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Modeling the effects of farming management practices on soil organic carbon stock at a county-regional scale

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ABSTRACT

Farming management practices are paramount for soil organic carbon (SOC) sequestration in carbon cycling at different scales. However, due to a lack of detailed data, estimating the impacts of different farming management alternatives on overall SOC stock remains inadequately quantified, especially at the county-regional scale. Here, an agricultural county-region, Yucheng County, which covers an area of 988.5 km^2 in the North China Plain, was selected as a case to estimate the impacts of different farming management practices on SOC stock using explicit spatial information and the DeNitrification-DeComposition (DNDC) model. We constructed a database by creating 524 polygon-based homogeneous modeling units using climate, soil and farming management information, which were linked to the DNDC to support the county-regional-scale simulations. Four experiments lasting from 2003 or 2004 to 2010 and 247 soil samples collected in 2009 from a soil depth of 0–20 cm across the study area were used for field- and regional-scale model validation, respectively. Validation results indicated that the DNDC model was acceptable for modeling SOC stock in Yucheng County. Seven farming management scenarios were designed for predicting the SOC stock from 1980 to 2020. Simulation results indicated that the changes in farming management practices had strong effects on carbon sequestration, with the maximum SOC stock ranging from 3.99 to 6.34 Mt. C across the county. The simulation results improved our understanding of the comprehensive impacts of management practices on the soil C pool when upscaling to larger regional or national scales.

1. Introduction

Soil organic carbon (SOC) accounts for more than half of the global soil carbon (C) pool, and the SOC in active exchange with the atmosphere constitutes approximately two-thirds of the carbon in terrestrial ecosystems (Eswaran et al., 1993; Lal, 2004a). Land management drives changes in regional and global soil C balances through changes in biogeochemical processes (for example, C and N cycling) and biophysical processes (for example, surface albedo, surface roughness, and evapotranspiration) (Lal, 2004b; Luyssaert et al., 2014). Improved land management practices that increase soil C gains or decrease soil C losses have been considered as one of the win-win strategies that can advance food security through enhancing soil productivity and mitigate climate change by acting on C cycling and soil C sequestration (Batjes, 2006; Lal, 2004a; Singh and Lal, 2005). The SOC can be restored in soils by the adoption of improved land management practices, including conservation tillage, decrease in fallow periods, use of cover crops, change from monoculture to crop rotation systems, and increase in primary production through irrigation, fertilizer, and manure (Jarecki et al., 2005). So far, however, there is a lack of understanding in how to quantitatively assess the confounding effects of different land management practices on soil C sequestration and how to identify the best land management practices that enhance the SOC pool (Anikwe, 2010; Liu et al., 2006; Luo et al., 2010). The main challenges inhibiting our understanding are the high spatial variability of SOC, which is determined by the soil and its environment and management (Cotching

Abbreviations: SOC, soil organic carbon; DNDC, DeNitrification-DeComposition; C, carbon; MSF, most sensitive factor

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et al., 2013), and the limited number of spatially explicit reconstructions that describe the type and intensity of various land management practices (Luyssaert et al., 2014).

Agriculture may be considered as an anthropogenic manipulation of C through the uptake, fixation, emission and transfer of C among different pools (Lal, 2004b). Conservation agriculture, involving minimum or zero tillage and a largely continuous protective cover of living or dead vegetal material on the soil surface (FAO, 2001), can be an important instrument for SOC sequestration. Farming management practices aimed to develop conservation agriculture to enhance SOC sequestration almost always produce additional environmental benefits, including reduced erosion and improvements in soil fertility, soil and water quality, fossil energy economies, and biodiversity (Komatsuzaki and Ohta, 2007; Manna et al., 2015). The main farming management practices that affect soil carbon stock include the types of residue management, tillage management, and fertilizer management (both mineral fertilizers and organic amendments), the choice of crop and intensity of crop management, the irrigation management, and the system of crop rotation (IPCC, 2004). Many studies have focused on the impact of different farming management practices on soil carbon sequestration through statistical inference of observed data from soil surveys or field experiments (Derner and Schuman, 2007; D'Haene et al., 2009; Huang and Sun, 2006). However, these studies do not adequately explain the complex processes of carbon biogeochemical cycles in terrestrial ecosystems in combination with crop, soil, climate, and management conditions (Chen et al., 2015). Additionally, these studies ignore the interactive effects and highly non-linear relationships among the above factors in a complex ecosystem (Ring et al., 2010; Tang et al., 2010). All of these limitations also apply to the biophysical processes.

