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## Soil organic carbon budget and fertility variation of black soils in Northeast China

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**Abstract** Black soils in Northeast China are characteristic of high soil organic carbon (SOC) density and were strongly influenced by human activities. Therefore, any change in SOC pool of these soils would not only impact the regional and global carbon cycle, but also affect the release and immobilization of nutrients. In this study, we reviewed the research progress on SOC storage, budget, variation, and fertility under different scenarios. The results showed that the organic carbon storage of black soils was 646.2 TgC and the most potential sequestration was 2887.8 g m<sup>-2</sup>. According to the SOC budget, the net carbon emission of black soils was 1.3 TgC year<sup>-1</sup> under present soil management system. The simulation of CENTURY model showed that future climate change and elevated CO<sub>2</sub> concentration, especially the increase of precipitation, would increase SOC content. Furthermore, fertilization and cropping sequence obviously influenced SOC content, composition, and allocation among different soil particles. Long-term input of organic materials such as manure and straw renewed original SOC, improved soil structure and increased SOC accumulation. Besides, soil erosion preferred to transport soil particles with low density and fine size, decreased recalcitrant SOC fractions at erosion sites and increased activities of soil microorganism at deposition sites. After natural grass-

lands were converted into croplands, obvious variation of soil chemical nutrients, physical structure, and microbial activities had taken place in surface and subsurface soils, and represented a degrading trend to a certain degree. Our studies suggested that adopting optimal management such as conservation tillage in black soil region is an important approach to sequester atmospheric CO<sub>2</sub> and to slow greenhouse effects.

**Keywords** Soil organic matter · Soil carbon budget · Soil fertility · Black soils · Northeast China

### Introduction

The black soil region in Northeast China (43–50°N, 124–127°E) covers an area with 5.96 million hectare, most of which locates in the middle of Heilongjiang and Jilin province, where accounting for 79.6 and 20.1%, respectively (Fig. 1). Black soil region belongs to semi-humid climate region in temperate zone, the annual precipitation ranges from 500 to 600 mm, and about 90% of the precipitation falling as rain between April and September (Xiong and Li 1987). The original vegetation is temperate steppe with characteristics of high ratio of cover and return of litter to soils, which results in relative high accumulation of soil organic matter (SOM). The terrain characterizes as undulating plateau with slopes of 3–8%. The soil is a clay loam (Typic Hapludoll, based on Soil Survey Staff 1999) developed on loess-like parent material and almost has been cultivated as cropland because of high fertility and arability. The black soils are prone to be eroded by wind and water due to concentrated rainfall in growing season plus no-residue covered soil surface in early spring and late autumn (Fan et al. 2004). In addition, intensive tillage is an important factor resulting in the decline of soil organic carbon (SOC) and variation of soil properties (Yang et al. 2003). Presently, the SOC content is less than 50% of their initial content (HLMB-SSO 1992; JGSSF 1998), which is higher than those of other soils in

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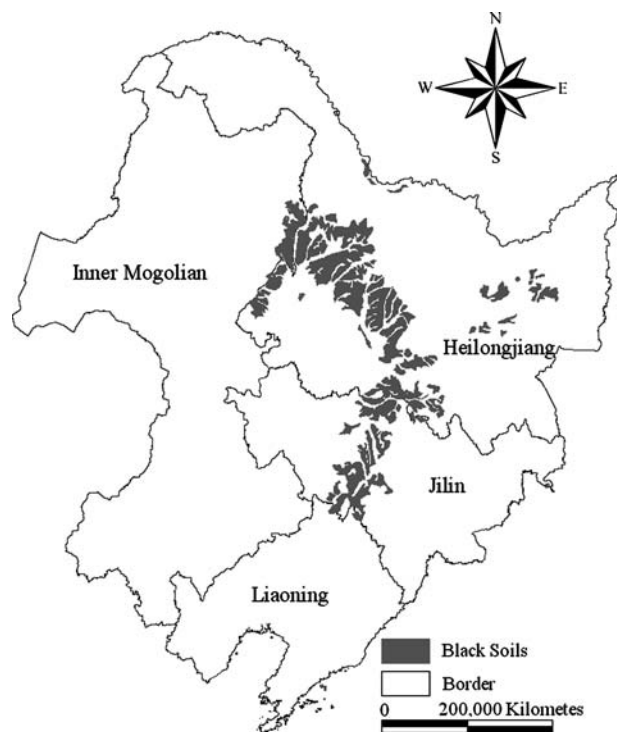


Fig. 1 Distributing plot of black soils in Northeast China

temperate zone (Somebroek et al. 1993; Burke et al. 1995). Black soil region in Northeast China is also one of the most sensitive regions to global climate change (Wang et al. 2002c). Recently, the climate in this region tends to become warm and drought. In the past 50 years (1950–2000), the mean annual temperature elevated 1.3°C and that of the winter equaled to 2.1°C (Guo et al. 2005). The mean annual precipitation, especially in summer season, increased from the early years of 1980s, and then obviously decreased in the end of 1990s (Zu et al. 2004; Wang et al. 2004a, b). The elevating CO<sub>2</sub>, increasing air temperature, and decreasing precipitation could also affect the turnover rate of organic carbon of black soils.

The aim of this study was to quantify the carbon storage and sequestration of black soils, the budget between input and output of organic materials, the effects of agricultural managements, climate change, and soil erosion on variation of SOC and other nutrients. The results will be helpful to deeply understand the roles of black soils to climate change and food safety, and to provide a basis for taking reasonable soils management.

## Materials and methods

### Description of CENTURY model

Five plots in Hailun city, Heilongjiang province were selected to simulate dynamics of organic matter of black

soils under environment changes and managements. Site parameters of running CENTURY model including climate, soil physical controls, external nutrients, initial crop/grass organic matter, initial soil mineral N, erosion, and deposition, etc. Data on climate, soil, and vegetation were listed in Appendix. First, we used CENTURY model to simulate change of SOC of natural black soils after being reclaimed for 150 years. Three treatments as convention tillage, conservation tillage, and unreasonable management including moving crop residues and soil erosion were selected. Then, the responses of SOC in surface layer (20 cm) to climate changes and elevated CO<sub>2</sub> in future 100 years was simulated. Eight climate change scenarios were listed as following: TP (no change of temperature and precipitation, the values are means from the year of 1953 to 2000), TiP (an increase of temperature by 2°C), TiPi (an increase of temperature by 2°C and a 20% increase in precipitation), TiPd (an increase of temperature by 2°C and a 20% decrease in precipitation), TPC, TiPC, TiPiC, TiPdC were scenarios of increasing atmospheric CO<sub>2</sub> concentration from 350 ppm at present to 700 ppm in the future based on TP, TiP, TiPi, TiPd, respectively.

