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Modeling nitrogen loading from a watershed consisting of cropland and livestock farms in China using Manure-DNDC

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ABSTRACT

Nitrogen (N) losses from agro-ecosystems have become a serious issue over the past decades, causing a series of environmental problems, such as water eutrophication and air pollution. Estimating N discharges at a watershed scale to quantify the N fluxes released across various land-use components has long been a problem, especially for croplands and livestock farms, the two major sources of excess N, because of fertilizer use and livestock manure management. This study used Manure-DNDC, a biogeochemical, process-based model, to calculate N discharge fluxes from both crop fields and livestock farms within the Xiaoqinghe watershed in Shandong Province, China. The newly developed Manure-DNDC was tested against the crop growth, soil climate, and N leaching loss data measured in the watershed and showed encouraging results. A database containing daily weather data, soil properties, livestock farms, and cropping systems for the 182 towns included in the watershed was created to provide input information to support the model simulations at a watershed scale. The Manure-DNDC model was used to evaluate the 652,881 ha of cropland and 728 livestock farms in the watershed in 2008. The modeled N influxes to and effluxes from the agro-ecosystem in all towns were summarized to obtain the watershed-scale N fluxes. The modeled results indicated that about 184 million kg of N was applied annually as synthetic fertilizer in croplands, 297 million kg of N as feed introduced into the livestock farms, and 9 million kg N came from atmospheric deposition in the Xiaoqinghe watershed in 2008. The cropland soils received about 260 million kg of N, of which only 25.6% (67 million kg of N) came from manure amendment. The entire watershed released 127 million kg of ammonia-N into the air, including 42% from croplands and 58% from livestock farms. Other N gases, such as nitrous oxide, nitric oxide, and dinitrogen, were released into the atmosphere at a rate of 35 million kg of N per year. The N loads to surface water from livestock farms and crop fields were 47 and 7 million kg of N, respectively. About 24 million kg of nitrate-N was leached from the cropping systems, which could be loaded to both surface water and groundwater. The modeled results were compared with observations, which yielded encouraging results.

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1. Introduction

Chemical fertilizer application substantially increased crop production in China during the 20th Century. However, the overuse of nitrogenous fertilizer has introduced excess nitrogen (N) into the environment in various forms (Carpenter et al., 1998). Over the past decades, livestock industries have grown rapidly to meet the increasing demand for dairy and meat in China, which has increased the discharge of more activate N into the air, soil, and rivers (Fei et al., 2011). Surplus N from agriculture production has an important function in non-point source N pollution and water quality degradation, causing serious environmental problems across the country (Qin et al., 2011; Wang et al., 2011). Nitrous oxide (N_2O) and ammonia (NH_3) emissions from arable land and livestock manure management are vital atmospheric pollutants that contribute to global warming and acid precipitation. The Chinese First National Census on Pollution Sources showed that the national total N discharge in 2007 reached 4.7289 million t, with more than half coming from agricultural sources, i.e., 1.6 million t of N from crop production and 1.0 million t of N from livestock production (The Ministry of Environmental Protection, 2010). Livestock excreta and fertilizer are the two major N sources in agricultural land. An estimated 94 million t of N from livestock excreta was produced worldwide in 1996, 36% of which was recovered as manure (Sheldrick et al., 2003). N losses during livestock breeding and manure management have an important function in agricultural non-point source pollution (AGNPS) (Fei et al., 2011).

