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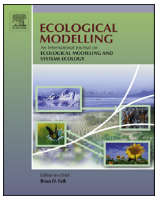

Review

The development of China-DNDC and review of its applications for sustaining Chinese agriculture

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ABSTRACT

During the past century Chinese agriculture has been struggling to produce more food to support the ever growing population, while dealing with the increased degradation of air, water and soil quality in the agricultural regions. Lessons learnt from the long-term efforts indicated that scientifically sound methodology could play a crucial role in understanding the complex interactions among climate, soil, water and farming management practices, all of which collectively control the agroecosystem services including crop yield, greenhouse gas emissions, nutrient loading and other environmental issues. Therefore, the development of a more process-based approach is needed. The process-based model, DNDC (Denitrification-Decomposition) has been widely used internationally to simulate detailed carbon and nitrogen biogeochemical cycles occurring in agricultural systems. However, this model is not fully suitable for China as it lacks a number of features which are crucial for representing Chinese agro-ecosystems, including paddy rice cultivation, complex and multiple cropping systems, and intensive management practices, etc. Recently a new version of DNDC, China-DNDC, was developed. The new model improved its capability of predicting the fluxes of all three terrestrial greenhouse gases: nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), as well as other important indicators such as crop phenology, soil C sequestration, and nutrient leaching from different cropping systems across all the major agricultural regions in China. This paper reported how China-DNDC was developed, tested and applied for sustaining Chinese agriculture. And then, it identified the weaknesses and potential improvements for the model.

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1. Introduction

From the 1950s to present, China's national grain production increased from 132 to 602 million tons, while the total area of arable land decreased from 196 to 121 million hectares (National Bureau of Statistics of China, 2015). The increase in crop yields mainly resulted from intensification of agricultural management practices, especially irrigation and fertilization. During the past 50 years, the water used for irrigation increased by 3.6 times from 10 to 37 billion $m^3 y^{-1}$, and land application of synthetic fertilizer increased by 6.3 times (National Bureau of Statistics of China, 2015). Meanwhile, the annual water used for agriculture accounts for 61.3% of the total national water consumption (Ministry of Water Resources of China, 2010). The national average fertilizer application rate is now as high as 146.5 kg N/ha/year (National Bureau of Statistics of China, 2015). The water and fertilizer used for China's agriculture will continue increasing to meet the demands for food in future. The high input of water and fertilizer along with other intensive cultivation practices have unavoidably induced a number of environmental issues such as soil fertility degradation (Qiu et al., 2004; Tang et al., 2006), water resource depletion (Xia and Jiang, 2007), eutrophication of rivers and lakes (Zhang et al., 2004) and greenhouse gas emissions (Qiu et al., 2009a,b; Li et al., 2007; Zheng et al., 2008). The sustainability of Chinese agriculture is facing challenges at local, national and global scales.

In the 1990s, reviewing all the issues threatening the agricultural sustainability, Chinese researchers had realized that a better understanding of the complex interactions among climate, soil, water and cropping management practices could provide a foundation for them to address the twin challenges of maintaining optimum yields while mitigating environmental impacts (Zhang, 2000). The direct measurement approaches are essential but expensive and usually limited by their spatial or temporal coverage. Therefore, the development of a more process-based approach is desirable. Several process-based models, such as APSIM (Keating et al., 2003), CropSyst (Stöckle et al., 2003), DSSAT(Jones et al., 2003), DAISY (Hansen et al., 1991), DNDC (Li et al., 1992a,b; Tonitto et al., 2007), LEACHM (Hutson, 2000), and WNMM (Li et al., 2007), etc., are widely accepted and used in different ecosystems. The models vary in the level of detail or number of C and N pools and transformation processes, as well as in the way different processes are described. Most models have only been tested for some processes or outputs and over a limited range of systems, soils and climates. However, these models available at that time were not fully suitable for China as most of them lacked a number of features which were important for the Chinese agro-ecosystems. The missing features included (1) paddy rice cultivation, which dominated the land-use in southern China; (2) complex cropping systems, including multi-cropping, crops, inter-planting, and multi-year rotations, and (3) intensive management practices such as alternative irrigation methods (e.g., midseason drainage, drip, sprinkler), alternative fertilization methods (e.g., slow-release fertilizer, nitrification inhibitor, fertigation), and water and temperature conservation practices (e.g., greenhouse shelter, plastic film mulching). After careful screening studies, the Chinese researchers adopted a process-based model, Denitrification-Decomposition or DNDC, as a basis to develop their own modeling capacity, because the model had been substantially enhanced along with more and more international researchers involved in the modeling development effort. It has become a generic agro-ecosystem model for predicting crop growth, C sequestration, greenhouse gas emissions, nitrate leaching, and water use efficiency for all terrestrial ecosystems including upland, wetland, grassland, forest, etc. In the mid-1990s, a joint China-US research team was organized to develop the new features to enable DNDC to be applicable across the agricultural regions in China. Through the two-decade efforts jointly made by the Chinese and U.S. researchers, a new version of DNDC, China-DNDC, was built up. And then, a large number of field campaigns were launched in China to collect a wide range of data to support the modeling effort. The observation data covered crop phenology, soil C and N dynamics, greenhouse gas fluxes and N leaching losses across all the major agricultural regions in China. These observations were used to either test China-DNDC or develop new functions for the model. The objectives of this study are to: (1) provide a detailed description of the scientific basis and the new features of China-DNDC model; (2) report how this model is tested and applied to serve the sustainability of Chinese agriculture; (3) identify the weaknesses and potential improvements for

Table 1
Crop physiological and phenology parameters adopted in China-DNDC for 23 major crop types in China.

Crop type	Optimum yield kg dry matter/ha	Grain C/N	Shoot C/N	Root C/N	Total C/N	Grain Fraction	Shoot Fraction	Root Fraction	Water requirement kg water/kg	TDD °C
Corn	4800	35.0	50.0	50.0	43.2	0.37	0.47	0.16	250	2550
Winter wheat	3900	18	50	71	33.7	0.3	0.53	0.17	200	2000
Soybean	1653	10	45	24	18.8	0.35	0.45	0.20	541	1500
Hay	22000	50	50	90	62.5	0.01	0.80	0.19	550	2500
Spring wheat	3000	25	60	60	41.0	0.33	0.52	0.15	600	1400
Sugarcane	64000	400	400	400	400.0	0.5	0.3	0.2	212	7250
Barley	2600	26	57	44	40.0	0.3	0.47	0.23	508	1000
Oats	3500	18	51	50	35.8	0.23	0.54	0.23	509	1650
Alfalfa	8000	10	10	13	10.7	0.01	0.69	0.3	300	2000
Sorghum	4000	20	69	85	37.5	0.35	0.56	0.09	304	2600
Cotton	1500	12	30	35	20.6	0.32	0.52	0.16	646	1200
Rye	2134	20	50	50	35.2	0.28	0.47	0.25	551	2000
Vegetables	6000	30	30	50	30.6	0.65	0.3	0.05	800	1400
Potato	14000	40	40	60	40.7	0.7	0.25	0.05	415	2100
Beets	21000	58	50	80	56.6	0.75	0.2	0.05	318	2550
Wetland rice	6400	27	43	45	34.8	0.4	0.53	0.07	508	2200
Peanuts	2650	25	40	50	34.1	0.35	0.47	0.18	554	2900
Upland rice	3375	35	55	40	39.4	0.37	0.43	0.2	400	2250
Rapeseeds	1600	12	45	52	46.7	0.23	0.69	0.08	450	700
Tobacco	1800	15	15	40	15.7	0.45	0.48	0.07	700	3400
Millet	1900	20	40	50	37.9	0.32	0.52	0.16	331	1750
Sunflower	1500	10	45	50	22.0	0.3	0.67	0.03	495	1500
Beans	1500	9.2	33	35	17.2	0.36	0.46	0.18	300	1900

the model. We hope that these efforts in this paper can improve process understanding and enhance further applicability of the China-DNDC model.

