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Simulation on the Future Change of Soil Organic Carbon from Phaeozems under Different Management Practices in Northeast China

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Abstract: The Phaeozem region is an important grain production base in China and soil fertility has declined under long-term cultivation. Studying soil organic carbon (SOC) change in the upland phaeozem of Northeast China under different tillage modes has great theoretical and practical significance for reducing greenhouse gases emissions, increasing soil carbon stocks, and ensuring food security. This study applied the DAYCENT model to simulate six long-term experimental sites in the phaeozem region, and through calibration and validation analysis, it concluded that the DAYCENT model could effectively simulate the dynamic change of SOC in the upland phaeozems; hence, the relevant parameters of each site were determined. Under future climate scenarios (Representative Concentration Pathway 4.5, RCP 4.5), SOC change in agricultural soils (0–20 cm topsoil) of four different management scenarios (fertilizer application, manure amendment, straw return, no-tillage) was simulated. The overall simulated trend was no-tillage > straw return > manure amendment > fertilizer application. Fertilizer had no evident effect on increasing SOC, but the effect would be better if combined with manure; both straw return and no-tillage had the general effect of improving SOC and the simulated values rose rapidly with a large increasing rate within a short period; however, the increasing rate became gentle after 2050, reached a relatively stable level after 2080, then gradually reached carbon saturation. Untill 2100, the SOC content of each site reached a relatively higher level by adopting the no-tillage treatment, where the SOC contents of Harbin, Hailun, Nehe, Dehui, Gongzhuling and Lishu were 2.36 g/100 g, 2.81 g/100 g, 2.22 g/100 g, 2.38 g/100 g, 1.97 g/100 g and 2.01 g/100 g, respectively. The SOC contents increased by 52.47% when compared with the initial value, and the simulated average annual increase of SOC for 84 years was 0.0082 g/100 g.

Keywords: soil organic carbon (SOC); climate scenario RCP4.5; phaeozem; no-tillage

1. Introduction

Phaeozem is mainly distributed in China's northeast plain, located in the region of 122–132°E, 43–50°N. Its distribution can be described as a crescent-shaped area in Northeastern China, with the contour north from the right bank in Heilongjiang, south to Changtu in Liaoning Province, west to the border of the meadow steppe in the Songliao Plain, and the east side extends to the piedmont of the Lesser Khingan Range. The area of phaeozems is approximately 11 million hectares in the Northeastern Plain, of which 8.15 million hectares is cultivated land. Due to the higher soil organic carbon (SOC) content and appropriate texture, it produced around 40% of total grain production on only 21% of the arable land in the three provinces in the northeast of China [1]. Therefore, the phaeozem region is one of the most important grain production bases in China.

The SOC content is an important indicator of soil quality [2,3]. The decline of SOC in the phaeozem region has negative impacts on both national food security and the regional carbon cycle. Soil is an important reservoir of carbon (C), as well as an important component of global carbon cycling [4]. Zhu et al. [5] estimated that the global SOC pool at the topsoil was 455 Pg. According to the report by Panet et al. [6], the total SOC pool of China was 49 Pg in 1980s, of which approximately 40% was distributed in the topsoil (0–20 cm) and accounts for 4.4% of the total global SOC pool. It had been estimated that the total SOC pools of China in 1 m soil layer and topsoil were 12.6 Pg and 7 Pg, respectively, among which the SOC pool in Northeastern China accounted for one quarter. Many other studies have shown the importance of phaeozem [7,8].

Phaeozems in Northeastern China is sensitive to global change due to continuous long-term cultivation, lower input of organic carbon materials (e.g., straw and manure) and relatively higher initial SOC content [9,10]. SOC can be improved through organic material amendment, crop rotation, tillage methods, fertilization and irrigation adjustment, and other management practices [11–13]. However, the quality of phaeozem has experienced severe degradation through intensive cultivation and the removal of above-ground crop residues after harvest for several decades [14,15]. To promote sustainable development in agriculture, it is necessary to study the effects of different management regimes on SOC changes under future climate change scenarios in the phaeozem region.

Long-term experiments are important in evaluating the mechanisms and effects of different management practices on soil quality and grain production [16–18]. Furthermore, biogeochemical models are a useful and powerful tool in predicting the long-term effects of various factors on SOC change in these future scenarios [19,20].

China has paid intensive attention on conservation tillage and protective farming management due to phaeozem degeneration and potential threats. Since the 1980s, several agricultural experimental demonstration sites and scientific observation stations have been established in the phaeozem region, including Harbin, Hailun, and Nehe in Heilongjiang Province; and Dehui, Gongzhuling, and Lishuin in Jilin Province. Through the study of SOC changes under different agricultural management practices such as fertilizer application, organic fertilizer amendment, straw return, no-tillage, we can obtain optimal management practices for maintaining soil organic carbon levels and achieving sustainable agricultural development.

The carbon turnover models of terrestrial ecological system can be used to simulate soil organic carbon content based on long-term observation data to predict long-term temporal and spatial SOC dynamics. Currently, the most widely used carbon turnover models include CENTURY [21], RothC [22], DNDC [23], and EPIC [24], which have all been applied in the research of SOC of phaeozems, and have become an important tool to study the effects of different management practices on soil organic carbon change.

Such models are not only time-saving and economical, they can also assist in improving the understanding of internal mechanisms to explain the observed results and their influencing factors [25]. The CENTURY model was initiated by Parton et al. of Colorado State University [26], which was originally used to simulate grassland ecosystems, and was then extended to forests, grasslands, and agriculture ecosystems. Some researchers have simulated the change of SOC in the phaeozem region [27]; however, it needs further and deepening study in several areas. First, it is necessary to collect additional data from more representative long-term sites with continuous observed data in a specific area to calibrate and validate the model. Second, the model requires data from more management practices adopted at specific sites to test and prove its applicability.

This study utilized the measured data of six long-term experiments, representing most of the majority phaeozem area in Northeastern China, to calibrate and validate the DAYCENT model, and then simulated the future changes of SOC under different management practices (i.e., chemical fertilizer application, 30% of nitrogen substituted with manure, straw incorporation, no-tillage combined with straw mulching) under future climate scenarios. It can provide strategic soil management practices for improving soil quality, and soil carbon sequestration, as well as achieving sustainable agriculture in phaeozems.