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N balance is one of the most important indicators for agricultural non-point source N pollution and N efficiency analysis (Eerdt and Fong, 1998; Salo et al., 2007). A number of methods have been applied to calculate the global, national, and regional agricultural N balance over the past three decades (Kudeyarov and Bashkin, 1980; Roberts, 1987; David et al., 1997; Lord et al., 2002; Qiu et al., 2003; Woli et al., 2010; Decock and Six, 2013; Valkama et al., 2013). Most studies on N balance have focused on agricultural catchment with relatively uniform soil and climate conditions. A previous report showed that the N concentration in groundwater from an intensively farmed river basin in Russia from 1969 to 1979 reached 0.8 mg N L^{-1} to 6.5 mg N L^{-1} when the N input increased five times through mineral fertilizers and 1.5 times through organic fertilizers (Kudeyarov and Bashkin, 1980). Regional N input and output balance studies have been carried out in Africa (Powell and Mohamed-Saleem, 1987; Zougmoré et al., 2004), the eastern part of the United Kingdom (Roberts, 1987), southeastern Norway (Bechmann et al., 1998), India (Jacks and Sharma, 1983), Japan (Mishima, 2002), and so on. These studies indicated that increasing cropland area or fertilizer application rate was the main reason for the increase in N losses from agricultural ecosystems (Jansons et al., 2003). From 1990 to 2003, the Organization for Economic Cooperation and Development (OECD) countries decreased their N surplus by about 10%, but the intensity remained higher than the global average (Viet Ngu and Alauddin, 2010).

Three main approaches are widely used for evaluating N balance: the farm gate, soil surface, and soil system scales. All these methods were developed based on nutrient mass balance considering the difference between the total nutrient inputs and outputs. They differ from each other regarding their definition of boundary conditions (Viet Ngu and Alauddin, 2010). National statistics, FAO website, OECD report, and so on usually provide data sources for assessment (Jacks and Sharma, 1983; Messer and Brezonik, 1983; Lord et al., 2002). In most methodologies, an agro-ecosystem is considered a "black box" with little mechanism involved in the N life cycle analysis. N transport and transformation are subject to a wide range of factors, such as climate, soil texture, crop rotation, and other farm management practices (Li et al., 2005). Several process-based models, such as Soil and Water Assessment Tool (SWAT) (Gong et al., 2011), AGNPS model (Emili and Greene, 2013), and DNDC, have been proposed for evaluating agricultural non-point source N pollution. However, most of these models have the ability to simulate N movement only in croplands. Few studies have reported modeling assessment using both cropping and livestock operation systems. The new biogeochemical model Manure-DNDC was recently developed to meet the need (Li et al., 2012). This study applied the Manure-DNDC model in a watershed with intensively managed crop fields and livestock farms in North China. The study aims to assess the contribution of mixed agriculture ecosystems to environmental N loading at a watershed scale. Both statistical and GIS data were used to create a database to support the regional study. This study is expected to improve the reliability of N loading assessment for watersheds consisting of complex agricultural management systems.

2. Watershed description

The Xiaoqinghe watershed is located in Shandong Province in north China (Fig. 1). Xiaoqinghe means "Small Clean River" in Chinese, but this river is no longer small or clean. Given the discharge from agricultural areas and from industries, Xiaoqinghe, which has a total area of 13,000 km^2, is severely polluted and loads 9600 t of N into the Pacific Ocean annually. Xiaoqinghe is 240 km long and crosses nine counties, where agriculture is intensively managed to produce vegetables, grain, and dairy products to supply both the locals and people from other parts of the country. Investigations in 2008 showed that the quality of the surface water in the Xiaoqinghe watershed is below the national environmental standards (GB3838-2002) (Tang et al., 2008). Ground water from a depth of 20 m was unsuitable for drinking. For example, about 57% of the groundwater is polluted in Huantai County within the Xiaoqinghe watershed; 20.5% is seriously contaminated with nitrate concentrations higher than 10 mg L^{-1} (Liu et al., 2005).

The Xiaoqinghe watershed is adjacent to the Yellow River basin and has been cultivated for more than 500 years. The watershed soils are mainly classified as Cinnamon (Brown, Ustic, Cambosols) Soil and Fluvo-Aquic (Alluvial) soil. This watershed has a typical continental monsoon climate in the temperate zone with high temperature and abundant precipitation in summer. The annual mean temperature is 12–14 °C. The annual mean precipitation is about 620 mm, and more than 60% of the rainfall occurs in June, July, and August. Croplands are mainly distributed in the central and northern areas of the watershed. The southern part is dominated by forest and grassland. The croplands comprise 63.2%, forests occupy 9.5%, and grasslands take up 7.7% of the watershed. The major crops are maize, winter wheat, cotton, and vegetables. The application rates of nitrogenous fertilizer are high (with an average of 280 kg N ha^{-1} per year), and the population of livestock (mainly dairy cow, beef cow and swine) has been increasing dramatically in recent years. Most of the livestock waste is applied onto fields without extensive pretreatment. The N losses to the environment occur in both livestock farms and croplands through air emission, surface runoff, or ground leaching.

