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Evaluation of the DSSAT-CSM for simulating yield and soil organic C and N of a long-term maize and wheat rotation experiment in the Loess Plateau of Northwestern China

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A B S T R A C T

The aim of this study was to evaluate the potential of the Decision Support System for Agrotechnology Transfer – Cropping System Model (DSSAT-CSM) using the CENTURY-based soil module to simulate long-term trends of grain yield, soil organic C (SOC) and soil organic N (SON) based upon 14-year data from a spring maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) cropping system study conducted in the Loess Plateau of Northwestern China. There were four treatments including no fertilizer (N0), 90 kg N ha^{-1} from urea (N90), 30 kg N ha^{-1} from straw plus 90 kg N ha^{-1} from urea (SN90), and 40 kg N ha^{-1} from cattle manure plus 90 kg N ha^{-1} from urea (MN90) selected in this study. The DSSAT-CSM showed a good to excellent agreement for simulating maize yields with normalized root mean square error ($nRMSE$) ≤ 19%, index of agreement (d) > 0.91 and modeling efficiency (EF) ≥ 0.56, and a moderate to good agreement for wheat yields with $nRMSE$ ≤ 22%, d > 0.89 and EF > 0.46 for N90, SN90 and MN90 treatments. The model simulated SOC in the 0–20 cm depth for both SN90 and MN90 very well with $nRMSE$ < 13% and d > 0.63 and moderately for N90 and N0. The simulated topsoil SON matched the measured data for N90, SN90 and MN90 very well with $nRMSE$ < 7%, d > 0.77 and EF > 0.15, whereas the simulation for N0 was poor. Both maize wheat yields were found to be more sensitive to the fertilizer N rates in humid than drought soil conditions. The sensitivity of grain yields for either maize or wheat to generated growing season precipitation was affected by fertilizer N rate. The simulated soil nitrate-N (NO_3-N) in soil profile and the NO_3-N leaching below 150 cm increased with the increased fertilizer N rates as expected. The periods occurring high NO_3-N leaching were along with drainage events mainly in the next fallow periods. Therefore, this study found that the DSSAT-CSM has a large potential to assess the impacts of various agricultural practices on crop growth, soil C and N dynamics in the semi-arid to semi-humid region of the Loess Plateau, and could contribute to selecting the optimum management practices.

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1. Introduction

Interdisciplinary analysis using a systems approach is required to better understand the complexity of agricultural systems and the need to fulfill multiple objectives in sustainable agro-ecosystems (Kropff et al., 2001). Model simulation is one of the specific techniques used in a systems approach as it takes less time, is more cost effective and does not have the space requirements associated with running long-term field trials (Jones et al., 2003). Most importantly, the modeling study could help to interpret experiments and explain why the observed results were achieved and what factors could be manipulated to change them (i.e., understand the processes within the system). The APSIM (Agricultural Production Systems Simulator) (Keating et al., 2003), STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) (Brisson et al., 2003) and DSSAT (Decision Support System for Agrotechnology Transfer) (Jones et al., 2003) models are among the most popular and widely used process-based crop growth simulation models. These three models can be used to simulate crop biomass, grain yields, soil water and nitrogen balances in daily time steps under different cropping systems, agricultural practices, and climatic zones. The CENTURY model (Parton et al., 1987, 1988) was found to be among the best models used to simulate soil organic carbon, N and residue dynamics (Gijsman et al., 2002; Parton and Rasmussen, 1994). The soil organic matter-residue module in the CENTURY model was incorporated to the DSSAT model, and using

Abbreviations: DSSAT, Decision Support System for Agrotechnology Transfer; CSM, Cropping System Model; SOC, soil organic carbon; SON, soil organic nitrogen; NO_3-N, nitrate nitrogen.

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experimental data, it was found to improve the simulations for low-input cropping systems and for conducting long-term sustainability analyses (Gijsman et al., 2002). The DSSAT model and the CENTURY-based soil module option were selected for the present study as described below.

The DSSAT model has been used worldwide to simulate crop biomass and yield, and soil N leaching under different management practices and various climatic conditions (Jones et al., 2003). It has also proven to be a useful tool for selecting improved agricultural practices (Sarkar, 2009). In terms of model structure, the DSSAT model is a collection of independent programs (such as crop, weather, soil and water modules) that operate together, with the cropping system model (CSM) as the core of the DSSAT model which greatly simplifies the simulation of crop rotations (Jones et al., 2003). The Sequence Analysis program in DSSAT is used to simulate crop sequences over any number of years, such as would occur in crop rotations and it is also used for studying the long-term effects of different management practices on growth, development and yield of a crop, as well as the soil water, carbon and nitrogen processes, with emphasis on time trends and variability (Thornton et al., 1994, 1995; Tsuji et al., 1994).

If the DSSAT model could accurately predict responses using observed data from long-term experiments, then it could also be used to provide credible predictions of changes in management practices under various site-specific conditions on crop yields and soil quality (Timsina and Humphreys, 2006). In recent years, a few studies have been conducted to evaluate the performance of the DSSAT-CSM and CENTURY-based soil module using data from long-term rotation or continuous cropping system experiments. For example, Timsina and Humphreys (2006) reviewed the performance of CERES-Rice and CERES-Wheat models for the long-term rice–wheat rotation systems in Asia and Australia, and found that both the models performed reasonably well in predicting the long-term (20 year) trends in rice and wheat yields under no water and N stress conditions. Thorp et al. (2007) simulated the long-term effects of different N application rates on corn production and subsurface nitrate-N concentration in drainage water in Iowa using the DSSAT model. Liu et al. (2011) simulated the crop yield and nitrogen dynamics under a 50 year continuous maize production experiment in Canada using the DSSAT model. Tojo Soler et al. (2011) evaluated the performances of the DSSAT-CSM and CENTURY-based soil module in predicting crop yield and SOC dynamics for different crop rotations and fertilizer levels using the observed data set from an experiment conducted in a semi-arid region of West Africa during 1993 to 2004, and found that the model performed differently with different treatments.

In China, a network of long-term fertilizer experiments have been established since the early 1980s across the main croplands of China (Zhao et al., 2010), which could provide the data sources for evaluating and improving a crop-soil simulation model, such as DSSAT. Based on the yield data from agricultural experimental stations (1998–2000) and county-scale census (1980–2000), Xiong et al. (2008) evaluated the performance of the CERES-Wheat module of DSSAT in simulating regional spatial and temporal patterns of wheat production in China. Using the DSSAT and its CENTURY-based soil module, Yang et al. (2013) simulated the effects of long-term fertilization on maize yield and soil C, N dynamics from 1990 to 2007 under continuous maize system based on the experimental data in northeastern China. However, in China, the evaluation of the DSSAT model performance in predicting long-term trends in grain yields, soil organic C (SOC) and soil organic N (SON) under two or more crop rotation system has rarely been reported. A well maintained long-term spring maize and winter wheat rotation experiment was conducted in Gansu province of northwestern China (Fan et al., 2004, 2005a; Liu et al., 2013a), and this paper will describe the modeling of this experimental data.

Gansu province is geographically a part of the Loess Plateau located in northern China (Shi and Shao, 2000), and it is among the most ecologically fragile and vulnerable areas. In this region, the climate varies from semi-arid to semi-humid. The soils were mainly developed from the Quaternary loess sediments (Liu, 1999) with low soil fertility due to dry climate, sparse vegetation, long periods of intensive farming and erosion (Fan et al., 2008). The main crops are maize and wheat, and the maize–wheat rotation system is the dominant cropping system producing about 40% of local food requirements (Fan et al., 2005a). This region accounts for a larger portion of China's rural poor due to the low soil fertility and the high population density. Therefore, investigating the optimum agricultural practices that can enhance soil fertility and productivity through well designed long-term experiment is crucial for enhancing local economic development, and restoring ecological balance. Evaluating the performance of the DSSAT model based on the long-term experiment is valuable for its potential application in optimizing agricultural practices when considering the benefits of modeling compared with traditional research methods (i.e., field studies). Thus, the objectives of the present study were: (1) to evaluate the performances of the CERES-Maize and -Wheat module of DSSAT-CSM using the CENTURY-based soil module in simulating long-term trends in the grain yields, SOC and SON using the dataset from a rotation experiment in the Loess Plateau of northwestern China; (2) to investigate the sensitivity of the simulated grain yields to different fertilizer N application rates, and to various weather data generated internally; and (3) to address the sensitivity of simulated nitrate-N leaching losses to different fertilizer N application rates under various water stress conditions.

2. Materials and methods

2.1. Long-term experimental data

The data used in this study were collected from a long-term fertilizer experiment which was conducted from April 1979 to October 1992 at the Gaoping Agronomy Farm, Pingliang, Gansu province, northwestern China (Fan et al., 2004, 2005a, 2005b, 2008; Liu et al., 2010a, 2013a). The experimental field is located in the central part of the Shizi highland plateau (35°16′ N, 107°30′ E, elevation 1254 m) (Fan et al., 2005a) which is located in the Loess Plateau. In the Chinese soil classification system, the soil group of the experimental field is dark loessial soil with silty loam textured top soil (0 to 20 cm) (Fan et al., 2005a). This dark loessial soil is developed from Quaternary loess sediments classified as Mollisols in USDA soil taxonomy (Li et al., 2013).

The details of the experimental design and crop management have been described by Fan et al. (2004; 2005a; 2008) and Liu et al. (2013a), thus, only a review of information pertinent to this study is presented. There were six treatments arranged in a randomized complete block design with three replications (Fan et al., 2004, 2005a). For this study, four treatments were selected for comparison with the DSSAT-CSM model: (1) no fertilizer (N0), (2) 90 kg N ha^{-1} from urea (N90), (3) 30 kg N ha^{-1} from maize or wheat straw plus 90 kg N ha^{-1} from urea (SN90), (4) 40 kg N ha^{-1} from cattle manure plus 90 kg N ha^{-1} from urea (MN90).

In this experiment, the cropping systems were a 2-year spring maize (*Zea mays* L.) followed by a 4-year winter wheat (*Triticum aestivum* L.) rotation, with only one crop each year from 1979 to 1992 (Table 1) (Fan et al., 2004). Maize was seeded around 20 April each year with a density of around 5 plants m^{-2} and a 66.5 cm row spacing. Winter wheat was seeded with a row spacing of 14.7 cm at a 165 kg ha^{-1} seeding rate, which equaled to a 471 plants m^{-2} density using an average 1000-kernel weight of 35 g (Zhou et al., 2007). The planting times were around 20 September each year when wheat followed wheat, and in early October when wheat followed maize. Crops were harvested manually and the plants were

Table 1
Field management data for N0, N90, SN90 and MN90 treatments from 1979 to 1992 at Gaoping, Gansu, China.