### Budget of SOC

The form of soil organic matter depended on the input of organic materials and their decomposition rate. Soil organic carbon budget can be expressed by the following equation,

$$dCs/dt = hA - kC \quad (1)$$

where  $A$  is return of organic materials to soils;  $h$  is humification coefficient of organic materials;  $K$  is mineralization coefficient of SOC; and  $Cs$  is SOC content. The humification coefficient  $h$  is determined by decomposing bag method (Li et al. 2002). Mineralization of SOC is determined by method of soil nitrogen balance. Namely, mineralization of soil nitrogen was calculated based on input of nitrogen through atmospheric deposition and biology fixation, and loss of nitrogen through leaching, runoff, and denitrification in experimental plots, where no nitrogen fertilization was applied (Li et al. 2002). Mineralization of SOC is calculated based on C/N and mineralized nitrogen. Amount of organic materials' application was estimated by statistical data, and then return of organic materials was calculated based on the average quantity of roots, straw, and their utility ratio. The ratio of seed to straw to root for corn, wheat, and paddy was 1:1.2:0.35, 1:1.4:0.4, 1:0.9:0.3, respectively.

### SOC loss resulting from soil erosion

In Dehui county, Jilin province, a typical sloping farmland including five representative slope units, namely

summit, shoulder-slope, back-slope, foot-slope, and toe-slope, was selected to study the effects of soil erosion on dynamics of SOC fractions (Fang et al. 2005a). Surface soil samples (20 cm) were collected and analyzed the content of carbon fractions with different activities such as microbiomass carbon (MBC), water soluble organic carbon (WSOC), and organic carbon associated with soil particles and aggregates. The rate of soil redistribution was calculated by  $^{137}\text{Cs}$  tracer technique.

In addition, CENTURY model was used to simulate dynamics of SOC and its fractions since it was reclaimed. Data on climate and soil was listed in Appendix. During the first 80 years (1852–1932), wheat-millet rotation and soybean-millet rotation had been carried out for 40 years, respectively. After that, corn-corn-soybean rotation became dominant in the region. The practices of soil management in the study area have experienced three stages: (1) crop production only relying on the native fertility of soil and with limited manure application before 1970s, (2) increasing use of chemical fertilizer and decrease of manure use during 1970s–1990s. These two stages were also characterized by removing all crop residues (aboveground biomass and stubble), and (3) the land management in the region entered the three stages—chemical fertilizers plus remaining stubble and main roots in soils since 1990s (Yang et al. 2003). In our study, fertilizer addition was assumed very low before 1972; fertilization addition rate was set as  $12 \text{ g N m}^{-2}$  from 1972 to 1992, and  $18 \text{ g N m}^{-2}$  from 1992 to 2002.

### Fertilization experiments

The fertilization experiments were established in 1979 at the Gongzhuling Research Farm of the Jilin Academy of Agricultural Science ( $42^{\circ}57'\text{N}$ ,  $148^{\circ}57'\text{E}$ ), Jilin Province, China. The experiments consist of 24 fertilizer treatments with each plot covering an area of  $400 \text{ m}^2$ . Four fertilization treatments were listed as follows: no fertilizer or manure addition ( $M_0 + \text{CK}$ ), adding only manure ( $M_2 + \text{CK}$ ), received NPK fertilizers without manure addition ( $M_0 + \text{NPK}$ ), adding manure to NPK fertilizer ( $M_2 + \text{NPK}$ ). In addition, six mixed treatments of culture and fertilization were selected including continuous cropping without fertilizer addition ( $\text{C}/\text{CK}$ ), long-term fallow ( $>20$  years), continuous cropping and NPK fertilizers addition ( $\text{C}/\text{NPK}$ ), continuous cropping and manure and NPK fertilizers addition ( $\text{C}/\text{M}_1 + \text{NPK}$ ), continuous cropping and straw and NPK fertilizers addition ( $\text{C}/\text{S} + \text{NPK}$ ), crop rotation and manure, NPK fertilizers addition ( $\text{R}/\text{M}_1 + \text{NPK}$ ) (Liu 2002). Fertilization addition and cropping system were described as follows:  $M_0$  means 0 ton manure per hectare per year;  $M_1$  means 15 ton manure per hectare per year;  $M_2$  means 30 ton manure per hectare per year; NPK means 150 kg N, 75 kg  $\text{P}_2\text{O}_5$ , 75 kg  $\text{K}_2\text{O}$  per hectare

per year; S means 7.5 ton straw per hectare per year. C means continuous cropping, R means crop rotation, and fallow means no fertilization, cultivation, and weed. Soil physical and chemical prosperities were measured by methods described by Lu (1999).

### Evolution and evaluation of black soil quantity

From the north to the south, three sites such as Beian ( $48^{\circ}13'\text{N}$ ,  $126^{\circ}30'\text{E}$ ), Hailun ( $47^{\circ}26'\text{N}$ ,  $126^{\circ}58'\text{E}$ ), and Gongzhuling ( $43^{\circ}31'\text{N}$ ,  $124^{\circ}48'\text{E}$ ) were selected to collect soil samples, which have 0 (i.e., barren land), 5, 10, 20, 60 and 100 years of cultivation ( $n = 21$ ). Among of them, four phase of soil quality such as uncropped, slaking, balanced, degraded black soil at each sites was selected to measure quantity of soil microorganism and enzyme activities. In addition, another 115 soil profiles were collected in the whole black soil region to evaluate spatial pattern of black soil fertility. Physical, chemical, and microorganism properties of topsoils (0–20 cm) was measured by Lu (1999).

Soil organic carbon, total nitrogen (TN), total phosphorus (TP), total kalium (TK), available phosphorus (AP), rapidly available kalium (AK), clay, and pH were selected as index of black soil fertility. An integrated fertility index (IFI) was established and defined as following (Ma et al. 2004).

$$\text{IFI} = \sum Q_i + W_i \quad (2)$$

where  $Q_i$  is the membership value of the  $i$ th index to soil fertility,  $W_i$  is weight coefficient of the  $i$ th fertility index. The membership values of each fertility index were calculated by their actual measure value and two membership functions which are expressed as following:

“S” function

$$f(x) = \begin{cases} 1.0 & X \geq U \\ 0.1 + 0.9(X - L)/(U - L) & L < X < U \\ 0.1 & X \leq L \end{cases} \quad (3)$$

Parabola function

$$f(x) = \begin{cases} 0.1 & X \leq L, X \geq U \\ 0.1 + 0.9(0.1 - L)/(O_1 - L) & L < X < O_1 \\ 1.0 & O_1 \leq X \leq O_2 \\ 1.0 - 0.9(X - O_2)/(U - O_2) & O_2 < X < U \end{cases} \quad (4)$$

where  $X$  is the actual measurement,  $U$ ,  $L$ , and  $O$  are the upper limit, lower limit, and optimum value that could be determined by the actual measures. Then weight coefficient of each index was estimated by its communality through principal component analysis. IFI ranged from 0 to 1. The higher is the value of IFI, the better is soil fertility.

