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Simulating and Predicting Crop Yield and Soil Fertility under Climate Change with Fertilizer Management in Northeast China Based on the Decision Support System for Agrotechnology Transfer Model

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Abstract: The risks of climate change and soil degradation for the agricultural environment and crop production are increasingly prominent. Based on the limitations of land resources, it is important to explore a sustainable and effective fertilization strategy to reduce risks and ensure there is a high yield of grain and sustainable development of agriculture. Soil fertility underpins cultivated land, which is the most important resource of agricultural production, and is also the key for maintaining agricultural sustainability. The central elements of soil fertility are soil organic carbon (SOC) and soil nitrogen (SN). This study applied the Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM) and the CENTURY-based soil module to simulate the trends of crop yields, SN storages and SOC storages until the end of this century under different climate change circumstances, based on a 36-year long-term experiment established at Shenyang site, China. Four fertilizer practices were applied: control (CK), combined chemical fertilizer of nitrogen, phosphorus, and potassium (NPK), NPK with manure (MNPK), and NPK fertilizers plus a high application rate of manure (hMNPK). The outcomes indicated that the DSSAT model can fully simulate the yields of maize and soybean as well as the dynamic stocks of the SN and SOC. Three Representative Concentration Pathways (RCP 2.6, RCP 4.5, RCP 8.5) for future development were chosen from the fifth assessment report of the United Nations Intergovernmental Panel on Climate Change (IPCC). Moreover, a baseline was installed. Crop yields, SN, and SOC storages from 2016 to 2100 were estimated under four climate scenarios (RCP 2.6, RCP 4.5, RCP 8.5, and Baseline). The RCP scenarios in some treatments reduced SN and SOC stocks and maize yield, and had no effect on soybean yield. However, the application of NPK with manure could improve crop yields, while it increased SN and SOC storages substantially. To some extent, the negative effects of climate scenarios could be mitigated by applying manure. In the RCP 4.5, maize yields of NPK, MNPK, and hMNPK treatments declined by 14.8%, 7.7%, and 6.2%, respectively, compared with that of NPK under Baseline. The NPK fertilizers plus manure treatments could cut the reduction of maize yield caused by climate change in half. Additionally, the SOC storage and SN of chemical fertilizers plus manure treatments under RCP scenarios increased by 20.2%–33.5% and 13.7%–21.7% compared with that of NPK under baseline, respectively. It was concluded that a rational combination of organic and inorganic fertilizer applications is a sustainable and effective agricultural measure to maintain food security and relieve environmental stresses.

Keywords: climate change; sustainability; yield; soil fertility; DSSAT

1. Introduction

The trend of global warming is becoming clearer. With the increase of global temperatures, surface solar radiation in many areas shows a significant weakening trend [1]. At the same time, the annual variation of rainfall is increasing, and extreme precipitation events are occurring more frequently. Climate change will have an important impact on agricultural production and sustainable development of the environment. Climate change is characterized by climate warming, frequent occurrences of extreme weather, changes in the spatial distribution of precipitation, shortening of crop phenology, and increased aggravation caused by diseases and insect pests, all of which will affect crop production and food security. Moreover, frequent extreme precipitation and soil nutrient loss caused by climate change will intensify the impact of long-term cultivation on soil degradation. At present, the impact of climate change on agricultural production and sustainable development has been widely viewed as an area of concern by many scholars around the world [2–4]. On a global scale, the increase of temperature will have a negative impact on the yields of wheat, barley, and maize [5]. In 1980–2008, climate change led to a 3.8% and 2.5% reduction in the global yield of maize and wheat, respectively [6]. Climate change has a clear adverse effect on the yield of grain crops, especially maize. Some studies have shown that climate change in China led to a 12% decrease in corn yields [7], and the contribution rate of climate change to maize yield reduction could reach up to 40% [8]. The decrease of sunshine hours and the rise of temperature in the growth stage are the main climate factors underpinning a potential yield decline in Northeast China [9]. Similarly, the estimated results based on meta-analysis showed a decrease in the northeast between 1980 and 2009 [10]. Wan et al. [11] used the Roth-C model to simulate the soil organic carbon of farmland areas in most parts of China. They showed that, under either an A2 or B2 scenario (future climate scenarios of high and low emissions in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), soil organic carbon (SOC) would decline, especially in the north. Zhang et al. [12] showed that, from the tillering stage of wheat to the maturity stage, the increase of CO_2 concentration reduced the content of N-NH^{4+} in the soil. However, there is a contrary view that climate warming has a favorable effect on crop production and soil nutrient accumulation [13]. Therefore, investigating the impact of climate change on crop yield and soil fertility is needed to ameliorate agricultural management measures, improve crop adaptability to climate change, ensure food production safety, reduce the risk of continuous farming and climate change on land degradation, and maintain the sustainable development of agriculture [14].

The crop growth simulation model is capable of analyzing the effects of various climatic factors on crop growth and soil condition in the context of interactions with fertilizer, soil, cultivar, and agronomic factors. Several studies have been conducted using dynamic modeling frameworks for comprehensive assessments of climate change and its impact on both regional and global supply and demand [15]. Thus far, the DSSAT model has been widely used for yield gap analysis, decision and planning making, strategic and tactical management, and climate change research [16–19]. In China, several studies have shown the usefulness of different crop models in assessing the impact of climate change [20–22]. Soil organic matter is the most important indicator of soil health, which influences the crop yield. The mass of soil organic matter is composed of SOC and soil nitrogen [23,24]. In this study, we chose a maize-soybean-maize single cropping system site-based field experiment performed in 36 consecutive years from a maize cropping area. The research objectives of this experiment are as follows: 1. Verify the applicability of the DSSAT model on brown soil in Northeast China by using data accumulated in long-term fertilization experiments; 2. Evaluate the impacts of climate change on the yield of maize and soybean, which are the two main crops in Northeast China, and the soil carbon and nitrogen cycle in brown soil under different fertilizations; 3. Explore a sustainable strategy of fertilization to estimate crop yields and soil fertility under climate change conditions based on the DSSAT model.

2. Objectives and Methods

2.1. Experimental Site and Design

The study was conducted in Shenyang (41°48′ N and 123°33′ E), China. The climate is mid-temperate. The annual average temperature is 7.0 °C–8.1 °C, and the annual precipitation is 574 mm–684 mm. The cumulative temperature over 10 °C is estimated to be 3300 °C–3400 °C. A total of 148–180 days are free from frost each year with the annual average sunshine hours of 2373 hours. The soil type is classified as Typic Hapli-Udic Argosols (China classification) and Haplic Luvisol (FAO classification). Table 1 shows the physicochemical properties when the experiment started. Farming system was applied as maize (*Zea mays* L.)—soybean (*Glycine max* L. *Merr.*)—maize rotation during the experiment.

In this study, a long-term site-based experiment provided the data, and could be confirmed that the change in nutrients have a major role in the potency of soil fertility. The experimental details have been presented by Luo et al. and Gao et al. [25,26]. A split plot experiment included 15 treatments has been designed since 1979. The plot was divided into three groups: chemical fertilizer, chemical fertilizer plus low levels of organic manure, and high levels of organic manure.

Therefore, four of the fifteen fertilization treatments were concerned: (1) no fertilization (CK), (2) combination of N, P, and K chemical fertilizer (NPK), (3) organic manure plus NPK combination (MNPK), and (4) two times of organic manure fertilizer plus NPK (hMNPK). Table 2 shows the specific fertilizer quantities applied in different years. The mineral fertilizers were in the form of urea (N 46%), calcium phosphate (P_2O_5 12%), and potassium sulphate (K_2O 50%). Pig compost (dry) as organic manure contains 119.6 g kg^{-1} organic matters, 5.6 g kg^{-1} total N, 8.3 g kg^{-1} P_2O_5, and 10.9 g kg^{-1} K_2O on average. All the fertilizers were applied basally at one time before sowing. Because the continuous application of manure tended to reduce the yields of soybean, no manure has been applied in soybean planting years by the fine-tuned experimental scheme since 1992. In 1994, the site was fallow for a year by reason of highway construction. The major varieties in Liaoning Province, Northeast China, were selected for planting, which were changed once every two-round rotation cycles. In each experimental year, maize or soybean was planted around April 27 and harvested in late September. Crop yields were calculated from one square meter (1 m × 1 m). After being air-dried and threshed, the plant samples were oven dried at 70 °C to a constant weight, and then were weighed separately.

