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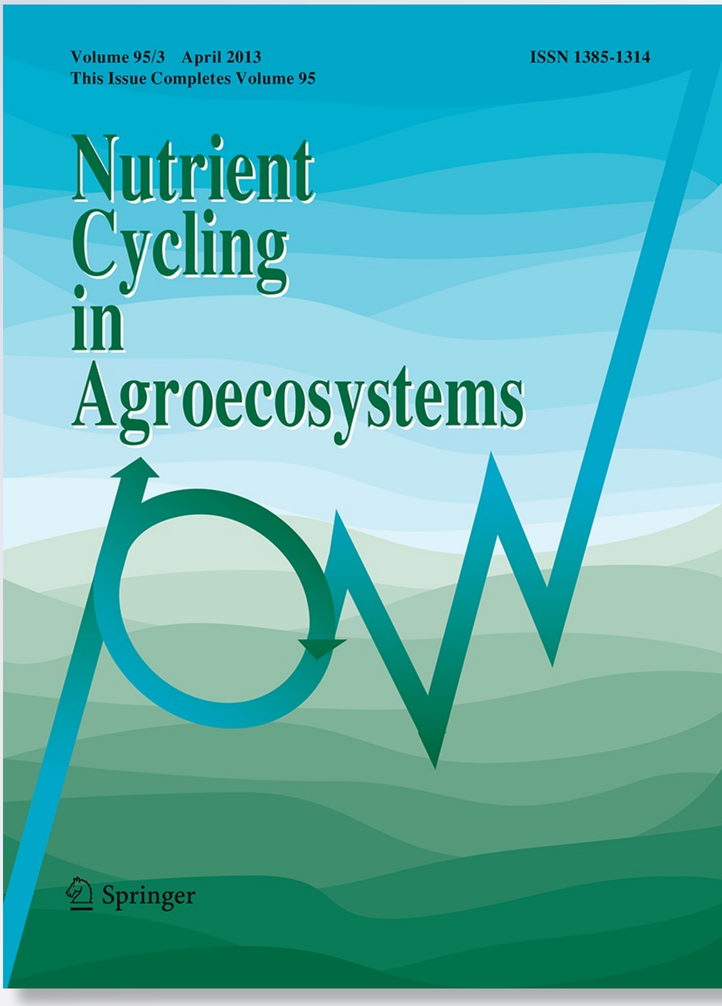

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ORIGINAL ARTICLE

Simulating the effect of long-term fertilization on maize yield and soil C/N dynamics in northeastern China using DSSAT and CENTURY-based soil model

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Abstract Simulation models are being regarded as an important tool to simulate crop growth, soil nutrient dynamics and soil carbon sequestration and fast use of the embedded knowledge of crop-soil processes. The Decision Support Systems for Agrotechnology Transfer (DSSAT) model was used to simulate long-term continuous maize growth from 1990 to 2007 in Gongzhuling, Northeast China. Three levels of N treatments were simulated, including: (1) no N (N0), (2) 165 kg N ha^{-1} from synthetic fertilizer (N165) and (3) 50 kg N ha^{-1} from synthetic fertilizer plus 115 kg N ha^{-1} from farmyard manure (N165M). Both measured and simulated results showed that the maize yield was significantly lower in the N0 treatment. The measured maize yield was higher in N165M than N165 treatments after 2003. The maize yield was also affected by the weather, especially during drought years. The simulated soil organic C (SOC) content was in good agreement with the measured data in the 0–30 cm depth for all treatments. The SOC density in the 0–30 cm depth decreased by 4,393 kg C ha^{-1} (18 %) in the N0 treatment and 4,186 kg C ha^{-1} (17 %) in the N165 treatment, while it increased by 13,628 kg C ha^{-1} (54 %) in the N165M treatment during 1990–2007, indicating that the combination of inorganic fertilizer and organic manure improved soil quality after 27 years of organic amendment from 1980. Soil mineral N levels were significantly higher in the N165 treatment just before planting (averaged 289 kg N ha^{-1}), associated with more soil N leaching during the growing seasons (24–155 kg N ha^{-1}) in some wet years, while soil mineral N levels were much lower in both the N0 (averaged 52 kg N ha^{-1}) and N165M treatments (averaged 54 kg N ha^{-1}) associated with less N leaching (<10 kg N ha^{-1}) compared with the N165 treatment. This indicated that the use of farmyard manure increased the soil organic matter and immobilized mineral N. The model results further indicated that complete crop residue removal from the field after harvest was a main reason for the decline of the SOC in the N165 treatment, suggesting that crop residue should be left on the soil to maintain the SOC balance and promote sustainable agriculture. Thus, we conclude that the DSSAT CENTURY-based module is a useful tool to simulate soil nitrogen dynamics and predict soil organic carbon sequestration in long-term field conditions.

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Introduction

Long-term field experiments are important to improve understanding of crop growth, soil carbon and nitrogen changes in relation to fertilization and crop management. About 600 long-term experiments have been established during the last half century in the world (Poulton 1995; Körschens 2006). Some notable long-term fertilizer experiments with continuous or rotation cropping for annual crops have been maintained for over 100 years including the Rothamsted long-term field experiment in England established in 1843 for evaluating fertilizer effects on wheat and barley (Barnett 1994; Leigh and Johnston 1994), long term experiments in Grignon, France in 1875 under wheat-sugar-beet rotation with different rates of fertilizer and manure (Houot et al. 1989), the Morrow Plots in Illinois, USA established in 1876 (Odell et al. 1984; Reeves 1997) under continuous corn, corn-oat or corn-soybean rotations, long-term experiment in Alberta, Canada in 1951 under continuous wheat or wheat-fallow rotation with or without chemical fertilizer or lime (Johnston et al. 1995) and a long-term experiment in Halle, Germany in 1878 under continuous rye, which was partly changed to continuous maize cropping in 1961 (Flessa et al. 2000).

Most long-term experiments have shown that the combination of synthetic fertilizer and organic manure and crop residue returns were the best management practices resulting in the highest yields and a stable soil organic C (SOC) balance, (an important soil quality indicator) (Reeves 1997; Rasmussen et al. 1998). Long-term field experiments are valuable for evaluating the simulation models because the short-term data might not closely reflect the field management (irrigation, fertilization and tillage etc.) that tend to be more sensitive to the climatic or environmental shifts, particularly for extreme changes occurring in a short-term evaluation period. Examples for the evaluations of the SOC models with long-term field experiments that have been conducted during the last decades include van Veen and Paul (1981); Parton and Rasmussen (1994); Probert et al. (1995); Kelly et al. (1997); Gijsman et al. (2002); Yang et al. (2003).

Some soil variables, i.e., N leaching loss, however, might not be measured in a long-term field experiment due to labor and cost limitations. In this situation, a process-based simulation model can be a useful tool to obtain additional outcomes from the long-term experiments. This includes the consequences of soil N leaching loss under variable management practices. Once the model has been evaluated with the measured dataset, it can be used to predict the effects of long-term agricultural management on crop yields, soil water, carbon and nitrogen dynamics for both current and future climate or management scenarios (Körschens 2006; Saseendran et al. 2007; Liu et al. 2011a, b).

Some models have been integrated with crop growth, soil water balance and soil organic C and N turnover modules to simulate the long-term effects of cropping, fertilization, rotation and tillage on crop growth and soil water, carbon and nitrogen dynamics. Examples of these models, include the STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) (Brisson et al. 2003), APSIM (Agricultural Production Systems sIMulator) (Keating et al. 2003), RothC model (Yang et al. 2003), CENTURY model (Paustian et al. 1995; Parton et al. 1988) and the Cropping System Model (CSM) of DSSAT (Decision Support Systems for Agrotechnology Transfer) model (Jones et al. 2003; Hoogenboom et al. 2010).