2. Development of new features in China-DNDC

The original version of DNDC model (Version DNDC9.2) contained a relatively complete set of biogeochemical reactions, such as decomposition, hydrolysis, nitrification, denitrification, ammonia volatilization etc., which enabled it to track C and N cycling in upland crop soils. In conjunction with the soil hydrology and crop growth modules embedded in the model framework, DNDC well served for greenhouse gas (GHG) studies in the U.S. in the early 1990s (Li et al., 1992a,b; Li et al., 1994; US EPA, 1995). However, to turn DNDC to serve Chinese agro-ecosystems, we had to make a series of modifications or additions to enable the model to simulate wetland crops (e.g., paddy rice), complex crop rotation systems (e.g., inter-planting, multi-year rotation) and alternative cropping management practices (e.g., slow-release fertilizers, nitrification inhibitor, plastic film mulching, greenhouse sheltering, fertigation).

2.1. Modeling paddy soil biogeochemistry

China possesses 30 million ha of paddy rice, accounting for 18.5% of total cropland (National Bureau of Statistics of China, 2015). Paddy rice cultivation is characterized with season-long inundation during the rice growth period. The flooding usually starts from the date of rice shoot transplanting and ends several days before harvest. Long-term flooding creates unique soil physical and chemical conditions that substantially differ from that in upland ecosystems. The soil redox potential (Eh) gradually decreases, driven first by aerobic decomposition consumption of dissolved oxygen, and then by the anaerobic heterotrophic microbes consuming the additional oxidants (e.g., nitrate, high-valent manganese, high-valent iron, sulfate etc.) existing in the soil. To predict soil Eh dynamics under both aerated and submerged conditions, a simple kinetic scheme was developed for DNDC (Li et al., 1992a,b) to capture the soil redox dynamics (Li, 2000).

In the original version, DNDC computes soil Eh based only on soil oxygen concentrations. When a soil is fully oxic, with oxygen concentration equal to that in the air, the soil Eh is set to 650 mV. Soil Eh decreases along with decrease in the soil oxygen concentration. A simple kinetic scheme was developed for DNDC such as decomposition (Reaction 1), nitrification, and denitrification (Reaction 2) which occurred in upland soils under different redox conditions.

$$\text{Oxidation}: CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad (1)$$

$$\text{Denitrification}: 5CH_2O + 4HNO_3 \rightarrow 5CO_2 + 2N_2 + 7H_2O \qquad (2)$$

However, oxygen in a flooded profile can be depleted quickly, and the soil Eh will continue to decrease driven by other oxidants such as high-valent manganese (Mn^{4+}), high-valent iron (Fe^{3+}), sulfate ($SO_4{}^{2-}$) or carbon dioxide (CO_2). To simulate the Eh-determined biogeochemical processes occurring in the flooded paddy soils, the researchers (Li, 2000; Li et al., 2002) added several new redox reactions in China-DNDC, which are as follows:

$$\text{Manganese reduction}: CH_2O + 2MnO_2 \rightarrow CO_2 + 2MnO + H_2O \qquad (3)$$

$$\text{Iron reduction}: CH_2O + 2Fe_2O_3 \rightarrow CO_2 + 4FeO + H_2O \qquad (4)$$

$$\text{Sulfate reduction}: 2CH_2O + H_2SO_4 \rightarrow 2CO_2 + H_2S + 2H_2O \qquad (5)$$

$$CO_2\ \text{reduction}: 4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \qquad (6)$$

where CH_2O (representing soil organic carbon or SOC) or H_2 is the electron donor, and MnO_2, Fe_2O_3, H_2SO_4 and CO_2 are the electron acceptors in the redox reactions, respectively. In comparison with the original version of DNDC that tracked the soil Eh in the range of +650 to 0 mV, China-DNDC simulates the soil Eh in a range of +650 to −350 mV driven by the additional redox reactions (3) – (6), that has enabled China-DNDC to simulate a series of biogeochemical processes occurring under anaerobic conditions, including anaerobic hydrolysis and methanogenesis. The above described modifications enabled China-DNDC to model CH_4 emissions from the flooded paddy soils that have essentially extended the model applicability for China where rice paddy or other wetland ecosystems are prevalent (Li et al., 2002; Zhang et al., 2009; Sun et al., 2011, 2010).

2.2. Modeling multiple cropping systems

Double- and even triple-cropping systems are common in China, which allow Chinese farmers to elevate the crop production per unit of land by consecutively or simultaneously planting two or more crops in a same field, if the weather conditions allow. A variety of crop types meet the requirements for successful multi-cropping across various climatic zones and soil properties in China. China has a national multiple-cropping index of 1.3 (National Bureau of Statistics of China, 2015). Multi-cropping systems require more water and nutrients and leave more crop residues in the fields that substantially altered the soil C and N dynamics s well as the water regimes. Three major modifications were made to enable China-DNDC to model these rotation systems at site or regional scale for China.

At first, all the crop parameters used for DNDC were recalibrated by the authors for the crop varieties grown in China. DNDC simulates crop growth and yield based on six crop physiological and phenology parameters: maximum yield, biomass partitioning into and C:N ratios of grain, shoot and root, cumulative thermal degree days to maturity (TDD), water requirement (kg water/kg dry matter), and a nitrogen fixation index. Through a thorough investigation of published and unpublished data sources, a new crop parameter database was developed for 23 major crops (Table 1); these crop areas account for nearly 95% of total cropland in China (National Bureau of Statistics of China, 2015).

In addition, the published agricultural census data in China include the total area of arable land and total harvested area for each crop type at county scale. However, the census data do not include the areas for each of the single cropping systems such as rice-wheat system, maize-wheat system, etc. (Frolking et al., 2002). However, it is the cropping system but not the single crop type that determines the soil biogeochemistry including soil C or N dynamics. To meet the gap in the census data, researchers in the Chinese Academy of Agricultural Scientists reanalyzed all the original crop area data and developed a prioritized list of most possible cropping systems for each of the six agricultural regions in China (Table 2; Qiu et al., 2003). These prioritized lists were merged with the census data to determine the areas of the most possible cropping systems at county scale for all the ~2400 counties in China (Qiu et al., 2003). The establishment of the database set a sound basis for applying China-DNDC at national scale for the country.

Finally, algorithms for simulating multiple cropping systems, allowing up to six crop types to grow simultaneously or consecutively within a year, were developed in China-DNDC. When several crops are planted within a same field, they share same climate and soil conditions, but compete for water and nutrients from the soil. If the rotated crops contain legume plants, the legumes will fix the atmospheric nitrogen and hence benefit other co-growing crops.

Equipped with the three major modifications, China-DNDC is capable of modeling all major cropping systems across this country.

2.3. Modeling alternative cropping management practices

To accommodate various natural conditions or socio-economic demands, Chinese farmers have adopted a variety of alternative cropping management practices to elevate crop production meanwhile save energy or other resources. For example, to save water resources, the rice farmers have adopted midseason drainage or alternative wet and dry irrigation, and the upland crop farmers utilized various new irrigation technologies (e.g., drip, sprinkler), plastic film mulch, or greenhouse shelters. To increase fertilizer-use efficiency, farmers used slow-release fertilizers, nitrification inhibitors, or fertigation technique. Algorithms for these alternative management practices were developed and added upon the baseline farming practices (i.e., tillage, fertilization, irrigation, manure amendment, etc.) originally developed in DNDC (Li et al., 1994).