2. Materials and Methods

2.1. DAYCENT Model

DAYCENT is a biogeochemical model and is the daily time step version of the CENTURY model [28]. The DAYCENT model simulates C and N dynamics and trace gas emissions for grasslands, croplands, and forest ecosystems [29–31]. Additionally, the DAYCENT model can be applied across a broad range of agricultural management methods, including fertilizer and manure application, and tillage operations. Crop residues and external nutrient additions are exogenous organic carbon input. These inputs were disintegrated, then SOC was divided into three soil pools (active, slow, and passive) and two surface organic matter pools (active and slow). Each pool decomposed at a different rate, and the rate was influenced by temperature, soil water, soil texture, tillage, and crop residue decomposability and lignin content. The DAYCENT model is powerful with a large number of parameters that include a weather file (such as daily maximum/minimum temperature, precipitation, soil texture), site based value including three SOC pools (active, slow, and passive), initial values, management events (e.g., fertilization, organic fertilization, tillage, harvest, irrigation), crop parameters setting, model characteristic parameter setting (fix. 100), and the establish command file (*.SCH) to invoke parameters to operate the DAYCENT model.

2.2. Study Area

Since the 1980s, several phaeozem agricultural experimental demonstration sites and scientific observation stations were established by the Northeast Institute of Geography and Agroecology, Shenyang Institute of Applied Ecology, Department of Agriculture, China Academy of Agricultural Sciences and other research institutes. We selected typical long-term sites with continuous measured data including Hailun, Harbin, Gongzhuling, Dehui, Lishu and Nehe for our study area (Figure 1). The Lishu site in Jilin Province has a temperate semi-humid continental monsoon climate with a mean annual temperature of 6.8 °C and a mean annual precipitation of approximately 580 mm, concentrated in June, July, and August. The other five study sites (Hailun, Harbin, Gongzhuling, Dehui and Nehe) have a temperate continental monsoon climate with mean annual temperatures of approximately 1 °C in Helen and Nehe, and 3.5–5.6 °C in Harbin, Dehui and Gongzhuling. With the exceptionof mean annual precipitation of Nehe being below 500 mm, the other four sites were within 500–600 mm. All sites are warm and rainy in summer and cold with dry in winter. The specific site characteristics and treatment information are shown in Table 1.

Table 1. Basic soil properties in the soil profile and experiment information of study sites.

Site	Latitude	Longitude	Particle Fraction (%)			pH	Soil Classification	Mean Annual Temperature (°C)	Bulk Density	Initial SOC	Calibration	Validation	Crop Rotation	Treatment
	°N	°E	Sand	Silt	Clay				(g/cm^3)	(g/100 g)	(Year)	(Year)		
Harbin	45.67	126.58	13.2	48.2	38.6	7.23	Luvic Phaeozems	3.5	1.18	1.55	1980–2000	2001–2015	W-C-S	NPK MNPK
Hailun	47.45	126.93	31	29	40	6.2	Luvic Phaeozems	1.3	0.98	3.13	1985–1995	1996–2003	W-C-S	NPK MNPK
									0.98	2.66	2004–2006	2007–2012	C-S	CK SNPK
Nehe	48.56	124.88	35	23	42	6.1	Luvic Phaeozems	1.1	1.15	1.88	2004–2006	2007–2010	S(4)-C(3)	NPK
Dehui	44.2	125.55	40.11	24	35.85	6.48	Luvic Phaeozems	4.4	1.33	1.63	2001–2007	2008–2013	C-S	MP NT
Gongzhuling	43.51	124.81	39.08	29.9	31.05	7.6	Luvic Phaeozems	5.6	1.19	1.35	1989–2000	2001–2009	C-C	NPK MNPK SNPK
Lishu	43.31	124.23	24.81	47.7	27.54	7.1	Luvic Phaeozems	6.8	1.1	1.16	2007–2009	2011–2015	C-C	NT

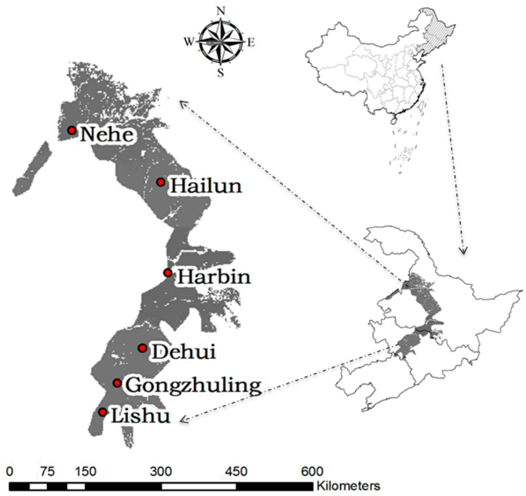

Figure 1. Distribution of the sites in the study area.

2.3. Experiment Design

The simulation of SOC changes in this paper was divided into two sections. In the first section, the model performance is evaluated. The long-term measured datasets of the six sites (Hailun, Harbin, Gongzhuling, Dehui, Lishu and Nehe) were used for model calibration and validation. During this process, four treatments were simulated, and included the fertilizer application only (NPK), organic fertilizer incorporation (MNPK), straw return (SNPK), and straw return combining with no-tillage (NT) (Table 1). Through parameter adjustment of crop parameters (crop. 100), and management parameters (fert. 100, cult. 100, harv. 100, omad. 100), optimal parameters were obtained when the measured data fit with the simulated data; after, the adjusted parameters were used for model validation to test the applicability of model. Second, the calibrated and validated model was used to simulate future SOC changing trends of different management practices (NPK, MNPK, SNPK, NT) under the IPCC RCP 4.5 climate scenario at each site.

2.3.1. Agricultural Management Practices Adopted in Each Site

History SOC simulation setting: At the Harbin site, the rotation cropping system was wheat-corn-soybean, and the specific fertilizer application regime was 150 kg N/(ha·yr), 75 kg P_2O_5/(ha·yr), and 75 kg K_2O/(ha·yr) applied during both the wheat and corn growing seasons, and 75 kg N/(ha·yr), 150 kg P_2O_5/(ha·yr), and 75 kg K_2O/(ha·yr) were applied during the soybean growing season; horse manure was applied every three years (one rotation cycle) equivalent to 75 kg N/ha.