Soil organic matter (SOM) and C, N turnover models have been developed and integrated with different crop simulation models. A comparison of nine simulation models using 12 long-term field experiments showed that the CENTURY model (Parton et al. 1988; Parton and Rasmussen 1994) had the best performance (Kelly et al. 1997). The CENTURY SOM turnover model was integrated with the DSSAT model and performed well compared with the CERES-based soil organic model for the simulation of the SOM and SOC and soil total N (Gijsman et al. 2002).

China initiated long-term field experiments in the early 1980s. Some long-term experiments were designed to investigate the effects of long-term applications of synthetic fertilizers and manure on crop yield and soil fertility across the country (Zhang et al. 2009). These long-term experiments used the standard field experimental design (such as factorial $2 \times 2 \times 2$ randomized block design for N, P and K fertilizers) and data collection methods and some experimental results have been reported in recent years (Yang et al. 2003; Zhang and He 2004; Cai and Qin

2006; Jiang et al. 2006; Yu et al. 2006; Gong et al. 2009).

Rasmussen et al. (1998) stated that returning crop residue to the soil after harvest was a common practice in the developed nations but not in developing countries. Similarly, in most of China's long term field experiments, the entire aboveground crop residue was removed for feeding animals, fuel or bedding purposes (Yang et al. 2003; Zhang et al. 2009). In addition, continuous maize cropping with inorganic fertilizer is the most common practice for farmers in the Black soil zone, Northeast China since the 1970s, which substantially threatened the long-term agricultural sustainability and soil quality. The objective of this paper was to evaluate the effect of fertilization on the maize yields and soil organic C and soil N dynamics using the CSM-CERES-Maize model and the CENTURY-based soil module with data from a long-term continuous maize experiment in Gongzhuling, Northeast China.

Materials and methods

Long-term experiment site

A long-term fertilizer experiment was established in Gongzhuling at the center of China's 'maize belt' (43°30′ N, 124° 48′ E, elevation 220 m) in 1980, and it is part of the national soil fertility and fertilizer effects long-term monitoring network. The experimental field is located in a temperate zone with a continental monsoon climate in the Black soil (*Mollisols*) zone in the center of the Northeast Plain with an annual average air temperature of 5–7 °C, and annual sunshine hours of 2,500–2,700 h. The highest air temperature in summer (i.e., June to August) can reach up to 30 °C, and the lowest temperature in winter period (i.e., January to February) ranges from −30 to −35 °C (Fig. 1a). Average annual precipitation was 582 mm, ranging from 420 to 770 mm from 1990 to 2008, with about 70 % of the precipitation in June to August (Fig. 1b). Soils in the Black soil zone have been used for agriculture for about 100 years.

Nitrogen treatments

The original long-term fertilizer experiment includes 24 fertilizer treatments with continuous maize and each treatment was laid out in a non-replicated plot of 400 m^2 (Zhu et al. 2007). In the current study, only 3 treatments were selected for modelling: (1) N0 (zero N application), (2) N165 containing 50 kg N ha^{-1} as basal dressing and 115 kg urea N ha^{-1} as top dressing applied in late June each year (Table 1), and (3) N165M, containing 50 kg N ha^{-1} from synthetic fertilizer plus 115 kg N ha^{-1} from farmyard manure. In the N165M treatment, 16 kg N ha^{-1}, 36 kg P ha^{-1} and 68 kg K ha^{-1} were applied each year from urea, single superphosphate, and KCl, respectively, as basal dressing before planting; 22.5 Mg ha^{-1} farmyard manure (containing 115 kg N ha^{-1}, 39 kg P ha^{-1} and 77 kg K ha^{-1}) was also applied as basal dressing in the spring tillage before planting and 34 kg N ha^{-1} (urea) was applied as top dressing in late June each year (Table 1). The planting date, density, fertilization and tillage dates are summarized in Table 1.

Crop and soil management

The soil in the study site is the typical Black soil (Typic Hapludoll in USDA Soil Taxonomy) that has a clay-loam soil texture of 32 % clay, 41 % silt and 27 % sand with a profile depth of 150 cm. The average SOC in the soil profile was 12.2 g C kg^{-1}, and the total N, P and K were 1.53, 1.41 and 23.1 g C kg^{-1}, respectively at the beginning of the long-term experiment in 1980 with a soil pH value of 7.6 (Zhang et al. 2009). The measured soil physical and chemical properties in 1990 were used for this simulation study (Table 2).

The farmyard manure was applied before maize planting, usually from April 15 to 25 each year with conventional tillage (i.e., moldboard plow) and a basal dressing of synthetic fertilizers was applied on planting day (Table 1). Maize seeds were treated using carbofuran, triram and triadimefonto just prior to planting to prevent pests and fungi, and maize was planted at 8–10 cm soil depth. The planting dates varied from April 20 to April 25. Four maize cultivars were used during the 1990–2008 period (Table 1). The seedling stage was 3–4 weeks after sowing, depending on soil water content—a main limiting factor for maize seed germination and emergence in this study area, where spring is often dry. During the growing season (May to September), maize was thinned mannually to 5.0–6.0 plants m^{-2} at the three-leaf stage, then all maize treatments were cultivated twice

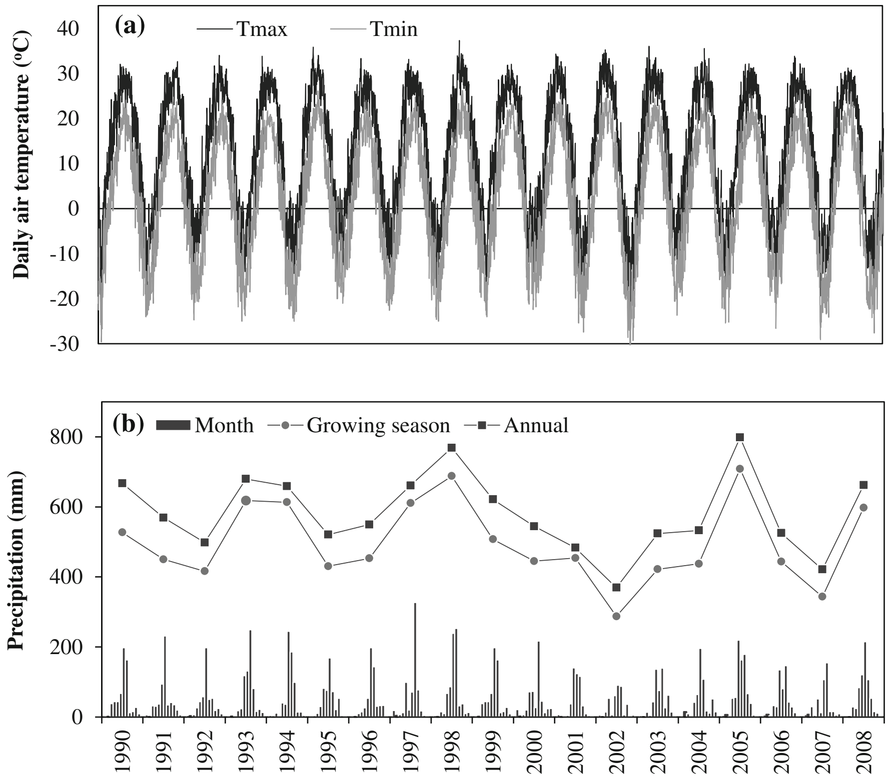

Fig. 1 **a** Daily maximum temperature (Tmax) and minimum temperature (Tmin) and **b** monthly, growing season (May to September), annual precipitation (mm) from 1990 to 2008 at Gongzhuling, Jilin, China

before June 20. Weeds were controlled by hoeing and no herbicides or pesticides were used during the growing season. After harvest, all above-ground crop residues were removed from the field, but roots were rotary tilled into the soil (20–30 cm) in late fall.

Crop yield was measured for each treatment each year, and the dry yields were calculated based on the reported yields (14 % water content). The SOC and soil total N contents were determined for the surface soil (0–30 cm) each year for each treatment.