Table 1. Soil properties (0–60 cm) at the beginning of the long-term fertilization experiment in 1979.

Properties	Units	Shengyang Site		
Clay mineral type		Hydromica, Kaolinite		
Soil texture		Clay loam		
Soil depth	cm	0–20	20–40	40–60
Bulk density	g cm^{-3}	1.18	1.5	1.48
pH in water (1:2.5)		6.5	6	5.78
Clay (<2 μm)	%	23	22	22
Silt (2–50 μm)	%	29	33	38
Sand (50–2000 μm)	%	48	45	40
Organic carbon	g kg^{-1}	9.2	6.4	4.2
Total nitrogen	g kg^{-1}	0.80	0.62	0.53
Total phosphorus	g kg^{-1}	0.38	0.32	0.53
Available phosphorus	mg kg^{-1}	6.5	5.1	1.5
Total potassium	g kg^{-1}	20.1	20	15.9
Root growth factor		1.00	0.549	0.368

Table 2. Annual fertilizer quantity for each crop.

Treatments	Chemical Fertilizer (kg ha^{-1} yr^{-1})			Animal Manure (kg N ha^{-1} yr^{-1})
	N	P_2O_5	K_2O	
Control (CK)	0/0	0/0	0/0	0/0
Combined chemical fertilizer of nitrogen, phosphorus, and potassium (NPK)	120/30[1]	60/90	60/90	0/0
NPK with manure (MNPK)	120/30	60/90	60/90	20/20[2]
NPK fertilizers plus a high application rate of manure (hMNPK)	120/30	60/90	60/90	40/40

[1] The years before and after represent maize year/ soybean year separately. [2] During 1992–2015, no organic manure were applied among the years of planting soybean (M= 0 kg N ha^{-1}, hM= 0 kg N ha^{-1}).

2.2. *Soil Sampling and Analysis*

The sample was taken before sowing each year. Randomly selected, five points in each plot with an 'S' shape and collected 20-cm depth of soil mixed the five soil samples as a composite soil sample. The composite soil sample was divided into two portions for further testing. One portion of the sample was a fresh soil sample, which was put into self-sealed bags and transferred to lab by chilly bins for testing N-NH^{4+} and N-NO^{3-} with a continuous flow analyzer. The other portion of the sample was dried indoors and sieved through a 2-mm screen for removing small stones, roots, and litters. Furthermore, 10 g of the soil sample was taken from the composite soil sample for measuring pH in water (1:2.5). Then, the composite sample was further milled to 0.25 mm for analysis soil N and organic carbon (SOC) by an Element III elemental analyzer on the combustion oxidation method. The above testing was conducted 3 times. Other soil data, including soil components, bulk density, total phosphorus and potassium contents, were derived from the database of long-term experiment on brown soil site-based in the Shenyang Agricultural University.

2.3. *Weather Data and Climate Scenarios*

For calibration and validation, the data of historic weather between 1979 and 2015 (about 12 rounds of rotation) were downloaded from the National Meteorological Information Center of China (http://data.cma.cn/). The Shenyang meteorological station is 7.4 km away from the experiment site.

In this study, the weather of future climate events started in 2016. The future climate scenarios between 2016 and 2100 were based on three Representative Concentration Pathways (RCPs): RCP 2.6, RCP 4.5, and RCP 8.5 [27]. The data of the future climate scenarios used in this study were operated by a HadGEM2-ES climate model driven by IPCC. The low-resolution data were corrected and reduced to 0.5° × 0.5° by a quantile mapping method before entering data in the crop model [28]. The data were compiled by ISIMIP (the Intel-Sectoral Impact Model Intercomparison Project) team, which was initiated by the Potsdam Institute for Climate Impact Research (PIK) and the International Institute for Applied Systems Analysis (IIASA). The grid data corresponding to the research site were extracted and obtained by Matlab 2016a.

The weather data include daily precipitation (mm), minimum temperature (°C), maximum temperature (°C), and solar radiation (MJ m^{-2}) (Table 3). A baseline was set to analyze the potential impacts of climate change on yields, soil nitrogen (SN) and SOC, so that we can circulate the use of historical data between 1996 and 2015, with 380 ppm CO_2 concentration constantly.

Table 3. Annual averaged weather data under climate changes between 2016 and 2100 at the Shenyang site.

RCPs	Solar Radiation (MJ m^{-2})	Maximum Temperature (°C)	Minimum Temperature (°C)	CO_2 Concentration in Atmosphere (ppm)	Precipitation (mm)	Precipitation Events	Precipitation Intensity (Times)	
							>10 mm	>50 mm
Baseline	14.31	15.27	3.25	380.00	667.51	7227	1673	153
RCP 2.6	14.58	15.61	4.69	432.31	930.95	7602	2318	171
RCP 4.5	14.63	16.50	5.50	489.59	893.80	7307	2191	176
RCP 8.5	14.71	17.70	6.98	615.54	871.09	6912	2182	181

2.4. Crop Simulation Model Inputs

The simulations were conducted by CERES-Maize and CROPGRO-Soybean modules and CENTURY-based soil C and N module in DSSAT v4.7 [29]. The DSSAT model is a software application program that comprises the crop simulation models for 32 crops and is supported by data base management programs for soil, weather, crop management, experimental data, and by utilities and application programs to make it functional for users [30–32].

Input data, including daily weather data, crop management, cultivar coefficients, and initial soil conditions, were required by the model. To transfer the soil water and nutrients for simulation running, the sequence analysis program in DSSAT was made [33]. In this study, the time between the harvest of the previous year and the planting of the next year was set as a fallow period. The field was tillaged to 20 cm depth in April before crops were planted. In addition, at the beginning of each crop period, the atmospheric nitrogen deposition was set as 20 kg N ha^{-1}, which was used as the annual effective N input of all treatments [34]. The field management data is shown in Table 4.

Table 4. The management data for all the treatments from 1979 to 2015 at the Shenyang site.

Year	Crop	Cultivar	Planting Date	Plant Density (Plant m^{-2})	Row Space (cm)	Fertilizer Date	Manure Date	Tillage Date	Harvest Date
1979	Maize	MZ1990	110	4.2	60	110	107	107	284
1980	Soybean	SB1980	111	16.5	60	111	108	108	303
1981	Maize	MZ1984	110	4.2	60	110	107	107	299
1982	Maize	MZ1984	110	4.2	60	110	107	107	297
1983	Soybean	SB1980	110	16.5	60	110	107	107	267
1984	Maize	MZ1984	111	4.2	60	111	108	108	294
1985	Maize	MZ1984	116	4.2	60	116	113	113	278
1986	Soybean	SB1980	124	16.5	60	124	121	121	295
1987	Maize	MZ1993	107	4.2	60	107	104	104	293
1988	Maize	MZ1990	109	4.2	60	109	106	106	267
1989	Soybean	SB1980	123	12	60	123	120	120	283
1990	Maize	MZ1990	105	4.2	60	105	102	102	266
1991	Maize	MZ1993	112	4.2	60	112	109	109	272
1992	Soybean	SB1992	113	12	60	113	—	110	279
1993	Maize	MZ1993	110	4.2	60	110	107	107	268
1995	Maize	MZ2004	118	4.5	60	118	115	115	280
1996	Soybean	SB1992	119	12	60	119	—	116	273
1997	Maize	MZ1997	113	4.5	60	113	110	110	273
1998	Maize	MZ1997	112	4.5	60	112	109	109	262
1999	Soybean	SB1992	112	15	60	112	—	109	267
2000	Maize	MZ2004	120	4.5	60	120	117	117	267
2001	Maize	MZ2004	114	4.5	60	114	111	111	264
2002	Soybean	SB1992	117	15	60	117	—	114	268
2003	Maize	MZ2004	113	4.5	60	113	110	110	265
2004	Maize	MZ2004	116	4.5	60	116	113	113	266
2005	Soybean	SB1992	130	15	60	130	—	127	268
2006	Maize	MZ1997	117	4.5	60	117	114	114	263
2007	Maize	MZ1997	121	4.5	60	121	118	118	270
2008	Soybean	SB1992	131	15	60	131	—	128	272
2009	Maize	MZ2010	118	6	60	118	115	115	269
2010	Maize	MZ2010	135	6	60	135	132	132	272