At the Hailun site, the rotation cropping system was wheat-corn-soybean and there were four treatments (MNPK, NPK, SNPK, and CK). In treatment NPK, 58.5 kg N/(ha·yr), 12 kg P_2O_5/(ha·yr) and 75 kg K_2SO_4/(ha·yr) were applied during each growing season; for treatment MNPK, on the basis of fertilizer application of NPK, pig manure was applied; in treatment SNPK, during 2004–2009, 96 kg N/(ha·yr), and 15 kg P_2O_5/(ha·yr) were applied during the maize growing season and 23 kg N/(ha·yr) and 12 kg P_2O_5/(ha·yr) were applied during the soybean growing season while after 2010, the application rates increased to 138 kg N/(ha·yr), 70 kg P_2O_5/(ha·yr) and 20 kg K_2O/(ha·yr) for maize, and 64 kg N/(ha·yr), 70 kg P_2O_5/(ha·yr) and 20 kg K_2O/(ha·yr) for soybean, and the nitrogen contained in maize straw returned to fields was equivalent to 200 kg N/(ha·yr) and soybean straw was 70 kg N/(ha·yr). CK denoted the control treatment without any fertilizer application [32].

At the Nehe site, the rotated cropping system was corn-soybean, and the specific fertilizer application regime was 210 kg N/(ha·yr), 60 kg P_2O_5/(ha·yr) were applied during the corn growing season, and 65 kg N/(ha·yr), 50 kg P_2O_5/(ha·yr) were applied during the soybean growing season.

At the Dehui site, the rotated cropping system was corn-soybean and there were two treatments (MP and NT). Both treatments had the same specific fertilizer application regime of 150 kg N/(ha·yr), 45.5 kg P_2O_5/(ha·yr), and 80 kg K_2O/(ha·yr) were applied during the corn growing season, and 40 kg N/(ha·yr), 60 kg P_2O_5/(ha·yr) and 80 kg K_2O/(ha·yr) were applied during the soybean growing season. Straw was returned to fields as amulched soil surface. The difference was that treatment NT adopted the no-tillage practice and did not disturb soils for the whole year except sowing, while treatment MP adopted plowing tillage practice after harvest in the autumn, and soil preparation and intertillage were carried out in spring [33–39].

At the Gongzhuling site, a continuous corn cultivation system was adopted and there were three treatments. In treatment NPK 165 kg N/(ha·yr), 82 kg P_2O_5/(ha·yr) and 82 kg K_2O/(ha·yr) were applied during the corn growing season; in treatment MNPK,50 kg N/(ha·yr), 82 kg P_2O_5/(ha·yr) and 82 kg K_2O/(ha·yr) were applied, and 115 kg N/(ha·yr) of pig manure was applied; in treatment SNPK, 112 kg N/(ha·yr), 82 kg P_2O_5/(ha·yr), and 82 kg K_2O/(ha·yr) were applied with a straw incorporation amount of 53 kg N /(ha·yr).

At the Lishu site, a continuous corn cultivation system was adopted and treatment NT meant that 210 kg N/(ha·yr), 110 kg P_2O_5/(ha·yr), and 75 kg K_2O/(ha·yr) were applied during the corn growing season, with an annual straw return amount equivalent to 200 kg N/(ha·yr) [40–43]. The experimental data from the Hailun, Nehe, Gongzhuling, Harbin sites were provided by Guo Liping a researcher at the China Academy of Agricultural Science.

The future SOC simulation setting of each site was as follows: (1) NPK treatment (fertilizer application only) adopted the recommended fertilizer application rates for maize and soybean from References [44,45]; (2) MNPK (30% fertilizer substituted by manure) consisted of 30% of the total nitrogen provided by manure and the other 70% was from fertilizer with the total nitrogen application rate remained unchanged; (3) SNPK, i.e., 4500 kg maize straw/(ha·yr) and 1200 kg soybean straw/(ha·yr) were returned with the fertilizer application rates unchanged [46,47]; (4) NT: no-tillage practice was conducted on the basis of SNPK treatment. The future SOC simulating treatments and fertilizer setting are summarized in Table 2.

Table 2. Future soil organic carbon (SOC) simulating treatments and fertilizer setting.

Site	Crop Rotation	Simulated SOC Period	Corn/Wheat		Soybean		Straw Quantity (kg/ha)
			N (kg/ha)	P_2O_5 (kg/ha)	N (kg/ha)	P_2O_5 (kg/ha)	
Harbin	W-C-S	2016–2100	157	56	60	40	corn and wheat 4500 soybean 1200
Hailun	C-S	2013–2100	157	56	60	40	
Nehe	C-S	2011–2100	157	56	60	40	
Dehui	C-S	2014–2100	180	75	60	40	
Gongzhuling	C-C	2010–2100	180	75			
Lishu	C-C	2016–2100	180	75			

2.3.2. Meteorological Data and Basic Soil Datasets

Historical meteorological datasets were used for model calibration, and validation was obtained from the official website of the China Meteorological Data Service Center and the datasets of the observation stations closest to the six studied sites were selected. Future climate data were derived from IPCC RCP 4.5 climate scenarios. The specific items included maximum temperature (°C), minimum temperature (°C), precipitation (cm), solar radiation (langleys), wind speed (miles/h) and relative humidity (%).

The physical and chemical properties of the soil from each site were collected and the allocation percentages of three different SOC turnover pools were: 3.81% of the active SOC pool, 40.08% of the slow SOC pool, and 56.11% of the passive SOC pool [48].

2.4. Model Performance Evaluation

This paper selected multiple methods to evaluate the fitting degree between the simulated and measured values. A scatter plot and regression analysis between simulated values and measured values were used [49], and three evaluation indices were adopted including normalized root mean square error (NRMSE) [50], model efficiency (EF) [51], and mean absolute error (MAE) [52] to evaluate the simulation performance. The equations are as follows:

$$\text{NRMSE} = \frac{100}{O}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - O_i)^2} \tag{1}$$

$$\text{EF} = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - O)^2} \tag{2}$$

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}|P_i - O_i| \tag{3}$$

where n is the number of data pairs; and P_i and O_i are the predicted and measured values, respectively. O is the mean of the observed data and NRMSE ranges from 0 to 1. The closer the NRMSE value is to 0, the more accurate the model. EF ranges from $-\infty$ to 1, and EF = 0 indicates that the model predictions are the same as the mean of the observed data. Meanwhile, EF < 0 implies that the observed data is better than the model prediction. An ideal fit is indicated by NRMSE = 0, MAE = 0, and EF = 1.