Soil mineral N process

Soil mineral N varies over time due to the daily changes in weather, crop growth, soil microbial activities and soil water movement. In this study, the DSSAT CSM-CERES-Maize, the CENTURY-based soil C N turnover module and the soil water module were used to simulate all mineral N processes on a daily basis for the entire profile by soil layer using the daily weather data. The daily cumulative soil N dynamics and N leaching were summarized in two seasons from the N balance summary output. One cropping simulation was separated into two seasons; the maize growing season and the fallow season. The soil mineral N balance, therefore, can be simulated for the growing season (i.e., planting to harvest) and for the fallow season (i.e., post-harvest to planting the next spring) by the CENTURY-based soil module. Total mineral N input (*Ninput*) into the soil and total mineral N output (*Noutput*) of soil in the growing season can be calculated as below;

$$Nh = Np + Ninput - Noutput \quad (1)$$

$$Ninput = Nfert + Nfix + Ndepo + Nmin \quad (2)$$

$$Noutput = Ncrop + Nleach + Ndeni + Nvola + Nimob \quad (3)$$

where *Nh* and *Np* are soil mineral N after harvest and before planting, respectively; *Nfert* is fertilizer N addition; *Nfix* is the biological N_2 fixation from legume crops ($Nfix = 0$ for maize field in this study); *Ndepo* is the dry and wet deposition of atmospheric N (i.e., 20 kg N ha^{-1}, see model and calibration section for details); *Nmin* is N mineralization from the SOM N pool; *Ncrop* is N uptake by the crop; *Nleach* is N leaching loss by drainage; *Ndeni* is N denitrification via N_2O and N_2; *Nvola* is the ammonia volatilization

Table 1 Field management data for continuous maize for the N0, N165 and N165M treatments from 1990 to 2008 at Gongzhuling, Jilin, China

Years	Cultivar	Planting (date)	Plant density (plant m^{-2})	Harvest (date)	N165		N165M[a]			Farmyard manure (date)	Starter fertilizer (date)	Dress fertilizer (date)
					Starter fertilizer (kg N ha^{-1})	Dress fertilizer	Farmyard manure (kg N ha^{-1})	Starter fertilizer	Dress fertilizer			
1990	Dany13	21-Apr	5.0	25-Sep	50	115	115	16	34	19-Apr	21-Apr	23-Jun
1991	Dany13	20-Apr	5.0	24-Sep	50	115	115	16	34	19-Apr	20-Apr	22-Jun
1992	Dany13	23-Apr	5.0	27-Sep	50	115	115	16	34	19-Apr	23-Apr	25-Jun
1993	Dany13	21-Apr	5.0	25-Sep	50	115	115	16	34	19-Apr	21-Apr	23-Jun
1994	Dany13	22-Apr	5.0	26-Sep	50	115	115	16	34	19-Apr	22-Apr	24-Jun
1995	Jid304	24-Apr	5.0	28-Sep	50	115	115	16	34	19-Apr	24-Apr	26-Jun
1996	Jid304	21-Apr	5.0	25-Sep	50	115	115	16	34	19-Apr	21-Apr	23-Jun
1997	Jid209	23-Apr	5.0	27-Sep	50	115	115	16	34	19-Apr	23-Apr	25-Jun
1998	Jid209	24-Apr	5.0	28-Sep	50	115	115	16	34	19-Apr	24-Apr	26-Jun
1999	Jid209	21-Apr	5.0	25-Sep	50	115	115	16	34	19-Apr	21-Apr	23-Jun
2000	Simi25	23-Apr	6.0	27-Sep	50	115	115	16	34	19-Apr	23-Apr	25-Jun
2001	Simi25	25-Apr	6.0	25-Sep	50	115	115	16	34	19-Apr	25-Apr	27-Jun
2002	Simi25	24-Apr	6.0	28-Sep	50	115	115	16	34	19-Apr	24-Apr	26-Jun
2003	Simi25	23-Apr	6.0	27-Sep	50	115	115	16	34	19-Apr	23-Apr	25-Jun
2004	Jid209	24-Apr	5.0	28-Sep	50	115	115	16	34	19-Apr	24-Apr	26-Jun
2005	Jid209	23-Apr	5.0	27-Sep	50	115	115	16	34	19-Apr	23-Apr	25-Jun
2006	Jid209	23-Apr	5.0	27-Sep	50	115	115	16	34	19-Apr	23-Apr	25-Jun
2007	Jid209	23-Apr	5.0	27-Sep	50	115	115	16	34	19-Apr	23-Apr	25-Jun
2008	Jid209	23-Apr	5.0	27-Sep	50	115	115	16	34	19-Apr	23-Apr	25-Jun

[a] In N165M treatment, 36 kg P ha^{-1} and 68 kg K ha^{-1} were applied from single superphosphate and KCl, respectively as basal dressing, plus 39 kg P ha^{-1} and 77 kg K ha^{-1} from farmyard manure

Table 2 Soil profile data in 1990 at Gongzhuling, Jilin, China

Soil depth (cm)	Bulk density ($g\ cm^{-3}$)	Organic C N0 ($g\ kg^{-1}$)	Organic C N165 ($g\ kg^{-1}$)	Organic C N165M ($g\ kg^{-1}$)	Total N N0 ($g\ kg^{-1}$)	Total N N165 ($g\ kg^{-1}$)	Total N N165M ($g\ kg^{-1}$)	Clay (<0.002 mm) (%)	Silt (0.05–0.002 mm) (%)	Gravels (>2 mm) (%)	CEC (cmol kg^{-1})	pH in water
0–15	1.19	14.12	13.94	15.02	1.21	1.17	1.49	31.1	29.9	0.8	31.9	7.6
15–30	1.27	13.16	12.98	14.04	1.13	1.09	1.39	27.2	37.2	0.0	31.5	7.5
30–45	1.33	11.50	11.70	13.60	1.08	1.05	1.40	13.0	45.3	1.2	35.7	7.5
45–60	1.35	10.00	10.20	12.70	1.04	1.00	1.30	14.7	44.2	0.8	37.2	7.6
60–90	1.35	8.00	9.00	10.00	0.99	0.99	1.20	14.7	44.2	0.0	37.2	7.6
90–120	1.35	7.00	8.00	8.00	0.99	0.99	1.05	14.7	44.2	0.0	37.2	7.6
120–150	1.35	6.10	6.00	6.00	0.85	0.85	0.85	14.7	44.2	0.0	37.2	7.6

and *Nimob* is N immobilization by the SOM. Note that N loss by runoff was not considered in the above N balance.

Model and calibration

The DSSAT model was first released in 1989 and has been used widely to simulate crop growth and soil C and N dynamics at the field scale (Tsuji et al. 1994; Jones et al. 2003; Hoogenboom et al. 2010; Sarkar 2009). The DSSAT CSM includes six cereal models, such as CERES-Maize, CERES-Rice; one generic legume model to simulate a group of legume crops, such as CROPGRO-Soybean and CROPGRO-Bean and root crop models, such as SUBSTOR-Potato as well as the fallow model (Jones et al. 2003). DSSAT 4.5 encompasses models for 28 different crops as well as two soil modules for the simulation of soil organic C and N dynamics (CERES-based soil module, and CENTURY-based soil module) and one soil water module to simulate nutrient dynamics between plant, soil, water and atmosphere at a daily step at the field scale and/or on a rotation simulation (Gijsman et al. 2002; Porter et al. 2010). So far the dynamics of long-term crop rotations have been evaluated to a limited extent (Porter et al. 2010; Liu et al. 2011a, b; Soler et al. 2011).

Input data and format

The CSM CERES-Maize model and crop rotation option of DSSAT were used to simulate both maize growth and soil processes by the CENTURY-based SOM turnover module. Three crop management input files (i.e., SQX) were established to provide detailed information on crop planting, fertilization and tillage management for selected treatments of N0, N165 and N165M (Table 1). An atmospheric dry and wet N deposition of 20 kg N ha^{-1} was added as input of available N in three treatments in one dose at the beginning of planting based on the information obtained from other reports as below. Atmospheric dry and wet N deposition varied from 11.30 to 19.81 kg N ha^{-1} in Jilin, China (Lü and Tian 2007) and atmospheric N input of 14 kg N ha^{-1} was reported in maize fields, but 48.6 kg N ha^{-1} was reported in ryegrass fields from May to September in the North China Plain (He et al. 2007). The initial SOC conditions for N0, N165 and N165M were different at the beginning of the 1990 simulation year because the long-term field experiment was initiated in 1980.