## Results and discussion

### Storage, loss, and potential sequestration of organic carbon of black soils

The SOC storage is significantly impacted by geographic location, cultivation history, climate change, soil erosion, and agricultural management practices. After the natural black soils were reclaimed, the potential variation of SOC content was simulated by CENTURY model and was divided into three stages such as rapid decline in earlier stage, slow decline in the middle stage, and close to equilibrium state in latter stage (Fig. 2), and the duration in each stage depended on soil type, depth, and cultivation system. In the first 20 years, SOC content rapidly decreased and lost 1/4–1/3 of the initial content; then black soils turned into the stage of slow decline after they had been cultivated for 40–50 years, the SOC loss in this stage accounted for 1/4–1/3 of the initial content again. After about 60 year's tillage, the SOC content almost approached a relative stable state and was 1/3–1/2 of initial content (Fig. 2). Currently, the SOC in black soils in Jilin province has been close to a stable equilibrium state where soil erosion was not serious and cultivation history was relative long (Yang et al. 2004), which reflected that the high yield corn had balanced organic carbon of black soils between roots input and mineralization output. However, SOC content in Heilongjiang province may continue to decrease for a certain time due to the relative shorter history of reclamation, especially in its northern regions. Based on the data of the second national soil survey, the mean SOC density of black soils to 1 m depth was 12.54 kgC m<sup>-2</sup> (Fang et al. 2003), which was 1.2 times as high as the mean of soils in China (10.53 kgC m<sup>-2</sup>) (Wang et al. 2000). The SOC stock was 646.2 TgC, about 52.7% of which accumulated at surface layer 30 cm (Fang et al. 2003).

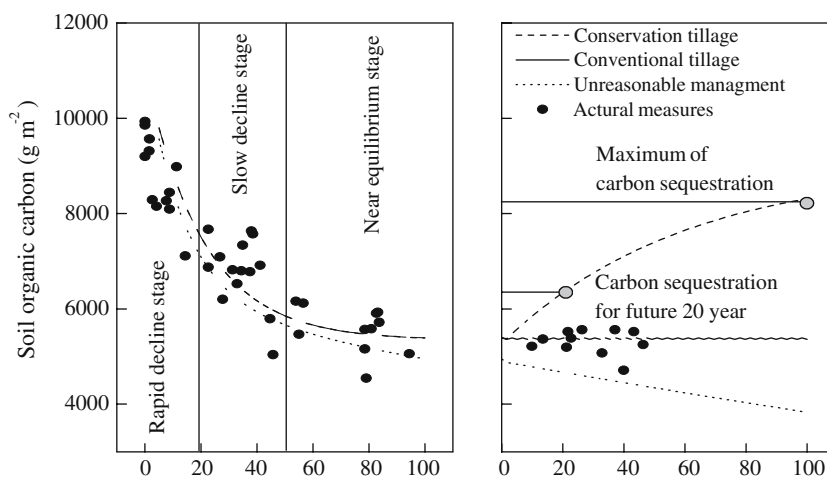
Soil erosion results in SOC loss at eroded sites, subsequently sediments are transported and deposited in

deposition sites, where sequestering a certain quantity of SOC (Vanden Bygaart 2001; Liu et al. 2003; Fang et al. 2006). In black soil region, the transport of SOC calculated by RUSLE model ranged from 0.34 to 2.84 TgC year<sup>-1</sup>, about 70% of them were distributed in landscape (Fang et al. 2003). Black soils have a 150-year reclamation history, the net loss of SOC was 434.6 TgC since natural grass being converted to cropland, which was 88.9% as much as that calculated by soil body (488.6 TgC) (Fang et al. 2003). Adopting reasonable soil management practices such as conservation tillage in degraded black soils could promote accumulation of SOC in topsoil and sequestration of atmospheric CO<sub>2</sub>, which could delay the increase of atmospheric CO<sub>2</sub> concentration. CENTURY model was run to simulate the original accumulation of SOC and its fractions for 3,000 years, which deduced the initial SOC density was 11,164 g m<sup>-2</sup>. The SOC density in equilibrium status was 5388.5 g m<sup>-2</sup>, which accounted for 48.3% of initial content of SOC (Fig. 2). Most studies indicated that the potential sequestration of SOC resulting from conservation practices was 20 g m<sup>-2</sup> year<sup>-1</sup> in cold and arid climate region in the future 20 years and that of other climate region was 40 g m<sup>-2</sup> year<sup>-1</sup>, with an average of 30 g m<sup>-2</sup> year<sup>-1</sup> (Bruce et al. 1999). Moreover, the most retrieval was 50% of the lost SOC, which need about 100 years to get this status (Cole et al. 1996; Bruce et al. 1999). Based on these hypotheses, the carbon density of black soil will increase and reach 5988.5 g m<sup>-2</sup> under adopting conservation management for 20 years, and the most potential sequestration was 2887.8 g m<sup>-2</sup> (Fig. 2).

### Budget between input and output of organic matter of black soils

Budget between annual account of SOC formation and mineralization in typical arable soils in Eastern China was calculated to evaluate their functions as source or sink of atmospheric CO<sub>2</sub>. Humification coefficient of

**Fig. 2** Simulating process of SOC variation in black soils under different soil managements



black soils was slightly higher than those of agricultural area of Eastern China (Table 1). Humification coefficient did not change proportionately with temperature and rainfall and influenced by environmental factors, especially soil properties such as clay content, and pH (Li et al. 2002). It was because of higher clay content and lower air temperature in black soil region that restricted the decomposition of organic materials (Xiong and Li 1987). Although black soils had less annual rate of SOC decomposition, the annual amount of SOC mineralization was significantly higher than those of other soil types because of higher SOC content ( $P < 0.05$ ), mineralization rate of soil nitrogen, and C/N (Table 1). Under present return of organic materials to black soils, the annual formation of SOC was  $577.3 \text{ kg ha}^{-1}$ . The carbon budget suggested that the net SOC loss was  $337.8 \text{ kg ha}^{-1}$  and the total deficit of SOC was about  $1.3 \text{ TgC year}^{-1}$  in black soil region with 3.85 million hectare cropland.

There are some uncertainties for the level of carbon source calculated by Li et al. (2002). Firstly, black soils are similar as Mollisoll region in USA, but the seed to root ratio (1:0.35) used to calculate SOC budget of black soils is obviously less than that of Mollisoll (Buyanovsky and Wagner 1986), which overestimates the loss of SOC of black soils. Secondly, black soils should be divided into northern and southern part. The SOC in southern black soils was near to the equilibrium due to longer cultivation history and not serious soil erosion (Yang et al. 2004), where the budget of organic materials input and output is closely equal to zero. But the black soils in northern part have relative shorter cultivation history, higher SOC content and more serious soil erosion, where soils may be a source of atmospheric  $\text{CO}_2$ . The above viewpoint has been tested by monitoring flux of  $\text{CO}_2$ . During the growing season (from May to September), the efflux of  $\text{CO}_2$  from cropland ranged from 5258.1 to 7484.7  $\text{kg ha}^{-1}$  (Ding et al. 2003). Finally, besides input of organic materials, carbon source or sink of one soil also depends on SOC saturation, which is strongly correlated to soil clay and silt content (Hassink 1997; Carter et al. 2003). Generally, the clay and silt content in black soils is about 60%, so black soils have also high potential SOC sequestration.