3. Results

3.1. Evaluation of Model Calibration

This study selected the measured data of six sites during the corresponding periods to determine the relevant parameters of the DAYCENT model to obtain parameters within the acceptable ranges. Through repeated adjustments of model parameters of different management treatments, simulated SOC contents and crop yields reached approximate to the measured data. This paper focused on the effect of different management practices on SOC by considering the simulation of crop yields. The relative error between the simulated crop yields and measured values of each treatment fell within 10%. And regression analysis, $R^2 = 0.8313$ and $K = 0.8443$ ($n = 80$, $p < 0.001$). However, we mainly analyzed the effect of simulating SOC by using calibrated parameters through several aspects including scatter diagram, normalized root mean square error (NRMSE), model efficiency (EF), and mean absolute error (MAE). The scatter diagrams regarding simulated SOC values and measured values at 0–20 cm soil under the different management scenarios were plotted respectively (Figure 2). These results showed that under the four different management practices (NPK, MNPK, SNPK, NT), the determinant coefficients of the regression equations were 0.9849, 0.9837, 0.9914 and 0.9912, respectively, where all reached highly significant level ($p < 0.001$).

The calculation results of the evaluation indices, NRMSE, EF, and MAE (Table 3) showed that the NRMSE values were within 0.225–8.816%, MAE < 0.053 g/100 g, and EF values were approximate to one except for a few treatments in Harbin, Hailun, and Nehe. The simulated results of the MNPK treatment in Harbin reflected the long-term dynamics and trend of changes to SOC well; however, the drastic change of SOC in the drought year of 1988 (with a precipitation of only 345 mm) and the rainy year of 1994 (with a precipitation of 818 mm) was not reflected effectively. As for the Dehuisite, the model could simulate the long-term changing trend of SOC well, but the abrupt increase of SOC under the NT treatment was simulated; the reason might be that the SOC was measured annually by different research personnel which resulted in an annual systematic error. Nevertheless, through parameter adjustment, the DAYCENT model could simulate SOC dynamic changes well at the six sites, and the calibrated parameters reflected the SOC changing trends at these sites except in years with climatic anomalies.

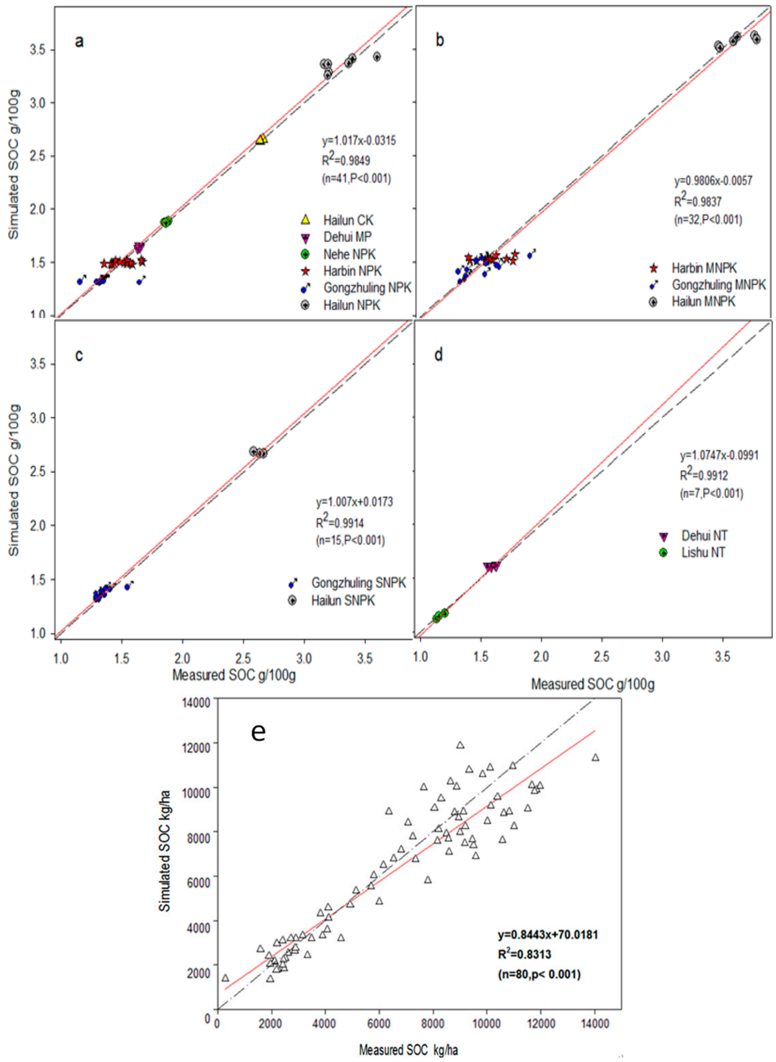

Figure 2. Calibration: comparison of simulated and measured SOC values of fertilizer application only (NPK) Treatment (**a**); organic fertilizer incorporation (MNPK) Treatment (**b**); straw return (SNPK) Treatment (**c**); and no-tillage (NT) Treatment (**d**). All treatments yielded values of simulated and measured compared scatter diagram (**e**).

Table 3. Statistical indices of calibration for simulated results determined by the DAYCENT model.

Site	Treatments	NRMSE (%)	EF	MAE (g/100 g)
Harbin	NPK	5.64	0.35	0.015
	MNPK	7.523	−0.02	0.041
Hailun	CK	0.225	0.73	0.003
	SNPK	2.355	0.58	0.047
	NPK	3.749	0.3	0.053
	MNPK	2.712	0.29	0.046
Nehe	NPK	0.756	0.05	0.009
Dehui	NT	2.089	−0.35	0.007
	MP	2.752	0.53	0.022
Gongzhuling	MNPK	8.816	0.96	0.048
	NPK	7.967	0.92	0.017
	SNPK	4.059	0.95	0.025
Lishu	NT	1.578	0.61	0.015

3.2. Analysis of Model Validation

Based on the adjusted parameters under different management practices of the six sites above-mentioned, the crop yields and SOC contents of the following years (Table 1) of each site were simulated by using the climate datasets of the following years from corresponding sites, to validate the simulation capability of the calibrate model. The validation results of parameter applicability were evaluated through scatter diagram and evaluation indicators including NRMSE, EF, and MAE. The scatter diagrams of simulated SOC values and measured values at 0–20 cm soil under different management scenarios were plotted respectively (Figure 3), and 85% of the predicted values fell within the confidence interval of 1:1 line. Furthermore, under the four different management practices (NPK, MNPK, SNPK, NT), the determinant coefficients of the regression equations were 0.9754, 0.966, 0.9797, and 0.9065, which all reached the highly significant level ($p < 0.001$). This indicated that the simulation of SOC under different management scenarios by the model was suitable.