In this study, three soil profiles were established for the N0, N165 and N165M treatments based on the measured SOC and soil total N in the N0, N165 and N165M fields in 1990 (Table 2). The runoff curve number was set to 60 in treatment N165M compared with 71 in the N165 and N0 treatments due to the fact that the manure-amended soil significantly improved in SOM after 15 years of continuous maize cropping (Yang et al. 2003; Zhang et al. 2009). Daily weather data including daily solar radiation, precipitation, and maximum and minimum air temperature from 1990 to 2008 were collected from the nearby weather station and were formatted to a weather data file (i.e.,.WTH) using the *WeatherMan* program in the DSSAT model (Pickering et al. 1994). The yearly field-measured dry maize yields, soil organic C and soil total N data from 1990 to 2007 were used for model evaluation.

To initialize the SOM fractions, the field history code (FLHST) in the DSSAT management (X file) was initially set to cultivated land with good management practices (i.e., 44 % of the SOM3 at the initial year). In this paper, the long-term field experiment was initialized in 1980 but the simulation started in 1990 (i.e., after 10 years of field management). Therefore, the ratio SOM1/SOM2/SOM3 in 1990 was set to 0.02:0.39:0.59 for N0, N165 and N165M treatments, respectively, based on the information provided by the standard data/parameter file (i.e., SOMFR045.SDA) in the DSSAT CENTURY-based soil module.

Cultivar calibration

Four maize cultivars were calibrated under normal weather conditions (i.e., growing season precipitation >400 mm) in 1990, 1995, 1998 and 2001 and with the addition of 200 kg N ha^{-1} treatment to make sure that there were no nitrogen and water stresses on maize growth during the growing season (Boote 1999; Liu et al. 2011a). The cultivar parameters included three phenological parameters to control the vegetative growth of maize in the early stage: two grain fill and yield related parameters to control grain filling and yield and one leaf parameter to control successive leaf tip appearances (Table 3). A default cultivar, IB3475, was selected from the DSSAT cultivar file for calibration, since this cultivar is in a similar climate zone to our study area (Gongzhuling, Northeast China). Four crop management files were developed for the calibration years of 1990, 1995, 1998 and 2001. The cultivar coefficients were calibrated using a *GenCalc* v2.0 program (i.e., a DSSAT support software), developed by Hunt et al. (1993). The calibration process employed a "Trial and Error" method by setting up a small change (i.e., ±5 %) of each parameter, and then setting up the maximum levels of the changes (i.e. 5 or 10). Root mean square error (RMSE) was used to find the best matched coefficient (i.e., the minimum RMSE). After calibration, the calibrated cultivar coefficients could obtain the least differences of RMSE between the simulated yields and the measured average yields under each of the calibration years (Table 3).

Table 3 The calibrated maize cultivar coefficients under no nitrogen stress condition on the experimental field using CSM-CERES-Maize in DSSAT 4.5

Cultivar	Default	Calibrated coefficients			
Calibration year Cultivar name	1990 IB3475	1990 Dany13	1995 Jidan304	1998 Jidan209	2001 Simi25
Cultivar coefficients					
P1 Time from seedling emergence to the end of the Juvenile (degree days >8 °C)	200	260	260	260	260
P2 Extent to which development is delayed for each hour (increase in photoperiod > the longest photoperiod 12.5 h)	0.7	0.725	0.725	0.725	0.725
P5 Thermal time from silking to physiological maturity	800	913	840	924	890
G2 Maximum possible number of kernels per plant	797.5	567	660	592.4	594
G3 Kernel optimum filling rate during the linear filling stage (mg day^{-1})	8.6	8.113	9.32	9.684	7.156
PHINT Phylochron interval between leaf tip to emergence (degree days)	39.8	37.9	38.9	38.9	38.9

Statistical evaluation methods

A simulated variable is represented by y_i and a measured variable by x_i ($i = 1, 2, \ldots, n$). Several evaluation statistics were employed to evaluate the performance of the model. They are mean error (E) and the normalized RMSE (nRMSE) (Willmott 1982; Liu et al. 2011a, b). In addition, a paired t statistic was employed to test significance of the mean error E, and R^2 (using the $y = a+bx$ model) was used to test the linear relationship between simulated and measured data (Yang et al. 2000). The EasyGrapher program was used to carry out graphical and statistical evaluation of the model outputs with measured data (Yang and Huffman 2004; Yang et al. 2010). There are no statistically significant levels for using the nRMSE ($0 \leq$ nRMSE ≤ 100 %) statistic. For the purposes of evaluating the degree of match between simulated and measured values in a small sample dataset of 18 (Table 4) in this study, here we arbitrarily consider nRMSE ≤ 15 % as a"good" match; 15–30 % as a"moderate"match; and $\geq$30 % as a "poor"match.

Results and discussion

Crop yield evaluation

During the 1990–2007 period, the maize grain yields varied from 1,319 to 4,666 kg ha^{-1} (average of 3,218 kg ha^{-1}), 3,736–9,430 kg ha^{-1} (average of 6,623 kg ha^{-1}) and 3,928–10,263 kg ha^{-1} (average of 7,674 kg ha^{-1}) for the N0, N165 and N165M treatments, respectively (Table 4; Fig. 2). The lowest and highest yields were found in 2002 and 1999, respectively, for all treatments. The lowest yield in 2002 was mainly caused by both drought? and soil N stresses for the N0 treatment, and by only water stress for the N165 and N165M treatments during the grain filling stage as precipitation during the growing season was only 287 mm in 2002 compared to 507 mm in 1999 (the normal year) (Fig. 1). Grain yield was doubled for the N165 treatment compared to the N0 treatment, and the yield increased on average by 16 % for the N165M treatment compared to the N165 treatment (Fig. 2). Other studies also showed that organic manure with synthetic fertilizer applications increased the grain yields compared to pure synthetic N, P and K fertilization (Yang et al. 2004; Cai and Qin 2006; Pypers et al. 2012; Vanlauwe et al. 2011). Significant improvement of yield in the maize cropping system was achieved during 2003–2007, i.e. after 23 years of the long-term experiment (Zhang et al. 2009).

The simulated dry yield generally mimicked measured yield for most years although larger discrepancies were found in 1999–2001 and 2003 for the N0 treatment (Fig. 2a), in 1992, 1995, 1997, 2001, 2004 and 2005 for the N165 treatment (Fig. 2b), and in 1992, 1994, 1999–2000 and 2003 for the N165M treatment (Fig. 2c). An overall R^2 value of 0.65 was achieved between the simulated and the measured maize yield for the three treatments (Table 4). As affected by these larger differences, the model generally showed larger RMSE values of 1,146, 1,482 and 1,749 kg ha^{-1} for the N0, N165 and N165M treatments; however, the mean errors E were 602, 685 and $-1{,}050$ kg ha^{-1} for the N0, N165 and N165M treatments, respectively (Table 4). An overall paired t of 0.39 ($p = 0.70$) indicated no statistical significant differences between the simulated and the measured maize yields although the mean error, E values were significant for each treatment with certain significant levels (i.e., the paired-t was 2.55 ($p = 0.021$) for N0, 2.15 ($p = 0.046$) for N165 and -3.10 ($p = 0.007$) for the N165M treatments (Table 4). nRMSE values were 36, 22 and 23 % for the N0, N165 and N165M treatments, respectively, indicating that a "poor" match was achieved for the N0 treatment, while "moderate" agreement was achieved for the N165 and N165M treatments between the simulated and the measured maize yields (Table 4).