3. Manure-DNDC model

3.1. Model description

The Manure-DNDC model was recently developed by integrating a livestock operation component with the original DNDC model to allow the new model to simulate carbon (C) and N biogeochemistry for both cropping fields and livestock manure systems (Fig. 2). The original DNDC model simulates soil organic matter (SOM) turnover based on its quantity and quality (Li et al., 1994). Similarly, the Manure-DNDC tracks the changes in quantity and nutrient concentrations in manure during its on-farm life cycle. A group of biochemical and geochemical processes have been integrated in the model to track transport and transformations of C and N across cropping and livestock systems. The sub-models of decomposition, nitrification, and denitrification calculate N turnover in both SOM and manure organic matter driven by a group of environmental factors, such as temperature, moisture, pH, redox potential, and substrate concentration gradients. N losses through air emissions or water drainage flow are quantified by Manure-DNDC for livestock operation components (e.g., feedlot, compost, lagoon, anaerobic digester) as well as cropland soils. For air emissions, Manure-DNDC calculates the daily fluxes of N_2O, nitric oxide (NO), NH_3, and dinitrogen (N_2) from livestock farm facilities and cropping fields (Li et al., 1992, 1994, 2000, 2012). Soil water flows, including surface runoff and subsurface leaching, are simulated in Manure-DNDC to quantify N losses in the liquid phase (Li et al., 2006a; Tonitto et al., 2007, 2010). The Soil Conservation Service (SCS) curve and the Modified Universal Soil Loss Equation functions (MUSLE) were incorporated into the DNDC model to simulate a 2D soil hydrology both in field and watershed scales (Deng et al., 2011a,b). Detailed crop growth process with the simulation of crop physiology, water, and N stress was integrated into the DNDC model. Thus, the new model simulates complete C, N, and water cycles in agro-ecosystems by coupling crop growth algorithms with soil biogeochemical components (Zhang et al., 2002). A variety of

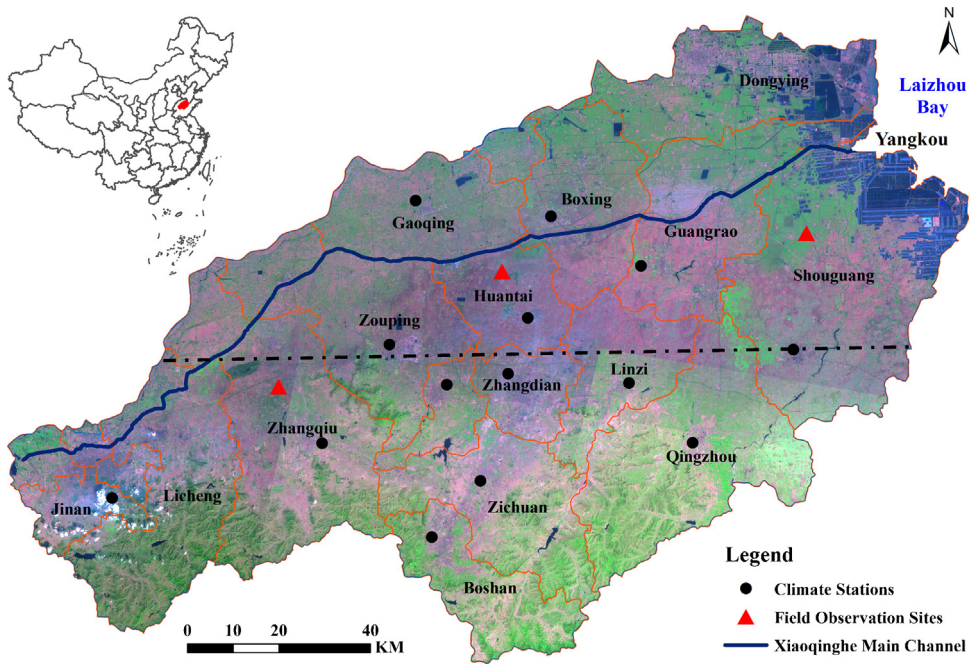

Fig. 1. Geographic location of the Xiaoqinghe watershed in China, as well as distribution of climate stations and field observation sites in the study region. Laizhou Bay is the receiving body of water and Yangkou is the estuary of the Pacific Ocean. The dashed line represents the profile for the analysis of correlation between nitrogen leaching and fertilizer input.

