Soil & Tillage Research 165 (2017) 302–314

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Simulating the effects of long-term discontinuous and continuous fertilization with straw return on crop yields and soil organic carbon dynamics using the DNDC model

Jing Zhang[a], Kelin Hu[a,*], Kejiang Li[b], Chunlian Zheng[b], Baoguo Li[a]

[a] College of Resources and Environmental Sciences, China Agricultural University, Key Laboratory of Arable Land Conservation (North China), Ministry of Agriculture, Beijing 100193, PR China
[b] Dry-Land Farming Institute of Hebei Academy of Agricultural and Forestry Sciences, Hengshui City, Hebei Province, 053000, China

ARTICLE INFO

Article history:
Received 20 January 2016
Received in revised form 6 August 2016
Accepted 9 September 2016
Available online xxx

Keywords:
DNDC model
Long-term fertilization
Straw return
Crop yield
Soil organic carbon

ABSTRACT

The objectives of this study were to investigate the applicability of the DNDC model under long-term discontinuous fertilization (three years of fertilization followed by three years of no fertilization) in the winter wheat-summer maize rotation cropping system, and to analyze the effects of long-term fertilization and straw return on soil organic carbon (SOC) and crop yields and to optimize the ratio of straw incorporation to fertilization rate. A 30-year (1981–2011) long-term experiment was conducted at the Hengshui

Experimental: Station in Hebei Province with combinations of four inorganic fertilization rates and four maize straw incorporation amounts. Crop yields and SOC contents in the topsoil (0–20 cm) were measured for each treatment, and the data were used to calibrate and validate the DNDC model.

Results: indicated the good performance of DNDC model in simulating crop yields and SOC contents with modeling efficiency $\geq$0.55, normalized root mean square error $\leq$31.3%, and index of agreement $\geq$0.85. However, the model performed relatively poorly in four treatments without fertilizers. Determination coefficients between simulated and measured values of the winter wheat yields, summer maize yields, and SOC contents were 0.747, 0.671, and 0.425, respectively. Crop yield and SOC content predictions were better during periods with fertilization than that during periods without fertilization. The rate of increase in crop yields induced by increasing fertilization rates was higher than that induced by increasing amounts of incorporated straw. However, rate of increase in SOC content resulting from increasing fertilization rate was lower than that from increasing amount of incorporated straw. Over 52 scenarios combining 13 levels of fertilizer rates with four levels of maize straw incorporation were simulated.

Results: from yields, soil fertility, and greenhouse gas emission showed that the optimal ratio for discontinuous fertilization was 420 kg N ha^{-1} yr^{-1} combined with straw incorporation of 10000 kg ha^{-1} yr^{-1}, whereas that for continuous fertilization was 300 kg N ha^{-1} yr^{-1} combined with straw incorporation of 10000 kg ha^{-1} yr^{-1}. Thus, the DNDC model could effectively predict crop yields and SOC dynamics under discontinuous fertilization conditions in Hengshui. High and stable crop yields and enhanced soil fertility could be achieved by optimizing the ratio of fertilization rate to amount of incorporated straw.

1. Introduction

Crop yields in China have increased by 3.2-fold in the last five decades because of high fertilizer inputs (Zhang et al., 2011). However, excessive use of fertilizers has also resulted in environmental problems and degradation of soil fertility (Zhu and Chen, 2002; Guo et al., 2010). Soil organic carbon (SOC), which is an important indicator of soil fertility and functions, is closely related to crop yield and land production (Lal, 2009). In China, crop yields can increase by 0.17–3.74 Mg ha^{-1} yr^{-1} by increasing SOC contents by 1 g kg^{-1} (Kong et al., 2014). Therefore, methods to achieve high yields as well as maintain soil fertility simultaneously should be investigated.

Both crop yield and SOC content in agricultural soils are influenced by a lot of factors, including farming practices (e.g. tillage, fertilization and irrigation), climate, soil properties,

* Corresponding author.
E-mail address: hukel@cau.edu.cn (K. Hu).

http://dx.doi.org/10.1016/j.still.2016.09.004
0167-1987/

Table 1
Basic soil properties in soil profile of the Hengshui experimental site.

Soil layer (cm)	Bulk density ($g\,cm^{-3}$)	Particle fraction (%)			Soil texture	pH	*FC* ($cm^3\,cm^{-3}$)	θ_{wp} ($cm^3\,cm^{-3}$)	θ_s ($cm^3\,cm^{-3}$)	K_s ($cm\,d^{-1}$)
		Sand	Silt	Clay						
0–20	1.42	21.3	69.5	9.2	Silt loam	8.3	27.7	14.1	0.47	10.4
20–50	1.43	1.7	64.6	33.7	Silty clay Loam	7.9	38.4	20.6	0.41	7.9
50–80	1.43	1.2	54.8	44.0	Silty clay	8.0	41.3	26.0	0.48	7.3
80–120	1.46	9.8	45.2	45.0	Silty clay	7.9	41.8	27.1	0.47	6.7
120–150	1.50	1.9	64.4	33.7	Silty clay Loam	7.9	38.5	20.6	0.48	7.9

FC represents field capacity, θ_{wp} represents wilting point, θ_s represents saturated water content, and K_s represents saturated hydraulic conductivity.