Further analysis showed that the low simulated and measured maize yields in 2000 and 2002 were typically caused by water stresses due to low rainfall in July 2000 (27 mm) and in May 2002 (6 mm) (Fig. 1). From the simulated summary record, it was found that the lower rainfall in May 2002 resulted in a smaller maximum leaf area index of 0.97 compared with the large ranges of the maximum leaf area index values of 4.0–4.5 in normal rainfall years. The low rainfall in July 2000 resulted in a low harvest index of 0.18 compared with average ranges of harvest index values of 0.40–0.50 in normal years.

Maize yield was overestimated in 1995 and 2001 for the N165 treatment, but not for the N165M treatment. This can be explained by a shortage of P and K nutrients in the N165 treatment compared with the

Table 4 Statistical evaluation of final grain yield, soil organic C and N at the 0–30 cm soil depth

Variables	Treatments	Simulated	Measured	Sample No	RMSE	n-RMSE (%)	E	Paired t	P[a]	Paired t (3 treatments)	P (3 treatments)	R^{2b}
Dry grain yield	N0	3,820	3,218	18	1,146	36	602	2.55	0.021			0.65
(kg ha^{-1})	N165	7,308	6,623	18	1,482	22	685	2.15	0.046	0.39	0.70	
	N165M	6,624	7,674	18	1,749	23	−1,050	−3.10	0.007			
Soil organic C	N0	11.80	12.86	18	1.58	12	−1.07	−3.77	0.002			0.66
(g C kg^{-1})	N165	11.89	12.73	18	1.26	10	−0.85	−3.76	0.002	−3.13	0.00	
	N165M	16.69	16.59	18	1.72	10	0.10	0.23	0.817			
Soil total N	N0	1.41	1.25	18	0.19	15	0.16	6.84	0.000			0.57
(g N kg^{-1})	N165	1.43	1.25	18	0.22	18	0.18	5.49	0.000	7.45	0.00	
	N165M	1.72	1.60	18	0.23	15	0.12	2.58	0.019			

[a] Significant probability levels for the corresponding t values

[b] R^2 was calculated from N0, N165 and N165M for yield, and only from N165M for soil organic C and soil total N

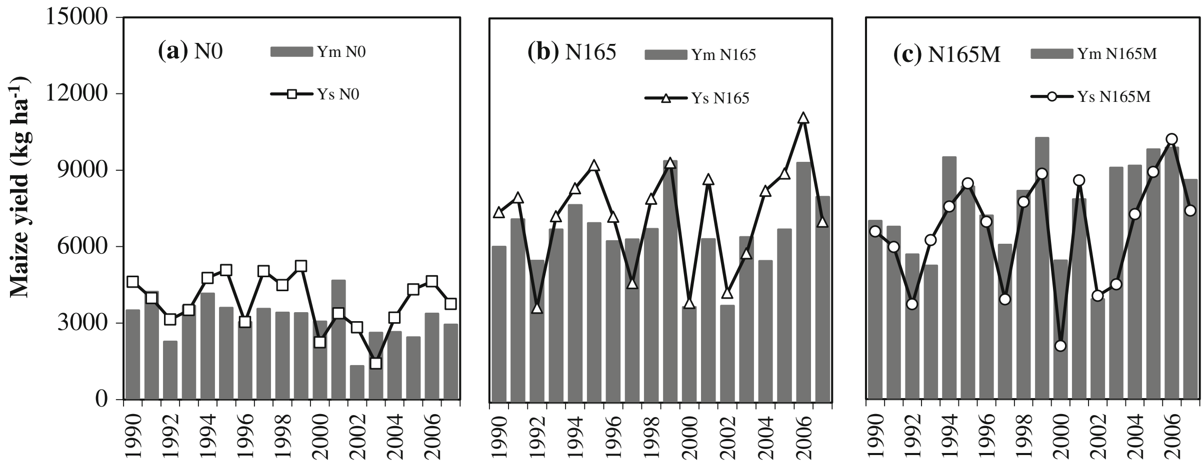

Fig. 2 Comparison of measured (Ym) and simulated (Ys) maize grain yield under N0, N165 and N165M treatments from 1990 to 2007 at Gongzhuling, Jilin, China

N165M treatment which contained ample P, K and other nutrients. Nevertheless, our results showed that the accuracy of the simulated maize yields was comparable to other model's performances (O'Neal et al. 2002; Liu et al. 2011a; Monzon et al. 2012).

SOC and soil total N evaluation

The measured SOC concentration fluctuated through the years, and changed from 12.4 g C kg^{-1} in 1990 to 13.4 g C kg^{-1} in 2007 for the N0 treatment, from 11.7 g C kg^{-1} in 1990 to 12.9 g C kg^{-1} in 2007 for the N165 treatment, and from 13.6 g C kg^{-1} in 1990 to 21.0 g C kg^{-1} in 2007 for the N165M treatment. The simulated SOC decreased gradually from 13.0 g C kg^{-1} in 1990 to 11.0 g C kg^{-1} in 2007 for the N0 treatment, from 13.0 g C kg^{-1} in 1990 to 11.2 g C kg^{-1} in 2007 for the N165 treatment, but it increased from 14.1 g C kg^{-1} in 1990 to 18.7 g C kg^{-1} in 2007 for the N165M treatment (Fig. 3a, b, c).

The simulated SOC for the N0 and N165 treatments were 1.3–3.0 g C kg^{-1} lower than the measured values in 1998–2001 and 2005–2007 (Fig. 3a, b). For this reason, the mean errors E of −1.07 and −0.85 g C kg^{-1} for the N0 and N165 treatments respectively showed significant differences from zero for the paired t tests (Table 4). However, the simulated SOC matched the measured data well from 1990 to 2007 for the N165M treatment (Fig. 3c) and the mean error E of 0.10 g C kg^{-1} for the N165M treatment

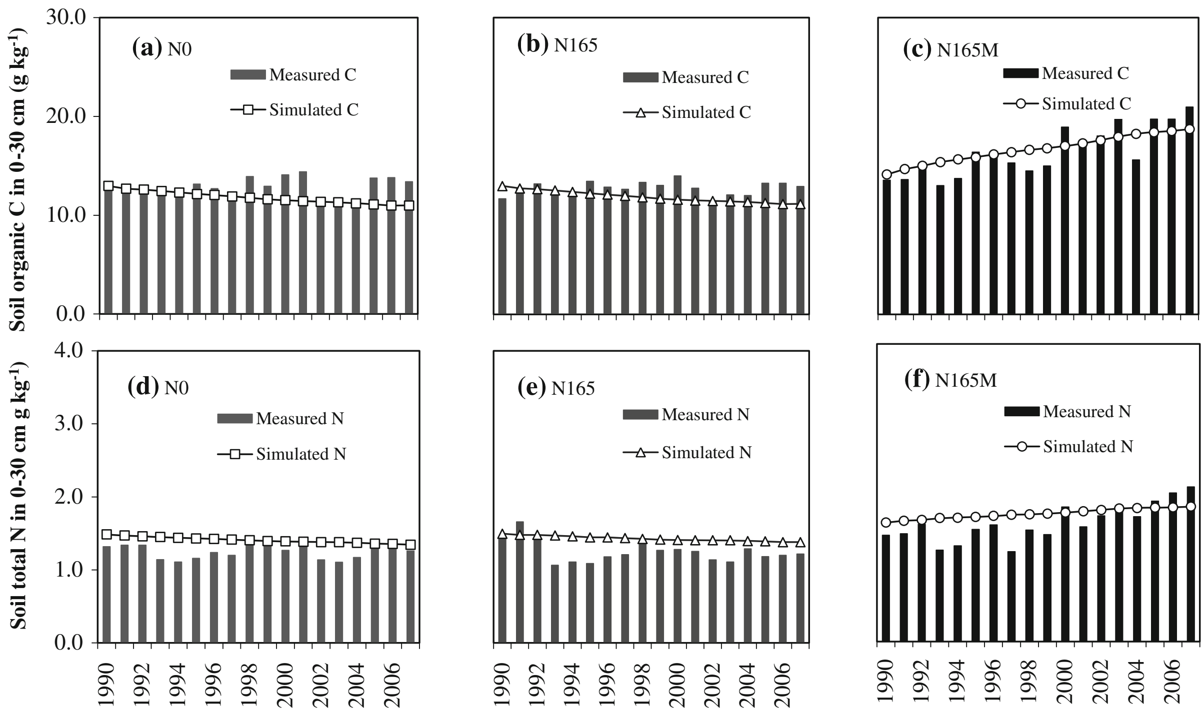

Fig. 3 Comparison of measured and simulated soil organic C and total N contents under N0, N165 and N165M treatments from 1990 to 2007 at Gongzhuling, Jilin, China