Year	Crop	Cultivar	Planting date	Plant density (plant m^{-2})	Row space (cm)	Harvest date	Deep tillage date	N0 Start fertilizer	N90 Start fertilizer	SN90 Start fertilizer	SN90 Straw residue	MN90 Start fertilizer	MN90 Farmyard manure	Start fertilizer date	Straw residue date	Farmyard manure date
								(kg N ha^{-1})								
1979	Maize	MZ1985	20-Apr	5	66.5	30-Sep	01-Oct	0	90	90	30	90	40	20-Apr	01-Oct	20-Apr
1980	Maize	MZ1985	20-Apr	5	66.5	04-Oct	05-Oct	0	90	90	30	90	40	20-Apr	05-Oct	20-Apr
1981	Wheat	WH1983	06-Oct	471	14.7	01-Jul	02-Jul	0	90	90	30	90	40	20-Sep	02-Jul	20-Sep
1982	Wheat	WH1983	20-Sep	471	14.7	04-Jul	05-Jul	0	90	90	30	90	40	20-Sep	05-Jul	20-Sep
1983	Wheat	WH1983	20-Sep	471	14.7	09-Jul	10-Jul	0	90	90	30	90	40	20-Sep	10-Jul	20-Sep
1984	Wheat	WH1983	20-Sep	471	14.7	03-Jul	04-Jul	0	90	90	30	90	40	20-Sep	04-Jul	20-Sep
1985	Maize	MZ1985	20-Apr	5	66.5	30-Sep	01-Oct	0	90	90	30	90	40	20-Apr	01-Oct	20-Apr
1986	Maize	MZ1985	20-Apr	5	66.5	30-Sep	01-Oct	0	90	90	30	90	40	20-Apr	01-Oct	20-Apr
1987	Wheat	WH1988	02-Oct	471	14.7	30-Jun	01-Jul	0	90	90	30	90	40	20-Sep	01-Jul	20-Sep
1988	Wheat	WH1988	20-Sep	471	14.7	30-Jun	01-Jul	0	90	90	30	90	40	20-Sep	01-Jul	20-Sep
1989	Wheat	WH1988	20-Sep	471	14.7	30-Jun	01-Jul	0	90	90	30	90	40	20-Sep	01-Jul	20-Sep
1990	Wheat	WH1988	20-Sep	471	14.7	30-Jun	01-Jul	0	90	90	30	90	40	20-Sep	01-Jul	20-Sep
1991	Maize	MZ1985	20-Apr	5	66.5	30-Sep	01-Oct	0	90	90	30	90	40	20-Apr	01-Oct	20-Apr
1992	Maize	MZ1985	20-Apr	5	66.5	16-Oct	17-Oct	0	90	90	30	90	40	20-Apr	17-Oct	20-Apr

cut close to the ground and all harvested biomass were removed from the plots with the exception of SN90 treatment where wheat or maize straw containing 30 kg N ha^{-1} was returned.

In this experiment, the maize and wheat grain samples were collected at harvest, oven-dried at 70 °C for 48 hours, and then weighed for the period from 1979 to 1992 (Fan et al., 2004; Liu et al., 2013a). Surface soil (0 to 20 cm) samples were also collected randomly during 1979 to 1991 fifteen days after harvest, and then soil organic C and total soil N concentrations were measured (Fan et al., 2005a; Liu et al., 2013a). The measured total soil N in the soil includes both organic N as well as inorganic N. At harvest, due to crop uptake, nitrate leaching, etc., the inorganic N concentrations were found to be very low in this field and, as a result, the total soil N was assumed to be primarily soil organic N (Wu et al., 2003).

2.2. Weather data

The weather data used in this study were from the Changwu weather station (35°12′ N, 107°48′ E, elevation 1207 m) which is located 33 km away from the Gaoping experimental site. These weather data were obtained from the China Meteorological Data Sharing Service System (available at http://cdc.cma.gov.cn/cdc_en/home.do; user login is required). The weather data varied from temperate semi-arid to semi-humid with the average annual temperature ranging from 8.6 to 10.3 °C (Fig. 1a), and the annual precipitation ranging from 323 to 822 mm from 1979 to 1992, and a majority of the precipitation occurring from June to September (Fig. 1b, c). The precipitation for the spring maize growing seasons (i.e., April to September) ranged from 300 to 506 mm (Fig. 1b), and for the winter wheat growing seasons (i.e., previous September to June) ranged from 190 to 500 mm (Fig. 1b). For 1981 and 1987, the years in which wheat followed maize, the winter wheat growing seasons were from previous October to June.

2.3. Crop simulation

2.3.1. Model input data

In this study, the CERES-Maize and CERES-Wheat modules and the CENTURY-based soil module in DSSAT (version 4.5) (Hoogenboom et al., 2010) were used to conduct simulations. The model required input data include crop management, daily weather data, soil profile data, initial soil conditions and cultivar coefficients. The crop management data contain crop planting date and density, row space, tillage method and date, fertilization (inorganic and manure) dates and rates, and harvest date, etc. These crop management data were obtained from the published data for this field site as described by Fan et al. (2004, 2005a, 2005b, 2008) and Liu et al. (2010a, 2013a), and this information was summarized (Table 1). For the SN90 treatment, maize or wheat straw residue was cut to around 10 cm in length and then was returned to the soil after harvest, whereas the maize and wheat straw was removed from the plots for N0, N90 and MN90 treatments (Fan et al., 2005a). The field was plowed to 23 cm depth in July after wheat harvest or in October after maize harvest except for the years in which wheat followed maize. For these years, i.e., 1980 and 1986, the fields were cultivated with a shallow disk after maize harvest and wheat was subsequently seeded (Liu et al., 2013a). The period between crop harvest and the next crop planting was set as fallow in the study. In addition, an atmospheric N deposition of 10 kg N ha^{-1} were included as an annual available N input for all the treatments at the beginning of each crop period (Liu et al., 2010b). The initial soil conditions (i.e., soil water content, NH_4-N and NO_3-N contents by layers) were set based on report by Wu et al. (2003).

The minimum daily weather data required to run the DSSAT model includes daily solar radiation (MJ m^{-2}), daily maximum and minimum temperatures (°C) and daily precipitation (mm). These

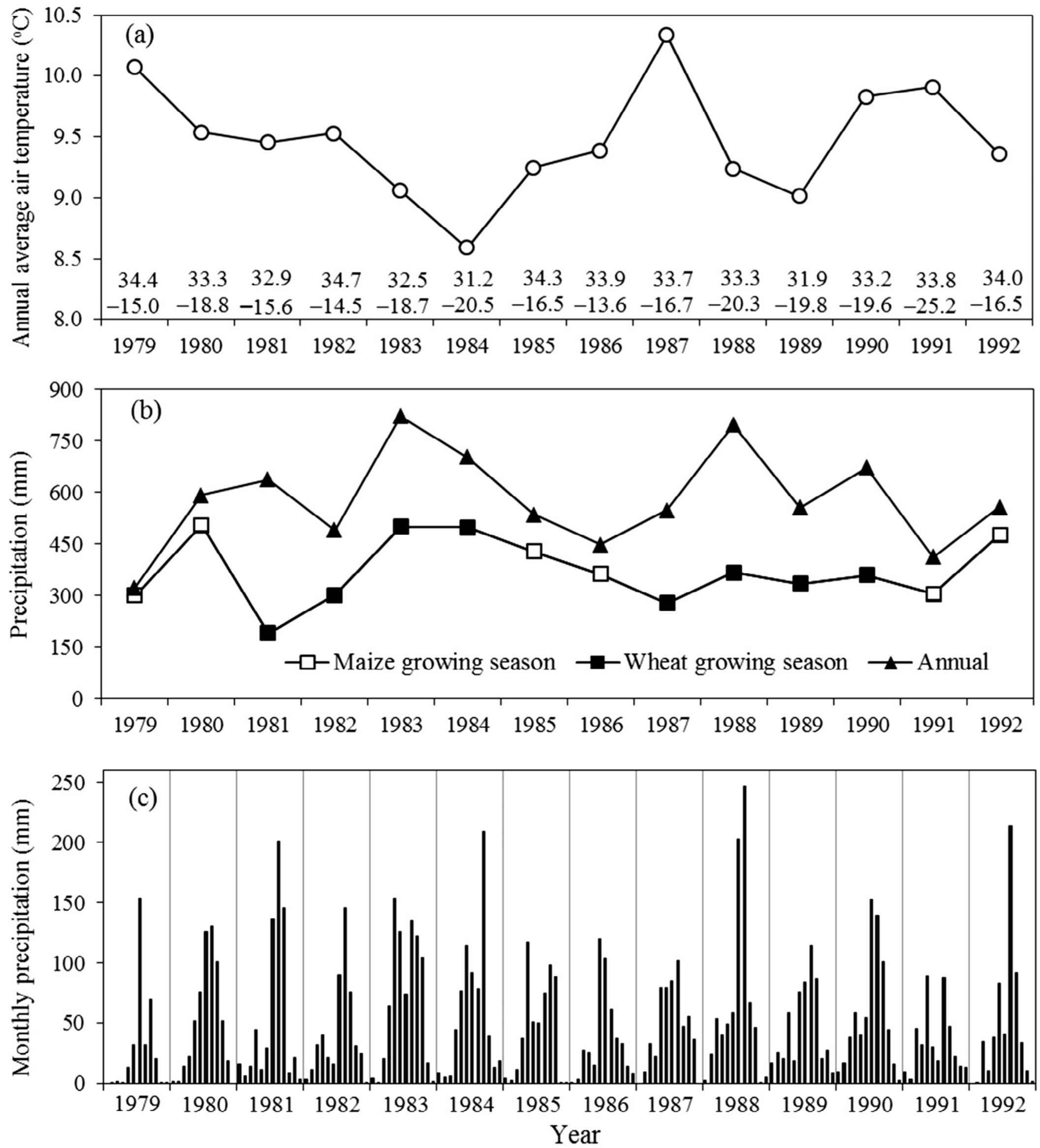

Fig. 1. The weather data from 1979 to 1992: (a) annual average temperature with the maxmum and minimum values, (b) annual and growing season precipitation and (c) monthly precipitation of each year (data available at http://cdc.cma.gov.cn/cdc_en/home.do; user login is required).

daily weather data were collected from 1979 to 1992. The daily solar radiation was calculated from daily sunshine hours using the Weatherman program in DSSAT model (Pickering et al., 1994).

The soil profile (0 to 150 cm) data were obtained from published data measured in Changwu Loess plateau with the same soil type by Zhang and Liu (2005). The profile data included soil water lower limit, drained upper limit, saturation, saturated hydraulic conduct, bulk density, soil organic C, total N, soil clay, silt contents, etc. (Table 2). These soil profile data were saved in DSSAT soil file.

To simulate soil organic C and N, we need to initialize the program with the field history (FLHST) and the C/N ratio parameters to support the DSSAT Century-based soil module (Gijsman et al., 2002). In this study, the initial field soil fertility might be depleted as very little fertilizer was applied before the start of the experiment (Fan et al., 2008). Therefore, the FH301 which corresponds to an initially degraded field was selected as the FLHST. The measured initial topsoil SOC was 6.2 g kg^{-1}, total N was 0.95 g kg^{-1} (Liu et al., 2013a) and the topsoil mineral N was less than 0.01 g kg^{-1} (Wu et al., 2003), thus, the C/N ratio was around 6.6 in this experiment. Therefore, the soil C/N ratio in the DSSAT standard data file (i.e., SOMFX045.SDA) was initialized with the measured value 6.6 based on Gijsman et al. (2002).

2.3.2. Cultivar calibration

The DSSAT crop cultivar coefficients control the crop growth stages which can vary with different weather data (Jones et al., 2003). Therefore they must be calibrated under the optimum conditions (i.e., minimum stress in weather and nutrients) for the region (Boote, 1999; Liu et al., 2011). In this study, the default maize cultivar 990002 (in MZCER045.CUL file), and default wheat cultivar IB1015 (in WHCER045.CUL file) were selected for calibrating new cultivars. The calibration was made using a 'Trial and Error' method by setting up a small change (i.e., ± 5%) of each parameter. The root mean square error (RMSE) between the simulated and measured grain yields was used to find the best matched coefficients. In addition to the grain yield, the phonological stages were also taken into account in the calibration of the cultivar coefficients. The simulated

Table 2
Soil profile data[a] of the experimental field.

