting from reduced tillage (this is similar to the baseline scenario) to no-tillage increased the C sequestration rate in the top soils (0–30 cm) by 93–147 kg C ha^{-1} yr^{-1} in China's paddy soils. Zhao et al. (2013) evaluated the effect of different agricultural managements on SOC storage and crop yields in the North China Plain using five experimental stations. Their results indicated that the annual increasing rate of SOC storage in the top 30 cm under no-tillage management was the highest, compared to the other tillage treatments. Chen et al. (2015a) investigated the temporal effect of different tillage systems and residue management on distribution, storage and stratification of SOC under double rice cropping system in the southern China. They showed that SOC stocks in soil under the no-tillage with residue retention at 0–5, 5–10, 10–20, and 20–30 cm depths increased by 33.8, 4.1, 6.6, and 53.3%, respectively, relative to the plow tillage with residue removed. Moreover, adoption of conservation tillage would be beneficial in the reduction of greenhouse gases emission in double rice cropping regions (Chen et al., 2015b).

It is worth noting to increase the N fertilizer application rates during the initial processes of converting conventional tillage to no-tillage practices in the region, because the increased N application rates could reduce N immobilization from a C:N ratio transformation (Farahbakhshazad et al., 2008). In addition, although the no-tillage management is less efficient than increasing crop residue return on C sequestration, a combination of both could be better than any individual management (Yan et al., 2007). Therefore, one soil management option recommended is a combination of no-tillage and increasing crop residue return.

3.1.5. Water management

Over the past three decades, midseason drainage has been adopted in the Tai-Lake region (Li et al., 2006). In contrast to traditional water management, an episode of midseason drainage for 7–10 days is commonly employed to inhibit ineffective tillers, remove toxic substances and improve roots activities (Zou et al., 2007). Compared to conventional water management (1 time of midseason draining, MD1), no midseason draining (MD) showed significant decreases of average annual SOC changes of about 12 kg C ha^{-1} yr^{-1} during the period of 2001–2019 (Figs. 4c and 5a). Because the midseason drainage tends to increase rice yield by increasing N mineralization in the soil and by increasing rice root development (Li et al., 2006), more straw was fed to the soil carbon pools. However, when the frequency of midseason draining was doubled (MD2), the average annual SOC change was 16% lower than the MD1 scenario (Figs. 5a and 6). The main reason is that doubling midseason draining could produce more oxygen to flow into the soil, which facilitates microbial growth and stimulates the decomposition of soil C (Luo et al., 2010b). This study indicates that the current water management practice is an appropriate measure to reduce greenhouse gas emissions (e.g., CH_4) as well as to improve the crop production (Li et al., 2006).

3.1.6. Climatic factors

Climatic shifts in temperature and precipitation have great impacts on C sequestration potentials in agricultural soils (Grace et al., 2006). With air temperature rises of 2 °C and 4 °C, the average annual SOC changes would decrease 26 and 57 kg C ha^{-1} yr^{-1} compared to the baseline scenario, respectively (Fig. 5a). This is because increases in air temperature are associated with higher SOC decomposition rates due to increasing soil microbial activities according to thermodynamic mechanism (Johnson et al., 2007). However, it is critical to point out that paddy soils tend constantly to be a sink of atmospheric CO_2 under warming scenarios, even if the air temperature increased to 4 °C (Fig. 4d). According to IPCC (2013), the global mean temperatures will increase by 0.3 to 4.8 °C by the end of the 21st century. This implies that the rice cultivation in this region is likely to contribute to climate mitigation in the future, despite any negative effects derived from warming.

Precipitation has been recognized as an important factor controlling the SOC decomposition (Grace et al., 2006; Gabarrón-Galeote et al., 2015). In this study, two precipitation scenarios were set by decreasing and increasing precipitation by 20% during the period of 2001–2019 (Table 2). The decreasing and increasing proportions were applied for

Table 4
Variations of the average annual SOC change (AASC, kg C ha^{-1} yr^{-1}) and the total SOC change (TSC, Tg C) under different scenarios at soil subgroup level in the Tai-Lake region during the period of 2001–2019, China.