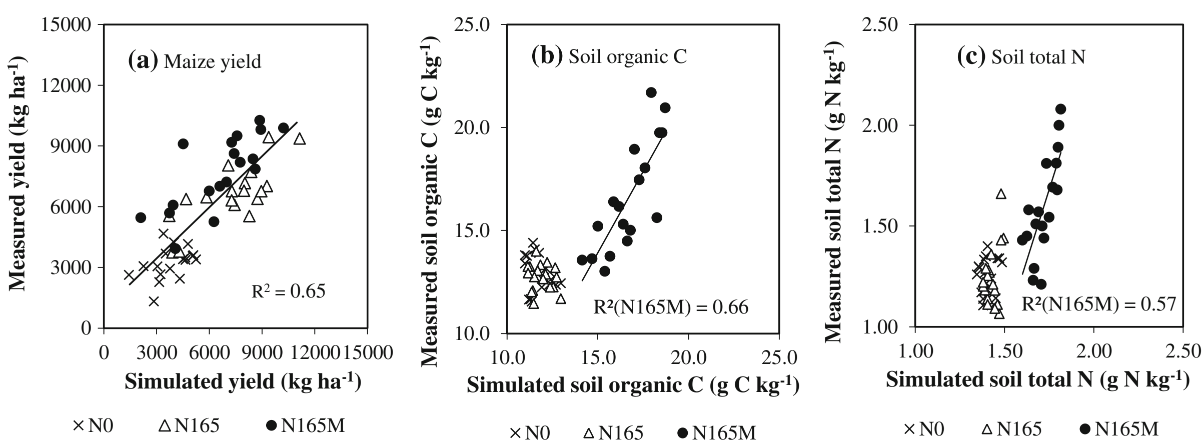

Fig. 4 Relationship between measured and simulated maize yield (**a**), soil organic C (**b**) and total N (**c**) at the 0–30 cm depth from 1990 to 2007 at Gongzhuling, Jilin, China. An overall $R^2 = 0.65$ (Fig. 4a) was achieved between the simulated and measured yield for the three treatments; the separated $R^2 = 0.66$ (Fig. 4b) and $R^2 = 0.57$ (Fig. 4c) were achieved between the simulated and measured SOC and soil total N, respectively, for the N165M treatments and there were no linear relationships for the N0 and N165 treatments (i.e., $R^2 = 0.1$)

showed no statistical difference from zero for the paired t test ($t = 0.23$, $p = 0.82$) (Table 4).

Based on nRMSE criteria, the SOC was in the "good" match range with the measured data under the N0 (nRMSE = 12 %), the N165 (nRMSE = 10 %) and the N165M (nRMSE % = 10 %) treatments. In addition, it was found that the groups for N0 and N165 were different from the N165M treatment between the simulated and measured SOC (Fig. 4b). The simulated SOC under the N165M treatment moderately mimicked the linear increasing trend of the measured SOC (i.e. $R^2 = 0.66$). Joint analysis by three treatments dataset did not improve the R^2 and group analysis of both N0 and N165 dataset did not obtain a linear trend (i.e., $R^2 = 0.1$) (Table 4; Fig. 3c; Fig. 4b). Our results indicated that the CENTURY based soil module simulated SOC in good agreement with the measured data, similar to or better than the performance of other soil carbon models (Smith et al. 1997; Yang et al. 2003).

Measured soil total N varied from 1.11 to 1.40, 1.07–1.66 and 1.21–2.08 g N kg^{-1} for the N0, N165 and N165M treatments, respectively during 1990–2007. Comparing the initial values of 1.32, 1.44 and 1.43 g N kg^{-1} with their final values of 1.26, 1.22 and 2.08 g N $kg^{-1}$for the N0, N165 and N165M treatments, respectively, soil total N declined by 4.6 and 15.3 % for the N0 and N165 treatments, but increased by 45.5 % for the N165M treatment (Fig. 3a, b, c).

The simulated soil total N changed from 1.49, 1.50 and 1.60 g N kg^{-1} in 1990 to 1.35, 1.38 and 1.82 g N kg^{-1} for the N0, N165 and N165M treatments, respectively. Similar to the measured data, the simulated soil total N declined by 9.4 and 7.7 % for the N0 and N165 treatments, respectively, but increased by 13.4 % for the N165M treatment during the same 17 year period. The results also showed that the simulated soil total N had a small yearly variation compared with the measured soil total N (Fig. 3a, b, c).

Statistical evaluation showed significant mean errors of E = 0.16, 0.18 and 0.12 g N kg^{-1} for the N0, N165 and N165M treatments (Table 4). Nevertheless, the nRMSE values of 15, 18 and 15 % showed that the simulated soil total N was in "good" agreement with the measured data for the N0 and N165M treatments, and "moderate" agreement for the N165 treatment. Similar to SOC, the simulated soil total N under the N165M treatment generally mimicked the linear increasing trend of the measured data ($R^2 = 0.57$) while the groups for N0 and N165 showed a different cluster (Fig. 4c). Joint analysis of soil total N by three treatments dataset did not improve the R^2, and group analysis of both the N0 and N165 dataset did not obtain a linear trend (i.e., $R^2 = 0.1$) (Table 4; Figs. 3f, 4c).

Simulated soil mineral N balance

The above section discussed only soil total N changes (soil mineral N plus soil N in organic matter) from 1990 to 2007. Based on the Eqs. (1–3), the simulated cumulative daily soil mineral N and N leaching losses at planting and harvest time for three treatments were depicted in Fig. 5.

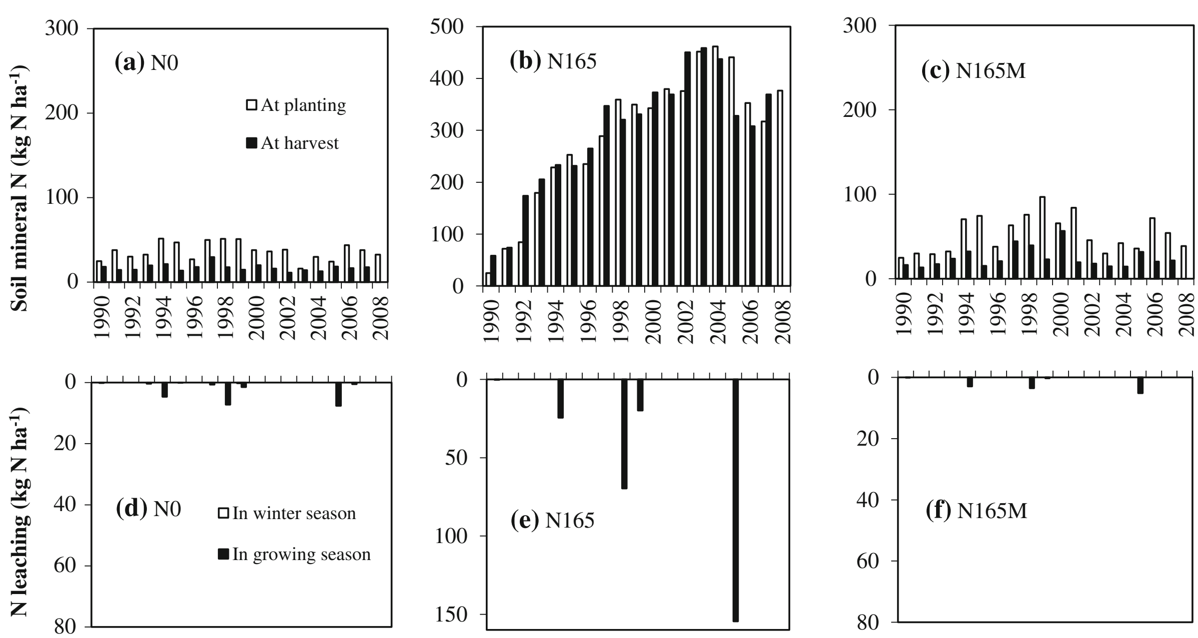

Fig. 5 Comparison of the simulated soil mineral N and N leaching loss prior to planting and post-harvest under N0 (**a, d**), N165 (**b, e**) and N165M (**c, f**) treatments from 1990 to 2008 at Gongzhuling, Jilin, China