## Responses of SOC to climate change and elevated atmospheric $\text{CO}_2$

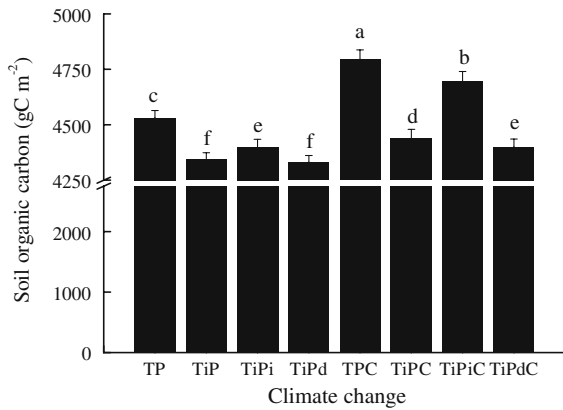
Climate change and elevated atmospheric  $\text{CO}_2$  concentration can affect SOC content (Gao et al. 2005). The simulation showed that SOC significantly decreased in all scenarios of increasing temperature by  $2^\circ\text{C}$  (TiP, TiPi, and TiPd) contrasting to that of the control (TP). The decrease of SOC resulting from increasing temperature was significantly reduced by precipitation in TiPi scenario, while there was no significant difference of SOC between the scenario TiP and TiPd (Fig. 3). The results indicated that temperature was the main climate factor that affects SOC in black soil region, and precipitation increase could reduce the decline of SOC resulting from the increase of temperature. Coughenour and Chen (1997) showed that the net loss of C in response to increased temperature resulted from decreased plant growth and increased decomposition, and that the effect was reduced by increasing precipitation because of increased plant growth. In addition, the two counteracting effects of increased precipitation, i.e., stimulation of biological processes through increasing water availability and decreasing temperature, determined the overall effect on net primary production (NPP) and SOC.

Equilibrium effects of elevated  $\text{CO}_2$ , increased temperature, and changing precipitation need to be synthetically discussed. Soil organic carbon of black soils under doubled  $\text{CO}_2$  scenarios was significantly greater than that affected only by corresponding climate change, which indicated that the increase of atmospheric  $\text{CO}_2$  concentration could compensate the negative effect of the increase of temperature and the decrease of precipitation on SOC of black soils (Fig. 3). Similarly, simulations with the grassland ecosystem model (GEM) predicted increased productivity and C storage in plant residue and SOM for temperate grasslands in response to doubled  $\text{CO}_2$  (Hunt et al. 1991). Soil organic carbon content in TiPC scenario was less than that of TP, which reflected that the negative of increasing temperature was more than the positive of increasing  $\text{CO}_2$ . Simulations with the CENTURY model produced a net loss of C caused by the combination of increased temperature and  $\text{CO}_2$  (Parton et al. 1995). In contrast, the linked model carbon

**Table 1** Comparison between budget of black soil and those of other soil types in Eastern China (modified by Li et al. 2002)

Soil types	Humification coefficients	OM returned to soil ( $\text{kg ha}^{-1}$ )	SOC formation ( $\text{kg ha}^{-1}$ )	SON mineralization ( $\text{kg ha}^{-1}$ )	C/N	SOC mineralization ( $\text{kg ha}^{-1}$ )	Budget of SOC ( $\text{kg ha}^{-1}$ )
Black soils	0.42a	1374.5b	577.3c	73.6a	12.3a	915.1a	-347.7d
Burozem	0.37ab	1941.5b	718.4bc	60.8b	11.9a	733.2c	-24.5c
Aquoll	0.29b	2820a	803.7b	61.8b	11.7a	733.8c	59.1b
Paddy soils	0.37ab	2860.5a	1044.1a	64.7ab	12.1a	778.9b	268.9a

There is significant difference with different letters following the value at the 0.05 level, and vice versa [least significant difference (LSD) comparison]



**Fig. 3** The response of black soil organic carbon to climate change and the elevated atmospheric CO<sub>2</sub> concentration in Hailun, Heilongjiang province

exchange between vegetation, soil, and atmosphere (CEVSA) revealed a strong increase in NPP and C stocks of terrestrial ecosystems in response to the combined effects of elevated CO<sub>2</sub> and higher mean temperature (Cao and Woodward 1998). This is due to the fact that the effect of elevated CO<sub>2</sub> on photosynthesis increases with temperature to a certain degree. The positive influence of increased temperature on the CO<sub>2</sub>-stimulation of NPP would reverse beyond temperature optimum of the plant processes (Riedo et al. 2000).

#### Effects of agricultural managements on the budget of SOC

Soil organic carbon and its fraction are strongly influenced by agricultural management practices such as fertilization and cropping system. Based on a long-term soil fertility monitor experiment, we found that the treatment without fertilizer or manure addition (M<sub>0</sub> + CK) resulted in loss of SOC and its fractions (Table 2). Adding manure to NPK fertilizer (M<sub>2</sub> + NPK) treatment showed similar positive effects on the change of SOC and its fractions as adding only manure (M<sub>2</sub> + CK). Moreover, the increasing effects in the former was greater than that in the latter (Table 2). The long-term effects of fertilization simulated by running Roth-C model also showed that SOC content remained relatively stable for soils that received NPK fertilizers without manure addition (M<sub>0</sub> + NPK). In 2002, M<sub>0</sub> + CK treatment resulted in a 14% loss of SOC, while M<sub>2</sub> + NPK treatment resulted in a 10% increase relevant to that in 1980 (Yang et al. 2003). In addition, long-term fallow (> 20 years), return of crop straw to soil (C/S + NPK), and crop rotation treatment (R/M<sub>1</sub> + NPK) also significantly increased the SOC and its fractions, decreased the oxidation stability coefficient (Kos), enhanced the FA to HA ratio compared with that of continuous cropping control treatment (C/CK). Similarly, the simulating results also showed that returning the aboveground crop residues

**Table 2** The effects of cultivation and fertilization on the SOC content and distribution among soil particles (modified by Liu 2002)