After plotting the scatter diagram of the simulated and measured crop yields of the six sites and regression analysis, $R^2 = 0.8091$ and $K = 1.0185$ ($n = 96$, $p < 0.001$) were obtained, indicating that DAYCENT could also simulate crop yields well, with reasonable and acceptable relevant parameters.

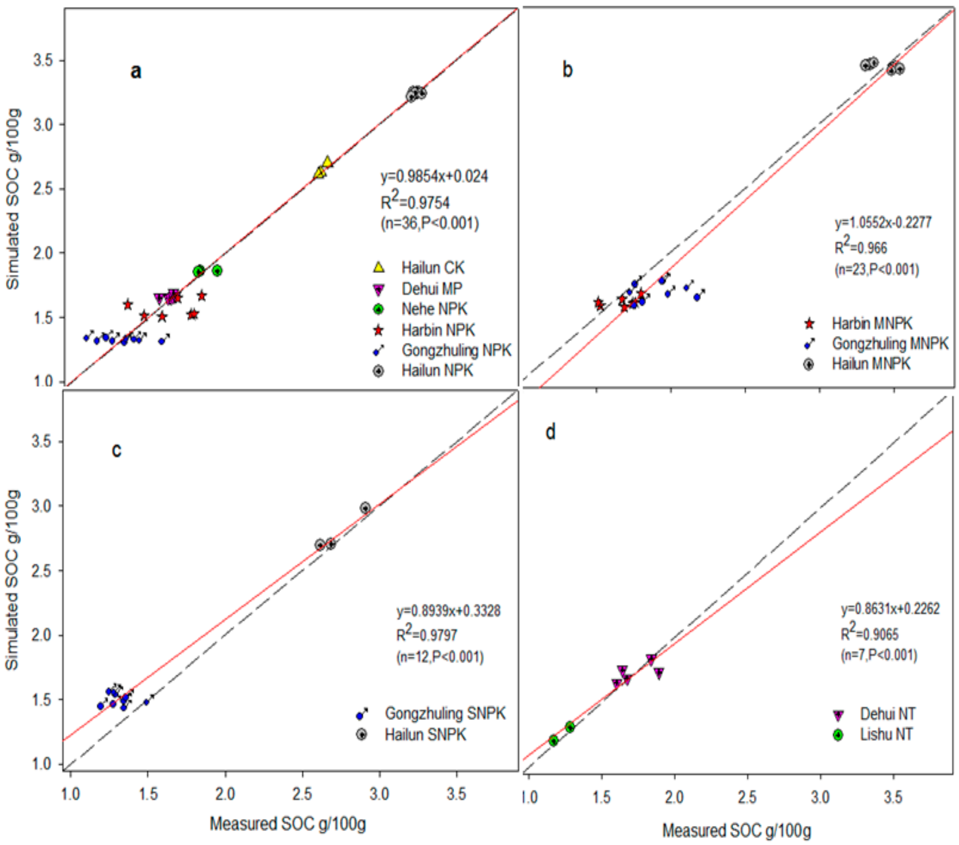

Figure 3. *Cont.*

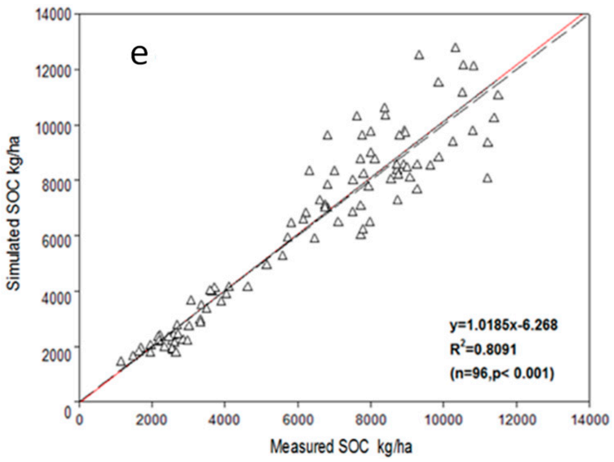

Figure 3. Validation: a comparison of simulated and measured SOC values of NPK Treatment (**a**); MNPK Treatment (**b**); SNPK Treatment (**c**); and NT Treatment (**d**). All treatments yielded values of simulated and measured compared in a scatter diagram (**e**).

The EF, NRMSE, and MAE of each site were calculated (Table 4) and the results showed that NRMSE values fell within 0.582–13.85%, MAE < 0.188 g/100 g, and most EF values were approximate to one except for a few treatments at the sites of Harbin, Hailun and Nehe. Among these, Harbin had less precipitation (328 mm) in 2001 and lower sun radiation in 2008, and thus lodging occurred. In addition, the change of simulated values was relatively smooth under the condition of stable fertilizer application rates; however, the measured SOC contents of each year obviously fluctuated, which might have been due to SOC in different years being measured by different personnel which resulted in systematic error, and this phenomenon occurred now and then in the long-term experiments. It also indicated that there was a certain error in the simulation by the DAYCENT model under extreme climatic conditions, but its ability of simulating long-term changing trends of SOC was better, which can be applied to evaluate the effect of climate change on long-term SOC change.

Table 4. Statistical indices of validation for simulated results determined by the DAYCENT model.

Site	Treatments	NRMSE (%)	EF	MAE (g/100 g)
Harbin	NPK	6.635	–0.13	0.059
	MNPK	10.99	–0.18	0.073
Hailun	CK	0.964	0.11	0.022
	SNPK	2.186	0.77	0.054
	NPK	0.582	0.54	0.003
	MNPK	2.968	–0.39	0.007
Nehe	NPK	2.711	0.21	0.022
Dehui	NT	1.068	–0.26	0.013
	MP	5.225	0.96	0.003
Gongzhuling	MNPK	11.14	0.88	0.011
	NPK	13.85	0.66	0.216
	SNPK	4.796	0.98	0.188
Lishu	NT	2.067	0.788	0.004

3.3. The Future Changing Trend of SOC under Different Management Practices

By employing the parameters of the corresponding treatments at each site through calibration and validation (Sections 3.1 and 3.2), we obtained the future SOC changing trend of four management scenarios, i.e., fertilizer application only (NPK), 30% nitrogen fertilizer substituted by manure (MNPK), fertilizer application combined with straw return (SNPK), and fertilizer combined with straw return and no-tillage (NT), under the IPCC RCP4.5 climatic conditions. The future SOC changes were simulated from the end of the measured years until the year 2100.

