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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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ABSTRACT

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.

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