2.3.1. Water-saving management alternatives

Water use for agriculture accounts for 60% of total water consumption in China. Unsustainable water resources (e.g., ground water) are being depleted in many agricultural regions (Xia and Jiang, 2007). Water saving practices are strongly encouraged for both upland crops and rice paddies. The common approaches adopted in China include plastic film mulching, midseason drainage, alternative dry and wet, drip, sprinkler, etc. These practices have been newly parameterized in China-DNDC to assess their impacts on the agroecosystem services across the country. In China-DNDC, the effects of alternative water management practices are simulated by tracking the interactions among precipitation, evaporation, infiltration, transpiration, evaporation and leaching at hourly time.

2.3.1.1. Film mulching. Plastic film mulching has been widely adopted as a water-saving measure in North China where annual precipitation is <500 mm. Thin clear plastic film is applied to cover the soil surface of crop fields that substantially reduce evaporation rate but still allows the rainwater to infiltrate into the soil. This practice has effectively allowed a large number of crops to survive severe droughts in the arid or semi-arid areas in China. The original version of DNDC simulated interactions between crop growth and soil climate at daily time step. Driven by the weather data (i.e., air temperature, precipitation, wind speed etc.), it calculated daily potential evapotranspiration rate based on the Penman-Monteith Equation, and then calculated crop demand for water (i.e., potential transpiration) based on the crop growth rate. If there was enough water in the soil profile, the potential transpiration would be met; otherwise, water stress would occur to reduce the crop daily production. The original DNDC simulated soil temperature profile by tracking heat transfer between soil layers driven by the soil heat capacity, heat conductivity and temperature gradient. To add the film mulching practice onto the soil climate routine of DNDC, a new module to simulate the impacts of the applied plastic film on the soil temperature and water balance was developed. Given the film mulching coverage and duration, the module adjusted the soil surface temperature taking consideration of the effect of the film. The new soil surface temperature is determined by the air temperatures as well as the film thickness and thermal conductivity, and the new soil moisture is quantified by the soil evaporation rate with the film-covered fraction of ground (see details in Han et al., 2014). After the adjustment, the new soil surface temperature and moisture will be used to calculate the entire soil temperature and water profile based on the DNDC routines of soil heat transfer and water movement.

2.3.1.2. Midseason drainage. Driven by the market demand, the rice-producing areas in China have gradually expanded northward during the past two decades (Chen, 2013). However, the water resources are less abundant in North China. In the early 1990s, the rice farmers in North China attempted to change the traditional paddy water management practice, continuous flooding, to save the irrigation water. They allowed short-term (5–10 days) drying of paddy soils in mid-season to reduce the irrigation water use, and found that rice yields were not diminished (Li et al., 2002). This “midseason drainage” practice has spread through China over several decades and now is adopted by most rice farmers (Zou et al., 2007). In China-DNDC, the beginning and end dates of each flooding event can be defined by the users. During the flood period, the soil is inundated, and water is added as needed to maintain the water table about 5–10 cm above the soil surface. When the flooding period ends, ponded water will gradually decrease and the soil

Table 2
Regionally prioritized combinations of crop types involved in double- or triple-cropping systems in China.

Agricultural Region	Prioritized combinations of crop types in rotation systems
Northeast	Single-season spring maize, spring wheat, rice, soybeans
North	Winter wheat rotated with summer maize, vegetables or soybeans, single-season cotton
Northwest	Winter wheat rotated with summer maize, vegetables, and single-season spring corn, spring wheat, potatoes
Mid-South	Rice rotated with winter wheat, rapeseeds or vegetables, winter wheat rotated with cotton, double rice
Southwest	Rice rotated with winter wheat or rapeseeds, double rice, single-season corn, potatoes, rice or vegetables
South	Double-rice rotated with vegetables, triple-rice

will dry, due to evapotranspiration and leaching. During the dry period, the water table is calculated based on the water input from precipitation and the water output through evapotranspiration and leaking. The bund height (ridge at paddy edge to prevent lateral runoff of ponded water) defined by the users sets the highest level of the water table. Constrained by the bund height and the water balance, the water volume in the field can be calculated. Runoff flow is calculated during the heavy rainfall events when the water volume excess the capacity of the ponding pool. Based on observations at an experimental rice field equipped with lysimeter facilities in South China, the default height of the bund was fixed as 10 cm, and the default leaking rate set to be 0.8 mm/day (Zhao et al., 2014). For rainfed rice, China-DNDC simulates the fluctuation of the field water table based on the same routines as above described.

2.3.1.3. Drip irrigation. To sustain crop production with limited water resources, drip irrigation is a popular practice especially in the vegetable farms which are usually located around the large urban. This irrigation method has been parameterized in DNDC by prescribing the depth of the pipes as well as the water release rate. In addition, sprinkler irrigation was also added in DNDC by reducing the water input rate. Equipped with drip, sprinkler and the traditional furrow irrigation methods, China-DNDC can simulate the major irrigation options for their effects on crop yield as well as water use efficiency (Zhang et al., 2016).

2.3.2. Alternative fertilizer application methods

Overuse of fertilizer is common in Chinese agriculture, and has caused a series of environmental issues, including groundwater contamination, eutrophication, ammonia volatilization and nitrous oxide emissions. Several alternative practices are encouraged to increase fertilizer use efficiency and reduce fertilizer use. The impact of these practices on soil N balance have been evaluated in a number of experimental fields in China (e.g., Cui et al., 2013; Li et al., 2012). The data obtained from the experiments have been used to develop new algorithms for China-DNDC.

2.3.2.1. Nitrification and urease inhibitor use. Nitrate leaching is a major N-loss pathway in agricultural soils. Ammonium can be rapidly oxidized to nitrate in upland soils, making applied fertilizer-N (often urea) vulnerable to leaching. A number of nitrification inhibitors (e.g., DCD, ATC) have been put in market and utilized by farmers in China. To include the inhibitors in China-DNDC, the authors parameterized the application of nitrification inhibitors by defining their efficiency and effective duration. If any nitrification inhibitor is applied, it will decrease the simulated nitrification rate based on the user-defined efficiency during the time period based on the user-defined effective duration. Similarly, urease inhibitor has also been parameterized in China-DNDC to reduce the rate of urea hydrolysis. The two new features enable China-DNDC to estimate the effectiveness of fertilizers applied with the alternative practices on N cycling, including plant N uptake, ammonia volatilization and nitrate leaching.

2.3.2.2. Slow-release fertilizer. Nitrogen fertilizers such as urea can be coated with clay or an organic membrane to reduce the rate of N transferring from the fertilizer to the soil. A new parameter, RD or releasing duration, has been added in the model to redefine the N release rate from the fertilizer. Based on the releasing duration, China-DNDC evenly partitions the total amount of N in the fertilizer into the days of the defined time period; the daily N release rate is calculated as

$$R_f = TN/RD$$

where R_f is N release rate (kg N/ha/day), TN is total N content in fertilizer (kg N/ha), and RD is the user-defined releasing duration (days).

2.3.2.3. Fertigation. Fertigation is the application of fertilizer dissolved in the irrigation water. It can increase both water- and nitrogen-use efficiency (Li et al., 2003). A function was added to China-DNDC to enable it to read a fertigation file specifying the daily amount of irrigation water added as well as the fertilizer type and amount coming with the irrigation water. China-DNDC then simultaneously allocates the water and fertilizer at the defined depth in the soil profile on the specified dates.