Table 4. *Cont.*

Year	Crop	Cultivar	Planting Date	Plant Density (Plant m^{-2})	Row Space (cm)	Fertilizer Date	Manure Date	Tillage Date	Harvest Date
2011	Soybean	SB2011	132	15	60	132	—	128	272
2012	Maize	MZ2010	119	6	60	119	116	116	274
2013	Maize	MZ2010	124	6	60	124	121	121	270
2014	Soybean	SB2011	129	15	60	129	—	126	281
2015	Maize	MZ1997	114	6	60	114	111	111	269

Note: The planting date is represented by the Julian calendar, which was counted annually (365/366 days each year). Other date representations are the same as the planting date.

2.5. Calibration and Validation

To calibrate the cultivar parameters, which were related to the growth and development of maize and soybean, the observed crop developmental indexes and gain yields for NPK from 1979 to 2015 were chosen. The other treatments, CK, MNPK, and hMNPK, were used for validating the optimized parameters for the model. In this simulation, the maize cultivar 990002 (in MZCER047.CUL), and the soybean cultivar 990003 (in SBGR0047.CUL) were selected to calibrate the new cultivars. Through the use of a 'Trial and Error' method, the calibration was made by establishing a tiny change (±5%) of each parameter. The optimized parameters are shown in Table 5. Two cultivars, MZ2010 and SB2011, which are widely planted, were selected as models for future climate scenario analysis. Through the period of simulation, crop varieties that were parameterized were maintained the same in future climate scenarios.

Table 5. The crop calibrated cultivar coefficients for the experimental site in Decision Support System for Agrotechnology Transfer (DSSAT) (v4.7).

Cultivar	Calibrated Coefficients					
Maize cultivar coefficients						
Cultivar name	**MZ1984**	**MZ1990**	**MZ1993**	**MZ1997**	**MZ2004**	**MZ2010**
P1 Thermal time from crop seedling emergence to the end of the juvenile stage (°C day)	299	281	246	297	249	290
P2 Degree to which development is delayed for each hour rise in the photoperiod above the critical photoperiod (12.5 h for CERES) at which development proceeds at a maximum rate (day h^{-1})	0.90	0.67	0.92	0.93	0.79	0.80
P5 Thermal time from silking to physiological maturity	933	980	982	966	999	997
G2 Maximum possible number of kernels per plant	869	750	959	944	921	825
G3 Grain filling rate under optimum conditions (mg day^{-1})	5.2	7.9	6.0	14.6	9.8	8.6
PHINT Phyllochron interval between two successive leaf tip appearances	34.5	30.8	30.3	33.9	39.0	30.1
Soybean cultivar coefficients						
Cultivar name	**SB1980**	**SB1992**	**SB2011**			
CSDL Critical short-day length below which reproductive development progress with no day-length effect (hours)	13.3	13.2	13.5			
PPSEN Slope of the relative response of development to photoperiod with time (1 h^{-1})	0.295	0.286	0.288			
EM-FL Time between plant emergence and flower appearance (R1) (photothermal days)	14.5	17.9	23.0			
FL-SH Time between first flower and first pod (R3) (photothermal days)	6.0	6.0	6.0			
FL-SD Time between first flower and first seed (R3) (photothermal days)	13.5	13.5	13.0			
SD-PM Time between first seed (R5) and physiological maturity (R7) (photothermal days)	29.4	29.3	30.6			
FL-LF Time between first flower (R1) and leaf expansion (photothermal days)	26.0	26.0	26.0			
SLAVR Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	375	375	400			
SIZLF Maximum size of full leaf (three leaflets) (cm^2)	180	185	200			
WTPSD Maximum weight per seed (g)	0.19	0.20	0.20			
SFDUR Seed filling duration for pod cohort at standard growth conditions (photothermal days)	20	23	20			
SDPDV Average seed per pod under standard growing conditions (seeds pod^{-1})	2.2	2.2	2.2			
PODUR Time required for cultivar to reach final pod load under optional conditions (photothermal days)	10	10	10			
THRSH The maximum ratio of seed/ seed+ shell at maturity	77	77	77			

2.6. Statistical Analysis

A set of statistical methods were applied to evaluate the performance of this model, including mean error (E), root mean square error ($RMSE$), normalized root mean square error ($nRMSE$), forecasting efficiency (EF), and index of agreement (d) [35,36]. The significance of E was tested by a Paired-Samples T test, which was applied in this study. In addition, the effects of climate scenarios and treatments on crop yield, SN, and SOC storages were compared by a two-way ANOVA. All the analysis was performed with SPSS 22.0.

$$E = \frac{\sum_{i=1}^{n}(S_i - M_i)}{n} \tag{1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - M_i)^2}{n}} \tag{2}$$

$$nRMSE = \frac{RMSE}{\overline{M}} \times 100 \tag{3}$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \overline{M})^2} \tag{4}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(\left|S_i - \overline{M}\right| + \left|M_i - \overline{M}\right|\right)^2} \tag{5}$$

3. Results and Discussion

3.1. Model Calibration and Validation

Overall, the simulated crop yields agreed well with the observations (Figure 1). Several statistical parameters showed that crop yields for all fertilizer treatments on brown soil in Northeast China could be adequately simulated by using data accumulated in long-term fertilizer treatments by the DSSAT model. For instance, the coefficients of determination (R^2) between observed and simulated yields of maize and soybean were 0.83 (n = 84, $p < 0.01$) and 0.80 (n = 44, $p < 0.01$) with the $nRSME$ of 17.57% and 10.50%, and the index of agreement (d) of 0.88 and 0.93. According to the statistical analysis between the simulation value and the measured value ($R^2 \geq 0.8$, $d > 0.80$, $nRMSE < 20\%$), the model simulations showed good or excellent results. The calibration R^2 values were 0.86 (n = 21, $p < 0.01$) and 0.48 (n = 11, $p < 0.01$) with the $nRSME$ of 9.78% and 6.57%, and the R^2 values of the other treatments for validation were 0.85 (n = 63, $p < 0.01$) and 0.81 (n = 33, $p < 0.01$) with the $nRSME$ of 18.91% and 11.61%, respectively. The results showed that there was a good fit between the simulated data and the measured data. In most years, the simulated yields of corn and soybean were basically matched well with the measured values (Figure 2).

By comparing the values of the simulated and measured yields, E values for NPK, MNPK, and hMNPK treatments, respectively, had no statistical difference with zero based upon the Paired-Samples T test (p = 0.31–0.83), except hMNPK in maize (p = 0.01) (Table 6). The calculated values were $nRMSE < 20\%$, $d > 0.9$ and $EF > 0.8$ for NPK, MNPK, and hMNPK treatments. Thus, the maize yields for the fertilized treatments could be good to excellent when simulated by the DSSAT model. For soybean, NPK and MNPK treatments simulated better than hMNPK. However, it has shown a poor agreement in simulating grain yields without application of fertilizer by the model. It showed that the DSSAT model simulated poorer performance for N0 than the treatments with N, especially in maize yields. This is likely because the DSSAT model is more sensitive to the N stress than the real plant growth under the conditions of no fertilizer N [37].