Soil depth (cm)	Lower limit ($cm^3\ cm^{-3}$)	Drained upper limit ($cm^3\ cm^{-3}$)	Saturation ($cm^3\ cm^{-3}$)	Saturated hydraulic conductivity ($cm\ h^{-1}$)	Bulk density ($g\ cm^{-3}$)	Organic carbon ($g\ kg^{-1}$)	Clay (<0.002 mm) (%)	Silt (0.05–0.002 mm) (%)	Total nitrogen ($g\ kg^{-1}$)	pH in water	Cation exchange capacity ($cmol\ kg^{-1}$)
0–20	0.094	0.305	0.468	0.37	1.41	6.2	34.8	57.2	0.95	8.2	7.5
20–40	0.094	0.305	0.468	0.46	1.41	3.1	34.8	57.7			6.0
40–60	0.115	0.313	0.479	0.63	1.38	3.1	34.8	57.9			6.0
60–80	0.110	0.311	0.506	0.67	1.31	2.4	32.9	59.9			5.8
80–100	0.106	0.309	0.525	0.68	1.26	2.4	33.3	58.7			5.8
100–150	0.106	0.309	0.472	0.68	1.40	3.1	36.8	53.7			5.8

[a] These data were obtained from the published literatures by Zhang and Liu (2005) and Fan et al. (2004; 2005a).

Table 3
The calibrated cultivar coefficients of maize and wheat for the experimental field using CERES-Maize and -Wheat in DSSAT-CSM (v4.5).

Cultivar	Calibrated coefficients		
Calibration year	1985	1983	1988
Cultivar name	MZ1985	WH1983	WH1988
Maize cultivar coefficients			
P1 Time from seedling emergence to the end of the Juvenile (degree days >8 °C)	222		
P2 Extent to which development (expressed as days) is delayed for each hour (increase in photoperiod > the longest photoperiod 12.5 h)	0.52		
P5 Thermal time from silking to physiological maturity	820		
G2 Maximum possible number of kernels per plant	580		
G3 Kernel optimum filling rate during the linear grain filling stage (mg day^{-1})	8.0		
PHINT Phylochron interval between successive leaf tip appearances (degree days)	38.9		
Wheat cultivar coefficients			
P1V Days, optimum vernalizing temperature, required for vernalization		32	25
P1D Photoperiod response (% reduction in rate/10 h drop in pp)		83	52
P5 Grain filling (excluding lag) phase duration (degree days)		515	515
G1 Kernel number per unit canopy weight at anthesis (#/g)		15	17
G2 Standard kernel size under optimum conditions (mg)		38.0	40
G3 Standard, non-stressed mature tiller wt (incl. grain) (g dwt)		3.0	2.0
PHINT Phylochron interval between successive leaf tip appearances (degree days)		90	105

phonological stages (e.g., emergence, grain fill and maturity days) under the calibrated cultivar coefficients were roughly in the same phonological stages as field crops in this region. The normal rainfall year 1985 was selected as the calibration year for the maize cultivar. A wet year 1983 and a normal year 1988 were selected as calibration years for the two wheat cultivars. All of the calibration was conducted using the N90 treatment. One maize cultivar and two wheat cultivars were calibrated, and the calibrated coefficients are listed in Table 3.

2.3.3. Model runs and outputs

The simulation was made under DSSAT Sequence Analysis program so that the soil nutrient and water dynamics could be continuously transferred from the beginning to the end of the simulation (Thornton et al., 1994, 1995). Four management files (i.e., .SQX) were established for the respective four treatments based on the input data described above. The outputs can be readily visualized and statistically evaluated using the EasyGrapher graphical program (Yang and Huffman, 2004). In this study, we focus on evaluating the model performance by comparing the simulated grain yields, SOC and SON with respective measured values from the long-term experiment from 1979 to 1992.

2.3.4. Model evaluation statistics

Different statistics address particular aspects of a model performance. In order to carry out a comprehensive evaluation of the DSSAT model performance, five deviation statistics were used

Table 4
Statistical evaluation of simulated grain yields of spring maize and winter wheat against measured values.

Grain yield (kg ha^{-1})	Treatments	Measured	Simulated	Sample no.	E	RMSE	$nRMSE$ (%)	d	EF	Paired -t (p)
Maize	N0	2709 (1068)[a]	2744 (1416)	6	35	1288	47.6	0.63	−0.74	0.95
	N90	5830 (1821)	6359 (2315)	6	529	1100	18.9	0.91	0.56	0.28
	SN90	6192 (2544)	6413 (2408)	6	221	820	13.2	0.97	0.88	0.56
	MN90	7126 (3125)	6588 (2521)	6	−538	1049	14.7	0.96	0.86	0.24
Wheat	N0	2070 (749)	1956 (1024)	8	−114	751	36.3	0.76	−0.15	0.70
	N90	4394 (1435)	4365 (1993)	8	−29	882	20.1	0.92	0.57	0.93
	SN90	4481 (1413)	4311 (1814)	8	−170	839	18.7	0.92	0.60	0.60
	MN90	5216 (1640)	4671 (2121)	8	−545	1124	21.5	0.89	0.46	0.19

[a] Values in brackets are the S.D. for each treatment.

in this study, including mean error (E), root mean square error ($RMSE$), normalized $RMSE$ ($nRMSE$), index of agreement (d) (Willmott, 1982) and modeling efficiency (EF) (Loague and Freeze, 1985; Yang et al., 2000). In addition, a paired-t test was used to test the significance of E. The regression between the simulated and measured grain yields was also carried out. The five deviation statistics were calculated using the equations below based on Yang et al. (2014):

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

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

$$nRMSE = \frac{RMSE}{\bar{M}} \times 100 \quad (3)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}\left(|S_i - \bar{M}| + |M_i - \bar{M}|\right)^2} \quad (4)$$

$$EF = 1 - \frac{\sum_{i=1}^{n}(S_i - M_i)^2}{\sum_{i=1}^{n}(M_i - \bar{M})^2} \quad (5)$$

where S_i is the simulated value, M_i is the measured value, n is the number of values, and $\bar{M}$ is the average of the measured values.

The $RMSE$ summarizes the average difference between observed and predicted values (Willmott, 1982). The $nRMSE$ shows the relative size of the average difference without units and this statistic is unbounded (Willmott, 1982). For small sample datasets (e.g., $n = 6$, 8 or 13) that were used in this study, we consider $nRMSE \leq 15\%$ as "good" agreement; 15–30% as "moderate" agreement; and ≥ 30% as "poor" agreement (Liu et al., 2013b; Yang et al., 2013).

The index of agreement (d) ($0 \leq d \leq 1$) is intended to be a descriptive measure, and it is both a relative and bounded measure (Willmott, 1982). As recommended by Liu et al. (2013b), when $d \geq 0.9$ this indicates "excellent" agreement; when $0.8 \leq d < 0.9$, then we consider this as "good" agreement; when $0.7 \leq d < 0.8$, then there is "moderate" agreement; and when $d < 0.7$ there is "poor" agreement between measured and predicted values.

2.3.5. Model sensitivity analysis

Sensitivity analysis is a fundamental tool in the building, use and understanding of simulation models as it could provide information regarding the behavior of the model including the identification of important model inputs (parameters or variables) (Confalonieri et al., 2010). In this study, the sensitivity analysis of grain yields and soil N dynamics to fertilizer N application levels was carried out by varying fertilizer N from 0 to 210 kg ha^{-1} with a 30 kg ha^{-1} interval for each year using the DSSAT-Sequence Analysis program. This way, the optimum N application rates for the maximum grain yields can be investigated. The corresponding soil nitrate-N leaching loss below crop rooting zone under different fertilizer N rates was also predicted. In addition, the sensitivity of maize and wheat yields to various weather conditions were investigated by creating a climate file (i.e., .CLI) using the measured 14-year weather data from 1979 to 1992. Then, based on the climate file, different weather data were generated using the internal weather generator by setting up 30 replications for 30 sequences. Thus, the simulated grain yields under 30 generated weather data sets for each sequence were analyzed for the N0 and N90 treatments.

3. Results and discussion

3.1. Grain yield evaluation

The measured maize and wheat grain yields changed dramatically as a function of both years and fertilizer N levels (Fig. 2a–d). The measured maize yields averages were 2709 ± 1068 kg ha^{-1}, 5830 ± 1821 kg ha^{-1}, 6192 ± 2544 kg ha^{-1} and 7126 ± 3135 kg ha^{-1} for the N0, N90, SN90 and MN90 treatments, respectively, in the 6 years of 1979 to 1980, 1985 to 1986, and 1991 to 1992 (Table 4). The averages of measured wheat yields were 2070 ± 749 kg ha^{-1}, 4394 ± 1435 kg ha^{-1}, 4481 ± 1413 kg ha^{-1}, and 5216 ± 1640 kg ha^{-1} for the N0, N90, SN90 and MN90 treatments, respectively, in the 8 years between 1981 and 1984, and between 1987 and 1990 (Table 4). The simulated grain yields of maize and wheat generally matched the measured values well in most years (Fig. 2a–d), except that large deviations were found for several years (e.g., the dry years of 1982 and 1987) (Fig. 2). During the model run, neither the simulated nor measured maize yields showed obvious correlations with the growing season precipitation (GSP), while both the simulated and measured wheat yields showed strong positive correlations with the GSP for all respective treatments ($R^2 = 0.12$–0.73).

There was a strong linear relationship between the simulated and the measured grain yields with $R^2 = 0.84$ and 0.81 for respective maize and wheat of all treatment combination (Fig. 3a, b). Both regression slopes of 0.89 ($p > 0.10$) for maize and 1.04 ($p > 0.70$) for wheat were not statistically different from 1, and both respective regression intercepts of 668 ($p = 0.20$) and −357 ($p = 0.39$) kg ha^{-1} were not statistically different from 0, indicating that the simulated grain yields correlated with the measured dataset quite well for both maize and wheat.