2.3.3. Greenhouse shelter

Faced by ever-growing demand for vegetables, greenhouse shelters have been widely adopted in farms, especially in North China. This practice effectively lengthens the growing season. Covered with plastic film, the greenhouse shelters provide relatively stable interior temperature and moisture. However, the managed interior climate can impact not only the crops but also the soil biogeochemistry. To assess impacts of the greenhouses on soil fertility, C sequestration and trace gas emissions, the authors added this practice in China-DNDC. During the time period when the greenhouse shelter is applied, the indoor climate will be determined by the field-recorded (or user-specified) interior air temperature, and precipitation will be replaced by irrigation. Regulated by this interior climate, it simulates the changes in the crop phenology as well as the soil C and N dynamics based on biogeochemical routines embedded in the model.

2.4. N leaching simulation

Eutrophication is a growing threat to water bodies in China, largely due to nutrient loading from the agricultural production (Zhang et al., 1995, 2004). The DNDC model has been applied in China for many years with encouraging results. However, DNDC had not been previously used to simulate N loading in paddy and upland fields. It would not be applicable to apply DNDC for this objective to other sites with different soil conditions such as the special land-use configurations as well as the special water management practices in China. Long-term leaching experiments had been conducted in several research stations with the lysimeter facilities in Shandong, Sichuan, Shanghai and other locations in China (Zhou et al., 2013; Li et al., 2014; Deng et al., 2011a; Zhao et al., 2014), to better understand and quantify relevant processes

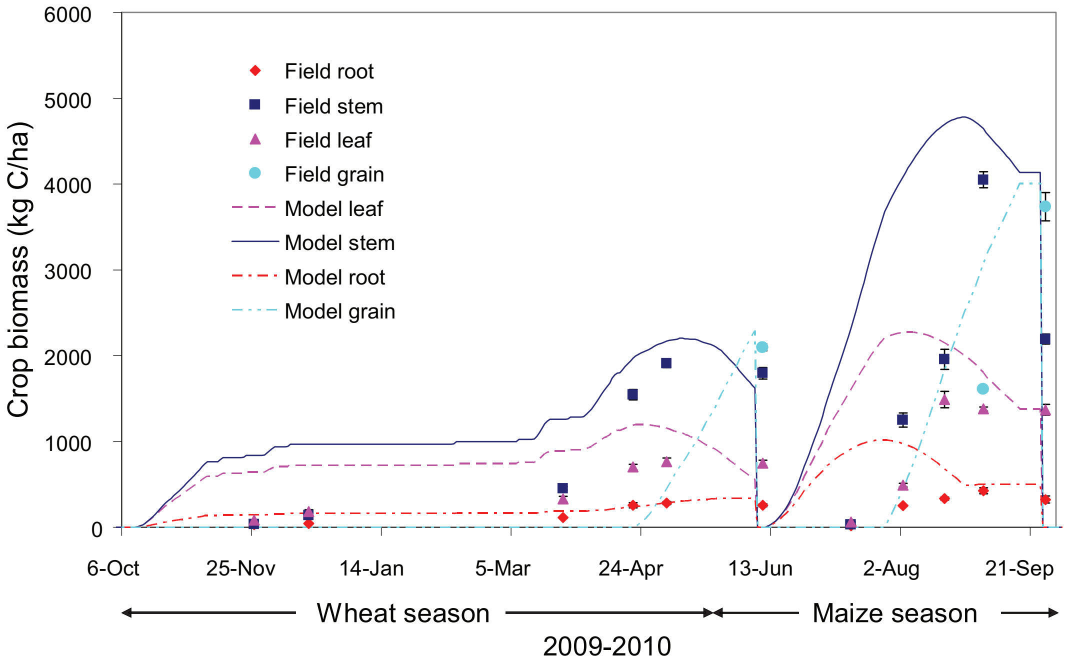

Fig. 1. China-DNDC simulated biomass C of grain, leaves, stems and roots compared to crop biomass data measured at a winter wheat-summer maize rotation system in Huantai County, Shandong Province in 2009–2010 (data source from Qiu and Wang, 2012).

under various land-use types (e.g., upland crops and paddy rice) and soil conditions (e.g., different slopes, varied surface cover). For the upland fields, 3 key parameters, i.e., dDVD, DF and FSF were preliminarily adjusted to improve capability of original DNDC in simulating water movement and N turnover for an intensively cultivated region in northern China. All the modifications were based on the field experiments and water movement characteristics from 6 sites representing the predominant cropping systems in northern China (Li et al., 2014). For the rice paddies, to improve the ability to correctly simulate N losses through surface runoff or subsurface leaching in rice paddies, two widely-used functions, the SCS Curves and the Modified Universal Soil Loss Equation (MUSLE), have been incorporated into this model to simulate N leaching processes. Water flow and dissolved N flux data, collected from the Yanting Agricultural Experimental Station of Chinese Ecological Research Network, in Sichuan, were utilized to improve hydrological and leaching simulations. All functions and parameters were calibrated against observations from the experimental stations (Deng et al., 2011a). Recently, to overcome the shortcomings that the model could not adequately simulate the impacts of rice field configurations on the field water dynamics, three internal parameters (field ridge height, fertilizer N partition ratio and urea dissolution) and two input parameters (leaching rate and N concentration in flood water) were added to the model. These modifications mainly focused on the specific configurations of the rice paddy fields in China, which apparently differ from that of upland crop fields (Zhao et al., 2014). With these modifications, the model was well calibrated, and its capacity for simulating the N biogeochemistry in flooded rice field was substantially enhanced.

3. Applications of China-DNDC for ecosystem services

During the past two decades China-DNDC has been tested against observations from numerous field measurements of crop yield, soil physical and chemical conditions, soil C dynamics, N_2O and CH_4 fluxes, and N leaching across the major cropping systems in China (e.g., Qiu and Wang, 2012; Li et al., 2010; Wang et al., 2008). And then, China-DNDC has also been used in ecosystem service studies which include yield prediction, water conservation, greenhouse gas inventory, and N leaching mitigation at site or regional scale.

3.1. Crop yield prediction

Crop yield is one of the major services of agricultural ecosystems. Crop growth status directly controls the soil water and C and N regimes, and hence it is crucial for a biogeochemical model to correctly simulate crop phenology and yield. Measurements of crop phenology and production were conducted in various cropping systems in China (e.g., Qiu and Wang, 2012), meanwhile yield data were collected from the national census (e.g., Yu et al., 2014). The data were utilized for model comparisons at site or regional scale.

3.1.1. Test for crop phenology

Crop biomass was measured at a field with a winter wheat and summer maize rotation in Huantai County, Shangdong Province in 2009–2010 (Qiu and Wang, 2012). Driven by the local weather data and management practices (e.g., with fertilizer application rates of 270 kg N/ha for the wheat and 330 kg N/ha for the corn), China-DNDC simulated total biomass production and its partitions to grain, leaf, stem, and root with encouraging results (Fig. 1).

3.1.2. Test for crop yield with alternative fertilization methods

At Linhai City, Liaoning Province, maize yields from fields treated with three different fertilizer application methods were measured in 2010 and 2011 (Yang et al., 2014). The three treatments included the farmer's traditional practice with fertilizer rate 265 kg N/ha (FP), the optimized fertilizer rate with reduced fertilizer rate as 210 kg N/ha (OPT), and the optimized fertilizer rate plus crop residue incorporation (7500 kg dry residue/ha) (OPTS). The observations and simulations both indicated that reduction in fertilizer application rate from FP to OPT led to a lower crop yield, but yields increased with the amendment of crop residue.