Scenario	Bleached		Gleyed		Percogenic		Degleyed		Submergenic		Hydromorphic	
	AASC	TSC	AASC	TSC	AASC	TSC	AASC	TSC	AASC	TSC	AASC	TSC
Baseline	203	0.79	−144	−0.28	209	1.48	−81	−0.63	253	0.0035	88	2.05
Management alternatives												
NFL	−179	−0.69	−582	−1.12	−209	−1.48	−481	−3.75	−132	−0.018	−321	−7.47
0.5FL	85	0.33	−245	−0.47	114	0.81	−186	−1.45	135	0.019	−29	−0.69
1.5FL	236	0.92	−122	−0.24	231	1.63	−49	−0.38	281	0.039	118	2.74
2.0FL	249	0.97	−115	−0.22	238	1.68	−34	−0.27	291	0.040	134	3.13
0.1R	144	0.56	−215	−0.42	145	1.02	−149	−1.16	195	0.027	23	0.52
0.5R	548	2.13	351	0.68	586	4.14	365	2.84	653	0.091	501	11.67
0.9R	1043	4.05	890	1.72	1140	8.05	865	6.73	1089	0.15	1014	23.60
NT	241	0.94	−95	−0.18	252	1.78	−18	−0.14	287	0.040	138	3.22
MD	199	0.77	−126	−0.24	205	1.45	−96	−0.75	260	0.036	70	1.64
MD2	188	0.73	−180	−0.35	197	1.39	−88	−0.68	233	0.032	76	1.76
2.0M	258	1.00	−71	−0.14	279	1.97	18	0.14	303	0.042	172	4.01
3.0M	395	1.53	0.93	0.0018	363	2.56	135	1.05	351	0.049	276	6.42
4.0M	363	1.41	67	0.13	416	2.94	212	1.65	399	0.056	351	8.16
Climatic factors												
IT2	190	0.74	−189	−0.36	193	1.36	−115	−0.90	233	0.032	62	1.45
IT4	166	0.64	−235	−0.45	170	1.20	−149	−1.16	200	0.028	29	0.67
DP	196	0.76	−134	−0.26	217	1.53	−75	−0.58	268	0.037	92	2.14
IP	190	0.74	−150	−0.29	199	1.41	−89	−0.69	244	0.034	75	1.75

The value of AASC is weighted average by the area of each polygon.
Baseline–Conventional management; NFL–No fertilizer; 0.5FL, 1.5FL and 2.0FL–0.5, 1.5 and 2.0 times of fertilizing amount under the conventional management, respectively; 0.1R, 0.5R and 0.9R–10%, 50% and 90% of above-ground crop residue incorporation, respectively; NT–No-till; MD and MD2–0 and 2 times of midseason draining, respectively; 2.0M, 3.0M and 4.0M–2.0, 3.0 and 4.0 times of manure amount under the conventional management, respectively; IT2 and IT4–Increasing air temperature by 2 °C and 4 °C, respectively; DP and IP–Decreasing and increasing precipitation by 20%, respectively.

each rainfall event at a daily time step. Compared to the baseline scenario, decreasing precipitation almost linearly increased SOC sequestration rates (by 29 kg C ha^{-1} yr^{-1}); by contrast, increasing precipitation slightly decreased SOC sequestration rates (by 11 kg C ha^{-1} yr^{-1}) (Fig. 5a). It is commonly observed that increasing precipitation results in soil carbon accumulation (Paul et al., 2002). However, our results indicate that the precipitation was negatively correlated with the SOC sequestration significantly (Fig. 4d). This is likely because the Tai-Lake region is located in the northern subtropical monsoon climate zone, which is associated with high mean annual precipitation (>1200 mm) (Table 3). High precipitation reduces crop yields and biomass production by causing N leaching to deeper soil layers (Peinetti et al., 2008), consequently, less organic matter was added to the soil carbon pools.