In the N0 treatment, the soil mineral N level was two times higher in the spring (before planting) than after harvest (Fig. 5a). For example, soil mineral N averaged 37.4 kg N ha^{-1} in the spring (range 16.1–51.4 kg N ha^{-1}) and averaged 17.1 kg N ha^{-1} after harvest (range 11.1–29.7 kg N ha^{-1}) from 1990 to 2008 (Fig. 5a). N leaching loss was less than 2 kg N ha^{-1} in most years except that notable N leaching of 4.6, 7.2 and 7.6 kg N ha^{-1} occurred during the 1994, 1998 and 2005 growing seasons, respectively (Fig. 5d). The lower values of soil mineral N after harvest under the N0 treatment were due to lower amounts of N input of 107 kg N ha^{-1} (i.e., 20 kg N ha^{-1} from atmospheric deposition plus 87 kg N ha^{-1} mineralization from root residue and SOM and relatively higher amounts of N output of 127 kg N ha^{-1} during the growing seasons from 1990 to 2007.

Soil mineral N levels were much higher in the N165 than in the N0 treatment, ranging 25–462 kg N ha^{-1} (average 289 kg N ha^{-1}) before planting, 58–459 kg N ha^{-1} (average 296 kg N ha^{-1}) at harvest from 1990 to 2007, and no difference was found between soil mineral N levels in spring and after harvest (Fig. 5b). Substantial soil N leaching of 24, 70, 20 and 155 kg N ha^{-1} was found in the 1994, 1998, 1999 and 2005 growing seasons, respectively, and no soil N leaching was found during the fallow season (Fig. 5e), because of dry weather conditions in the fallow season (Fig. 1) and the soil was frozen from November to March in the study area. Soil N leaching loss was highly correlated with the growing season rainfall. For example, the average growing season rainfall was 498 mm from 1990 to 2008, but the growing season rainfall was 613, 688 and 709 mm in 1994, 1998 and 2005, respectively (Fig. 1), with 23, 38 and 42 % more rainfall in 1994, 1998 and 2005 relative to the 1990–2007 average.

For the N165M treatment, soil mineral N ranged from 13 to 96 kg N ha^{-1} during the 18 year period (Fig. 5c), and it was also two times greater prior to planting (average 54 kg N ha^{-1}) than at post-harvest (average 25 kg N ha^{-1}) (Fig. 5c). Soil mineral N levels were also lower under N165M compared with the N165 treatment because N output (calculated by the Eq. 3) averaged 412 kg N ha^{-1} in the N165M, but N input averaged 382 kg N ha^{-1} during the growing season from 1990 to 2007. Consequently, this negative mineral N balance during the growing season consumed the most of the soil mineral N that was mineralized during the fallow season. Soil mineral N leaching was 3, 4 and 5 kg N ha^{-1} in 1994, 1998 and 2005 under the N165M treatments (Fig. 5f), similar to the N0 treatment (Fig. 5d) but much lower than the N165 treatment (Fig. 5e) which can be explained by both an increased plant N uptake and lower rate of synthetic fertilizer N application as well as a slow release of soil mineral N from the applied farmyard manure (Fig. 5c).

Our simulation results indicated that single synthetic fertilizer N (N165) treatment resulted in higher soil mineral N level in the soil profile and high N leaching loss compared to the synthetic fertilizer N plus manure treatment (N165M). This can be explained by the fact that the balanced fertilization treatment (N165M) contained 50 kg N ha^{-1} from synthetic fertilizer and 115 kg total N ha^{-1} (i.e., organic N plus mineral N) from manure, and organic N was mineralized in the soil slowly during the growing season.

Simulated SOC and total N density

The CENTURY-based soil module in DSSAT simulates SOC based on three SOM pools plus a surface/soil litter layer. This includes an active (microbial) SOM (SOM1) that exists in both the soil surface and soil profile as a result of decomposition of metabolic material from the surface or soil litter, an intermediate SOM (SOM2) pool that is a result of the decomposition of the SOM1 material or the structural material from the surface or soil litter, and a passive SOM (SOM3) pool that receives SOM materials from SOM1 and SOM2 and vice versa (Gijsman et al. 2002; Jones et al. 2003). There are default values of the C/N ratio in each SOM pool; i.e., C/N = 10 and 17 for SOM1 and SOM2 that can be updated by user-specified values, while C/N = 7 for SOM3 cannot be overwritten by users (Gijsman et al. 2002). The simulated SOC and soil total N density and C/N ratio in the 0–15 cm soil profile at planting from 1990 to 2007 are given in Table 5.

Total SOC density declined by 4,393 and 4,186 kg C ha^{-1} for the N0 and N165 treatments, respectively (Table 5), and most of the decrease in the SOC was from the SOM1 and SOM2 pools because no aboveground residue was returned to the soil after harvest and there was no manure application in the N0

Table 5 The simulated soil organic C and total N concentrations and C/N ratio in the active SOM (SOM1) pool, intermediate SOM (SOM2) pool, passive SOM (SOM3) pool in the 0–15 cm soil depth using the CENTURY-based SOM-residue module

Treatment	Years	C (kg C ha^{-1})				N (kg N ha^{-1})				C/N ratio				SOM1/SOM2/SOM3		
		Total				Total				Total						
		SOM	SOM1	SOM2	SOM3	SOM	SOM1	SOM2	SOM3	SOM	SOM1	SOM2	SOM3	SOM1	SOM2	SOM3
N0	1990	24,864	510	9,684	14,670	2717	51	570	2,096	9.2	10.0	17.0	7.0	0.02	0.39	0.59
	2007	20,471	210	5,155	15,106	2,465	15	293	2157	8.3	14.0	17.0	7.0	0.01	0.25	0.74
	Difference	−4,393	−300	−4,529	436	−252	−36	−277	61							
N165	1990	24,864	510	9,684	14,670	2,717	51	570	2096	9.2	10.0	17.0	7.0	0.02	0.39	0.59
	2007	20,678	209	5,343	15,126	2,509	18	330	2161	8.2	11.6	16.2	7.0	0.01	0.26	0.73
	Difference	−4,186	−301	−4,341	456	−208	−33	−240	65							
N165 M	1990	26,472	543	10,311	15,618	2,892	54	607	2231	9.2	10.1	17.0	7.0	0.02	0.39	0.59
	2007	40,100	2,164	21,026	16,910	3,696	165	1117	2414	10.8	13.1	18.8	7.0	0.05	0.52	0.42
	Difference	13,628	1,621	10,715	1,292	804	111	510	183							

and N165 treatments. More SOC loss was found in the N0 treatment than from the N165 treatment since there was less C input from root residue in the N0 than in the N165 treatment. Manure application with synthetic fertilizer resulted in a large SOC increase (13,628 kg C ha^{-1}) in N165M (Table 5). The increase of SOC mainly occurred for the SOM2 (10,715 kg C ha^{-1}) pool when compared to the SOM1 (1,621 kg C ha^{-1}) and the SOM3 (1,292 kg C ha^{-1}) pools, respectively (Table 5).