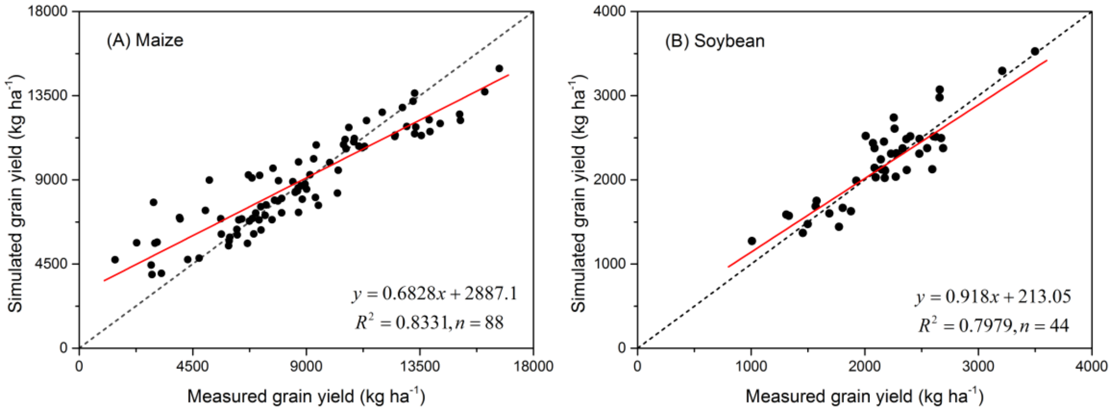

Figure 1. The regression and correlation analysis of measured and simulated yields of all treatments combined for (**A**) maize and (**B**) soybean.

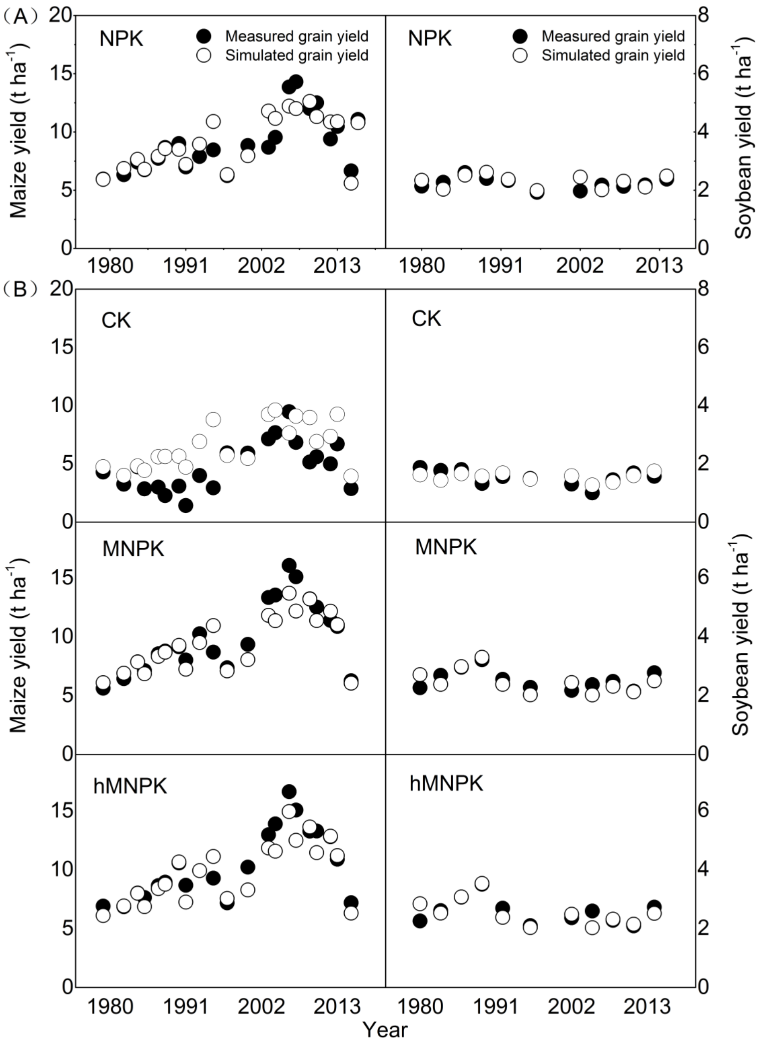

Figure 2. Measured and simulated yields of maize and soybean at the Shenyang site over the simulated period. (**A**) The grain yields of maize and soybean in combined chemical fertilizer of nitrogen, phosphorus, and potassium (NPK) treatments were used for parameterization. (**B**) The grain yields of maize and soybean in control (CK), NPK with manure (MNPK), and NPK fertilizers plus a high application rate of manure (hMNPK) treatments were used for verification.

Table 6. Statistical evaluation of measured yields against simulated values of maize and soybean.

Crop	Treatments	Grain Yields (kg ha^{-1})		Number of Samples	*E*	*RMSE*	*nRMSE* (%)	*EF*	*d*	*P* (Paired-*t*)
		Measured	Simulated							
Maize	CK	4740 (2019)[1]	6574 (1851)	21	1834	2395	50.55	−0.46	0.68	0.00
	NPK	9175 (2474)	9132 (2239)	21	−43	898	9.78	0.86	0.96	0.83
	MNPK	10039 (2955)	9526 (2360)	21	−513	1139	11.34	0.84	0.95	0.31
	hMNPK	10472 (2856)	9822 (2529)	21	−650	1140	10.92	0.83	0.95	0.01
Soybean	CK	1536 (255)	1550 (145)	11	15	204	13.29	0.30	0.68	0.83
	NPK	2257 (193)	2285 (197)	11	28	148	6.57	0.35	0.83	0.56
	MNPK	2435 (331)	2469 (380)	11	25	237	9.69	0.47	0.87	0.65
	hMNPK	2469 (422)	2532 (443)	11	56	324	13.08	−0.36	0.63	0.52

[1] The numbers in brackets are the standard deviation for the treatments.

The DSSAT model could also simulate the dynamic stocks of SOC and SN effectively for the whole treatments in the topsoil (20 cm) (Figure 3, Table 7). The R^2 of measured and simulated SOC and SN storages were 0.75 and 0.73 (n = 144, $p < 0.01$) with the *nRMSE* of 7.65% and 6.10%, and the *d* value of 0.90 and 0.86, respectively. For the organic manure plus chemical fertilizer treatments, the modeled change rates of SOC storage (121 and 153 kg C ha^{-1} yr^{-1}) were almost half trended with the measured value change rates (250 and 290 kg C ha^{-1} yr^{-1}) from 1979 to 2015. However, the DSSAT model was effective to simulate the decline (−84 and −92 kg C ha^{-1} yr^{-1} for actual field data and simulated value) of SOC storages for the CK treatment and a stable pattern (16 and 6 kg C ha^{-1} yr^{-1} for actual field data and simulated value) for the NPK treatment during the period. For MNPK and hMNPK treatments, the simulated SOC showed a moderate to good match with the measured data (Table 7). From 1979 to 2015, the modeled topsoil (20 cm) SN storages increased in all the treatments (Figure 3). For all the treatments, the simulated change rates of SN (from 6 to 15 kg N ha^{-1} yr^{-1}) were similar to the measured (from 3 to 22 kg N ha^{-1} yr^{-1}). The SN stocks of the CK treatment also showed a certain increasing trend, which may be caused by the design of the atmospheric N deposition condition in this simulation. In general, the DSSAT model could well simulate the dynamic of crop growth and SOC and SN storages in brown soil under different fertilization treatments and the typical maize-soybean-maize rotation model in Northeast China.