The future SOC changes under the different agricultural management scenarios of six sites in the phaeozem region is displayed in Figure 4. The results showed that up to 2100, SOC content at the Harbin site was the highest under the NT scenario which reached 2.36 g/100 g, and increased by 0.066 g/100 g every ten years on average during the 84 years into the future ; the lowest SOC content (1.68 g/100 g) occurred under the NPK scenario where SOC remained relatively stable during the 84 years and decreased slightly in 2016; the future SOC contents under the other two management scenarios (MNPK and SNPK) fell between that of the NPK scenario and that of the NT scenario and SNPK > MNPK.

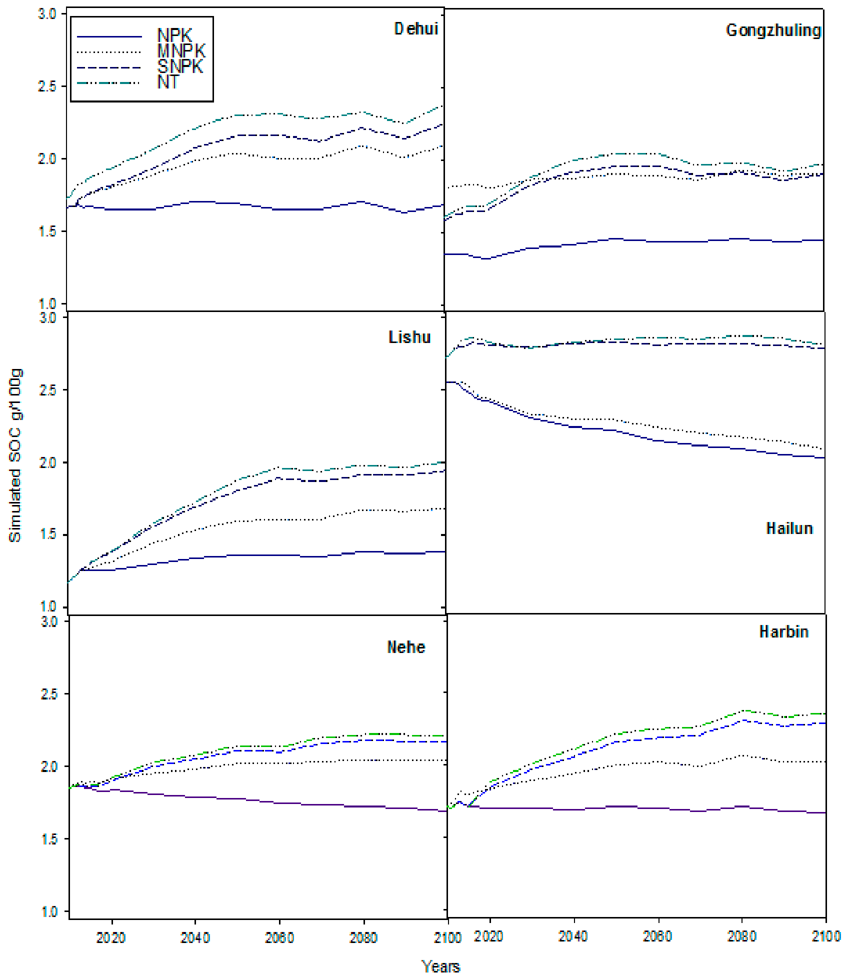

Figure 4. Future SOC change trends of NPK, MNPK, SNPK, and NT treatments under the RCP 4.5 scenario at the six sites.

The Hailun site had a slightly higher initial SOC content, and future SOC content under the NT scenario was also the highest (2.81 g/100 g) and increased by 0.001 g/100 g every ten years on average during the simulated 87 years; however, the SOC increase under the NT scenario was not significant; the simulated values under the SNPK scenario were slightly lower than those under the NT scenario; the SOC contents under the other two management scenarios at this site both presented decreasing trends, among which the decreasing rate of SOC under the NPK scenario was the largest and declined by roughly 20% when compared with the initial value in 2015, indicating that manure input was not sufficient to replenish SOC loss from decomposition.

At the Nehe site, the SOC content in 2100 reached 2.22 g/100 g under the NT scenario and the increasing rate was as high as 40%, and further increased by 0.04 g/100 g every ten years on average during the 89 years. The SOC increasing rate under the NMPK scenario was 20%, which was between that under the SNPK scenario and NPK scenarios; under the NPK scenario, SOC content presented a declining trend and the relative declining rate was 15%.

At the sites of Dehui, Gongzhuling, and Lishu, the SOC contents under four management scenarios all presented rising trends except under the NPK scenario where SOC remained stable, and the highest SOC contents reached 2.38 g/100 g, 1.97 g/100 g, and 2.01 g/100 g, respectively. Furthermore, every ten years, the average increasing rates were 0.064 g/100 g (duration of 86 years), 0.039 g/100 g (duration of 90 years), and 0.082 g/100 g (duration of 84 years), respectively. Of all the sites, SOC content at the Lishu site reached the highest under the NT scenario and increased by 52.5% when compared with the initial value. It was worth noting that at the Gongzhuling site (before the year 2040), the SOC content under the MNPK scenario was higher than under the SNPK scenario; yet after 2040, the SOC contents under the two scenarios remained the same. However, as the initial SOC content under the MNPK scenario was higher than those under other scenarios, it was predicted that the future SOC increasing rate under the MNPK scenario would be lower than those under the SNPK and NT scenarios.

Thus, simulation of future SOC changes across the six sites all showed that the increasing rate under the NT scenario was the highest, followed by that under the SNPK scenario, and the third highest was that under the MNPK scenario. The simulated results of all sites showed that under the NPK scenario, SOC could not remain at the decreasing trend and the SOC contents of most sites remained at the initial levels; however, at the Hailun and Nehe sites, the SOC contents presented declining trends, especially at the Hailun site where both the declining trend and the decreasing rate were significant. Moreover, the simulated results at the Hailun site indicated that even MNPK (30% fertilizer substituted by manure) management could not stop the declining trend of SOC. From these results, it was clear that straw return and no-tillage were the most effective agricultural management practices to promote SOC contents.