cropping systems and so on. Numerous long-term experiments have proven that farming management practices, such as tillage, fertilization, and straw return, can improve SOC contents effectively (Hao et al., 2008; Lu et al., 2009; Niu et al., 2011; Zhao et al., 2013; Lehtinen et al., 2014). Among all the farming management practices, straw return is one of the most economic and effective way of increasing SOC contents as well as achieving high crop yields. It is mainly because the annual straw production in China is approximately 820 Tg, and straw of main cereal crops, such as rice, wheat, and maize, accounts for 75% of the total straw production of the country (Ministry of Agriculture of China, 2010). Moreover, straw contains a number of nutrients, such as nitrogen (N), phosphorous (P), and potassium, which are needed by crops to grow and it also increases C input into soil directly. Zhao et al. (2015a,b) performed a *meta*-analysis of 142 experiments carried out over a span of more than three years and showed that crop yields in 92% (131) of these experiments increased with increasing straw incorporation; by contrast, yields decreased in only 8% of the experiments because of straw return. Wang et al. (2015a) conducted a regional *meta*-analysis in the main production regions of China and showed that straw incorporation can significantly increase SOC contents by 10.1%. Those results implied that straw returns can increase crop yields and SOC content in the majority of regions in China.

Currently, there have been a lots of long-term experiment sites around the world which can monitor SOC changes and provide fundamental research data, however, the observed data are usually limited within a certain study and they are temporally and spatially discrete. Hence, it is necessary to employ the quantitative tools (such as biogeochemical models) to realize long-term temporal and spatial predictions of SOC dynamics. Such model is not only time-saving and economical, but would also assist in improving the understanding of internal mechanisms to explain the observed results and their influencing factors (Jones et al., 2003). Numerous models, such as DNDC (Li, 1992), EPIC (Williams, 1990), CENTURY (Parton, 1996), RothC (Jenkinson and Rayner, 1997), and DayCent (Del Grosso et al., 2000), have been extensively used to predict SOC dynamics worldwide. And these models have also been calibrated and validated in various regions of China, such as the North China Plain (NCP) and Guanzhong region (Ludwig et al., 2010; Chen et al., 2015), for different cropping systems (Zhao et al., 2013; Ouyang et al., 2014), and under different farming management practices (Zhao et al., 2013).

Although most simulations of long-term experiments with inorganic and organic fertilization are conducted with continuous fertilization, few studies have focused on discontinuous fertilization to determine the effect of fertilization. Information on how to combine fertilization with straw return to enhance crop yields and promote soil fertility is insufficient.

A long-term experiment on the combination of fertilizer with straw return in Hengshui City of Hebei Province was considered in this study. The applicability of the DNDC model was tested under discontinuous fertilization conditions (three years with fertilization, followed by three years without fertilization), and the impact of long-term fertilization and straw return on crop yields and SOC contents was analyzed. Finally, the ratio of fertilization rate to amount of straw return was optimized.

2. Materials and methods

2.1. Study area

The long-term field experiment was established in 1981 at the Dry-land Farming Research Institute of Hebei Academy of Agricultural and Forestry Sciences (37°53′ N, 115°42′ E, 31 m above sea level), located at Hengshui City, Hebei Province in NCP. The area features a temperate continental monsoon climate and a mean annual precipitation (AP) of 550 mm, 70%–80% of which occurs in the summer maize (*Zea mays* L.) growing season (from June to September). The annual average temperature of the area is 12.4 °C. The winter wheat (*Triticumaestivum* L.) and summer maize rotation cropping system is prevalent in this area, and the soil is calcaric cambisol according to the FAO-UNESCO Soil Map of the World (FAO/UNESCO, 1988). The basic physical and chemical properties of the topsoil (0–20 cm) were measured prior to the experiment and found to be as follows: SOC content, 6.67 g C kg^{-1}; total N content, 0.83 g kg^{-1}; and total P content, 1.03 g kg^{-1}. A profile of the basic physical properties of the soil is shown in Table 1 (Zhao, 2012; Yang et al., 2015).

2.2. Experiment design

The experiment was established as a randomized block design with 16 treatments having four inorganic fertilizer application rates (A1, no fertilizer; A2, 90 kg N $ha^{-1}\,yr^{-1}$ with 60 kg P_2O_5 $ha^{-1}\,yr^{-1}$; A3, 180 kg N $ha^{-1}\,yr^{-1}$ with 120 kg P_2O_5 $ha^{-1}\,yr^{-1}$; and A4, 360 kg N $ha^{-1}\,yr^{-1}$ with 240 kg P_2O_5 $ha^{-1}\,yr^{-1}$) and four straw incorporation amounts labeled B1, B2, B3, and B4 representing 0, 1125, 2250, and 4500 kg $ha^{-1}\,yr^{-1}$ (equal to 0, 450, 900, and 1800 kg C $ha^{-1}\,yr^{-1}$) before 1987, which were doubled to 0, 2250, 4500, and 9000 kg $ha^{-1}\,yr^{-1}$ (equal to 0, 900, 1800, 3600 kg C $ha^{-1}\,yr^{-1}$) after 1987. Each treatment was replicated thrice, and the plot size was 67 m^2. Ten treatments were selected in this study, and detailed information is shown in Table 2. The experiment began in the fall of 1981 and was continued over periods of every six years. Fertilizer and maize straw were applied in the first three years according to the experiment design and then stopped for the next three years to observe follow-up effects. Periods with fertilization and straw return included 1981–1983, 1987–1989, 1993–1995, and 1999–2011. Periods without fertilization and straw return included 1984–1986, 1990–1992, and 1996–1998. Continuous increases in crop yields indicate more nutrient removal from the soil, leading to decline in soil fertility. Discontinuous fertilization was replaced by continuous fertilization in 1999.

Urea was used as the N fertilizer, and calcium superphosphate was used for P fertilizer. Half of the N fertilizer was applied to winter wheat and the other half was applied to summer maize. Then, 50% of the N fertilizer for winter wheat was applied at