3.1.3. Prediction of crop yield at regional scale

China-DNDC was applied for predicting yield at regional scale in Liaoning Province in Northeast China where rainfed maize dominated. County-average maize yield data for 14 years (1996–2009) of maize were collected for all 76 counties in Liaoning Province. Daily weather data for all the counties and all the years were also collected from the climate database of the Chinese Meteorological Agency to support the model simulations for the region. China-DNDC was run for each county for the 14 years based on the local climate, soil properties and crop-management practices (e.g., planting/harvest dates, fertilizer application rates, tillage etc.). Fig. 2 showed an example on comparison between census-reported and modeled yields for Changtu County in 1978–2005. Both measured and simulated yields became highly variable after 1995. China-DNDC successfully simulated the dynamics of maize yield for the 14 years, especially the yield reductions occurred in the drought years of 1997 and 2000 (Fig. 2). Regional modeled maize yields were also highly correlated ($R^2 = 0.88$) with the mean measured yields across all 76 counties in Liaoning Province for the 14 years from 1996 to 2009 (Yu et al., 2014).

3.2. Water-saving agriculture

Many areas in Northwest China are under arid to semiarid climatic conditions, with annual precipitation less than 600 mm. Droughts have impacted local agricultural production for centuries, and now are getting worse, with increased uncertainty ahead due to global climate change. Elevated drought threats have led to field testing of a number of water-saving management approaches such as film mulching, expansion of water collecting area, etc. to maintain the agricultural production. A field experiment was carried out at Heyang county, Shaanxi province, to test the effectiveness of film mulching against drought. The three-year measurements (2008–2010) indicated that application of the plastic film on the soil surface substantially reduced the water stress and sustained the crop yield. China-DNDC successfully simulated not only the dynamics of soil moisture but also the crop yields observed at the fields with and without the film mulch (Han et al., 2014). This model was then applied to the entire province and indicated that film-mulching-induced yield improvements are highly uneven across the climatic zones of the province, which provide quantitative recommendations to support policy and planning related to film mulching in Shaanxi province.

3.3. Soil C sequestration

Soil organic carbon (SOC) plays a key role in maintaining soil fertility as well as soil aggregate structure, which are crucial for sustaining agricultural production. Amendment of crop residue plus organic fertilizer (e.g., farmyard or green manures) is the sole SOC input for most agroecosystems. During the past century, there were significant changes in SOC inputs to croplands in China. In the first half of the 20th century, organic fertilizer from livestock or human manure was commonly used in the cropland in the country. However, during the period of 1950–1990 when synthetic fertilizer became available to Chinese farmers, manure fertilizer was gradually abandoned. Meanwhile, a large portion of crop residues were used for fuel, building materials or feed with not much left for soil incorporation. These practices from 1950 to 1990, with low C inputs, substantially affected the SOC balance in most Chinese croplands. To change the trend, a new policy was launched in the 1990s to encourage the farmers to maximize crop residue incorporation. A number of field experiments have indicated the recovery of SOC in Chinese cropland (Pan et al., 2004; Tang et al., 2010). China-DNDC was utilized to quantitatively review the historical trends of change in SOC content in China.

Table 3
Statistical analysis for comparison between measured and modeled SOC data for the six experimental sites in China.

Site	Treatment	R^2	Slope	Significance
Qiqihar		0.950	0.71	**
Quzhou		0.95	0.87	**
Hequ	CK	0.486	0.742	
	fertilizer	0.326	0.519	
	manure	0.919	0.832	**
Qiyang	fertilizer	0.953	0.913	**
	manure	0.963	0.894	**
Hangzhou	CK	0.911	0.656	*
	fertilizer	0.990	0.875	**
Chongqing	CK	0.945	0.730	*
	Fertilizer+ manure	0.975	0.836	*

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

3.3.1. Modeling long-term SOC dynamics at the site scale

China-DNDC was tested against SOC contents measured at a number of sites for multiple years. For example, six long-term (10–20 years) SOC datasets were collected at six crop fields, which had the predominant practice of the local farmers. China-DNDC was run with the local climate, soil and management conditions for the six cases (Wang et al., 2008). The measured data showed that the trends of change in SOC contents varied across not only the locations but also the treatments at each site. Statistical analysis indicated there were significant correlations between the measured and modeled SOC data for all the six sites (Table 3). Similar site-scale validation tests were conducted by other researchers, which demonstrated that China-DNDC was capable of quantifying long-term SOC dynamics for both upland and wetland cropping systems across climatic zones, soil types and management regimes in China (Zhang et al., 2006; Xu et al., 2011).

3.3.2. Quantifying SOC storage at national scale

The validated China-DNDC has been applied at regional scale to quantify SOC storage in Chinese agricultural soils. The database required by the regional/national application of the China-DNDC model was showed in Table 4. With the support of the regional database, Tang et al. (2006) calculated SOC storage in all croplands in whole China using China-DNDC. The modeled results revealed that the total SOC storage in croplands in China for year 1998 was 4.0 Pg C. Based on the modeled results, the Chinese cropland soils released 186 Tg C as CO_2 into the atmosphere, but received only 68 Tg C from the above-ground crop residue incorporation (only 15% of above-ground crop residues were returned back to the agricultural soils) and 39 Tg C from crop roots, resulting in a net SOC loss of 79 Tg C in China. Considering the change in residue management and other cropping management practices (e.g., tillage) gradually taking place in China, Tang et al. (2010) conducted a new simulation with updated database by including the lately compiled county-level soil, climate and land use data for year 2003. The new results indicated that the total SOC storage was 4.7–5.2 Pg C with an average of 4.95 Pg C. The study indicated that there were still great potentials for improving SOC status in most croplands of China by adopting alternative farming practices.

3.3.3. Prediction of impact of SOC on crop yield

A sensitivity test conducted by Qiu et al. (2009a,b) with China-DNDC focused on impacts of SOC contents on crop yields in China. In the test, the SOC content of the baseline scenario was collected from field observations and local records. Four alternative SOC contents were set to be 50%, 75%, 125% and 150% of the baseline SOC contents for each county. China-DNDC was run for all the five scenarios for 20 years using the actual weather data of 1983–2003. The modeled results indicated that the national crop production