Treatments <sup>a</sup>	TOC (g kg <sup>-1</sup> )	MBC (mg kg <sup>-1</sup> )	LF (g kg <sup>-1</sup> )	AOC (g kg <sup>-1</sup> )	Kos	HA-C (g kg <sup>-1</sup> )	FA-C (g kg <sup>-1</sup> )	HA/FA	Combined forms of humus (g kg <sup>-1</sup> )			Carbon associated with organic-mineral complexes (g kg <sup>-1</sup> )			Soil aggregates (%)			DC (%)				
									Loose	Stable	Tight	Clay	Silt	Fine sand	< 2 μm	2–20 μm	20–200 μm		> 200 μm	5.68a	4.87ab	4.57ab
M <sub>0</sub> + CK	15.99b	271c	2.37b	9.54c	0.68a	4.44c	2.65b	1.68b	6.49b	1.04a	7.13b	0.76b	41.32a	47.49b	5.52b	4.16a						
M <sub>0</sub> + NPK	20.08ab	279c	3.37ab	12.09bc	0.66a	5.88bc	3.83a	1.53b	7.70ab	2.45a	8.29b	1.52ab	40.34b	48.93ab	5.85ab	3.90ab						
M <sub>2</sub> + CK	21.98a	385b	4.34ab	13.92ab	0.58b	7.11ab	4.12a	1.72b	8.12ab	4.45a	9.00b	1.76a	40.20b	49.59a	5.65ab	3.58bc						
M <sub>2</sub> + NPK	25.97a	513a	5.79a	16.74a	0.56b	8.41a	4.35a	1.92a	9.03a	2.79a	12.37a	2.27a	40.00b	49.58a	6.09a	3.23c						
C/CK	12.58c	253.33c	1.18b	6.59c	0.91a	3.27c	2.40b	1.37b	5.40b	6.59c	4.87c	0.61c	41.91a	43.11d	7.43c	3.83a						
Fallow	19.28a	491.88a	2.53a	10.99a	0.76b	5.53a	3.01a	1.82a	4.37abc	2.56c	8.14a	1.39a	39.10c	49.16a	7.55bc	2.71d						
C/NPK	13.81bc	295.25c	1.72ab	7.29bc	0.90a	3.76bc	2.82a	1.33b	5.67ab	7.17c	5.425bc	0.76bc	40.84b	46.12c	7.95abc	3.25b						
C/M <sub>1</sub> + NPK	17.24ab	458.00ab	2.22ab	10.52a	0.64cd	5.23ab	3.06a	1.70a	5.11a	3.02ab	6.57a	1.16ab	40.36b	47.00bc	8.07ab	2.91cd						
C/S + NPK	16.65abc	439.38ab	2.31a	9.86a	0.69bc	4.93ab	3.04a	1.62ab	4.85ab	2.86abc	6.63a	7.80b	40.45b	46.82bc	8.03ab	3.01bc						
R/M <sub>1</sub> + NPK	17.74ab	502.93a	2.61a	11.24a	0.59d	5.33a	3.07a	1.73a	6.68a	8.04ab	7.53ab	1.24ab	39.89bc	47.30b	8.28a	2.74d						

LF light fraction, FA fulvic acid, HA humic acid

<sup>a</sup>There is significant difference with different letters following the value at the 0.05 level, and vice versa (LSD comparison)

into the soil in the future 20 years would significantly increase SOC (Yang et al. 2003). The above results suggested that original black soils has high quality and are apt to become worse after being reclaimed, and adding manure could restore the degraded soil fertility to a certain degree (Wang et al. 2004a, b).

Fertilization and cropping system could also obviously influence the composition and distribution of humus in soil particles of different size. Compared with  $M_0 + CK$  treatment, adding manure ( $M_2 + CK$  and  $M_2 + NPK$ ) increased the loosely combined humus content, and decreased those of stably and tightly combined humus, which resulted in the increase of the loosely to the stably ratio and the loosely to the tightly ratio (Liu 2002). The composition of soil organic-mineral complexes is an important index to assess the quality of soil fertility. Most of humus is distributed in clay and silt complexes, and little is combined with fine sand complex (Table 2). Moreover, adding manure treatments could obviously improve the carbon content combined with fine sand and silt complex (Table 2). The similar results were also found in fallow,  $C/S + NPK$ , and  $R/M_1 + NPK$  treatment. Accordingly, addition of organic materials could also increase the proportion of  $>20 \mu m$  aggregates and especially of  $20\text{--}200 \mu m$  size, meanwhile increased that of  $<20 \mu m$  aggregates (Table 2). The variation of soil aggregates resulted in the decrease of dispersion coefficient (DC) relevant to control treatment, which could decrease the erodibility of soils. The above results showed that long-term addition of organic materials could renew and activate the old soil humus, and help to increase the content of water stable macro-aggregate through increasing of binding materials and forming granular structure. The ability of black soils to hold and release nutrients is elevated accordingly.

#### The effects of soil erosion on dynamics of SOC

Soil erosion is a selecting process and prefers to transport low density and fine soil particles (Gregorich et al. 1998). Our results showed that MBC, WSOC of topsoil at shoulder- and back-slope were not obviously less than

that of summit even if their SOC content were less than that of the later (Table 3). The simulation of CENTURY model also showed that there was no significant difference on the decrease of active and slow carbon between eroded sites and control site (Fig. 4a, b) ( $P > 0.05$ ). The variation of particulate organic carbon (POC) and macro-aggregate associated organic carbon (Macro-AOC) among summit, shoulder-, and back-slope were similar and increased along the slope (Table 3). However, mineral integrated organic carbon (IOC) and micro-aggregate associated organic carbon (Micro-AOC) at shoulder-slope were obviously less than that of summit and back-slope ( $P < 0.05$ ) (Table 3). In CENTURY model, passive carbon decreased linearly with the increasing cultivation history, and the greater soil erosion rate was, the faster passive carbon decreased (Fig. 4c). In addition, the content of SOC at the control site without soil erosion attained the equilibrium after cultivated for 120 years. But the content of SOC at other erosion sites was always decreasing and there seemed no equilibrium to attain. Moreover, the greater the soil erosion rate was, the farther the SOC content was away from the equilibrium (Fig. 4d). Our results suggested that the differences among SOC content in different positions mostly resulted from the decrease of recalcitrant carbon associated with fine particles. In contrast, the effect of soil erosion on active and slow carbon was slight and indirect, whose decrease mostly resulted from microorganisms' decomposition.