Other studies have also indicated that zero fertilization results in significant loss of SOC compared to fertilized treatments (Odell et al. 1984; Jenkinson 1991; Reeves 1997) and in China (Yang et al. 2003; Jiang et al. 2006; Yu et al. 2006; Gong et al. 2009). The declines in SOC for the N0 treatment and increases for the N165M treatment were also reported by the simulated results from the Roth C model at the same research site (Yang et al. 2003). Similarly, CENTURY based module simulation by using the Rothamsted experiment showed that most of the decline of SOM was from the SOM2 pool after 40 years (Gijsman et al. 2002).

The annual soil total N balance ranged from −98 to 14 kg N ha^{-1} for the N0 treatment (Fig. 6a), −99–39 kg N ha^{-1} for the N165 treatment (Fig. 6b) and −44–119 kg N ha^{-1} for the N165M treatment (Fig. 6c). Total N for the above three SOM pools was calculated on a daily time step based on the C/N ratio of SOM. An annual balance of total N in the organic soil N pool can be calculated from the difference between total N inputs from all organic N sources (i.e., N from crop residue, from manure application, from senescence N in the later stage of plant growth and from N immobilized by organic materials) and total N output from the organic N pool (i.e., N mineralization from the SOM N pools).

Soil total N density in the 0–15 cm layer declined by 252 and 208 kg N ha^{-1} for the N0 and N165 treatments, respectively, while it increased by 804 kg N ha^{-1} for the N165M treatment during the 1990–2007 period (Table 5). The above results indicate that soil total N decreased annually at a rate of 14.9 kg N ha^{-1} (i.e., 252 kg N ha^{-1} divided by 17 years) for the N0 and 12.2 kg N ha^{-1} for the N165 treatments, but increased by 47.3 kg N ha^{-1} annually in the N165M treatment. The C/N ratios increased from 10.0 to 14.0 in the N0 treatment, to 11.6 in the N165 treatment and to 13.1 in the N165M

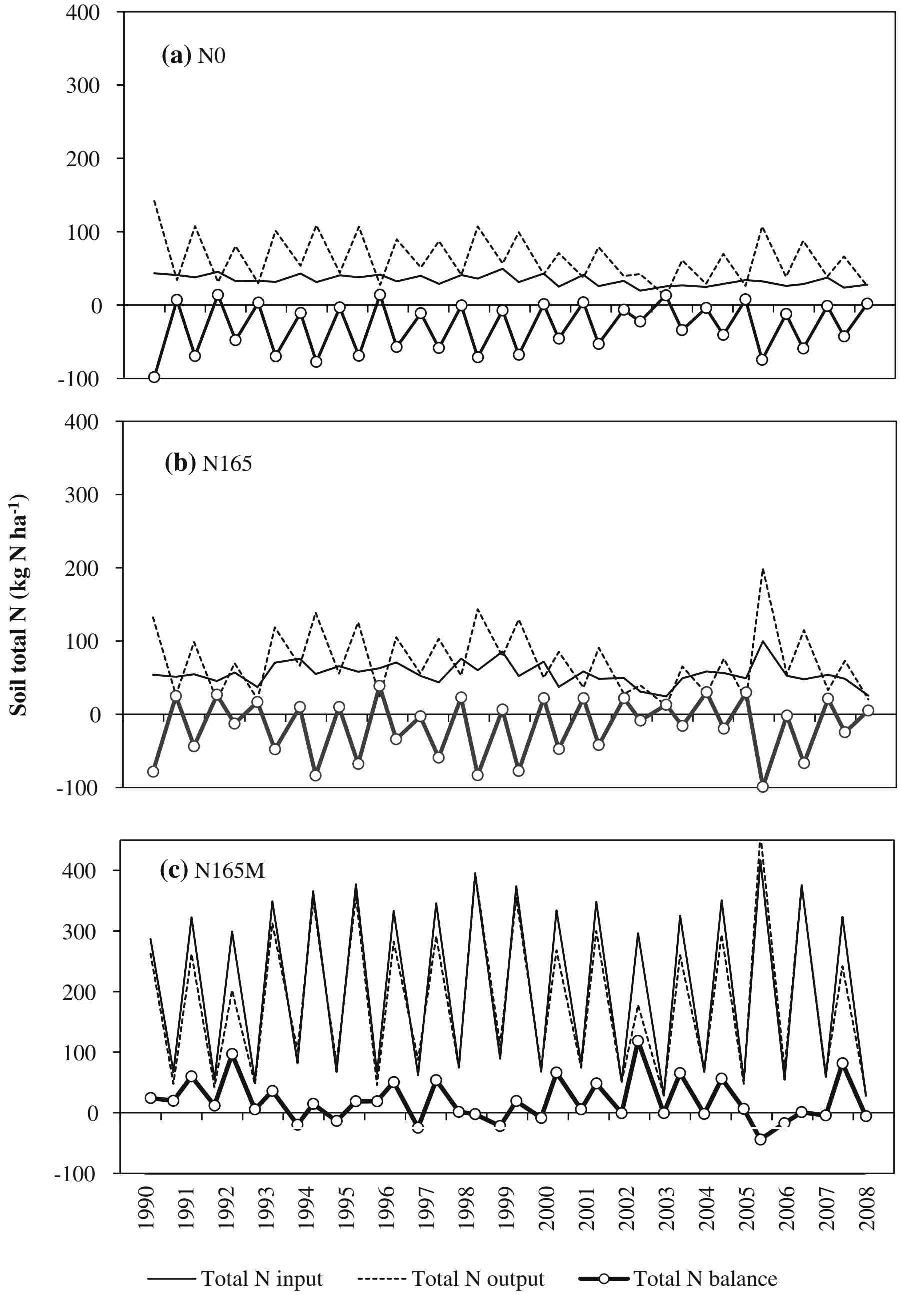

Fig. 6 Comparisons of the simulated seasonal soil total N balance under N0, N165 and N165M treatments from 1990 to 2008 at Gongzhuling, Jilin, China

treatment in the SOM1 pool. The C/N ratios for the SOM2 pool did not change significantly in the N0 and N165 treatments, but it increased from 17.0 to 18.8 in the N165M treatment. The weighted averages of the simulated C/N ratios of total SOM from three pools changed from 9.2 to 8.3, and from 9.2 to 8.2 for N0 and N165, respectively, but it increased from 9.2 to 10.8 in the N165M treatment from 1990 to 2007 due to the larger increases of SOC in the SOM2 pool from manure application in the N165M treatment.

The ratio of SOM1/SOM2/SOM3 was set to 0.02/0.39/0.59 for three treatments in 1990, and after 17 years, the ratio changed to 0.01/0.25/0.74 for the N0 treatment, to 0.01/0.26/0.73 for the N165 treatment, indicating larger decreases of SOM2 C in the N0 and N165 treatments, but the ratio changed to 0.05/

0.52/0.42 for the N165M treatment, indicating a larger increase in the SOM2 C in the N165M treatment because of the farmyard manure amendment effect.

Summary and conclusions

Under current continuous maize cropping production in Northeast China, higher crop yields have been maintained by applying higher amounts of synthetic nitrogen fertilizer since the 1980s. This research demonstrated that a balanced fertilization of synthetic and organic fertilizers not only maintained high maize yields but also improved soil organic carbon storage. On the other hand, not only the zero N fertilizer but also the single synthetic fertilizer N management led to a decline in SOC after 28 years (1980–2008) of continuous maize cropping in the Black soil region.

The CSM-CERES-Maize model with the CENTURY-based soil module was able to successfully simulate maize yield, soil nitrogen (mineral N and soil total N) and soil organic carbon dynamics in the long-term field experiment in Northeast China. The results showed in general a “moderate” match for crop yields and “good” match for SOC, and “moderate” to “good” match for soil total N. The model also successfully simulated soil mineral N balance and demonstrated that high soil nitrate leaching loss was the consequence of high amounts of synthetic fertilizer N (N165) application compared with the manure (N165M) addition.

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