3.1.1. Maize yield evaluation

By comparing the simulated maize grain yields and the measured values, the mean error E value for respective N90, SN90 and MN90 treatments was not statistically different from zero based upon the paired t test ($p = 0.24$–0.56) (Table 4). The calculated $nRMSE$ values ranged 13–19%, $d > 0.91$ and $EF > 0.56$ for N90, SN90 and MN90 treatments (Table 4), thus, the DSSAT model showed "good to excellent" agreements in simulating the maize yield for the

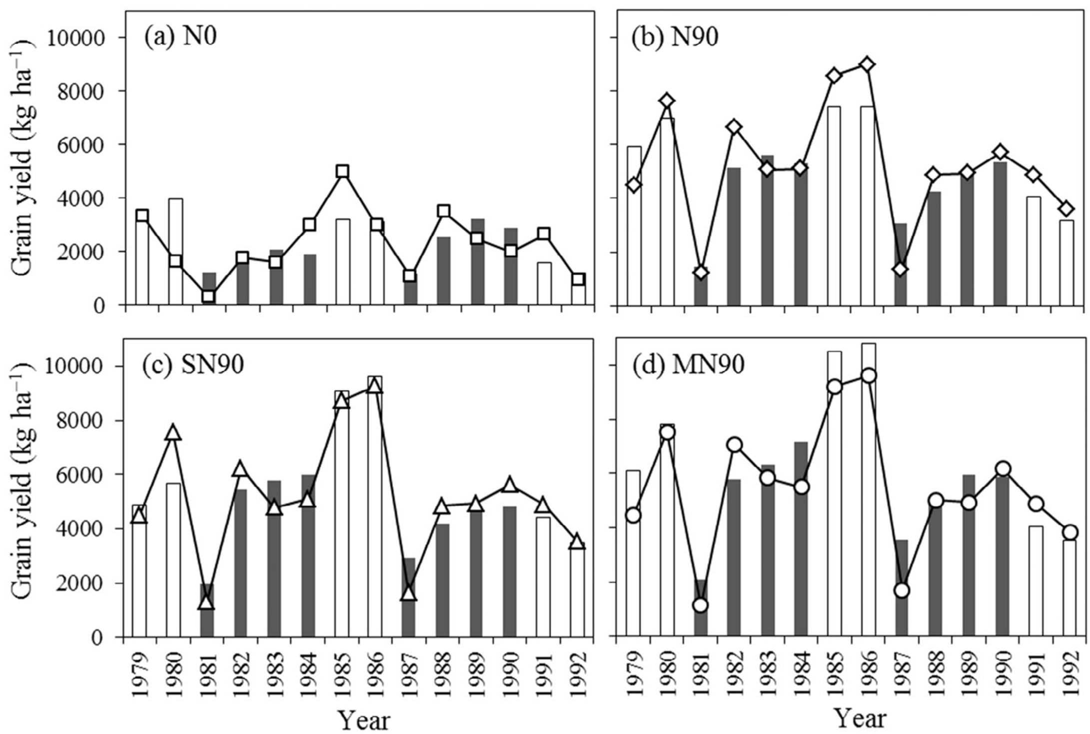

Fig. 2. Comparison of the simulated (line with markers) and the measured spring maize (blank bar) and winter wheat (black bar) grain yields under (a) N0, (b) N90, (c) SN90 and (d) MN90 treatments from 1979 to 1992 at Gaoping, Gansu, China.

treatments with fertilizer N application. However, the model showed poor performance in simulating maize yields under N0 with *nRMSE* = 48%, *EF* = –0.74 and *d* = 0.63, whereas there were no statistical differences between the simulated and measured maize yields for N0 ($p = 0.95$) (Table 4). A similar result was also reported by Timsina and Humphreys (2006), Liu et al. (2011) and Yang et al. (2013) that the DSSAT model showed poorer performance for zero fertilizer N than with fertilizer N treatments. This might be due to the DSSAT crop model being more sensitive to N stress than the real crop growth under no fertilizer N conditions.

3.1.2. Wheat yield evaluation

The simulated wheat yields were not statistically different from the measured values for all respective N0, N90, SN90 and MN90 treatments as indicated by the paired-*t* test ($p = 0.19–0.70$) (Table 4). The simulated wheat yields in the dry and hot year of 1987 were significantly lower than measured wheat yields for N90, SN90 and MN90 treatments (Fig. 2). This might be because that the effects of water stress on crop yields were over compensated in the crop models (Eitzinger et al., 2013). The calculated *nRMSE, d* and *EF* ranged from 20 to 22%, from 0.89 to 0.92, and from 0.46 to 0.60, respectively, indicating an overall "good" agreement for N90, SN90 and MN90 treatments (Table 4). The model showed a "moderate" agreement for the N0 treatment as indicated by the *nRMSE* = 36%, *d* = 0.76, and *EF* = –0.15 (Table 4).

3.2. Soil organic C and N evaluation

The measured topsoil (20 cm) SOC concentration increased obviously in N90, SN90 and MN90 treatments from 1979 to 1992 (Fig. 4b–d), while the SOC remained stable in N0 treatment (Fig. 4a). The simulated topsoil SOC showed the similar increasing trends with measurements. However, the model tended to overestimate SOC from the 5th until the 13th year (Fig. 4a–d), resulting in a significant mean error *E* from 0.73 to 0.80 g kg^{-1} ($p < 0.05$) for all treatments (Table 5). The overall overestimation of SOC was partly associated with the differences between the model soil C/N ratio and the measured C/N ratio parameter. In this study, the experimental field was initially degraded with a relative low topsoil C/N ratio (6.6). In the DSSAT model parameter, the initial topsoil C/N ratio is fixed around 9.5. Sensitivity analysis of SOC dynamics to initial soil C/N ratio showed that the low initial topsoil C/N ratio resulted in the quick increase in SOC during model run (data not shown). Although the topsoil C/N ratio was initialized with the measured value 6.6, the C/N ratio could be modified automatically during the model run. This might be the part reason that the model captured the SOC dynamics in the first 5 years, whereas the model sequestrated more SOC than reality under good agricultural practice.

Generally, the model performed moderately for N90, SN90 and MN90 treatments with the *nRMSE* = 12–13%, *d* = 0.63–0.84, although *EF* < 0. The simulated SOC did not match well with the measured values for N0 treatment with the *d* = 0.39 and *EF* < 0, although the *nRMSE* = 13% (Table 5).

From 1979 to 1992, the simulated topsoil (20 cm) SON concentration showed a similar increasing trend with the measured values for N90, SN90 and MN90 treatments (Fig. 5b–d), except for N0 treatment which had a slightly decreasing trend for both the simulated and measured topsoil SON (Fig. 5a). The simulated SON showed a "good" agreement with the measured values for N90 treatment with the *E* of 0.02 g kg^{-1}, *nRMSE* of 1.8%, *d* of 0.88, and *EF* of 0.50 (Table 5). The model significantly underestimated the topsoil SON for both SN90 and MN90 treatments with respective *E* values of –0.07 and –0.05 g kg^{-1} ($p < 0.05$). However, other statistics showed overall "moderate" to "good" agreements for SN90 and MN90 treatments with the *nRMSE* values of 6.6 and 6.0%, *d* values of 0.77 and 0.79, and *EF* values of 0.15 and 0.36, respectively (Table 5). The simulated SON for N0 treatment showed good matches with the measured data visually (Fig. 5a), and a small *nRMSE* value of 3.5% (Table 5). However, the calculated small *d* value (0.48) and negative *EF* value (–2.4) may indicate a "poor" match. This was possibly due to small ranges of

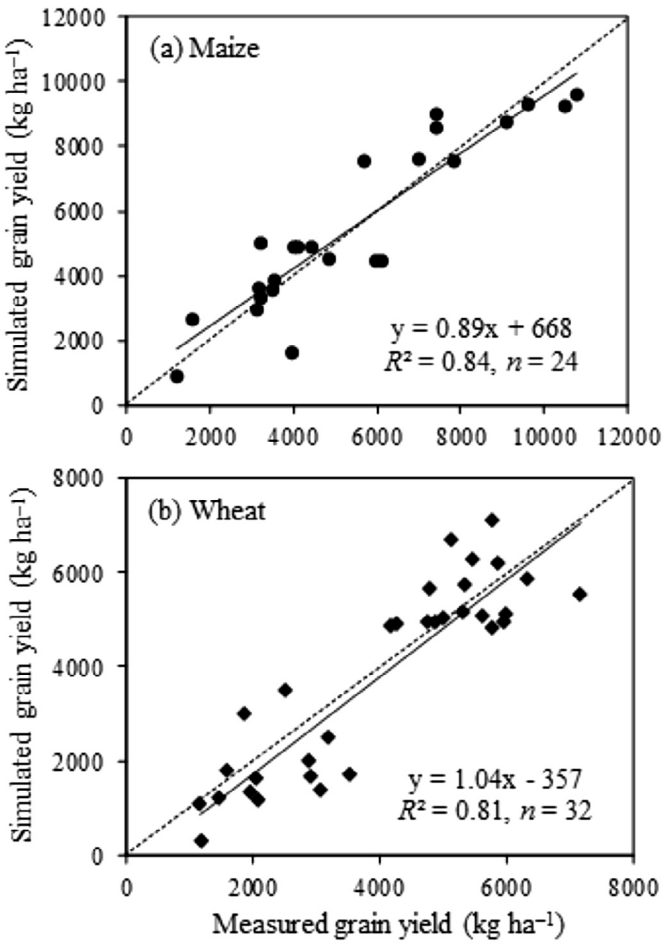

Fig. 3. The correlation and regression analysis between the simulated and the measured grain yields of all treatment combination for (a) maize and (b) wheat.

both the simulated and the measured SON dataset under N0 treatment. Thus, caution should be given to consider all statistics together with graphic evaluation to draw final conclusion on the model performance in SON simulation for N0 treatment.

3.3. Soil water dynamics

The simulated soil water contents in the 0–150 cm profile fluctuated greatly during the model run (Fig. 6a). Based upon the simulated soil water content in 0–150 cm profile (Fig. 6a), the years of 1979–1981, 1987 and 1991–1992 were referred as "drought year", and the rest years (i.e., 1982–1986 and 1988–1990) were referred as "humid year" in this study. The soil water contents showed similar dynamics under N0 and N90, while the soil water contents were obviously higher under N0 than N90 in drought years of 1981, 1987, 1991 and 1992 (Fig. 6a). This might result from the lower water uptake by crop under N0 than N90 in drought years. The changing trends in soil water contents were closely associated with the rainfall distribution pattern (Fig. 1b, c). For example, the soil water contents were generally lower in drought years (i.e., 1979–1981, 1987 and 1991) than humid years (i.e., 1983–1985, 1988–1990) (Fig. 6a). The soil water drainage events ocurred in the next fallow periods when there was heavy rainfall (Fig. 6b). For example, the first drainage event happened in September of 1981 when the field was fallow along with intensive rainfall of 200 mm. The effects of soil water dynamics on the changing trends in soil NO_3-N will be discussed in section 3.4.3.

3.4. Model sensitivity analysis

3.4.1. Yield sensitivity to fertilizer N

The simulated maize and wheat yields responded to fertilizer N application rates similarly under straw/farmyard manure application or without straw/farmyard manure condition and in this paper, we just showed the results for the treatments which did not receive straw or farmyard manure. Both the maize and wheat grain yields showed different responses to the increased fertilizer N levels under different soil water conditions during growing season. The soil water content generally depended on the rainfall distribution pattern. The simulated maize and wheat grain yield response curves to fertilizer N rates were grouped to three types: (1) no response lines (Fig. 7a, d), (2) linear plus plateau curves (Fig. 7b, e) and (3) typical diminishing return curves (Fig. 7c, f). The type (1) response line occurred in drought years, while the type (2) and (3) response curves happened in humid years.

The simulated maize yields were not sensitive to fertilizer N application rates in drought years of 1979, 1991 and 1992 (Fig. 7a) in which the soil water content in 0–150 cm profile was lower than 300 mm in growing season (Fig. 6a). In drought year of 1980 with even rainfall distribution, however, maize yield increased dramatically from 1000 kg ha^{-1} to 7000 kg ha^{-1} when increasing fertilizer N rates from 0 to 60 kg N ha^{-1} then leveled off (Fig. 7b). Our results suggested that the fertilizer N application rates for the maximum maize yields should be adjusted to 60 kg N ha^{-1} in drought years.