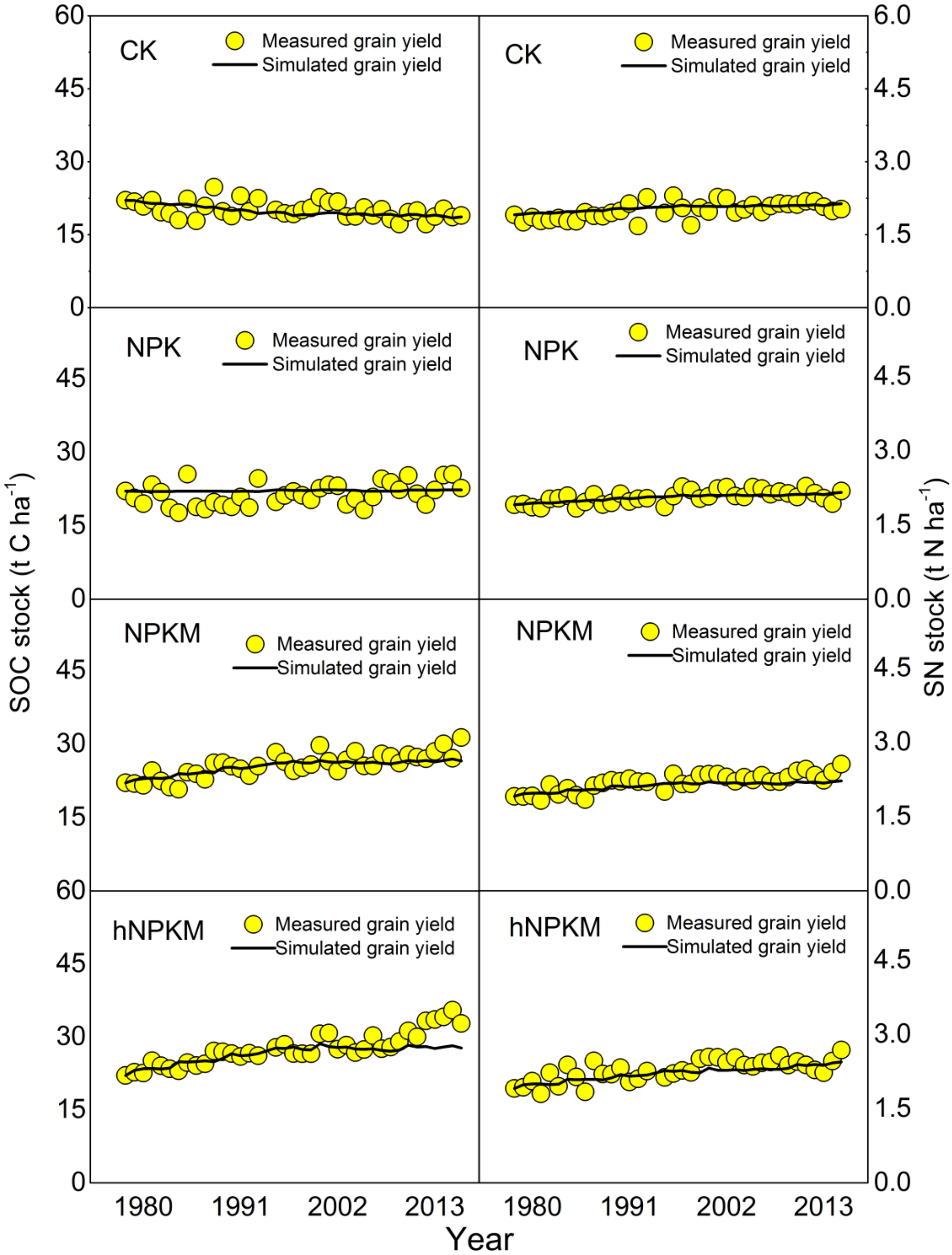

Figure 3. Measured and simulated soil nitrogen (SN) and soil organic carbon (SOC) storages over the simulated period in the top 20 cm of brown soil at the Shenyang site.

Table 7. Statistical evaluation of measured storages of SN and SOC at the top 0–20 cm soil against simulated values.

Variables	Treatments	Measured	Simulated	Number of Samples	*E*	*RMSE*	*nRMSE* (%)	*EF*	*d*	*P* (Paired-*t*)
SOC stock ($t C ha^{-1}$)	CK	20.07 (1.72) [1]	19.81 (0.99)	36	−0.27	1.66	6.99	0.03	0.57	0.35
	NPK	21.40 (2.32)	22.14 (0.13)	36	0.74	2.37	9.44	−0.07	0.35	0.06
	MNPK	25.76 (2.48)	25.43 (1.30)	36	−0.33	1.70	5.76	0.52	0.78	0.25
	hMNPK	27.76 (3.31)	26.58 (1.65)	36	−1.17	2.53	8.05	0.40	0.72	0.03
SN stock ($t N ha^{-1}$)	CK	2.00 (0.17)	2.05 (0.06)	36	0.05	0.15	6.44	0.21	0.59	0.25
	NPK	2.07 (0.13)	2.06 (0.07)	36	−0.01	0.10	4.13	0.37	0.7	0.53
	MNPK	2.20 (0.18)	2.12 (0.08)	36	−0.09	0.15	5.91	0.3	0.71	0.00
	hMNPK	2.29 (0.04)	2.22 (0.02)	36	−0.07	0.17	6.42	0.37	0.76	0.01

[1] The numbers in brackets are the standard deviation for the treatments.

3.2. Impacts of Climate Change on Crop Yield

Under the climate scenarios, the changes in average annual yields of maize and soybean for different fertilizer treatments in the maize-soybean-maize rotation system between 2016 and 2100 are shown in Figure 4. Under the same climate scenarios, the maize yields of each treatment, which was predicted in order: hMNPK > MNPK > NPK > CK ($p < 0.05$). The maize yields treated with organic manure increased by 9.29%–23.22% compared with what were treated with chemical fertilizers. Significant ($p < 0.05$) increases in yields of hMNPK under RCP 4.5 and RCP 8.5 scenarios were observed. However, with the same fertilization treatments, climate scenarios had a negative impact on maize yields. Compared to the baseline, maize yields of all the treatments under RCP scenarios were reduced. The decrease rates of maize yields were 6.96%–29.00% in each fertilization treatments. Especially under the RCP 8.5 scenario, the decrease rate was 24.14%–29.00%. Except for the insignificant changes of CK treatments, during 2016 and 2100 under the climate scenario of RCP 8.5, maize yields of other fertilizer treatments showed a significant decline in the middle of the century and the end of the century (Figure 5). This might be due to the fact that the CO_2 concentration in the atmosphere was continuously increasing under the RCP 8.5, which would be accompanied by the rise of temperature and the decrease of rainfall. An accelerating trend of the evaporation of soil water would lead to a decline in soil water content. Maize is sensitive to climate changes and leads to a drop of yields, as typical C4 crop properties. [38]. The same studies have shown that, if current varieties and management technologies were not improved by 2050, the maize yields in rain-fed areas came down by 14.50%–22.8% [39]. However, there were some other studies that resulted in the opposite results [40]. To some extent, the negative effects of climate scenarios could be mitigated by applying organic fertilizers. In the RCP 4.5, maize yields of NPK, MNPK, and hMNPK treatments declined 14.8%, 7.7%, and 6.2%, respectively, compared with that of the NPK under baseline. The NPK plus manure treatments could cut the reduction of crop maize caused by climate change in half.

For the same climate scenario, the soybean yields of fertilization treatments were significantly higher than that of the unfertilized treatments. Since no organic manure was applied in the soybean years, the three fertilizer application treatments (NPK, MNPK, and hMNPK) had the same amount of nutrient inputs. In Figure 4, the soybean yields of organic fertilizer plus treatments (MNPK, hMNPK) applied to the fore-rotating crop (maize) was not significantly increased compared with that of the single application of chemical fertilizers (NPK). It was indicated that the simulation was less influenced by the accumulation of C and N nutrients in the preceding soil and the increase in atmospheric CO_2 concentration. Under the scenario of RCP 8.5, soybean yields decreased slightly, but the drop trend was not significant. There was no significant difference in soybean yields under different climate scenarios. From 2016 to 2100, soybean yields fluctuated steadily with time under various climate scenarios. Therefore, the influence of climate change on soybean yields was less than that of maize.

