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RESEARCH ARTICLE

Impact of agricultural intensification on soil organic carbon: A study using DNDC in Huantai County, Shandong Province, China

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Abstract

Using the biogeochemical model denitrification/decomposition (DNDC), the dynamic changes of soil organic carbon (SOC) of farmland from the 1980s to 2030s were investigated in Huantai County, a typical intensive agricultural region in the Huang-Huai-Hai Plain of China. Prior to modelling, validation of the DNDC model against field data sets of SOC from Quzhou Experimental Station in the Huang-Huai-Hai Plain was conducted at the site scale. We compared the simulated results with the observed SOC in Huantai County during 1982–2011 under two different classification methods of simulation unit (the first method integrated soil type and land use of Huantai County to form the overlapped modeling units; the second selected the 11 administrative towns as the modeling units), and achieved a high accuracy in the model simulation with the improvement of the model parameters. Regional SOC (0–20 cm) density and stocks for Huantai County in the years 2012–2031 were predicted under different scenarios of farming management. Compared with current management practices, optimized fertilization (20% decrease of mineral N), crop straw incorporation (90%) and appropriate animal manure input (40 kg N ha^{-1} yr^{-1}) could achieve the highest level of SOC density (56.8% higher than 2011) in the period of 2012–2031. The research highlighted the importance of crop straw incorporation, optimized N fertilization and integration of crop production with animal husbandry on the farmland carbon sequestration for maintaining a high land productivity in the Huang-Huai-Hai Plain.

Keywords: agricultural intensification, soil organic carbon, DNDC, nitrogen fertilizer, straw incorporation, animal manure

1. Introduction

Soil organic carbon (SOC) dynamics in farmland reflect the comprehensive impact of various factors including climate, soil and farming practices (Triberti *et al*. 2008; Chabbi *et al*. 2009; Jagadamma and Lal 2010; Brar *et al*. 2013), of which farming practices could have a significant effect within a short period. Crop straw incorporation, animal manure application and non-/reduced tillage are the most effective measures so far determined worldwide for increasing the

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SOC level (Follett 2001; Carter 2002; Lal 2005; Lenka and Lal 2013). In addition, greater amounts of nitrogen (N) fertilizer application can enhance the growth of crops and therefore the available organic matter that can be incorporated into the soil to enhance the SOC (Lakaria *et al*. 2012; Powlson *et al*. 2012; Aguilera *et al*. 2013). Understanding SOC changes due to farming practices in developing countries like China, where agriculture has undergone a rapid intensification process during the past three decades, may help the farmers and local technicians to increase SOC stock and maintain high crop productivity (Pan *et al*. 2009).

Huang-Huai-Hai Plain (or North China Plain), including Beijing, Tianjin, Shandong, Hebei, and Henan, covers 27% of the nation's farmland but produces 60–80% and 35–40% of nation's wheat and maize, respectively (NBSC 2014). The plain has experienced a quick switch to intensive agriculture since the 1980s as the Household Contract Responsibility System was implemented in rural areas of China. Agriculture in this region has been characterized by a high fertilizer input (about 500 kg N ha^{-1} yr^{-1}) in the 2010s, which was even higher in the 1990s (amounting to 600 kg N ha^{-1} yr^{-1} for wheat/maize). Irrigation, mainly in the wheat season due to drought and little rain, was used about 3–6 times and more than 3 700 m^3 ha^{-1} in total (Wang 2011). A high grain output (15 000 kg grain of winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) ha^{-1} yr^{-1}) was achieved. Annual tillage (after autumn harvest) and crop straw incorporation (Wu *et al*. 2003; Kong *et al*. 2013) were also commonly adopted. The development of intensive agriculture has contributed significantly to securing a reliable food supply and improving the SOC (Liang *et al*. 2012; Dai *et al*. 2013). However, negative impacts also occurred during this intensification process, including the loss of N into water systems, atmosphere and deep soil layer (Chen *et al*. 2004; Ju *et al*. 2006, 2009; Zhang *et al*. 2011).

One critical question to be answered is: Will the SOC increase in the Huang-Huai-Hai Plain continue in the future and what will it be under changing farming schemes? The answering of this question will help to establish sound management with the holistic goal of agriculture development in the region, i.e., enhancement of ecosystem service like SOC improvement and maintaining high grain production. There are two ways in which changes in SOC under different farming practices can be measured or predicted: experiment observation (Poulton 1996; Smith *et al*. 1997) and modeling (Blanco-Canqui and Lal 2009; Alvaro-Fuentes *et al*. 2012; Smith *et al*. 2012). The biogeochemical mechanism model, denitrification/decomposition (DNDC), based on the four concepts of biogeochemical abundance, field, coupling and cycling, and the understanding of the mechanism of the migration and transformation processes of carbon and nitrogen elements in the soil, can trace and simulate the biogeochemical behavior of carbon and nitrogen in the agricultural ecosystem and make predictions on long-term soil fertility change (Li 2001, 2007). Previous work has shown that the use of DNDC has been promising in China for SOC simulation and determination of greenhouse gas emissions (Zhang *et al*. 2006; Wang *et al*. 2008; Qiu *et al*. 2009; Li *et al*. 2010). In this study, Huantai County, Shandong Province, a typical intensive agricultural county in the Huang-Huai-Hai Plain, was selected for modeling. We aimed to 1) validate the DNDC model for modeling SOC change due to farming measures and 2) predict the SOC change for the coming decades under different scenarios of farming management practices.

2. Results

2.1. DNDC model validation for site simulation

Data from the long term experiment station located in Quzhou County, Hebei Province (Quzhou station) was used to validate the DNDC model. Quzhou County is located at the same latitude as Huantai County, has similar natural conditions and similar farming systems as Huantai County. Quzhou has 543 mm of precipitation and 201 frost-free days annually. Annual mean temperature is 13.2°C. The soil developed from the alluvial deposits of the Yellow River basin is Camisol. Winter wheat and summer maize are also the typical crops in this region.

Two N levels for the experiment, N1 (135 kg N ha^{-1} yr^{-1}) and N2 (270 kg N ha^{-1} yr^{-1}), were selected to simulate the SOC change from 1985 to 2001. The correlation coefficients between the simulated and field values for N1 and N2 were 0.9431 and 0.9590, respectively, both reaching the very significant level (P<0.01). The values of root mean square error (RMSE) for the simulation of the two treatments N1 and N2 were 5.44 and 5.87, respectively. The values of model efficiency (EF) were 0.88 and 0.84, respectively (Fig. 1). This indicated the good consistence between the simulated and the measured data for the SOC. This was similar to other previously published research, which reported that the DNDC model could successfully simulate the SOC change due to farming practices (Wang *et al*. 2004).

2.2. DNDC model validation for regional simulation

For the regional simulation, two methods of modeling units were adopted in our study. The first method integrated the soil type and land use of Huantai County using the overlay command of the spatial analysis tools in ArcGIS. There were 18 soil types (Fig. 2-A) and 6 types of land use (Fig. 2-B) in Huantai, and the combination of them formed 104 combinations of soil-land use. As the wheat-maize rotation was