However, in humid years of 1985 and 1986 with soil water contents in 0–150 cm profile as high as 500 mm (Fig. 6a), the maize yields increased greatly from 2000 kg ha^{-1} to 10000 kg ha^{-1} with the increased fertilizer N rates from 0 to 150 kg N ha^{-1}, while the yield showed diminishing return patterns to additional N fertilizer from 150 to 210 kg N ha^{-1} (Fig. 7c). Therefore, to achieve the maximum maize yield in a humid year, the maximum fertilizer N rate should be increased to 150 kg N ha^{-1} (Fig. 7c) by topdressing in the middle of the growing season. The variation in sensitivities of the simulated maize yield to fertilizer N rates depended on both soil water condition and rainfall distribution in this study, which was in agreement with the experimental result reported by Liu et al. (2010c). The sensitivity result was also supported by the finding that there was a significant interaction between irrigation and N fertilization rates for maize yield (Paolo and Rinaldi, 2008).

Similar trends were found for winter wheat. In the drought years of 1981 and 1987 in which the total soil water content in 0–150 cm was around 200 mm (Fig. 6a), the wheat grain yields were less than 2000 kg ha^{-1} irrespective of fertilizer N rates (Fig. 7d) as affected by soil water stress during early growing stages (spikelet initiation to end ear growth). In humid 1988 and 1989, the wheat grain yield showed slight sensitivity to fertilizer N (Fig. 7e), this might result from the uneven rainfall distribution in these two years (Fig. 1c). However, in the humid years of 1982–1984 and 1990, the wheat yields increased in typical diminishing return curves with the fertilizer N rates from 0 to 180 kg N ha^{-1} (Fig. 7f). Our result was consistent with the experimental results that the N fertilizer use efficiency was affected by the rainfall level in the growing seasons (Dang and Hao, 2000), and that the wheat yields were limited by seasonal distribution of rainfall (Zhang et al., 2013). Dang et al. (2006) also reported that the maximum fertilizer N rates to winter wheat should be in the range of 100–150 kg N ha^{-1} in the normal years from a nearby experimental site. Thus, the fertilizer N should be increased in humid years especially when the rainfall is evenly distributed throughout the growing season, whereas N fertilizer should be decreased in drought years. This simulated result also agreed with the observed results from Ali et al. (2005) that the wheat yield increased with increasing rates of N under normal soil moisture condition, whereas, under limited soil moisture conditions, water

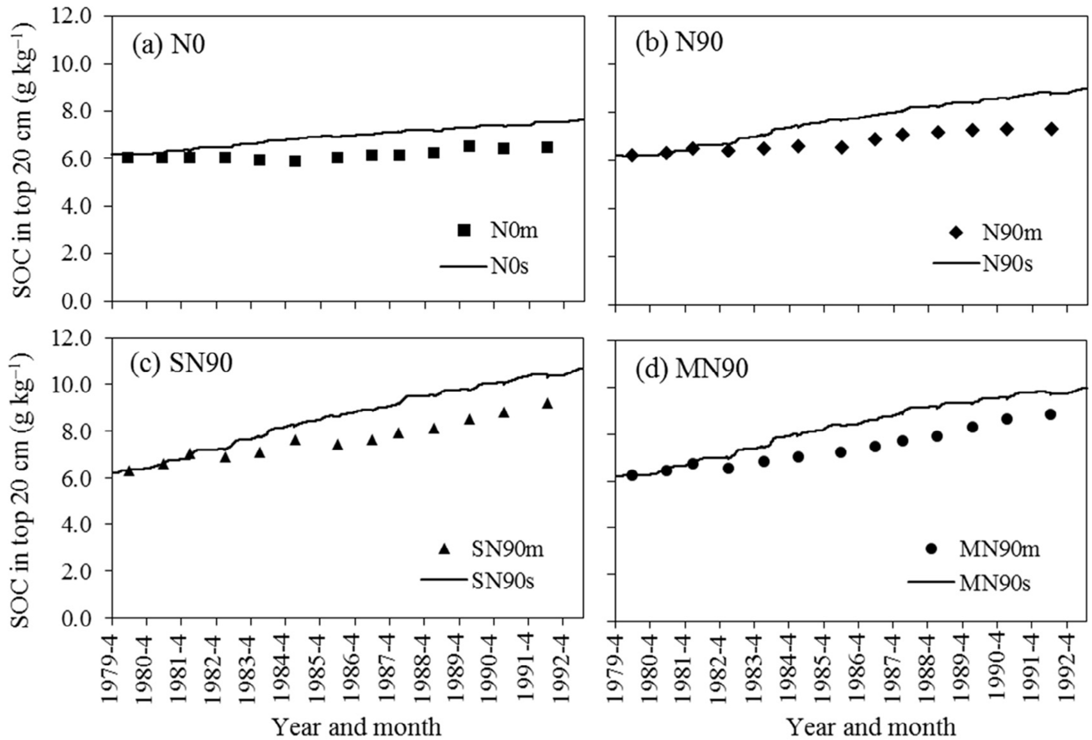

Fig. 4. Comparison of the simulated (line) and measured (marker) soil organic C (SOC) concentrations in the top 20 cm depth under: (a) N0, (b) N90, (c) SN90 and (d) MN90 treatments from April 1979 to October 1992 at Gaoping, Gansu, China.

stress was a more yield limiting factor than N fertilization for wheat production in hot and dry environments.

The DSSAT-CSM model was shown to be able to predict the responses of the grain yields or biomass of maize and wheat crops under different fertilizer N rates and other agricultural practices in the semi-arid and semi-humid regions of China and it was also used to select the optimum N management practices.

3.4.2. Yield sensitivity to generated weather data

The 30 weather data sets generated by the internal weather generator varied greatly among sequence years. The simulated grain yields for both maize and wheat varied based upon the variations in the generated weather data (Fig. 8). In general, the simulated maize grain yields ranged from 300 to 7500 kg ha^{-1} for N0 treatment and from 800 to 11000 kg ha^{-1} for N90 treatment, while the wheat yields ranged from 0 to 4000 kg ha^{-1} for N0 treatment and from 0 to 7000 kg ha^{-1} for N90 treatment. The overall higher grain yields for either maize or wheat in N90 than N0 treatments indicated that there were significant positive interactions between favorable weather conditions and fertilizer N rate in determining grain yields.

The sensitivity of grain yields to the generated growing season precipitation (GSP) was illustrated in Fig. 6 under N0 and N90 treatments, respectively. The simulated maize and wheat yields generally showed strong positive correlations with the generated GSP, and the overall response curves were fitted by the linear regression (Fig. 8a–d). Under N0 treatment, the simulated maize grain yields increased slowly with the increased GSP from 250 to 800 mm ($R^2 = 0.04$, $p < 0.01$, Fig. 8a), while the wheat grain yields increased gradually with the increased GSP from 100 to 450 mm ($R^2 = 0.10$, $p < 0.01$, Fig. 8c), indicating that nitrogen was the main limiting factor for crop growth when no N fertilizer was applied, especially for maize. Under N90 treatment, however, the simulated maize yield increased rapidly with the increased GSP from 250 to 800 mm ($R^2 = 0.14$, $p < 0.01$, Fig. 8b). The wheat grain yields also increased obviously when GSP increased from 100 to 450 mm ($R^2 = 0.09$, $p < 0.01$, Fig. 8d). These results indicated that the sensitivity of grain yields for either maize or wheat to GSP could be enhanced by higher fertilizer N rate.

Thus, it could be concluded that the generated weather data had an overall obvious impact on the grain yields for both maize and wheat. The different sensitivity of grain yields to generated weather

Table 5
Statistical evaluation of simulated soil organic C, N concentrations at the 0–20 cm soil depth against measured values.

Variables	Treatments	Measured	Simulated	Sample no.	*E*	*RMSE*	nRMSE (%)	*d*	*EF*	Paired-*t* (*p*)
Soil organic C (g C kg^{-1})	N0	6.12	6.86	13	0.73	0.79	12.9	0.39	−15.68	0.00
	N90	6.77	7.51	13	0.75	0.91	13.4	0.63	−4.55	0.00
	SN90	7.61	8.40	13	0.80	0.97	12.7	0.82	−0.34	0.00
	MN90	7.35	8.10	13	0.75	0.87	11.8	0.84	−0.11	0.00
Soil organic N (g N kg^{-1})	N0	0.89	0.92	13	0.03	0.03	3.5	0.48	−2.37	0.00
	N90	0.96	0.97	13	0.01	0.02	1.8	0.88	0.50	0.01
	SN90	1.10	1.03	13	−0.07	0.07	6.6	0.77	0.15	0.00
	MN90	1.07	1.02	13	−0.05	0.06	6.0	0.79	0.36	0.00

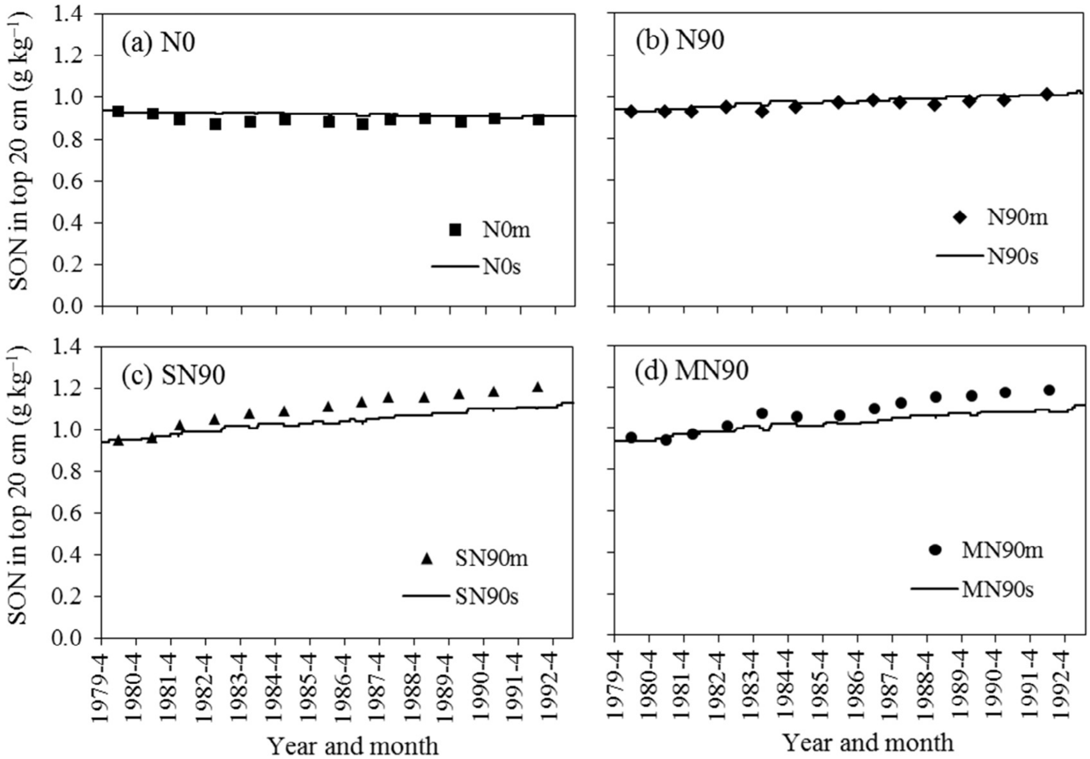

Fig. 5. Comparison of the simulated (line) and measured (marker) soil organic N (SON) concentrations in the top 20 cm depth under (a) N0, (b) N90, (c) SN90 and (d) MN90 treatments from April 1979 to October 1992 at Gaoping, Gansu, China.

data between N0 and N90 treatments was reasonable with practical experience. The DSSAT-CSM has a potential to investigate the effects of weather data generated internally on crop yields using Sequence Analysis program (i.e., simulation of long-term crop rotations).