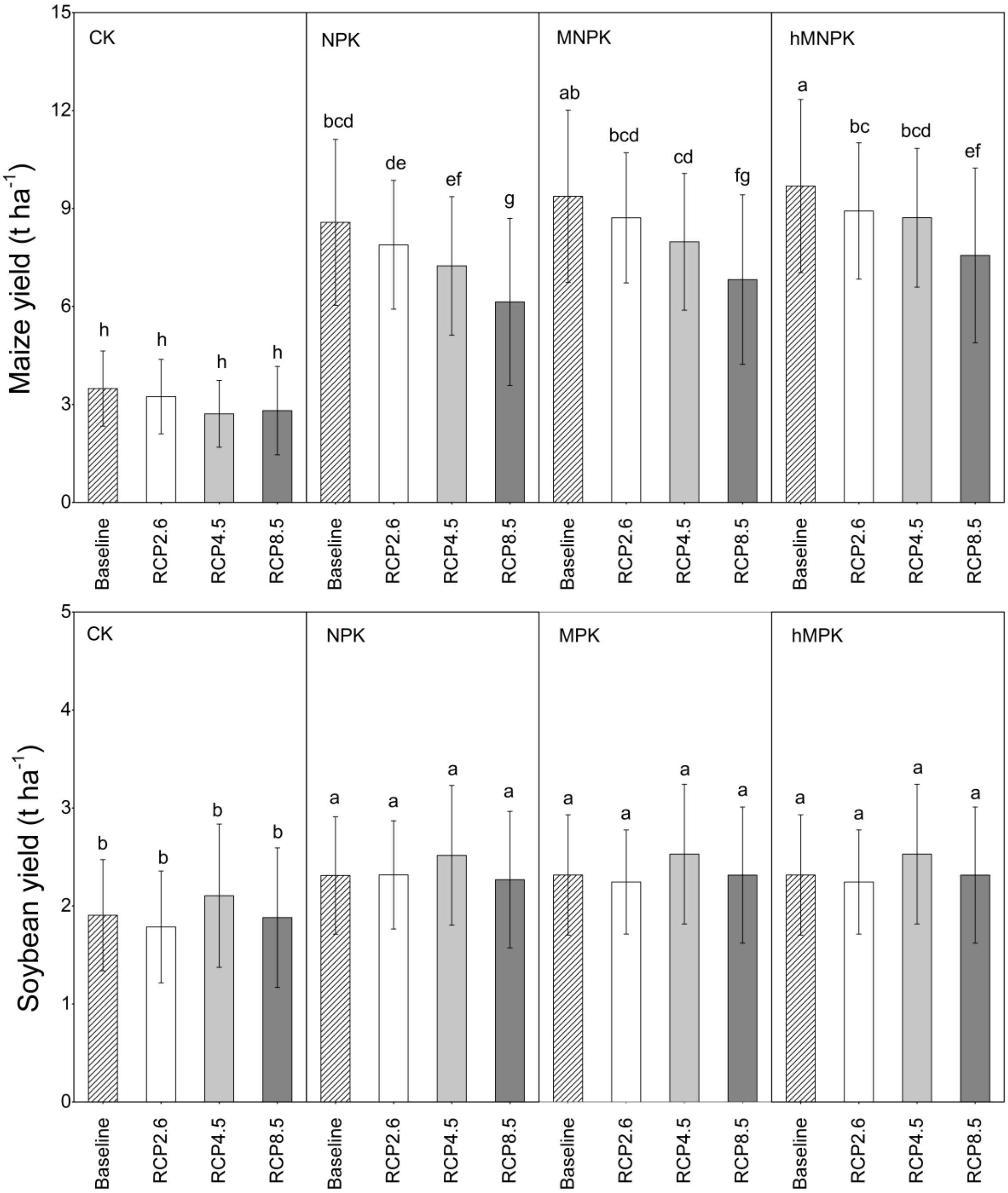

Figure 4. Average grain yields of maize and soybean under the baseline and the climate scenarios between 2016 and 2100 at the Shenyang site. Same letters mean that there is no clear difference ($p < 0.01$) under different scenarios and treatments. The standard deviation is the error bar in every treatment.

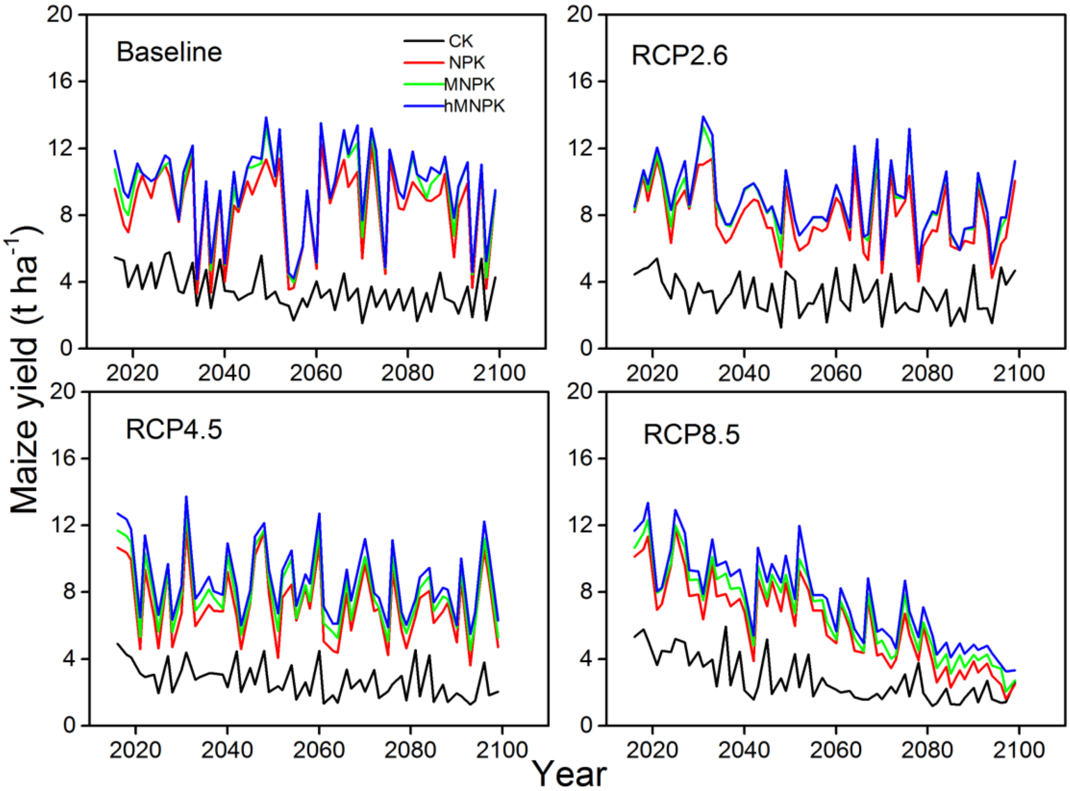

Figure 5. Annual grain yields of maize under the baseline and the climate scenarios between 2016 and 2100 at the Shenyang site.