In addition, Figure 5 shows the comparison of the periodical average annual change of future SOC under the four management scenarios, which can reflect the changing rate of SOC along with time as well as the time needed to reach stable level. Based on the SOC changing trend in Figure 5, we divided the change process into four time intervals for comparison analysis, which included the starting year to 2030, 2031–2050, 2051–2080, and 2081–2100. In general, under the four management scenarios, the periodical annual average SOC increase at most sites presented the highest increasing rate under the NT scenario, followed by the SNPK scenario, and the MNPK scenario. Under the NPK scenario, the SOC changes varied across the different sites, but the overall increasing rate was low, and the SOC increasing rate (per every ten years) was lower than 5 g/kg. The increasing rate remained stable overtime, indicating that with only fertilizer application, there would be lower possibilities of SOC increase in the phaeozem region and at Hailun, the SOC even decreased. When we looked at the later stages of 2051–2080 and 2081–2100, the average annual change of SOC at most sites under the NPK scenario showed negative values, indicating that the effect of NPK management on improving SOC in the long term was not significant. Under the MNPK, SNPK, and NT management scenarios before 2030, SOC increased greatly (except at some sites) and the average increasing rates per every ten years under the three scenarios were 0.3–1.1 g/100 g, 0.7–2.3 g/100 g and 0.9–2.5 g/100 g, respectively. The increasing rates during 2031–2050 declined slightly; during 2051–2080, the average increasing rates per every ten years declined greatly and turned negative at some sites; during 2081–2100, the increasing rates at most sites presented a slight decrease, except at some sites where it increased slightly. Therefore, the highest SOC content might occur during 2051–2080.

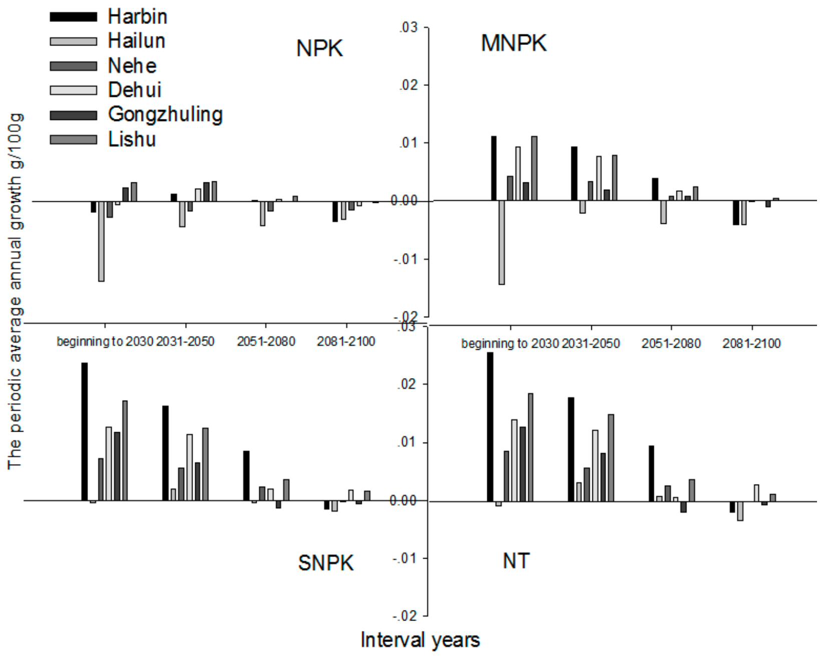

Figure 5. Four periods (from beginning to 2030, 2030–2050, 2050–2080, and 2080–2100) of average annual growth changes of six sites showing future SOC simulation under the NPK, MNPK, SNPK, and NT treatments.

Through the comprehensive analysis above-mentioned, we can conclude that the simulated SOC changing trends under the four management scenarios did not monotonically increase or decrease with time, instead there were patterns that showed that change in the early stages was drastic, and the average annual increase was relatively large; while during the later stages, it was stable, and SOC content reached saturation at the middle-late stages and then declined slightly at the later stages and remained at a relatively stable content.

4. Discussion

This paper employed the DAYCENT model to simulate the SOC (0–20 cm) in the phaeozem region. Under the future climatic conditions, the simulated SOC changes were different under the four management scenarios (NPK, MNPK, SNPK, and NT). Generally speaking, the effects of promoting SOC level were NT > SNPK > MNPK > NPK. The reason for this result included multiple factors such as climatic conditions, agricultural management practices, fertilizer application rates, crop types, tillage system, soil texture, and so on. Up until 2100, the SOC content under the NPK scenario at the sites of Lishu, Dehui and Gongzhuling all increased slightly, and the reason was that fertilizer can increase biomass production, and the roots and residues in the soil increased improved SOC content [53]. In the meantime, fertilizer can input exogenous nutrients directly into soil. Nutrient input was higher than nutrient loss through removal by harvest, resulting in SOC accumulation [54]. Furthermore, studies have shown that continuously planting maize is more beneficial for SOC accumulation than the maize-soybean-wheat rotated cropping system [55], which might be related to the fact that relatively less biomass of soybean and wheat returned to the soil. Some scholars obtained the same conclusion in their studies of red soil [56–58].

Compared with the initial values, the SOC contents of the other three sites (Harbin, Hailun, and Nehe) under the NPK scenario presented declining trends. The main reason for this was that long-term fertilizer application resulted in the imbalance of soil C/N ratio and increased the activity of microbes, which can promote the decomposition and mineralization of the original and fresh SOC in soil [57]. The soil organic matter decomposed continuously and nutrient input was insufficient to make up for the mineralization loss of soil organic matter. In addition, when soils covered with natural vegetation or grasslands were reclaimed into agricultural soils, the content of soil organic matter decreased evidently, which was the soil-ripening process, and the half-life of SOC in the phaeozem was over 40 years and even 65 years [59–62]. The SOC contents of Heilongjiang Province were relatively higher, especially given that the Hailun site may have been at the soil-ripening stage.

The simulated SOC contents under the MNPK scenario were higher than those under the NPK scenario. Up until 2100, compared with the NPK scenario, the SOC content at the Hailun site under the MNPK scenario increased by 3.05%, and the increasing rate at other sites were within 20.12–31.67%. The simulated SOC contents under the MNPK scenario were higher than the initial values, except at Hailunsite. Thus, MNPK management can evidently improve SOC levels, which has been previously widely recognized [55,63]. The reason for this was that manure combined with fertilizer not only replenished organic carbon sources, but also improved the physical properties of the soil which was beneficial for the formation of macro aggregates and the increase of particulate organic carbon inside aggregates. Thus, both the total SOC and the labile organic carbon increased [64]. Therefore, fertilizer combined with manure improved soil quality, enhanced nutrient regulation, and the storage capability of the soil. It is worth noting that the simulating effect of SOC at the Hailun site under the MNPK scenario was not satisfactory, which may have been related with soil texture and climatic factors. Hailun has a temperate continental monsoon climate and the soil there has a high sand content with good aeration. It has cold weather and heat with precipitation occurring during the same season. Wetting and drying alteration helps SOC decomposition, so the manure and fertilizer input cannot make up for loss of organic matter mineralization. Furthermore, given the relatively higher initial SOC content, the soil-ripening process was also an influencing factor. Therefore, ensuring the balance between carbon input and output is an important factor affecting SOC, and the fertilizer application in this region was not enough to satisfy the output of harvest. At the Harbin site compared with the long-term observation datasets before 2016 the simulated results under the MNPK scenario were evidently higher than the NPK scenario, this was because manure previously input every three years was adjusted into an annual application, which promoted manure quantity during the simulation.