3.2. Variations in SOC dynamics across soil subgroups

The effects of climate change and alternative management practices on SOC change vary significantly from soil subgroup to subgroup (Table 4). The 6 paddy soil subgroups of Tai-Lake region include: Submergenic (Hydragric Anthrosols), Hydromorphic (Hydragric Anthrosols), Gleyed (Gleyic-hydragric Anthrosols), Bleached (Hydragric Anthrosols), Degleyed (Gleyic-hydragric Anthrosols), and Percogenic (Hydragric Anthrosols) (Shi et al., 2010). The classification of these subgroups is based on the mapping between the Genetic Soil Classification of China (GSCC) system nomenclature and the World Reference Base Soil Taxonomy (WRB) system. The area of hydromorphic subgroup covers about 1.23 Mha, accounting for 53% of the total paddy soil area in this region (Table 3). The corresponding modeled average annual SOC changes under different scenarios in the period 2001–2019 ranged from −321 to 1014 kg ha^{-1} yr^{-1}. As Table 5 shown, the correlation between soil properties, especially initial SOC content, clay content, and pH, and average annual SOC change reached significant level at 5% or 1% in most scenarios. Further, initial SOC content and clay content in most scenarios are the most dominant parameters controlling SOC change among all soil factors according to the stepwise linear regression (Table 6). Specifically, initial SOC content accounts for 44.9%–78.8% of the variations in average annual SOC change for the entire region from 2001 to 2019, and clay content accounted for 0.9%–21.9% of the variations. Similar results were also reported by Lark et al. (2006) and Tan and Liu (2013). They observed a strong negative relationship between the rate of SOC change and the initial SOC content, compared to other soil properties. That is, soils with higher baseline SOC content tend to be C sources; otherwise, they are likely to turn into C sinks following conservation management practices. Additionally, as indicated by Tables 5 and 6, the finding of soils with higher clay content have slower SOC changes due to the protection against microbial decomposition were generally consistent with previous studies (Six et al., 2002). Similarly, based on 376 published laboratory incubation data from soils acquired from 73 sites, Xu et al. (2016) showed the essential roles of clay content in controlling decomposition of SOC at a large spatial scale. In most scenarios, hydromorphic paddy soils that possess relatively low initial SOC (15.4 g kg^{-1}) and high clay (28%) (Table 3) have large C sequestration rates (Table 4).

The submergenic paddy soils, bleached paddy soils, and percogenic paddy soils, account for 0.32%, 8.8% and 16% of the total paddy soil areas, respectively (Table 3). The modeled average annual SOC changes under different scenarios ranged greatly from 2001 to 2019 (submergenic: from −132 to 1089 kg ha^{-1} yr^{-1}, bleached: from −179 to 1043 kg ha^{-1} yr^{-1}, percogenic: from −209 to 1140 kg ha^{-1} yr^{-1}) (Table 4). These three paddy soil subgroups presented high C sequestration potentials in most scenarios, mainly due to the relatively low precipitation and initial SOC content, acidic pH (in bleached paddy soils), relatively high N-fertilizer application rate and low temperature (in percogenic paddy soils) (Table 3) (Li et al., 2004; Brar et al. 2013).

Table 5
Correlation coefficients (Pearson's test) between soil properties and average annual SOC change under different scenarios.

	Number of polygons	Initial SOC (g kg^{-1})	Clay (%)	pH	Bulk density (g cm^{-3})
Baseline		−0.854**	0.044**	0.207**	−0.018**
Management alternatives					
NFL	52,034	−0.887**	−0.148**	0.180**	−0.032**
0.5FL		−0.823**	0.031**	0.229**	−0.021**
1.5FL		−0.866**	0.040**	0.197**	−0.019**
2.0FL		−0.876**	0.025**	0.177**	−0.029*
0.1R		−0.865**	0.017**	0.205**	−0.015**
0.5R		−0.723**	0.209**	0.189**	−0.040**
0.9R		−0.670**	0.262**	0.239**	−0.022**
NT		−0.845**	0.060**	0.216**	−0.005
MD		−0.854**	0.037**	0.187**	−0011*
MD2		−0.842**	0.055**	0.192**	−0.017**
2.0M		−0.794**	0.078**	0.225**	−0.026**
3.0M		−0.709**	0.079**	0.224**	−0.001
4.0M		−0.630**	0.161**	0.256**	−0.045**
Climatic factors					
IT2		−0.858**	0.021**	0.208**	−0.020**
IT4		−0.864**	0.003	0.211**	−0.009
DP		−0.851**	0.050**	0.196**	−0.021**
IP		−0.848**	0.054**	0.198**	−0.019**