Some soil scientists thought that eroded materials accumulated in depression sites and could sequester a certain quantity of SOC through a series of processes (Stallard 1998; Ritchie and McCarty 2003). Microbiomass carbon and WSOC of topsoil at foot- and toe-slope were obviously higher than those of eroded sites such as shoulder- and back-slope (Table 3), which indicated that the input of eroded materials such as WSOC, POC, soil moisture, and available nutrients increased activities of microorganism at deposited sites. Although POC and Macro-AOC of topsoil at deposited sites were slightly higher than their IOC and Micro-AOC, and not significantly higher than those of shoulder- and back-slope, which indicated that POC was apt to be transported by surface water flow and

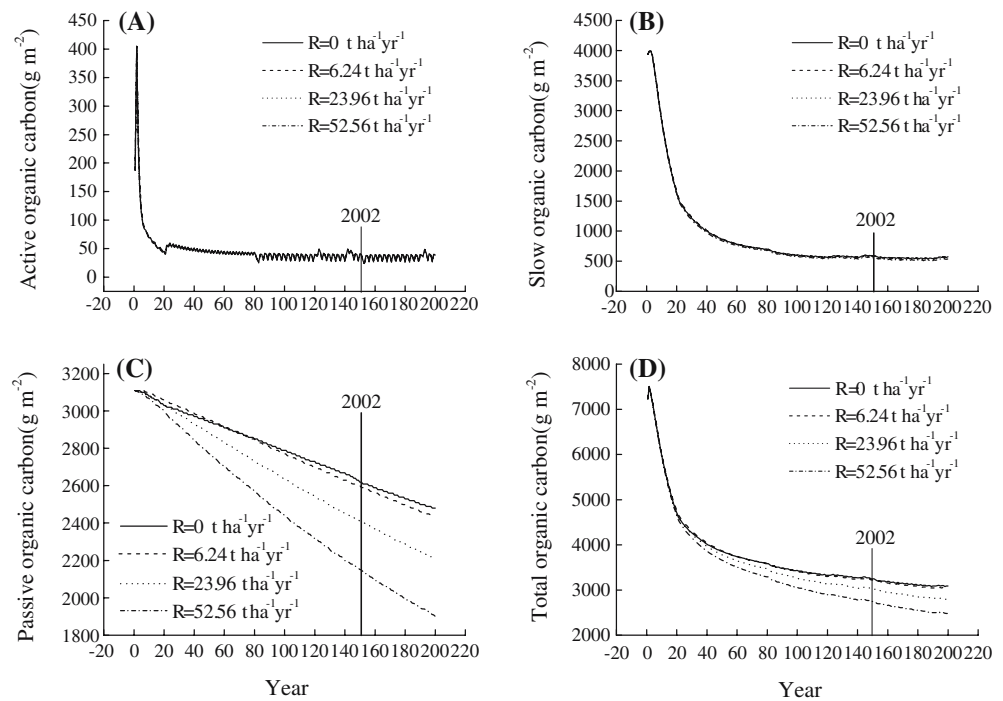
**Table 3** Effect of soil erosion and deposition on different SOC components in topsoil (0–20cm)

Sloping positions	Erosion rate <sup>a</sup> (t ha <sup>-1</sup> yr <sup>-1</sup> )	SOC <sup>b</sup> (g kg <sup>-1</sup> )	MBC <sup>b</sup> (mg kg <sup>-1</sup> )	WSOC <sup>b</sup> (mg kg <sup>-1</sup> )	POC <sup>b</sup> (mg kg <sup>-1</sup> )	IOC <sup>b</sup> (mg kg <sup>-1</sup> )	Macro-AOC <sup>b</sup> (mg kg <sup>-1</sup> )	Micro-AOC <sup>b</sup> (mg kg <sup>-1</sup> )
Summit	6.24c	15.2a	281.7c	16.1bc	7.3bc	7.9a	5.1b	10.1a
Shoulder-slope	52.56a	11.8b	221.5c	15.6c	8.70ab	3.10d	6.1a	5.72d
Back-slope	23.96b	14.4a	277.6c	18.2ab	9.25a	5.15c	6.5a	7.93c
Foot-slope	-19.12d	12.1b	449.9b	19.9a	6.36c	5.74c	4.4c	7.66c
Toe-slope	-79.78e	13.8a	583.6a	20.0a	7.03c	6.77b	4.9bc	8.89b

<sup>a</sup>Positive means erosion and negative means deposition

<sup>b</sup>There is significant difference with different letters following the value at the 0.05 level, and vice versa (LSD comparison)

**Fig. 4** Effects of soil erosion on dynamics of SOC and its fractions



was lost due to its lower density ( $\rho < 1.6 \text{ g cm}^{-3}$ ). Moreover, POC was an important substrate providing for soil microorganism, and input of POC into deposition sites could accelerate mineralization of SOC (Yakovchenko et al. 1998), which would be against the formation of water stable macro-aggregate ( $> 250 \mu\text{m}$ ) and decrease the content of Macro-AOC. The stable isotopes results also suggested that at deposited sites the loss of new carbon from near crop residues was greater and SOC in surface layer was mostly made up of old carbon from original plant (Fang et al. 2005b). So, SOC in deposition sites took Micro-AOC as the focus and accounted for over 60% of total SOC. Eroded carbon trapped in deposition positions increased the activities of microorganism and was apt to be mineralized other than be sequestered in oxidizing environment.

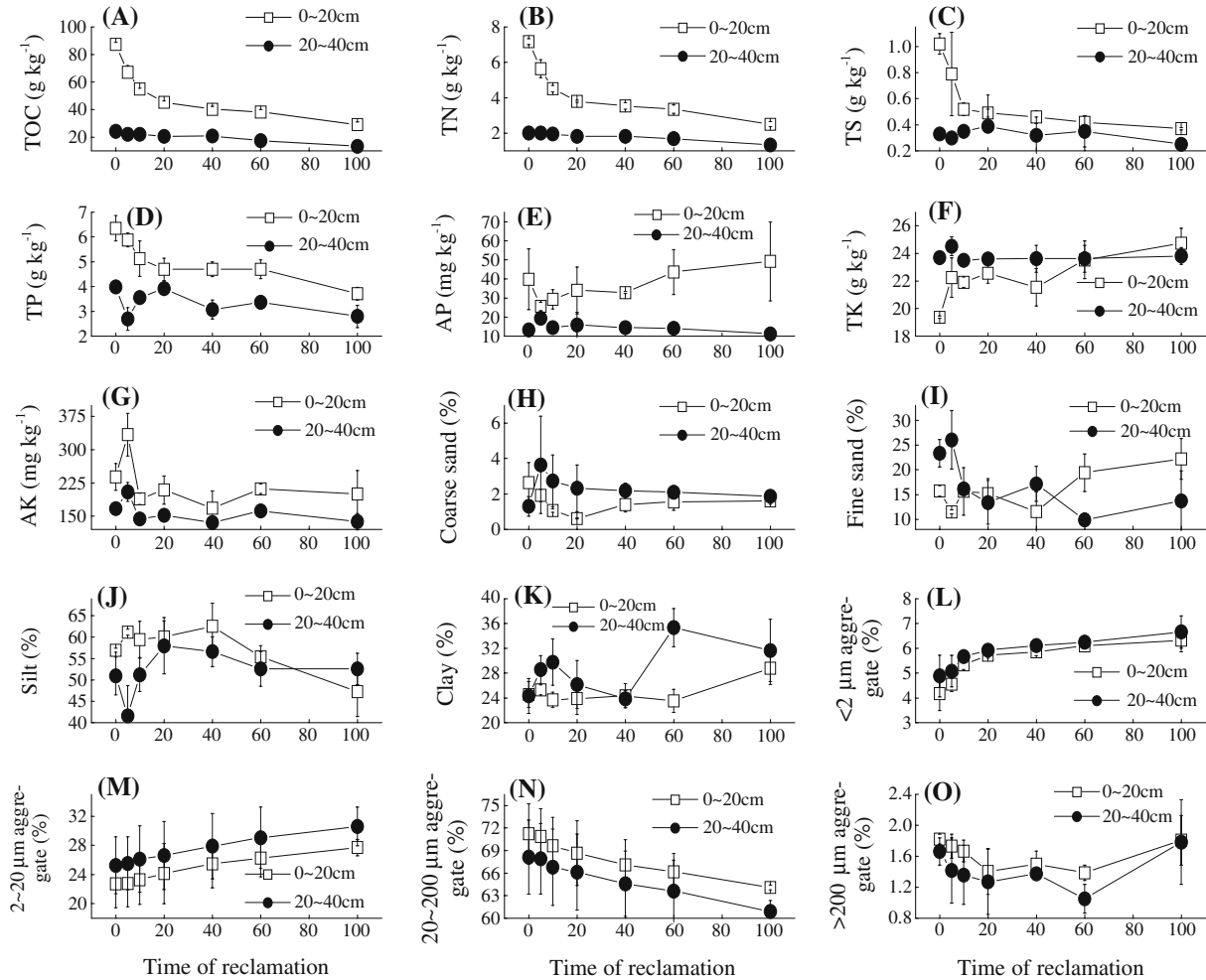
#### The variation of black soils fertility