3.4.3. Soil nitrate-N sensitivity to fertilizer N

The ammonium (NH_4^+) in most soils is usually low due to the rapid conversion to nitrate (NO_3^-) which can be a problem as nitrate is the dominant form of N leached in temperate regions

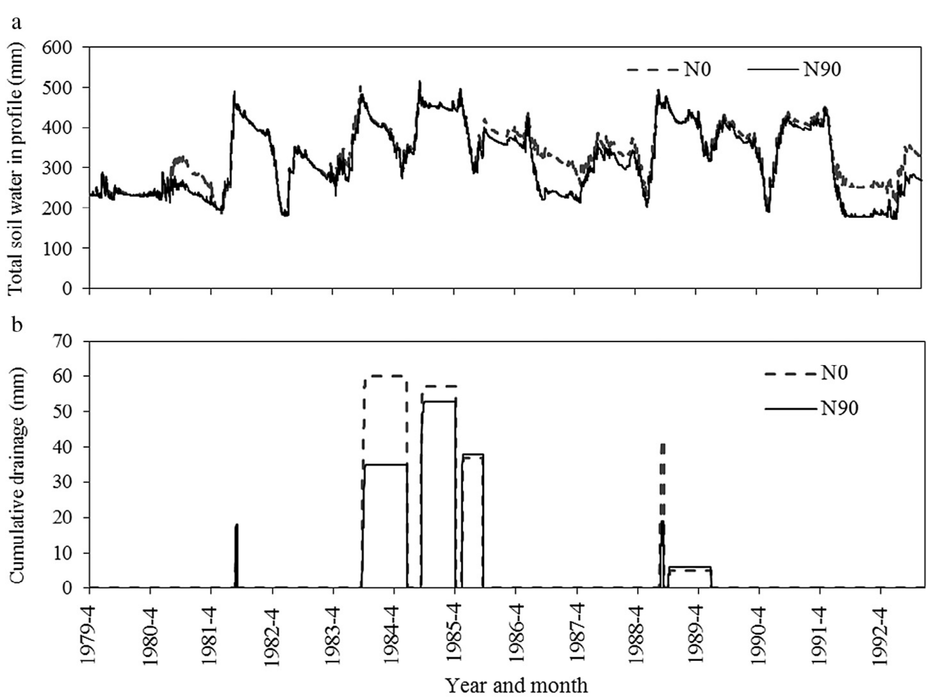

Fig. 6. The simulated soil water dynamics from April 1979 to 1992: (a) total soil water content in the 0–150 cm profile and (b) cumulative drainage events under N0 and N90 treatments.

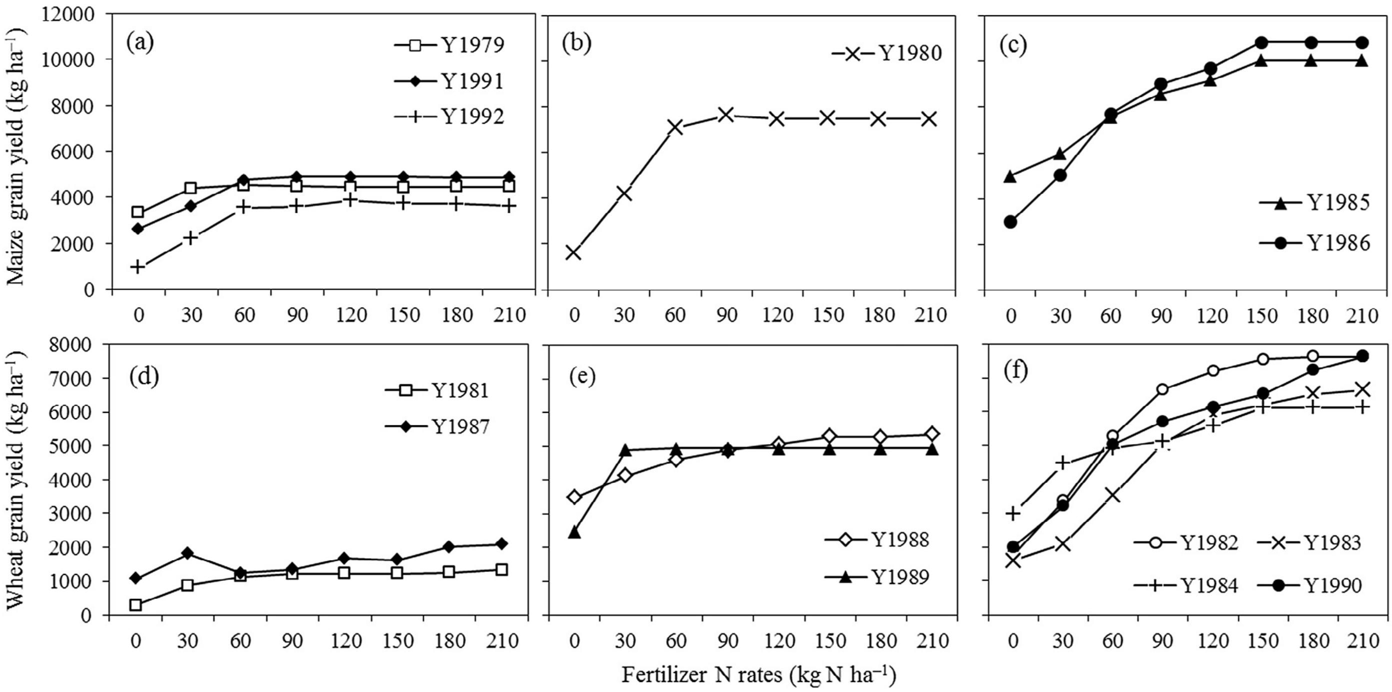

Fig. 7. The sensitivity of the simulated maize and wheat grain yields to fertilizer N rates from 0 to 210 kg N ha^{-1} under drought years (a, b, d), and humid years (c, e, f) from 1979 to 1992 at Gaoping, Gansu, China.

(Di and Cameron, 2002). Thus, in this study, we just showed the simulated NO_3-N concentration in soil profile and NO_3-N leaching loss as the $NH4^+$ concentrations were comparatively low.

The simulated soil NO_3-N concentration in all soil layers (0–150 cm) fluctuated greatly with time from April 1979 to 1992, while the NO_3-N concentration in the period following N application increased markedly with the increases of fertilizer N rates in top soil layers (Fig. 9a–c). Our simulation results were consistent with the experimental results by Liu et al. (2003) and Zhao et al. (2006). The changes in the NO_3-N levels in the 0–5 cm, 5–15 cm and

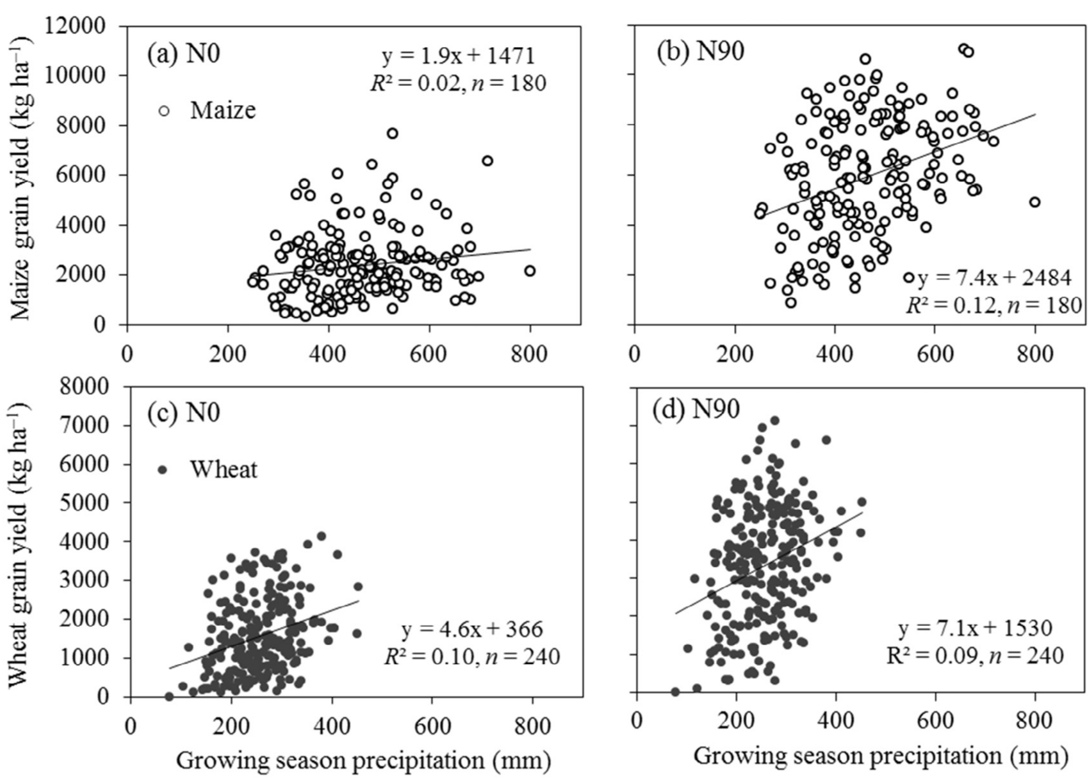

Fig. 8. The responses of simulated maize and wheat grain yields to the generated growing season precipitation under N0 (a, c) and N90 (b, d) treatments.

