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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.