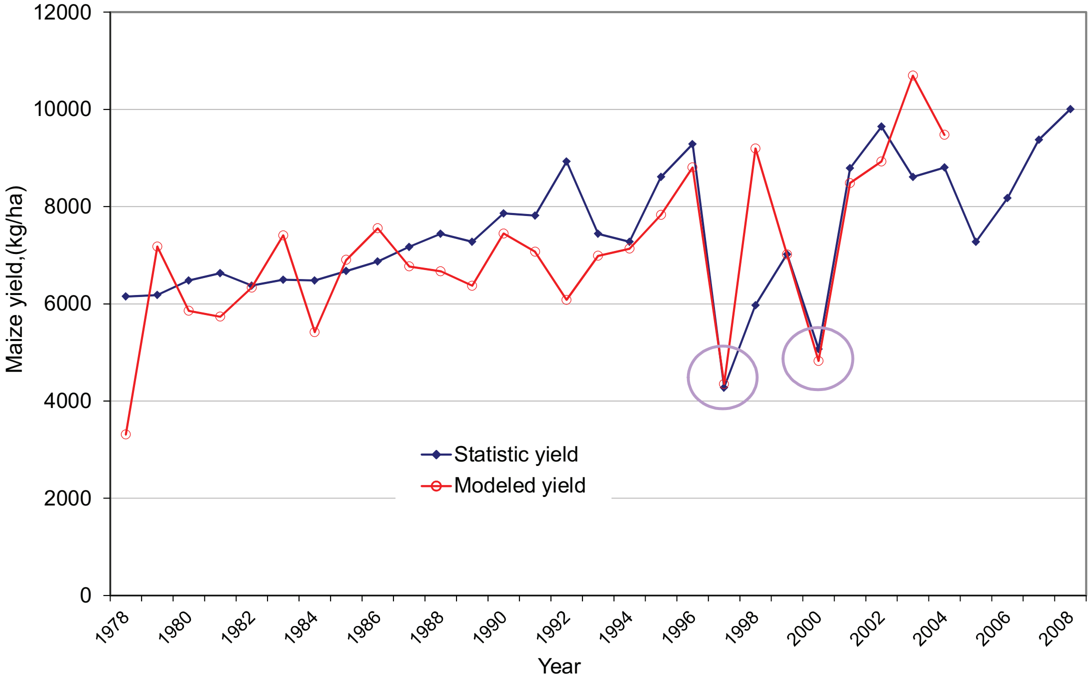

Fig. 2. Comparison between modeled and census-reported maize yields for Changtu County, Liaoning Province from 1978 to 2005. The circles represent the yield reductions occurred in the drought years of 1997 and 2000 (statistic yield Source: National Statistic Yearbook of China).

Table 4
Datasets required by the regional/national application of the China-DNDC model.

Sub-datasets	Detail description	Data sources
climate dataset	Daily weather data, i.e., precipitation, maximum and minimum air temperature within the study region	The national weather stations, each unit/county can share the weather data from the nearest weather station
soil properties	Maximum and minimum bulk density, clay content, initial SOC content and pH of each unit/county	The 1:1,000,000 Scale Soil Map of the People's Republic of China (Edited by the Office for the Second National Soil Survey of China);
crop types	Physiological data of typical crops and cropping data including planting date and harvest date, maximum yield, etc.	Field investigations of typical cropping areas.
management practices	Cropland acreages, sown acreages per crop, the rate and date of nitrogen fertilizer application, tilling date, crop area and fraction of above-ground residue returned into soil. All county-based agricultural census data and agricultural management practices were prepared from two sources: (a); and (b)	The Agricultural Statistics Yearbook of China(county-based), or field investigations (according to the basic geographic unit).

increased with increasing SOC contents. When SOC increased by 1 g/kg, the national average crop yield increased by 231 kg C/ha, which consisted of increase in corn yield by 176, 454 and 328 kg/ha in Northeast China, North China and Northwest China, respectively; in single-season rice yield by 185 kg/ha in Mid-south China; in double-season rice yield by 266 kg/ha in East China; and in rice-wheat rotation system yield by 229 kg/ha in Southwest China.

3.4. Nitrogen leaching

Nitrogen contamination of groundwater as well as eutrophication for surface water have been widely observed in the major agricultural regions in China (Zhang et al., 1995, 2004; Liu et al., 2001). This is largely related to N loading processes occurring in the agricultural lands where fertilizers are applied. To test China-DNDC for its ability in simulating N losses through surface runoff and subsurface leaching flows from the crop fields, experiments were conducted in upland crop and paddy rice fields in China.

3.4.1. Site scale

Li et al. (2014) measured N leaching rates based on lysimeters at three upland crop fields in three fields, which were planted with 3 different cropping systems (e.g., wheat-onion, wheat-maize, and vegetables) and managed with typical local practices, including fertilizer application rates 600, 600, 1450 kg N/ha, respectively, and irrigated with 500, 250, and 900 mm water per season, respectively. China-DNDC simulated the three sites, driven by local weather data, soil properties and cropping management practices. The modeled water leaching rates were 256, 40.5 and 304 mm and N leaching rates were 34, 1.54 and 190.2 kg N/ha for the three sites, respectively, in agreement with observations. The higher N losses were observed due to the higher N fertilizer rates and irrigation water application rates. Statistical calculations showed that the simulations could explain more than 50% of the variations of the measured water and N leaching losses for the 3 sites. China-DNDC was also applied to N-leaching studies in hilly areas in Southwest China (Deng et al., 2011b) and paddy rice fields in Southeast China (Zhao et al., 2014) with encouraging results.

3.4.2. Watershed scale

The DNDC algorithms for incorporating livestock manure production and management to simulate greenhouse gas and ammonia emissions recently developed by Li et al. (2012) have been incorporated into China-DND Gao et al. (2012, 2014) recently completed a China-DNDC watershed-scale study on regional N balance across livestock and cropping systems. Based on their results, the watershed of the Xiaoqinghe River, a tributary of the Yellow River basin in Shandong province where the Laizhou Bay was the receiving body of water and Yangkou was the estuary of the Pacific Ocean, received 222.2 million kg N from synthetic and manure fertilizer application in 2008 due to the intensive crop and vegetable cultivation. About 11% of this applied N was leached from the soil root zone. Livestock manure management accounted for about 20% of the total N loading in the watershed. The modeled results were comparable with the measured N loading fluxes for the watershed.

Another watershed-scale test was conducted in Yanting county, Sichuan province in Southwest China. The watershed had 19.3 ha of croplands, 11.0 ha of forests, 1.1 ha of grassland and 3.7 ha of residential areas. The natural and manmade channels in the Yanting watershed form a drainage system that produces steady water flows during the rainy season. By linking to the spatial database of topography, meteorology, soil, vegetation and management practices, China-DNDC simulated surface runoff flows, subsurface leaching flows, soil erosion, and N loadings from the watershed to the downstream (Deng et al., 2011b). The modeled total N loading rate (the sum of surface runoff and subsurface drainage flow) for 2008 was 904 kg N from the watershed, while the measured N loading rate was 760 kg N.

3.4.3. National scale

To quantify N loading at national scale, we applied China-DNDC for all croplands in China. Qiu et al. (2011) implemented national-scale simulations by linking China-DNDC to the Chinese agricultural database. Results from the simulations indicated that (1) the total amount of N leached from all Chinese croplands was about 4.6 million t N/year (or 48 kg N/ha) for the simulated year (1998); and (2) the N leaching rates highly varied across the country, ranging from 12 kg N/ha to 216 kg N/ha, driven by the interacting effects of climate, soil and management conditions. Alternative management practices such as decreasing amount of chemical nitrogen fertilizer were also simulated. The results indicated that the national N leaching loading could be reduced by 15–46% if the fertilizer application rate decreased by 20%-50% that would still maintain the optimum crop production.

3.5. Greenhouse gas emissions

Field campaigns for quantifying methane (CH_4) and nitrous oxide (N_2O) emissions from agricultural soils have occurred on almost all of the important agricultural regions in China since middle of the 1990s. The observed greenhouse gas (GHG) data have been utilized to test various models, including China-DNDC. These validation tests were mainly conducted at site scale, but predictions have been extended to regional or national scale. Several examples are provided below.