Process-based models are powerful tools that are increasingly being used to examine the potential impacts of management in agriculture (Gilhespy et al., 2014). Numerous studies have quantified the impacts of alternative farming management practices on SOC stock by process-based models (e.g., Roth-C, CENTURY, GEFSOC, LPJ-DGVM, and CEVSA) applied to global, national and regional scales (Eve et al., 2002; Gao et al., 2005; Milne et al., 2007; Olofsson and Hickler, 2008). Nevertheless, these studies with large spatial extents are still limited as they (i) struggled to delineate the high spatial heterogeneity of SOC stock as well as its impact factors caused by environment and soil properties (Falloon et al., 2006; Ross et al., 2013) and (ii) led to large uncertainties associated with the reported results due to the lack of data available to validate models (Pennock and Frick, 2001; Sleutel et al., 2006). The DeNitrification and DeComposition (DNDC) model is one of the few models that has been developed that includes both a site-specific mode and a regional mode, meaning it can be applied to evaluate numerous field observations regarding crop yields, SOC dynamics, trace gas fluxes, etc. (Kurbatova et al., 2008; Li et al., 1997; Smith et al., 2004; Zhang et al., 2012b) and to estimate C/N balance, SOC sequestration potential, global warming potentials incurred by greenhouse gas emissions, etc. at regional or national scales with sufficient validation (Li et al., 2003; Sleutel et al., 2006; Zhang et al., 2012b). DNDC has been widely used to simulate the process of C/N cycles at different scales but has seldom been used at a county-regional scale (Wang et al., 2008; Xu et al., 2012; Zhang et al., 2015b). Even though county-regional-scale modeling has limitations similar to the large-spatial-extent or landscape-scale modeling mentioned above, it is (i) still a basic evaluation of the SOC budget that can be upscaled to a whole-country or larger spatial region (Villarino et al., 2014), (ii) able to obtain more precise results for specific areas based on sufficient field observations compared to the large uncertainty resulting from a country or larger spatial-region scale (Li et al., 2013), and (iii) a more detailed description of the impacts of different farming management practices on SOC stock in the context of relatively homogeneous land-use types or landscape types across a county-regional scale than the larger spatial regional scale. A major challenge in applying the DNDC model at a county-regional scale is assembling spatially exhaustive data sets to run the model and quantify the uncertainty resulting from soil heterogeneity (Li et al., 2004; Qiu et al., 2005). Following management, the soil texture, climate and SOC content have the largest influence on SOC dynamics, and they exhibit strong spatial variability (Sleutel et al., 2006). Making full use of ground investigations and observations to obtain the above factorial data, and forming spatially explicit data sets to be aggregated into the fine-scale (a subdivision of geographic areas) simulation unit used in DNDC modeling, can improve simulation precision at a county-regional scale (Paustian et al., 1997; Zhang et al., 2014).

The aims of this paper are to quantitatively assess the effects of different combined farming management practices on SOC stock and its spatial patterns in Yucheng County in the Northern China Plain (NCP). Specifically, the objectives are (1) to validate the DNDC model at both the field level and the regional scale; (2) to simulate regional SOC stock and its distribution response to different farming management alternatives using a spatially explicit database; (3) to provide recommendations on optimal farming management scenarios that most efficiently sequester SOC and (4) to provide suggestions on how to reduce the uncertainty in estimating SOC. This research enhances our understanding of the comprehensive impacts of management practices on soil C pools when upscaling from a county-regional scale to larger regional or national scales.

2. Materials and methods

2.1. Study area

Yucheng County is located in the central NCP and extends from 36.69°N to 37.20°N and from 116.37°E to 116.75°E, covering an area of 988.5 km^2 that is divided into 11 towns (Fig. 1); of this area, 72.48% was arable land in 2009 (Chen et al., 2012). Yucheng County is located on the Yellow River alluvial plain with an average elevation of 21.8 m asl (Jia et al., 2010). The soil formed from the alluvium of the Yellow River and is categorized mainly as fluvo-aquic soils and salinized soils (Liu et al., 2006). The region belongs to a semi-humid and temperate monsoon climate zone, characterized by a mean annual temperature of 13.1 °C and a mean annual precipitation of 593.2 mm, mainly distributed in summer months (Zhang et al., 2016a). Yucheng is predominantly composed of agricultural landscape. Most of the agricultural fields are separated by ridges or ditches, are used for crops, and have a plain topography with slopes of 1/8000–1/10000. The dominant crops in the study area are winter wheat, summer maize, cotton and soybean. The rotation of winter wheat and summer maize was the most common type of cropping system, and the total sowing area for winter wheat and summer maize comprised an average of 75% of the total sowing area between 2001 and 2009. In general, summer maize is planted after the harvest of winter wheat in early June, and then winter wheat is planted after the harvest of summer maize in early October. In the wheat growing season, manure and nitrogen fertilizers were commonly used as basal fertilizer and topdressing before sowing and in the node elongation stage, respectively. In the summer maize growing season, nitrogen fertilizer was commonly applied all at once in the node elongation stage (Wu and Ouyang, 2008). Traditional flood irrigation was widespread. Generally, wheat fields were irrigated three to four times, and maize fields were irrigated one or two times. The ordinary farming method included one tillage applied after the autumn harvest and no tillage in the summer. The tilling method usually included moldboard plowing at a depth of 20 cm (Liu, 1993).

2.2. DNDC model

2.2.1. DNDC model description

DNDC (Version 9.5) is a process-oriented, soil biogeochemical model for simulating N and C cycles, including C sequestration, trace gas emissions, crop growth, water use efficiency and N leaching in agro-ecosystems (Li et al., 1992; Li et al., 1994). The model consists of two components. The first component consists of the soil climate, crop