Baseline–Conventional management; NFL–No fertilizer; 0.5FL, 1.5FL and 2.0FL–0.5, 1.5 and 2.0 times of fertilizing amount under the conventional management, respectively; 0.1R, 0.5R and 0.9R–10%, 50% and 90% of above-ground crop residue incorporation, respectively; NT–No-till; MD and MD2–0 and 2 times of midseason draining, respectively; 2.0M, 3.0M and 4.0M–2.0, 3.0 and 4.0 times of manure amount under the conventional management, respectively; IT2 and IT4–Increasing air temperature by 2 °C and 4 °C, respectively; DP and IP–Decreasing and increasing precipitation by 20%, respectively.
* Significant at the 0.05 level.
** Significant at the 0.01 level.

Table 6
Individual contributions of major soil properties to the variations of average annual SOC change under different scenarios.

Scenario	Number of simulation units	ΔR^2 [a]				Adjusted R^2
		Initial SOC (g kg^{-1})	Clay (%)	pH	Bulk density (g cm^{-3})	
Baseline	52,034	0.730***	0.086***	0.004***	0.056***	0.876***
Management alternatives						
NFL		0.786***	0.009***	0.001***	0.073***	0.868***
0.5FL		0.677***	0.074***	0.008***	0.054***	0.813***
1.5FL		0.750***	0.086***	0.002***	0.058***	0.896***
2.0FL		0.767***	0.079***	0.001***	0.065***	0.912***
0.1R		0.748***	0.072***	0.003***	0.056***	0.880***
0.5R		0.523***	0.182***	0.005***	0.048***	0.758***
0.9R		0.449***	0.219***	0.017***	0.035***	0.719***
NT		0.714***	0.095***	0.005***	0.049***	0.862***
MD		0.729***	0.082***	0.002***	0.053***	0.866***
MD2		0.709***	0.091***	0.002***	0.054***	0.856***
2.0M		0.630***	0.097***	0.008***	0.052***	0.788***
3.0M		0.503***	0.083***	0.011***	0.033***	0.630***
4.0M		0.396***	0.123***	0.024***	0.041***	0.584***
Climatic factors						
IT2		0.735***	0.073***	0.004***	0.058***	0.870***
IT4		0.747***	0.065***	0.004***	0.053***	0.868***
DP		0.724***	0.089***	0.003***	0.057***	0.873***
IP		0.719***	0.091***	0.003***	0.056***	0.869***

Baseline–Conventional management; NFL–No fertilizer; 0.5FL, 1.5FL and 2.0FL–0.5, 1.5 and 2.0 times of fertilizing amount under the conventional management, respectively; 0.1R, 0.5R and 0.9R–10%, 50% and 90% of above-ground crop residue incorporation, respectively; NT–No-till; MD and MD2–0 and 2 times of midseason draining, respectively; 2.0M, 3.0M and 4.0M–2.0, 3.0 and 4.0 times of manure amount under the conventional management, respectively; IT2 and IT4–Increasing air temperature by 2 °C and 4 °C, respectively; DP and IP –Decreasing and increasing precipitation by 20%, respectively.
*** Significant at 0.001 probability levels, respectively.
[a] The change in the R^2 statistic is produced by adding a soil property into stepwise multiple regressions.

The degleyed paddy soils and gleyed paddy soils account for 16% and 4.4% of the total paddy soil areas, respectively (Table 3). In contrast to other subgroups, the SOC balance of these two subgroups is negative in most scenarios (Table 4). The modeled average annual SOC changes under different scenarios in the period 2001–2019 ranged from −485 to 865 kg ha^{-1} yr^{-1} in degleyed paddy soils, and from −582 to 890 kg ha^{-1} yr^{-1} in gleyed paddy soils. This is likely because those two paddy soil subgroups possessed high mean annual temperatures and high initial SOC contents, as well as the nearly neutral pH (in gleyed paddy soils) (Table 3). Conditions of high temperature, high initial SOC content and neutral pH value for soils are favorable for CO_2 production by providing a better living environment and more substrates for microbes (Pacey and DeGier, 1986; Gaumont-Guay et al., 2006).