After natural black soils were reclaimed, the fertility of black soils rapidly degraded due to unreasonable management and soil pollution including variation of chemical nutrients, physical structure, and biological activities. The variation of soil fertility in the three stages mostly represented the dynamics of SOM. The total soil organic carbon (TOC), TN, total sulfur (TS) and TP in surface layer (0–20 cm) declined with the increase of reclamation years (Fig. 5a–d), but the TK hardly changed (Fig. 5f). The decline of SOC and other nutrients in subsurface soils with the increasing

reclaimed time was less than that in surface layers except TK. The AP had a trend of increasing with the history of reclamation (Fig. 5e), but the AK went up in the beginning and down with the time of reclamation (Fig. 5g). The possible reasons were that the TP and TK content depended on soil parent materials and clay minerals, while AP and AK were influenced by the time of reclamation, tillage and fertilization besides the content of TP and TK.

Physical degradation of black soils' fertility can embody changes of soil texture and structure. Generally, the clay content in subsurface soils was higher than those of surface soils because of the clay moving downwards through leaching process during black soils development. There was no significant difference between the texture of surface and that of subsurface soils in uncropped land (Fig. 5h–k), which reflected that there had a very thick humus layer. The clay content in topsoil increased slightly and accumulated at subsoil layer obviously with the increasing time of reclamation (Fig. 5k). The reason was that the content of coarse soil particles decreased and that of fine particles increased accordingly due to the increase of mechanical disturbance, physical, and chemical weathering. In addition, mechanical disturbance made topsoil loose, which favored fine particles leaching downwards and forming an illuvial clay horizon. Aggregates of different sizes played different roles in stabilizing soil structure and adjusting nutrients cycle, so they were used as an integrated index to assess soil fertility (Cheng et al. 1994). Reclamation preferred to decrease the content of aggregates of 20–200  $\mu\text{m}$  and  $> 200 \mu\text{m}$  size (Fig. 5o,





**Fig. 5** Variation of physical and chemical properties of black soils with the time of reclamation (modified by Wang et al. 2002a, b; Liu 2002)

**Table 4** Comparison of microorganism quality between black soils at different evolution stage

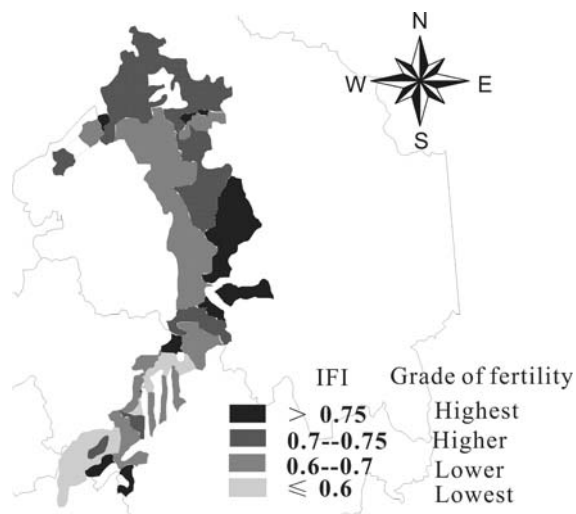
Soil status	Quantity of microorganism ( $\times 10^5$ g <sup>-1</sup> dry soil)			Activities of enzymes (mg reagent g <sup>-1</sup> dry soil) <sup>a</sup>		
	Bacteria	Actinomyces	Fungi	Urease	Phosphatase	Invertas
Uncropped phaeozem	71.1b	11b	1.30a	2.09b	1.50b	27.4a
Slaking phaeozem	112a	14.6a	1.70a	3.60a	2.10a	32.5a
Balanced phaeozem	58.3c	3.05d	0.274b	1.01c	0.307c	5.06b
Degraded phaeozem	4.46d	9.43c	0.348b	0.990c	0.254c	4.06b

<sup>a</sup>The reagent that determining urease, phosphatase, and invertas is NH<sub>3</sub>-N, hydroxybenzene, and Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub>, respectively. There is significant difference with different letters following the value at the 0.05 level, and vice versa (LSD comparison)

p), and to increase the content of aggregate of <2 μm and 2–20 μm size (Fig. 5l, m). Tillage and cultivation could break down soil structure directly, enhance aerobic decomposition and decrease the ability of cementation, which was useless to formation of soil water stable macro-aggregates. Decreasing water stability of aggregates would also make soil structure and soil quality became worse, physical degradation of soil

moisture represented the increasing bulk density, the declining soil porosity and water holding capacity, water supply and water permeability (Meng and Zhang 1998).