3.3. Impacts of Climate Change on Soil Organic C and N Stocks

The SOC storages in the topsoil (20 cm) of all the treatments presented in the same RCPs was in order: hMNPK > MNPK > NPK > CK ($p < 0.05$) (Figure 6). The SOC storages of manure plus treatments (MNPK and hMNPK) compared with CK and NPK was increased significantly. This means that fertilized soil is a carbon sink in every climate model. Under the four climate scenarios, the SOC stocks of MNPK and hMNPK treatments were 22.48%–27.88% and 26.85%–35.74% higher than those of NPK, respectively. For the same climate scenario, during 2016 to 2100, the SOC storages of CK showed a trend of decreasing first and then slowing down with time (Figure 7). Compared with CK treatments, the fertilization treatments increased the content of SOC pool. The annual average SOC growth rate of NPK treatment was 3.76–10.68 kg C ha^{-1} yr^{-1} with a small change and a basically flat performance in the whole simulation phase (Table 8). The trends of SOC stocks in MNPK and hMNPK treatments increased first and gradually slowed down with an annual increase of 59.21–80.63 kg N ha^{-1}yr^{-1} and 74.17–101.98 kg N ha^{-1}yr^{-1}, respectively. The effect of manure plus treatments on SOC reserves was significant ($p < 0.05$). The trends of SOC stocks with different farming measures were stable over time [41]. In addition, with the same treatment under different climate scenarios, the RCP scenarios also had a significant impact on the accumulation of SOC storages in the top soil. With the increase of CO_2 concentration in the atmosphere, the accumulation capacity of SOC treated by organic fertilizer would decrease. The reason was that the rising frequency of high temperatures and heavy rainfall caused by climate change promoted the decomposition of the soil organic matter [42]. The SOC storages were the highest at baseline, which was followed by RCP 2.6 and RCP 4.5. RCP 8.5 was the lowest ($p < 0.05$). Among others, hMNPK treatment showed a significant decrease in the accumulation capacity of SOC in RCP 8.5 compared with RCP 2.6 and RCP 4.5. However, CK and NPK treatments had no influence under climate scenarios.

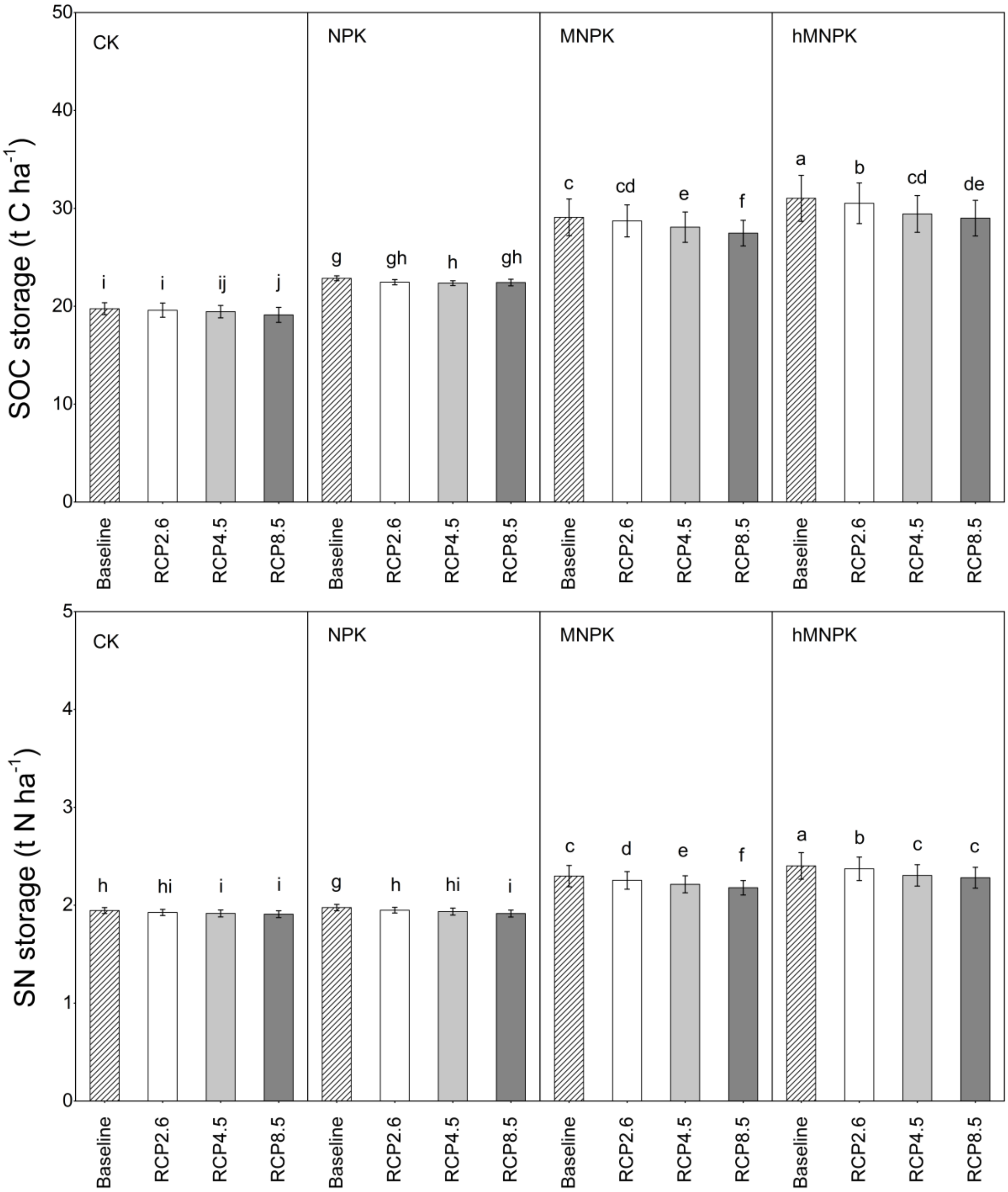

Figure 6. Simulated SN and SOC storages under the baseline and the climate scenarios by 2100 at Shenyang site. The same letters mean that there is no clear difference ($p < 0.01$) under different scenarios and treatments. The standard deviation is the error bar in every treatment.

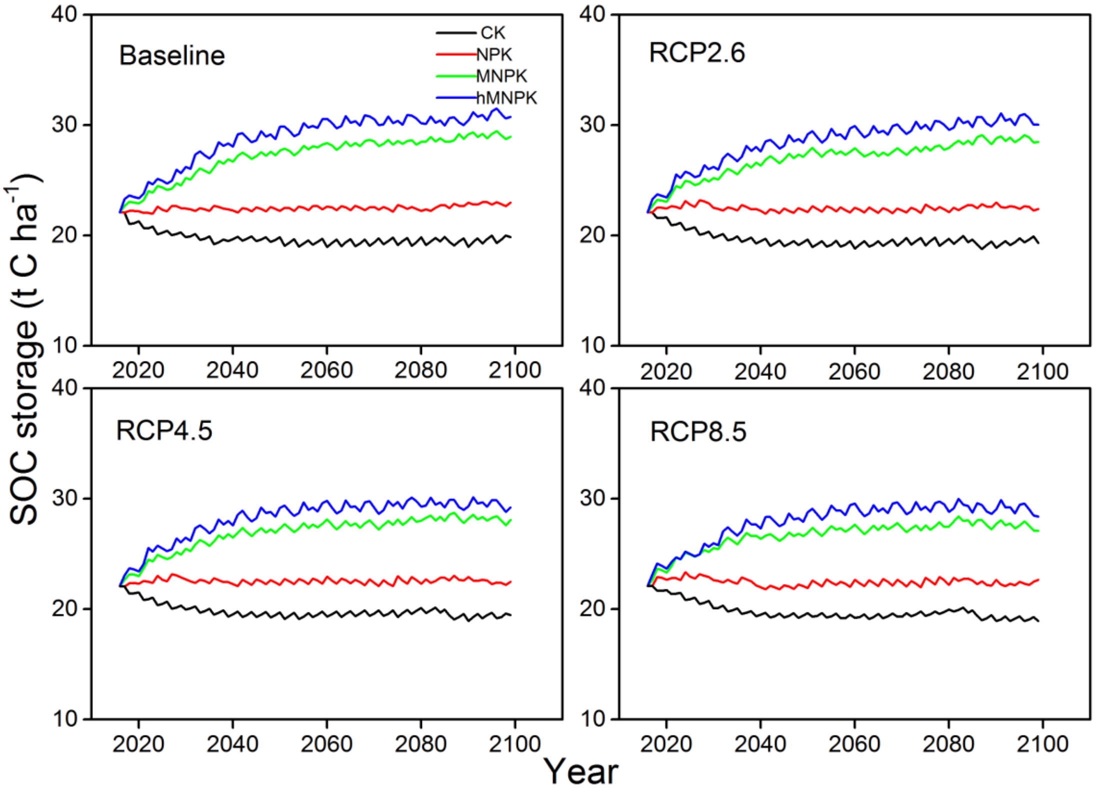

Figure 7. Annual SOC storages of brown soil between 2016 and 2100 under the baseline and the climate scenarios at the Shenyang site.