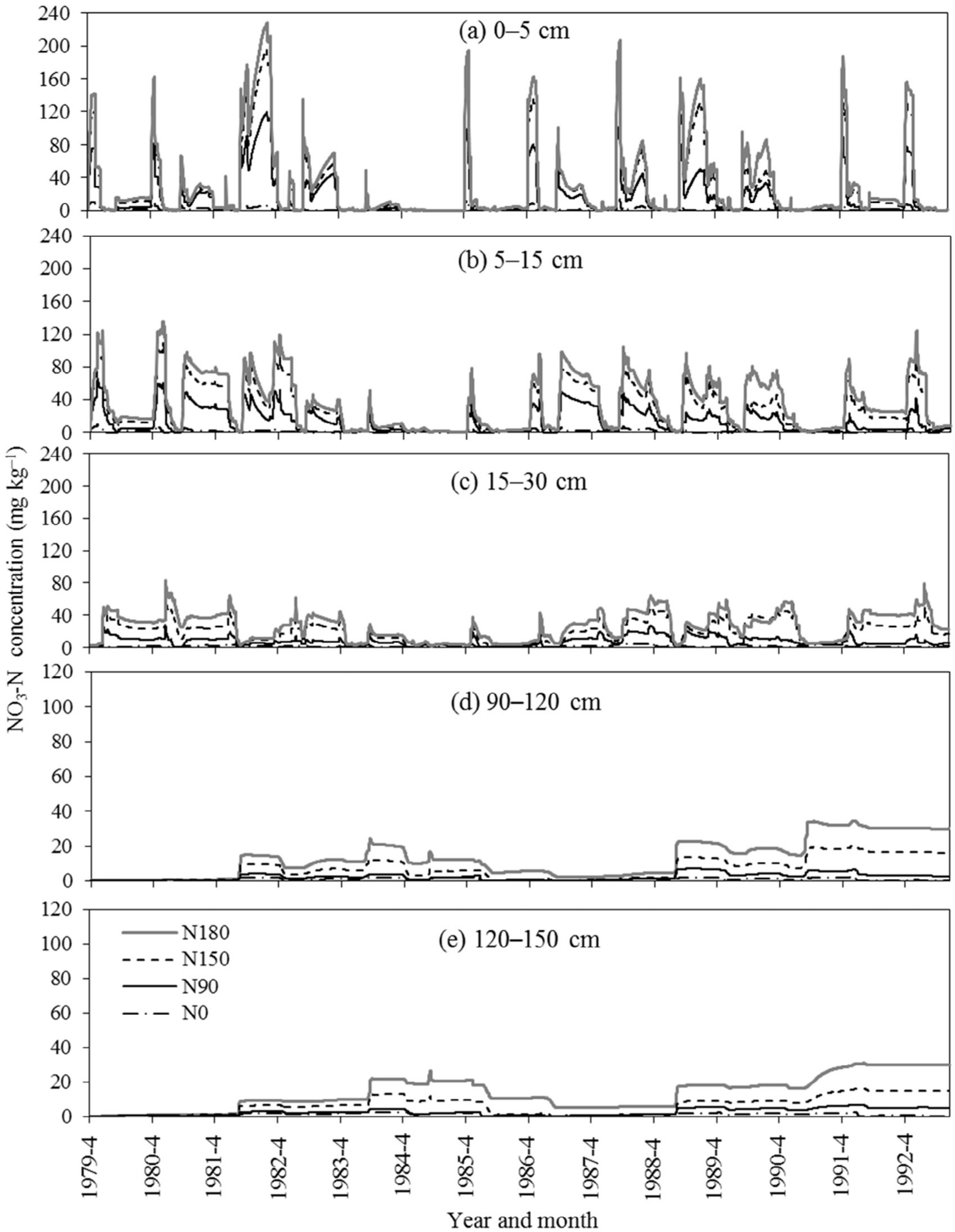

Fig. 9. The simulated changes of NO_3-N concentration at daily step in the soil depths: (a) 0–5, (b) 5–15, (c) 15–30, (d) 90–120, and (e) 120–150 cm under the N0, N90, N150 and N180 treatments from April 1979 to 1992.

15–30 cm depths were mainly affected by the time of fertilizer N application and the crop growth stage (Fig. 9a–c). The soil NO_3-N dynamics in 30–45 cm and 45–60 cm depths (data not shown) was similar with that in 15–30 cm depth, and soil NO_3-N dynamics in 60–90 cm (data not shown) was similar with that in 90–120 cm depth.

The amount of residual NO_3-N leaching into the deeper soil layers depended on water flux values during each drainage event (Godwin and Jones, 1991), which are obtained from the soil water module of DSSAT-CSM (Jones et al., 2003). Thus, the NO_3-N dynamics in the subsoil layers of 90–120 cm and 120–150 cm depths were mainly related to soil water condition, rainfall distribution and fallow period (Fig. 9d, e). In drought conditions (i.e., 1979–1981 and 1987), the residual NO_3-N was retained in the upper 0–45 cm soil depth, almost no NO_3-N leached to 60–150 cm depth (Fig. 9a–e). This residual NO_3-N in upper soil profile would benefit the following crop production if it had favorable soil water condition (e.g., in 1982). In the relative humid conditions (i.e., 1982–1986 and 1988–1992), however, there were quite amount residual NO_3-N leaching to 60–150 cm soil depth (Fig. 9d, e). The periods with high NO_3-N

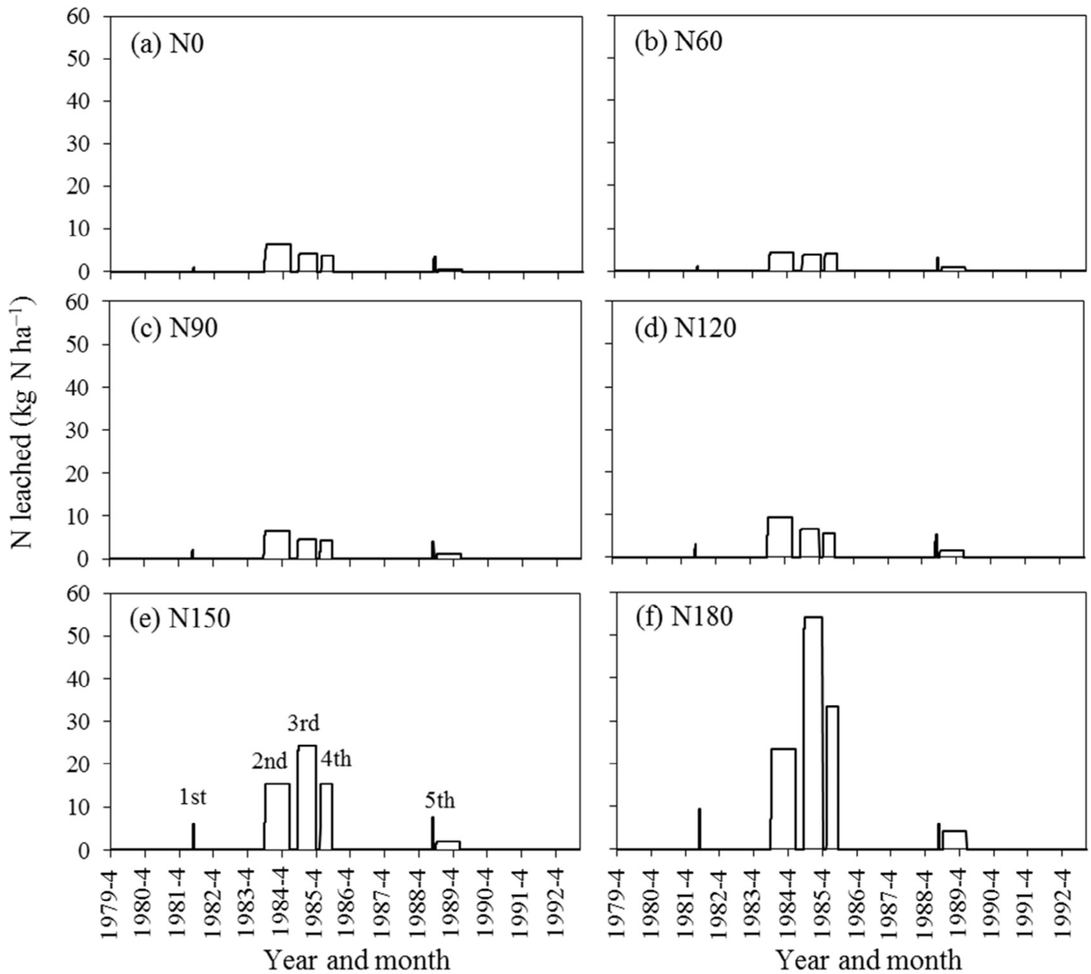

Fig. 10. The simulated NO_3-N leaching below 150 cm soil depth under: (a) N0, (b) N60, (c) N90, (d) N120, (e) N150, and (f) N180 treatments from April 1979 to 1992.

downwards movement to subsoil layers demonstrated that there was a high NO_3-N leaching potential below 0–150 cm soil depth (Fig. 10).

The simulated soil N leaching below 0–150 cm soil depth showed similar trends among different fertilizer N treatments from April 1979 to 1992 (Fig. 8a–f), while the quantity of NO_3-N leached obviously increased with the fertilizer N application rates particularly when N rates exceeded 120 kg N ha^{-1} (Fig. 10d–f). There were five periods (as labeled in Fig. 10e) in which high NO_3-N leaching below 0–150 cm soil depth happened (Fig. 10) along with the drainage events (Fig. 6b) over the 14-year simulation. The five periods mostly occurred in fallow periods or when there was heavy rainfall. Our simulation results were consistent with the observed results reviewed by Di and Cameron (2002) and Fan et al. (2010), as well as findings of many other studies (Liu et al., 2003; Xue and Hao, 2011; Zhao et al., 2006, 2007).

Among the five peak leaching phases, nitrate-N leaching in the 2nd, 3rd and 4th events were more sensitive to the high fertilizer N application rates compared with the other leaching events. For example, the nitrate-N leaching in the 2nd, 3rd and 4th events were more than 15–30 kg N ha^{-1} in N150, and 20–50 kg N ha^{-1} in N180 treatment while nitrate-N leaching losses in other peak leaching phases were less than 5 and 10 kg N ha^{-1} in N150 and N180, respectively (Fig. 10e, f).

The 1st NO_3-N leaching event occurred during fallow season (Sep. 3–19, 1981) (Fig. 10a–f) when there was high intensive rainfall (Fig. 1c). In 1981, the grain yield of winter wheat was very low due to the extremely dry weather during the growing seasons. This, in consequence, might cause high residual N accumulation in soil profile due to the low N uptake by crop. After harvest, however, heavy rainfalls in July to September 1981 (Fig. 1c) may have resulted in the downward movement of the high residual NO_3-N into the lower layers of the soil profile. In addition, large quantities of mineralized N were reported to occur upon re-wetting following a dry summer season (Di and Cameron, 2002). Similarly, the 5th leaching event occurred in the fall fallow period from Aug. 19 to Sep. 19, 1988 (Fig. 10a–f) and this event occurred because of the heavy rainfall. The 2nd leaching event occurred in the humid years during the fallow period from Sep. 8 to Sep. 19, 1983 and in the entire wheat growing seasons from September 1983 to July 1984 (Fig. 10a–f).

The 3rd NO_3-N leaching event occurred in the non-growing season from September 1984 to April 1985 (Fig. 10). For this year, the winter wheat was harvested in the late June of 1984, and maize was grown in April 1985, leaving a long fallow period between these two crops. These N leaching trends could be due to the leaching of accumulated NO_3^- in soil profile as evapotranspiration would be very low during the autumn to winter period as no crops were growing in this period (Di and Cameron, 2002). The 4th NO_3-N leaching events happened during the maize growing seasons in 1985, which was probably due to frequent rainfall events.

In addition to the NO_3-N leaching loss, the DSSAT model can also generate other soil N data dynamically during each crop growth and fallow period, including the amount of total soil inorganic N, the soil organic N mineralization, denitrification, N immobilization and soil N uptake by crop. The information is important for improving our understanding of the crop–soil N dynamic processes. Therefore, the DSSAT model has a high potential to be used to simulate a long term NO_3-N dynamics in different soil layers, to estimate the NO_3-N leaching loss out of the crop root zone, and to calculate the soil N balance during different biochemical processes.

4. Conclusions

Based on the data source from a 14-year experiment conducted in the Loess Plateau of northwestern China from 1979 to 1992, the DSSAT-CSM performed reasonably well in simulating grain yields for both spring maize and winter wheat, and showed moderate to good agreement for predicting topsoil SOC and SON, under regular fertilizer application condition. The sensitivity analysis showed credible responses of simulated grain yields to fertilizer N application rates under various soil water conditions. The DSSAT-CSM can also be used to investigate the effects of climate change on crop yield using generated weather data conducted under Sequence Analysis program. The DSSAT model successfully simulates the soil NO_3-N accumulation and leaching trends under a large range of fertilizer N application rates, rainfall conditions and maize–wheat–fallow cropping systems. Therefore, the results of this study support the potential for the DSSAT model to be able to simulate crop growth, soil N dynamics and NO_3-N leaching under various agricultural practices in the semi-arid and semi-humid region of the Loess Plateau of China.