3.5.1. Nitrous oxide

N_2O flux measurements were conducted with static chamber method at three cropping systems (i.e., winter wheat/green onion rotation, winter wheat/summer maize rotation, and greenhouse vegetables) in Zhangqiu, Huantai, Shouguang, respectively, in Shangdong Province, in 2009–2010 (Qiu and Wang, 2012). Magnitudes and patterns of the measured N_2O fluxes differed among the three sites, due to differences in local climate, soil and cropping management practices. For example, the highest N_2O fluxes were measured at the Shouguang greenhouse vegetable site, where fertilizer was applied at the highest rate (902 kg/ha) and the soil was intensively irrigated. The measurements indicated that high N_2O fluxes were detected following fertilization and irrigation events. Driven by the recorded weather (or indoor climate for the greenhouse) and management conditions, China-DNDC can simulate the magnitude and timing of most observed peaks in N_2O fluxes at the three sites. In addition, a field measurement was conducted in a spring maize field near Dalian City, Liaoning Province in 2009 and 2010. The measured N_2O fluxes were strongly related to the timing of fertilization and precipitation, with high peaks of N_2O flux usually associated with fertilization dates close to rainfall events. The modeled daily N_2O emission fluxes were in agreement with observations (Li et al., 2012).Other validation tests of China-DNDC N_2O emissions have been implemented by other researchers. Most of the tests were published with encouraging results (Xu et al., 2003; Xie and Li, 2004; Li et al., 2007) that indicated that China-DNDC is applicable for quantifying N_2O emissions from Chinese agricultural soils.

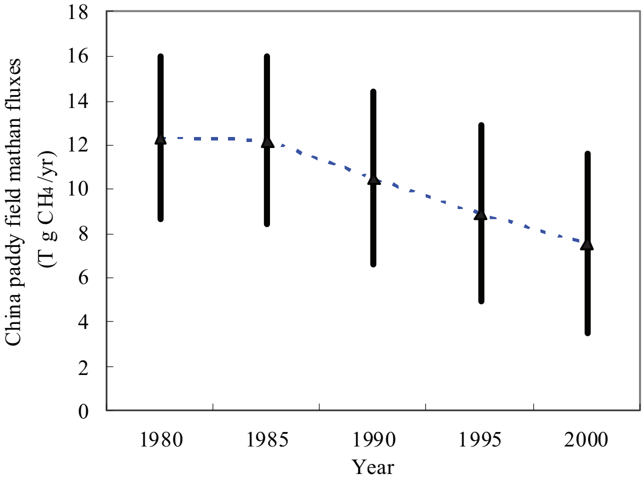

Fig. 3. Simulated total paddy field CH_4 emissions for 1980, 1985, 1990, 1995, and 2000. Regional CH_4 flux was expressed as ranges of high and low emission estimates that likely bound the true CH_4 flux. From 1980–2000 China's annual rice paddy CH_4 flux dropped from 8.6–16.0 Tg CH_4 yr^{-1} to 3.5–11.6 Tg CH_4 yr^{-1} (data source from Li et al., 2002).

3.5.2. Methane

Paddy rice production is an important source of CH_4 emitted from Chinese agricultural lands. Prior to the 1980s, paddy water management practice was continuous flooding, with which the rice farmers kept the fields flooded during all the season; this practice was replaced by the midseason drainage in the 1980s and 1990s to save water and labor (Li et al., 2002). As CH4 is produced only under low redox potential ($Eh < -250$ mV) conditions, the aeration of the paddy soil during the midseason drainage substantially elevates soil Eh and hence significantly reduced CH4 production. Zheng et al. (1997) measured CH_4 emissions from a rice field with midseason drainage. Their data showed that CH_4 fluxes gradually increased as flooding persisted, but rapidly decreased when the soil dried during the short-term midseason drainage. By tracking soil Eh dynamics, as well as the production of C substrates to support methanogens, China-DNDC simulated CH_4 emission dynamics related to midseason drainage that were consistent with field observations (Li et al., 2002).

China-DNDC has been applied for estimating the total CH4 emissions from Chinese rice production at national scale. Using spatial databases of soil properties, paddy distribution, crop rotations, daily weather, and additional agricultural management factors, simulations were conducted with China-DNDC for all the rice fields in the country but with different ratios of continuous flooding vs. midseason drainage that reflected the actual water management in 1980, 1985, 1990, 1995, and 2000. Results from the nation-wide simulations showed that the total CH_4 emission from China's paddy fields were reduced by ~5 Tg CH_4 yr^{-1} when the dominant water management practice in Chinese rice agriculture changed from the continuous flooding in the early 1980s to the midseason drainage in 2000 (Fig. 3). Decreased methane emissions from paddy rice may have contributed to the decline in the rate of increase of global atmospheric CH_4 concentration over the same time period (Li et al., 2002).

3.5.3. Global warming impacts

To understand the long-term effects of implementation of alternative management on GHG emissions, China-DNDC has been used to quantify cropland net greenhouse gas emissions (CO_2, CH4 and N_2O). Simulations were conducted for a 50-year wheat-maize rotation system in the North China Plain, using 4 different management scenarios: (1) decreased fertilizer application rate, (2) increased fertilizer application rate, (3) increased crop residue incorporation rate, and (4) increased manure amendment rate (Li et al., 2010). The modeled emissions of CO_2, N_2O and CH_4 were integrated to produce a net impact using the global warming potential (GWP) methodology. Simulations indicated the increasing SOC sequestration (net CO_2 uptake) was accompanied by increased N_2O emissions, which offset the climate-impact benefit of increased SOC storage. For long-term simulations, only manure amendment or increased crop residue incorporation could maintain a net benefit in comparison with the baseline practices (Li et al., 2010).

A similar test at the national scale was conducted by Qiu et al. (2009a,b). The impacts of the C sequestering strategies, i.e., crop residue incorporation and manure application, on CO_2, N_2O and CH_4 emissions were assessed for 50 years for all the six main agricultural regions in China, each possessing its own agro-meteorological and cropping management conditions. The model results indicated that overall, crop residue incorporation and manure application increased C sequestration rates but also elevated N_2O and CH_4 emissions relative to the baseline runs. The simulations showed substantial spatial heterogeneity in net impacts of the scenarios on GHG emissions, driven by spatially differentiated climate, soil and cropping management conditions. It hence recommended that the alternative crop management strategies to maintain yield and reduce net GHG impact should be implemented as regionally-specific strategies, rather than a single, national policy.

4. Weaknesses of this model

While we are encouraged by the recent test and improvement to China-DNDC for crop yields and environmental impacts estimation, we realize that there are still limitations for widespread application of this tool in China. The simplified parameterization, difficult process for modification, and uncertainties for regional modeling would be the major shortcomings.

4.1. The simplification of parameters

This model often has the advantage due to fewer input data requirements, which can make it easy to use for new users and save more time for preparing inputs. The comprehensive library of default settings for 62 crops and 12 soil types enables users to model a wide range of sites and situations without the need for considerable amounts of rarely measured input data. However, this simplification may reduce the accuracy of the model predictions. For instance, to account for the transport of nutrients through lateral flow, two fundamental hydrological features, the Soil Conservation Service (SCS) curve and the Modified Universal Soil Loss Equation (MUSLE) functions, which have been widely utilized to quantify surface runoff and soil erosion in a suite of hydrologic models, were incorporated into this model (Deng et al., 2011a). The value of soil surface cover and management factor in the MUSLE had been simplified to one constant value, but it ignored the impacts of the dynamic change of vegetation coverage and climate conditions. Thus, this simplification hindered the prediction of sediment yield, and subsequently of N losses. And also, to model the adsorption and desorption processes, we empirically determined the values of coefficients in the recession equation and the Langmuir equation through calibrating procedure for the selected field, but the values may not be applicable to other regions with different soil and climate conditions (Li et al., 2006). To verify or modify the default parameters was still needed to be carried out. In addition, the model treats the soil as a series of discrete horizontal layers. Within each layer all the soil properties are assumed to be uniform. Some of the soil physical properties such as bulk density, porosity and hydraulic parameters are assumed to be constant across all layers (down to a depth of 50 cm), however, most of the soil properties varied inherently between layers. This may lead to an overestimation of the soil water content and N leaching (Li et al., 2014). There are also issues with availability of input parameters for specific situations, e.g. some survey stated that the model parameters are lacking specificity for China's manure storage in livestock feedlot (Li et al., 2012), the sunlight greenhouse vegetable production systems (Li et al., 2014), as well as the rice transplantation from a seedling bed to paddy fields (Chen et al., 2016). The missed information in the direct simulation could influence modeling of the vegetable or rice growth and yields, as well as the environmental impact of the animal production chain. Therefore, more accurate parameterization may also helpful for improving the model's performance.