The simulation effects of the SNPK and NT scenarios were better than the MNPK scenario. Up to 2100, except for the Gongzhuling site, compared with the MNPK scenario, SOC contents had little superiority under the SNPK and NT scenarios. At the other five sites, the effects were obvious, and the SOC under the SNPK scenario increased by 6.24–32.8% compared with the MNPK scenario. Additionally, the SOC under the NT scenario increased from 0.95 to 5.69% when compared with the SNPK scenario. It was noted that the increasing rate at the Hailun site was the smallest where it was difficult to maintain soil fertility. This may have been related to the higher initial SOC content. The simulation results were the same to Gao [65], who used the CENTURY model to simulate phaeozem (Hailun) under different agricultural managements in the future, obtained similar simulation results. In short, SNPK and NT management practices had significant effects in promoting SOC, which has been confirmed by many scholars [4,66,67]. The SNPK management practice can facilitate SOC increase from two aspects: first, straw return can directly increase the input of organic matter; and second, maintaining water and temperature assists with crop growth. The NT management reduced soil disturbance on the basis of SNPK, inhibited hyperventilation in agricultural soils, and reduced the SOC oxidative decomposition, which can prevent soil erosion; moreover, the amount and stability of soil aggregates increased, therefore, the decomposition of organic matter inside aggregates decreased [68]. Long-term no-tillage practice would make the plowing layer shallower with most roots concentrated in the top soil, and increase SOC contents significantly.

In this study, NT and SNPK management practices had significant effects on promoting SOC, but the simulation effect differed greatly due to soil characteristics, climatic conditions, and other factors. First, at the Gongzhuling site, SOC content under the MNPK scenario was better than the SNPK scenario before 2030, but the SOC increase rate was higher under the SNPK scenario after 2030. Simulated SOC values under SNPK gradually caught up and surpassed those under the MNPK.

Up until 2100, the promoting effect on SOC of the two management scenarios were approximately the same. The reason behind this result was that the straw that was returned needed time to decompose and the effect cannot work within a short time-frame. Second, at the Harbin, Nehe and Hailun sites, in comparison to the SNPK scenario, the NT effect on prompting SOC did not have an obvious superiority. As the sand content of the soil was only 13% at Harbin site, the soil texture was heavy and long-term no-tillage may influence soil ventilation and result in soil compaction. The Hailun and Nehe sites were located at relatively higher latitudes with a cold and drought-prone climate, and results showed that straw return combined with tillage could help soil ventilation and accelerate SOC decomposition. Furthermore, the practice of no-tillage maintained a higher water content which was good for SOC decomposition. Both scenarios had their own disadvantages to offset the positive effects, so the results were similar. Third, up to 2100, the SOC at the Lishu site under the NT scenario reached 2.01 g/100 g, which was an increase of 52.47% when compared with the initial value. The NT promoting effect was the most significant, mainly due to the relatively lower initial SOC content. As SOC does not rise continuously with a continuous input of organic matter, the SOC pool had saturation points. Finally, at the Dehui site, SOC contents under the four scenarios increased in 2080 and evidently decreased in 2090. The unique change was mainly affected by the hydrological conditions in the area. Based on the predicted climatic condition IPCC RCP4.5 scenario, results showed that average annual precipitation would be 600 mm at Dehui, and in 2080, the precipitation amount would be 390 mm, of which 274 mm rainfall would be mainly concentrated between June and September; in 2090 the annual precipitation would be 1054 mm, within 838 mm rainfall occurring between June and September. This indicated that drought and flood had significant effects on the SOC change in this area.

The periodical change of SOC under four scenarios at each site showed that NPK and MNPK management treatments can change SOC within a short term, but promoting these effects were relatively smaller. The SNPK and NT scenarios required decomposition processes and the promoting effects on SOC gradually emerged with relatively ideal results. However, SOC promotion was limited and SOC would gradually reach the saturated value with organic matter input. The maximal SOC content usually occurred during the middle-late stage of 2050–2080 where the SOC content finally stabilized, and is consistent with the results of Campbell et al. [69]. In the meantime, we need to consider the effects of soil-ripening for newly reclaimed soil, which has a half-life of over 40 years.

5. Conclusions

This study selected six long-term experimental datasets in the phaeozem region to calibrate and validate the DAYCENT model. The results showed that DAYCENT model could effectively simulate the SOC changes under different management practices in the phaeozem region with reasonable parameter settings. Using future climatic conditions, DAYCENT was employed to simulate the SOC under four agricultural management scenarios (NPK, MNPK, SNPK, and NT). The results showed that NPK did not have any evident effects in promoting SOC (SOC were even on a down trend at some sites); and the effect of the MNPK treatment was better than the NPK. Up to2100, a comparison with the initial values of every site showed that the simulated SOC increased by 6.07–32.97% (except Hailun) in the MNPK scenario. However, sites with high initial SOC content could not restrain a reduction in SOC. SNPK and NT had general promoting effects on SOC, where until 2100, the simulated SOC increased by 6.07–32.97%(except for Hailun) under these two scenarios. Furthermore, the action of different management measures on SOC finally stabilized. Thus, it can be concluded that in Northeastern China, SNPK and NT would be an important path to maintain and promote soil fertility, as well as guaranteeing agricultural sustainable development, where straw return can eliminate straw burning in fields and reduce environmental pollution. No-tillage would reduce the input of mechanic equipment and labor, which is of significance in production practices.

The northeastern region has a large territory with various soil types and different climatic conditions and this study was based on quantitative simulation. Further investigation of SOC changes from observation based experiments are necessary. Additionally, more simulation scenarios could better research in SOC change trends. For soil types with higher clay contents, it is recommended that deep plowing every few years in combination with no-tillage can effectively prevent soil compaction; for soil with lower SOC contents, we recommend increasing fertilizer applications and straw return amounts to promote SOC content; for arid areas, assuming suitable conditions, irrigation can improve soil moisture to achieve more ideal effects.

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