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References

Ali, Z.I., Dawelbeit, S.E., Salih, A.A., 2005. Effect of water stress and nitrogen application on grain yield of wheat. Agron. J. 80, 902–908.
Boote, K.J., 1999. Concepts for calibrating crop growth models. In: Hoogenboom, G., Wilkens, P.W., Tsuji, G.Y. (Eds.), DSSAT v3, vol. 4–6. University of Hawaii, Honolulu, pp. 179–199.
Brisson, N., Cary, C., Justes, E., et al., 2003. An overview of the crop model STICS. Eur. J. Agron. 18, 309–332.
Confalonieri, R., Bellocchi, G., Bregaglio, S., Donatelli, M., Acutis, M., 2010. Comparison of sensitivity analysis techniques: a case study with the rice model WARM. Ecol. Modell. 221, 1897–1906.
Dang, T., Hao, M., 2000. The effect of nitrogen fertilizer under different moisture conditions and Soil Nitrogen adjustment in the Loess highland. Sci. Agric. Sin. 33, 62–67, (in Chinese with English abstract).
Dang, T.H., Cai, G.X., Guo, S.L., Hao, M.D., Heng, L.K., 2006. Effect of nitrogen management on yield and water use efficiency of rainfed wheat and maize in Northwest China. Pedosphere 16, 495–504.
Di, H.J., Cameron, K.C., 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. Nutr. Cycl. Agroecosyst. 64, 237–256.
Eitzinger, J., Thaler, S., Schmid, E., et al., 2013. Sensitivities of crop models to extreme weather conditions during flowering period demonstrated for maize and winter wheat in Austria. J. Agric. Sci. 151, 813–835.
Fan, J., Hao, M., Malhi, S.S., 2010. Accumulation of nitrate-N in the soil profile and its implications for the environment under dryland agriculture in northern China: a review. Can J. Soil Sci. 90, 429–440.
Fan, T., Zhou, G., Wang, Y., Ding, N., Gao, Y., Wang, S., 2004. Long-term fertilization on yield increase of winter wheat-maize rotation system in Loess Plateau dryland of Gansu. Plant Nutr. Fertil. Sci. 10, 127–131, (in Chinese with English abstract).
Fan, T., Stewart, B.A., Payne, W.A., Wang, Y., Luo, J., Gao, Y., 2005a. Long-term fertilizer and water availability effects on cereal yield and soil chemical properties in Northwest China. Soil Sci. Soc. Am. J. 69, 842–855.
Fan, T., Stewart, B.A., Wang, Y., Luo, J., Zhou, G., 2005b. Long-term fertilization effects on grain yield, water-use efficiency and soil fertility in the dryland of Loess Plateau in China. Agric. Ecosyst. Environ. 106, 313–329.
Fan, T., Xu, M., Song, S., Zhou, G., Ding, L., 2008. Trends in grain yields and soil organic C in a long-term fertilization experiment in the China Loess Plateau. J. Plant Nutr. Soil Sci. 171, 448–457.
Gijsman, A.J., Hoogenboom, G., Parton, W.J., Kerridge, P.C., 2002. Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter-residue module from CENTURY. Agron. J. 94, 462–474.
Godwin, D.C., Jones, C.A., 1991. Nitrogen dynamics in soil-plant systems. In: Hanks, J., Ritchie, J.T. (Eds.), Modeling Plant and Soil Systems. Agronomy monograph no. 31. ASA, CSSA, and SSSA, Madison, WI, pp. 287–321.
Hoogenboom, G., Jones, J.W., Porter, C.H., Wilkens, P.W., Boote, K.J., Hunt, L.A., et al. (Eds.), 2010. Decision Support System for Agrotechnology Transfer Version 4.5, vol. 1: Overview. University of Hawaii, Honolulu, HI.
Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., et al., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265.
Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., et al., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.
Kropff, M.J., Bouma, J., Jones, J.W., 2001. Systems approaches for the design of sustainable agro-ecosystems. Agric. Syst. 70, 369–393.
Li, Z.T., Li, X.G., Li, M., Yang, J.Y., Turner, N.C., Wang, X.Y., et al., 2013. County-scale changes in soil organic carbon of croplands in Southeastern Gansu Province of China from the 1980s to the Mid-2000s. Soil Sci. Soc. Am. J. 77, 2111–2121.
Liu, E., Yan, C., Mei, X., He, W., Bing, S.H., Ding, L., et al., 2010a. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. Geoderma 158, 173–180.
Liu, E., Yan, C., Mei, X., Zhang, Y., Fan, T., 2013a. Long-term effect of manure and fertilizer on soil organic carbon pools in dryland farming in Northwest China. PLoS ONE 8, e56536.
Liu, G.B., 1999. Soil conservation and sustainable agricultural on the Loess Plateau: challenge and prospective. Ambio 28, 663–668.
Liu, H.L., Yang, J.Y., Drury, C.F., Reynolds, W.D., Tan, C.S., Bai, Y.L., et al., 2011. Using the DSSAT-CERES-Maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production. Nutr. Cycl. Agroecosyst. 89, 313–328.
Liu, S., Yang, J.Y., Zhang, X.Y., Drury, C.F., Reynolds, W.D., Hoogenboom, G., 2013b. Modelling crop yield, soil water content and soil temperature for a soybean–maize rotation under conventional and conservation tillage systems in Northeast China. Agric. Water Manage. 123, 32–44.
Liu, X., Ju, X., Zhang, F., Pan, J., Christie, P., 2003. Nitrogen dynamics and budgets in a winter wheat–maize cropping system in the North China Plain. Field Crops Res. 83, 111–124.
Liu, X.J., Song, L., He, C.E., Zhang, F.S., 2010b. Nitrogen deposition as an important nutrient from the environment and its impact on ecosystems in China. J. Arid Land 2, 137–143.
Liu, Y., Li, S., Chen, F., Yang, S., Chen, X., 2010c. Soil water dynamics and water use efficiency in spring maize (*Zea mays* L.) fields subjected to different water management practices on the Loess Plateau, China. Agric. Water Manage. 97, 769–775.
Loague, K.M., Freeze, R.A., 1985. A comparison of rainfall-runoff modelling techniques on small upland catchments. Water Resour. Res. 21, 229–248.
Paolo, E.D., Rinaldi, M., 2008. Yield response of corn to irrigation and nitrogen fertilization in a Mediterranean environment. Field Crops Res. 105, 202–210.
Parton, W.J., Rasmussen, P.E., 1994. Long-term effects of crop management in wheat–fallow: II. CENTURY model simulations. Soil Sci. Soc. Am. J. 58, 530–536.
Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D.S., 1987. Analysis of factors controlling soil organic matter levels in great plains grasslands. Soil Sci. Soc. Am. J. 51, 1173–1179.
Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5, 109–131.
Pickering, N.B., Hansen, J.W., Jones, J.W., Wells, C.M., Chan, V.K., Godwin, D.C., 1994. WeatherMan: a utility for managing and generating daily weather data. Agron. J. 86, 332–337.
Sarkar, R., 2009. Use of DSSAT to model cropping systems. CAB Rev. 4, 1–12.
Shi, H., Shao, M., 2000. Soil and water loss from the Loess Plateau in China. J. Arid Environ. 45, 9–20.
Thornton, P.K., Wilkens, P.W., Hoogenboom, G., Jones, J.W., 1994. Sequence analysis. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), DSSAT v3, vol. 3–2. University of Hawaii, Honolulu, Hawaii, pp. 67–136.
Thornton, P.K., Hoogenboom, G., Wilkens, P.W., Bowen, W.T., 1995. A computer program to analyze multi-season crop model outputs. Agron. J. 87, 131–136.
Thorp, K.R., Malone, R.W., Jaynes, D.B., 2007. Simulating Long-term Effects of Nitrogen Fertilizer Application Rates on Corn Yield and Nitrogen Dynamics. Trans. ASABE 50, pp. 1287–1303.
Timsina, J., Humphreys, E., 2006. Performance of CERES-Rice and CERES-Wheat models in rice–wheat systems: a review. Agric. Syst. 90, 5–31.
Tojo Soler, C.M., Bado, V.B., Traore, K., McNair Bostick, W., Jones, J.W., Hoogenboom, G., 2011. Soil organic carbon dynamics and crop yield for different crop rotations in a degraded ferruginous tropical soil in a semi-arid region: a simulation approach. J. Agric. Sci. 149, 579–593.
Tsuji, G.Y., Jones, J.W., Hoogenboom, G., Hunt, L.A., Thornton, P.K., 1994. Introduction. In: Tsuji, G.Y., Uehara, G., Balas, S. (Eds.), DSSAT v3, vol. 1–1. University of Hawaii, Honolulu, Hawaii, pp. 1–11.
Willmott, C.J., 1982. Some comments on the evaluation of model performance. Bull. Am. Meteorol. Soc. 63, 1309–1313.
Wu, J.S., Guo, S.L., Dang, T.H., 2003. Mechanisms in the accumulation and movement of mineral N in soil profile of farming land in a semi-arid region. Acta Ecol. Sin. 23, 2040–2049, (in Chinese with English abstract).
Xiong, W., Conway, D., Holman, L., Lin, E., 2008. Evaluation of CERES-wheat simulation of wheat production in China. Agron. J. 100, 1720–1728.

Xue, X., Hao, M., 2011. Nitrate leaching on loess soils in north-west China: appropriate fertilizer rates for winter wheat. Acta Agric. Scand. B Soil Plant Sci. 61, 253–263.
Yang, J., Greenwood, D.J., Rowell, D.L., Wadsworth, G.A., Burns, I.G., 2000. Statistical methods for evaluating a crop nitrogen simulation model, N ABLE. Agric. Syst. 64, 37–53.
Yang, J.M., Yang, J.Y., Dou, S., Yang, X.M., Hoogenboom, G., 2013. 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. Nutr. Cycl. Agroecosyst. 95, 287–303.
Yang, J.M., Yang, J.Y., Liu, S., Hoogenboom, G., 2014. An evaluation of the statistical methods for testing the performance of crop models with observed data. Agric. Syst. 127, 81–89.
Yang, J.Y., Huffman, E.C., 2004. EasyGrapher: software for graphical and statistical validation of DSSAT outputs. Comput. Electron. Agric. 45, 125–132.
Zhang, S., Sadras, V., Chen, X., Zhang, F., 2013. Water use efficiency of dryland wheat in the Loess Plateau in response to soil and crop management. Field Crops Res. 151, 9–18.
Zhang, X.C., Liu, W.Z., 2005. Simulating potential response of hydrology, soil erosion, and crop productivity to climate change in Changwu tableland region on the Loess Plateau of China. Agric. For. Meteorol. 131, 127–142.
Zhao, B.Q., Li, X.Y., Li, X.P., et al., 2010. Long-term fertilizer experiment network in China: crop yields and soil nutrient trends. Agron. J. 102, 216–230.
Zhao, B.Z., Zhang, J.B., Flury, M., Zhu, A.N., Jiang, Q.A., Bi, J.W., 2007. Groundwater contamination with NO_3-N in a wheat-corn cropping system in the North China Plain. Pedosphere 17, 721–731.
Zhao, R.F., Chen, X.P., Zhang, F.S., Zhang, H., Schroder, J., Römheld, V., 2006. Fertilization and nitrogen balance in a wheat–maize rotation system in North China. Agron. J. 98, 938–945.
Zhou, Y., He, Z.H., Sui, X.X., Xia, X.C., Zhang, X.K., Zhang, G.S., 2007. Genetic improvement of grain yield and associated traits in the Northern China winter wheat region from 1960 to 2000. Crop Sci. 47, 245–253.