Reclamation and soil pollution obviously resulted in variation of soil microorganism composition and activities. Compared with the uncropped phaeozem, slaking process could increase the quantity of microorganism



**Fig. 6** The distributed pattern of soil fertility in black soil region (Ma et al. 2004)

and activities of enzymes in phaeozem, but that of polluted and degraded phaeozem (Table 4). Reasonable tillage and fertilization improved soil structure and aeration, which is in favor of development of soil microorganism. However, chemical fertilizer, pesticide herbicide as well as heavy metal pollutant in agricultural soils of black soil region significantly influences the growth and development of soil microorganism, and then influence the formation and decomposition of SOM and then change soil fertility (Zhang et al. 2004; Zhou et al. 2004). Earthworm plays an important role in formation of SOM through devouring stubble and excreting waste, while pesticide such as acetochlor and methamidophos have toxic effects on earthworm (*Eisenia foetida*) in black soils, and that of their combination with heavy metals (i.e., Cu or/and Pb) was even more serious. In a short, it is the decline of microbial activity and ability to metabolism that decrease the transform of available nutrients and change soil physical-chemical properties and fertility level.

#### Spatial pattern of black soil fertility

The distribution of black soil fertility was incompletely consistent with those of soil species. According to the IFI, black soil fertility was classified into 4 degrees as highest ( $IFI > 0.75$ ), higher ( $0.7 < IFI \leq 0.75$ ), lower ( $0.6 < IFI \leq 0.7$ ), and lowest ( $IFI \leq 0.6$ ). The highest level of soil fertility mostly distributed at central and eastern part of black soil region due to better soil development, reasonable tillage system, and application of inorganic and organic fertilizer (Fig. 6). Higher level of black soil mainly distributed at northern black soil region where was deep black soil distributed (Fig. 6). The lower level of soil fertility

mainly distributed at central western and southern part of black soil region where are adjacent to chernozem with lower SOC content (Fig. 6). Although the fertility level in this area underwent obvious decrease due to long-term extensive cultivation, the potential fertility was relative high because of great proportion of deep black soil and thicker humus layer. The lowest level of black soil fertility mainly distributed at southern of black soil region where was the shallow black soil distributed (Fig. 6). The humus layer was very thin due to its location, climate, and cultivation history. Moreover, crop straw had not returned to soil for a long time, which resulted in unbalance of soil nutrients and exhaust of soil fertility seriously. The highest and lowest level of black soil accounting for 16.84 and 9.52% of the total black soil area, respectively. In most of this region, soil fertility level was medium, and the area accounted for 73.6% of the whole black soil area.

#### Conclusion

Black soils developing under cold-humid climate, clay parent materials, meadow vegetation conditions have a relative high SOC density. Climate change, reclamation, agricultural managements and soil erosion strongly influence SOC content and composition of black soils. Present soil management system has resulted in the decrease of SOC and the increase of  $CO_2$  emission from soil to the atmosphere. However, the decrease of black SOC could be reduced, stopped, even converted into increase to a certain extent. Moreover, we should deal with the decrease of SOC in black soil region. For example, SOC in the northern black soils is in the rapid decline stage for short cultivation history. In this period, slowing the decrease of SOC other than inputting vast organic materials to recover the original SOC content is worthy advocating. In the middle part of black soil region, SOC is decreased slowly with more than 100 year's cultivation history. The optimal management could be taken against the decrease of SOC. Soil organic carbon has almost approached the equilibrium state in southern black soil region, and taking measurements to enhance SOM and soil fertility level is needed. For the future research on SOC and fertility of black soils, many methods and technologies such as long-term controlled experiment, isotope technique, mechanism models, remote sensing (RS), and geomorphic information system (GIS) should be integrated to understand and predict their dynamics and evolution.

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## Appendix

**Table 5** Characteristics of the test sites in CENTURY model

Parameter group	Parameters	Study sites	
		Hailun	Dehui
Soil physical controls	Location	47°26'N, 126°58'E	44°43'N, 125°52'E
	Sand (%)	9.08	41.0
	Silt (%)	61.64	35.37
	Clay (%)	29.28	23.63
	pH	6.8	6.2
	Bulk density (g cm <sup>-3</sup> )	1.08	1.10
Average precipitation (mm)	January	4	1.9
	February	4.4	3.1
	March	7.5	7.7
	April	24.1	18.7
	May	48.9	41.7
	June	101.9	83
	July	140.7	170.6
	August	121.6	117.5
	September	79.3	54.5
	October	24.1	20.9
	November	7.1	6.2
	December	4.4	2.6
Maximum temperature (°C)	January	-15.9	-6.2
	February	-9.9	-1.9
	March	1.4	6.1
	April	11.8	16.1
	May	20.3	22.5
	June	26	25.7
	July	26.2	26.9
	August	24	26.2
	September	19.5	21.0
	October	9.2	15.8
	November	-4	7.2
	December	-13.6	-1.5
Minimum temperature (°C)	January	-25.2	-24.8
	February	-21.7	-21.1
	March	-10.5	-12.5
	April	0.2	-1.1
	May	8.4	7.7
	June	13.9	13.9
	July	18.1	18.7
	August	14.4	16.6
	September	8.4	8.1
	October	-1.3	-0.2
	November	-14.3	-14.3
	December	-23.5	-21.7
External nutrients	Atmospheric N fixation versus annual precipitation: intercept	0.099	0.083
	Atmospheric N fixation versus annual precipitation: slope	0.016	0.014
	Non-symbiotic soil N fixation versus annual precipitation: intercept	-0.9	-0.9
	Non-symbiotic soil N fixation versus annual precipitation: slope	0.015	0.015
	Initial crop/grass organic matter	Surface organic matter fast rate pool: initial unlabeled C (g m <sup>-2</sup> )	127
	SOM fast rate pool: initial unlabeled C (g m <sup>-2</sup> )	454	203
	SOM intermediate rate pool: initial unlabeled C (g m <sup>-2</sup> )	6,260	4,240
	SOM slow rate pool: initial unlabeled C (g m <sup>-2</sup> )	4,450	3,240

Table 5 continued

Parameter group	Parameters	Study sites	
		Hailun	Dehui
Initial soil mineral N (g m <sup>-2</sup> )	Surface organic matter fast rate pool: initial C:N	16	16
	SOM fast rate pool: initial C:N	12	12
	SOM intermediate rate pool: initial C:N	17	17
	SOM slow rate pool: initial C:N	8	8
	Surface plant litter: initial unlabeled C (g m <sup>-2</sup> )	445	403
	Soil plant litter: initial unlabeled C (g m <sup>-2</sup> )	348	317
	Surface plant litter: initial C:N	95	95
	Soil plant litter: initial C:N	95	95
	Initial aboveground live unlabeled C (g m <sup>-2</sup> )	412	367
	Initial aboveground live N (g m <sup>-2</sup> )	25.9	26.6
	Initial belowground live unlabeled C (g m <sup>-2</sup> )	926	679
	Initial belowground live N (g m <sup>-2</sup> )	32.1	25.1
	Initial standing dead unlabeled C (g m <sup>-2</sup> )	41.6	37.1
	Initial standing dead N (g m <sup>-2</sup> )	2.57	2.49
	Initial mineral N in surface layer soil	7.87	4.96
	Parent material initial N	5.00	5.00
	Initial secondary N	1.50	1.50

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