In general, the SOC changes under different scenarios vary substantially from one subgroup to another, due to prominent heterogeneity in climatic factors (e.g., temperature and precipitation) and soil properties (e.g., initial SOC content, clay content, and pH) across different paddy soil subgroups. This explains why the identification of soil subgroups with high C sequestration potentials is of great importance in regulating global carbon cycling and mitigating global warming (Xu et al., 2011). Especially, the three paddy soil subgroups (hydromorphic, percogenic and bleached) show the potential of strong carbon sink in most scenarios (Table 4). With a coverage of ~80% of the total paddy soil area (Table 3), the three paddy soil subgroups will dominate C sequestration potential in the future. It is important to tailor management practices for these three soil subgroups to increase carbon sink under future global climate change conditions.

3.3. Model uncertainties and limitations

Uncertainty has always been an important issue for modeling at regional scales due to the spatial variation of input data and assumptions used in the model (Evrendilek and Wali, 2001), which may thus affect our quantification of SOC dynamics under different climate factor and crop management scenarios. Potential uncertainty sources are discussed below.

First, characteristics of the regional model input data are likely sources of uncertainties. In our dataset, the input parameters required by the DNDC model such as the application rates of N-fertilizer and manure were derived from statistical data at a county level, which is the most spatially detailed (Xu et al., 2011). Thus, uncertainties in model simulations may be out of the incapability of capturing the inherent heterogeneities of model input data during our upscaling/averaging process. For instance, fertilizer application rates are highly variable in space. Averaging various application rates of N-fertilizer and manure at county level mixes the complexity of crop yields and the field-specific fertilizer application within the county. In addition, there is a lack of detailed water management data, which might also influence SOC decomposition rates (Frolking et al., 2004). More detailed fertilizer application data and water management data with a high spatial resolution are required to reduce uncertainties.

Second, climate change is an important driver of SOC change (Lal, 2004a). In this study, global warming effects was not considered due to the limitation of available meteorological data. The recent 19-year climate data of 1982–2000 have to be taken as representative for the period 2001–2019 for all scenarios runs, and the 19-year shift in climate data may bias the model simulations.

The third possible source for the modeling uncertainty is the interactions between the climate conditions and management practices, which are often difficult to capture by the DNDC model (Liu et al., 2013). The intra-annual variability of weather, interactions between management decisions and crop growth and the management actions influenced by these weather conditions have not yet been sufficiently investigated in this study. Our foci are on the individual impacts of climate change and management practices on SOC changes in the period 2001–2019. These interactions, however, are important to consider for taking effective management measures so as to increase SOC in our study region, and will be examined in future studies.

4. Conclusions

Based on the current high-resolution soil database for the rice-dominated Tai-Lake region of China, the impacts of climate change and agricultural management practices on soil organic carbon (SOC) changes were analyzed. The process-based biogeochemistry model DNDC was used to evaluate the impacts of different agricultural management and climate scenarios. A significant SOC sequestration could be achieved by increasing N-fertilizer and manure application, applying no-tillage management and improving crop residue returns in this region during the period of 2001–2019. On the contrary, reducing/no N-fertilizer application, decreasing crop residues, and increasing/decreasing the frequency of midseason draining resulted in low carbon sequestration. To increase soil carbon sequestration, optimum measures of no-tillage and increasing of crop residue and manure application are recommended. Climate also greatly influences SOC sequestration. Under the conventional management, the SOC would decrease 1.13–2.51 Tg C and 0.49 Tg C with increases of 2–4 °C in temperature and 20% in precipitation, respectively; whereas the SOC would increase 0.20 Tg C by decreasing 20% precipitation. Therefore, optimal soil carbon sequestration should be pursued by combining the effects of temperature and precipitation and crop managements on SOC changes.

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