4.2. The difficult calibration process

The model was widely tested by researchers, and most of the test results indicated that the model was capable of simulating the magnitudes and dynamics of C and N pools with limited modifications. However, in common with similar biogeochemical process models, there remain discrepancies between the modeled results and the field measurements during some time periods. For example, this model overestimated the observed N_2O or NO fluxes during some periods following N fertilization events in the cold seasons because the model underestimated the restriction of low temperature on the nitrification or denitrification rates parameterized in the model framework (Deng et al., 2013). The model may also underestimate N_2O emissions in the absence of additional N fertilizer, because the available NO_3^--N had been absorbed by crops and no denitrification could occur in the modeling process (Yang et al., 2014). Inaccuracies in estimation of N_2O emissions for frozen soils have also been highlighted due to the insufficient description of the impact of soil freezing and thawing on N_2O production (Li et al., 2010). A report showed that the model can simulate the dynamics of N_2O emissions during soybean growth period in Beijing, but the model underestimated N_2O emission fluxes during the drought and nonagricultural activity periods (Xie and Li, 2004). And hence further improvements for the parameters or related processes of this model are still needed. For less experienced users, they are suggested that for the model calibration it is not necessary to make any adjustments to the internal parameters or processes in the DNDC manual, but it may be not enough by optimizing several combinations of parameters under some conditions, and hence modifying the default values in the codes is essential. However, it seems to be impossible since the codes for the model are not open. For advanced users with coding ability, greater access to the code is needed so that the way in which the model represents processes can be changed. However, it is hard to identify which processes are responsible for decreasing uncertainties and improving model performance. Any individual process such as crop absorption, soil N and water dynamics, soil types, climate conditions, etc., is responsible for the C and N dynamics, e.g., N_2O emissions. In addition, lack of detailed descriptions of each modification makes it very difficult to understand why changes have been made to the code and their impact. Therefore, to eliminate this inconvenience in the future, the need for improvements to the instruction manual including a good description of each process behind the model and detailed descriptions of the input and output parameters is emerging.

4.3. The uncertainty of regional modelling

One of the major purposes for developing process-based models is to extend our understanding gained at specific sites to regional, national or global scales. In fact, policy decisions can only be made based on their effectiveness at regional or national scales. However, scaling up from individual sites to large geographical regions is difficult due to spatial variation of climate environment, soil conditions, and management practices, even when the model may have been well calibrated and validated at a site scale. DNDC has the function of scaling up embedded in the regional module which was extended from site modeling, but the regional use is often limited mainly due to high uncertainties which mainly associated both with the quality of the available input data and the hydro-biogeochemical processes in the model. Firstly, the input parameters required for the regional modelling were usually derived from the statistical data reported by the Ministry of Agriculture, China, but unfortunately the data did not have practical irrigation rates and time, fertilizer application times, etc., which could cause inaccuracies for the county-scale simulations. Secondly, the hypothesis that all of the attributes in each grid cell were uniform was not in accord with the actual situation before we applied the model to the regional scale, e.g., the soil properties (e.g., texture, SOC content and pH) were inherently heterogeneous in space. Meanwhile, an approach, the most sensitive factors (MSF) method, was developed for the model to bring the uncertainty under control. According to the approach, the model was run twice with the maximum and minimum values of the most sensitive soil factors that formed a range covering the “real” value with a high probability (Li et al., 2004), but there may be a potential defect when applying it calculated total N_2O emissions to net N_2O emissions (i.e. the emissions remaining after the “background” N_2O emissions in the absence of applied N have been subtracted), because it likely did not produce the maximum range for net N_2O emissions when using the maximum and minimum SOC values (Giltrap et al., 2010). Thirdly, the inability to accurately simulate the growth of the rotation crops was a potential source of yield reductions because the currently crop database did not allow for a crop to seed in the last year, e.g., the winter wheat and summer maize rotation system, a practice commonly used by farmers, and hence probably led the overestimation of water losses and its consequent N dynamics. Fourthly, this model was capable of water and nitrate movements in the vertical dimension, but it lacked spatial distribution algorithms for simulating horizontal water surface runoff. This likely led to an increase in the leached water. Therefore, it still needed to continue improve the regional modelling process.

5. Prospects for the model

Throughout more than 20 years history, this model has undergone many improvements and its on-going value to the scientific community is reflected in the great number of users and the vast literature base. However, despite efforts to improve the model, there is still much work to be done to adequately quantify environmental impacts of regional or global agriculture, to provide guidance for agricultural sustainability in either China or the world. For example, livestock farming is a rapidly growing component of Chinese agriculture. However, strategies for optimizing production and minimizing environmental impacts in combined livestock/crop farming systems have not been well-established yet. Recently, the water contamination by the losses of phosphorus (P) has become a growing serious problem across intensive farming regions in China. A special key research project funded by the nation has been conducted since 2016 to research N and P transport and turnover processes, and hence derive management practices to mitigate such losses. In order to meet the challenge of estimating the spatial and temporal variability of nutrient loading on a regional and national scale, the new P module is urgently required to be supplemented. In addition, new crop cultivars are being developed, which could have shed new environmental impacts. For example, a new rice type so-called “Green Super-Rice” is being developed through an international joint program. Based on recent reports (Manuel et al., 2014), the new rice cultivar would require much less water and nutrients but have much higher yield. It will be important to predict impacts of the new crop on not only food security but also water resources and environmental safety.

More importantly, it should predict the regional and national inventories and serve agricultural policy makings in China. For example, in order to estimate N-fertilizer use efficiency and the N balance in croplands, China-DNDC was utilized to track the fate of the N applied as fertilizer in the agricultural soils at the national scale (Qiu et al., 2008), the simulation results indicated that agricultural soils received 36.7 Tg N, and only 12.17 Tg N were taken up by crop production, most were lost through NH3 volatilization, denitrification, and leaching. The N surplus was 7.09 Tg N for the whole country, which could be stored in soils. The largest nitrogen surpluses were in the eastern provinces which dominated the national food production as well as the fertilizer consumptions. Results from that study have raised suggestions with scientifically sound conclusions. We expect this report will enhance the understanding and applicability of China-DNDC for predicting GHG emissions, N leaching and crop yields that are attracting more and more attentions across China.

6. Conclusion

DNDC is a process-based model that originally developed to model N_2O emissions and SOC levels in US cropping system. Through the two-decade efforts it has subsequently been improved and applied in China as a new version, i.e., China-DNDC.

The China-DNDC can be used to predict the impacts of changes in either climate or farming management on a wide range of ecosystem services covering agricultural production, soil carbon sequestration, greenhouse gas emissions and nutrient leaching loads at field, regional or national scale in China. It is also being applied to assess new policies or mitigation strategies in the context of a whole suite of the ecosystem services, and more importantly, to serve agricultural policy makings in China.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2017.01.003.

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