Table 8. Annual change rates of soil nitrogen (SN) and soil organic carbon (SOC) (kg C/N ha^{-1} yr^{-1}) storages under different climate scenarios by 2100, compared with that in 2015 at the Shenyang site.

Treatments	**Baseline**		**RCP 2.6**		**RCP 4.5**		**RCP 8.5**	
	SOC	**SN**	**SOC**	**SN**	**SOC**	**SN**	**SOC**	**SN**
CK	−26.35	0.58	−32.54	0.18	−30.66	0.31	−37.09	−0.08
NPK	10.68	0.92	3.76	0.47	4.77	0.52	6.94	0.01
MNPK	80.63	4.42	75.28	3.85	70.78	3.55	59.21	2.87
hMNPK	101.98	5.56	93.58	5.08	83.95	4.47	74.17	3.91

In the same climate change event, the order of the SN storages under different treatments in the topsoil (20 cm) was similar to that of the SOC stocks, which was shown as follows: hMNPK > MNPK > NPK > CK ($p < 0.05$) (Figure 6). The manure plus treatments (MNPK and hMNPK) made the SN increase significantly when compared with non-fertilizing treatment (CK) and a single application of chemical fertilizer treatment (NPK). Under each climate scenario, the SN of MNPK and hMNPK were 14.11%–18.07% and 19.47%–23.46% higher than that of NPK, respectively. However, the SN stocks in the top soil of CK and NPK were basically maintained in a stable state with the change of time (Figure 8), which was different from SOC. It was likely because the factor of NO_2 settlement was considered in this simulation. Although the application of chemical fertilizer could promote the accumulation of crop biomass, the amount of residual returned to the SN pool was limited, so the trend of the SN storage was the same as that of CK. Compared with the base in 2015, the SN storages of MNPK and hMNPK increased by 2.87–4.42 kg N ha^{-1} yr^{-1} and 3.91–5.56 kg N ha^{-1} yr^{-1} on average annually (Table 8). It was indicated that the application of organic manure could effectively improve the accumulation of SN. In the simulation, the influence of RCP scenarios on the SN storage was significant. The SN storages were reduced by climate change, especially dropped more under the manure application, with the same trend as SOC. Perhaps more frequent, heavy rainfall caused by climate changes (Table 3) would enhance the soil N leaching. With the decomposition of soil organic matter increasing by manure application, the accumulation of the SN pool was decreased.

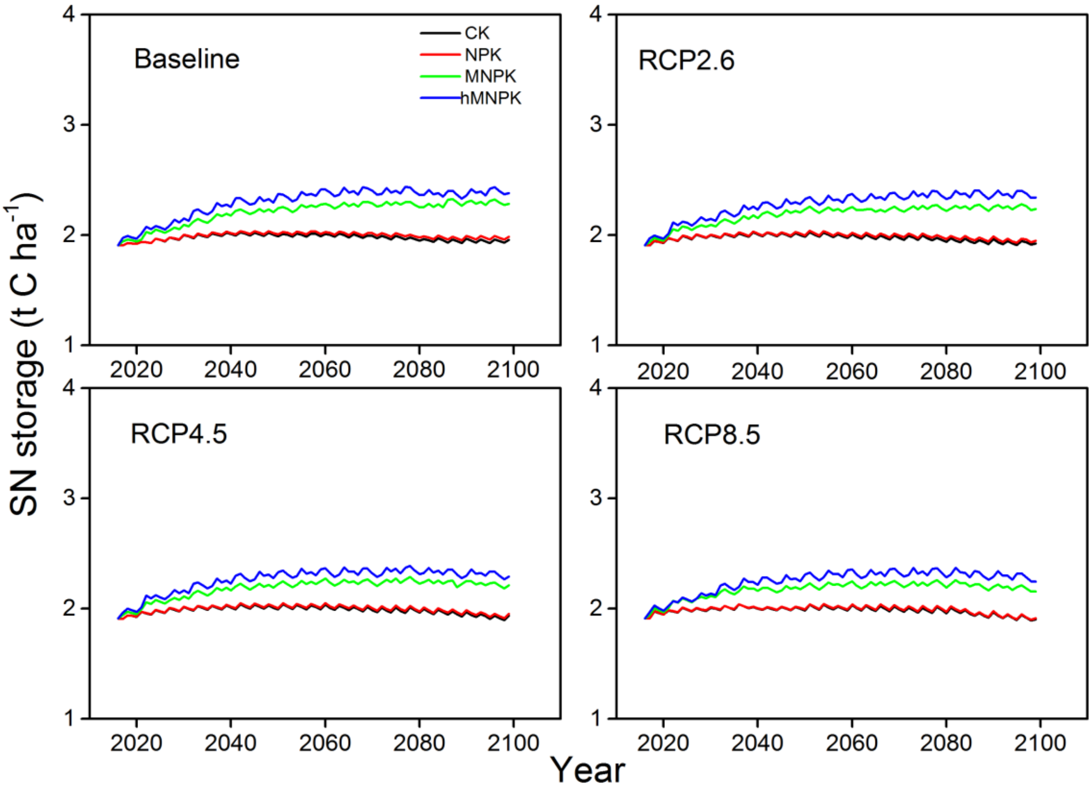

Figure 8. Annual SN storages of brown loam between 2016 and 2100 under the baseline and the climate scenarios at the Shenyang site.

4. Conclusions

According to the data sourced from a 36-year long-term experiment of typical brown soil conduced in Northeast China, this study showed the simulated adaption and validity of the DSSAT model were verified and evaluated. The model could simulate the dynamic changes of crop growth effectively. The soil organic carbon and nitrogen storage under different fertilization treatments was measured in the typical maize-soybean-maize rotation model in Northeast China. The simulation results of the model for fertilizer treatments (NPK, MNPK, and hMNPK) were better compared with no fertilizer treatment (CK). In this paper, the response of maize and soybean yields and the soil carbon and nitrogen balance were predicted under different climate scenarios in the future. Under the same climate scenario, the application of organic fertilizer increased the maize yields more clearly than that with the single application of chemical fertilizer, especially for the high amount of manure application. However, compared with applying chemical fertilizer, the soil nutrients accumulated by applying organic fertilizer to the former maize did not significantly increase the yields of soybean, which was planted the following year. In the entire simulation phase, the SOC and SN storages applied with organic fertilizer (MNPK and hMNPK) increased more significantly compared with that of non-fertilizing treatment (CK) and a single application of chemical fertilizer (NPK). From 2016–2100, the SOC stocks treated by CK showed a trend of decreasing at the beginning and then turning gradually with time under the same climate scenario while the NPK treatment showed a flat performance. In addition, a trend of increasing first and then turning gradually with time of MNPK and hMNPK treatments was observed. With the rise of CO_2 concentration in the atmosphere, the accumulation capacities of SOC and SN with organic fertilizer treatments decreased under different climate scenarios. At the same time, the trend of maize yield in the last 40 years started to decline in the mode of RCP scenarios, especially the RCP 8.5. It revealed that the climate change and increase of CO_2 concentration have negative effects on crop growth and soil fertility. However, the addition of organic fertilizer results in slowing down the trend of decline. A combination of organic and mineral fertilizers could maintain the soil fertility effectively and reduce the negative impacts of climate change on crop yields to a certain extent. The result shows that a rational combination of organic and inorganic fertilizer application is a sustainable and effective agricultural measure to maintain food security and relieve environmental risk. The amount and proportion of mineral and organic fertilizer application should be studied further to conquer increasing environmental stress.

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