alternative farm management practices have been parameterized in Manure-DNDC to estimate their effects on the N loading rate (Li et al., 2002, 2005, 2006b). In this study, we selected the new Manure-DNDC model with hydrologic enhancement and livestock breeding and manure management simulations.

When Manure-DNDC was used to conduct regional or watershed simulations, the whole study region was divided into many grid cells with spatial references and unique IDs. All the attributes in each grid cell were assumed to be uniform. Input data for the whole study region was stored in a series of text files with ID information for every record. For the result analysis, the ID number was used as the link between the modeled result and the spatial units using the GIS software. A town is only a grid cell in which the soil properties are inherently heterogeneous when Manure-DNDC was applied for watersheds such as Xiaoqinghe. Averaging the variations in soil properties may introduce uncertainties into the simulation of N balance, but the most sensitive factor approach was developed for DNDC to carry out uncertainty analysis. Using this method, the soil database was constructed with range values for each soil factor [e.g., texture, soil organic carbon (SOC) content, pH, and bulk density], which were commonly reported in the soil survey records for each town. DNDC was run twice with the maximum and minimum

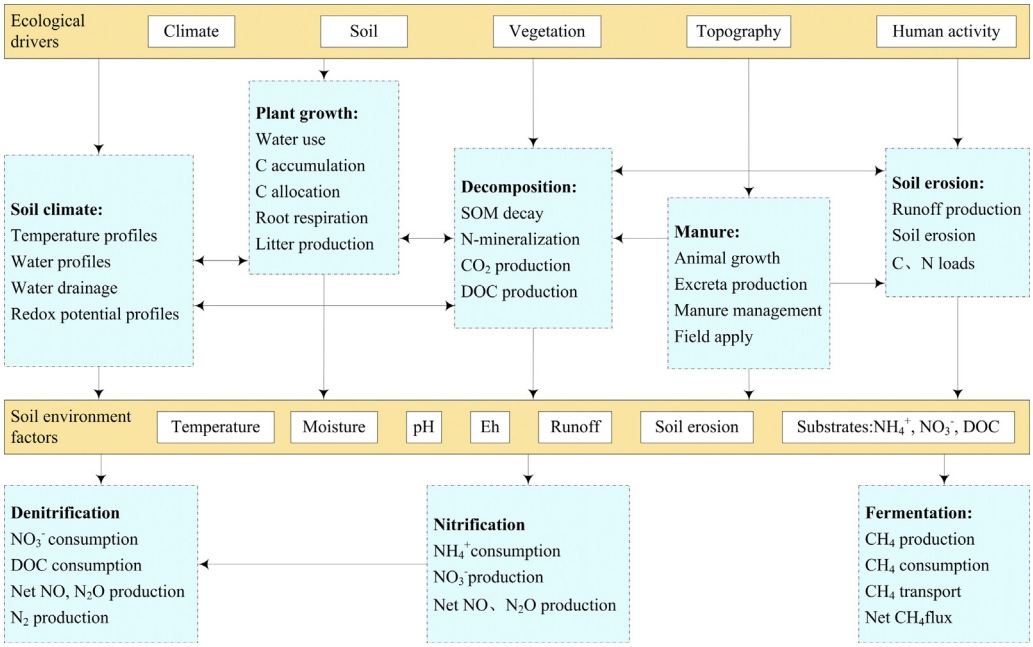

Fig. 2. Structure of the Manure-DNDC model.

Table 1
Crop types and observation time of field experiments.

Site name	Crop type	Observation period
Huantai	Winter wheat–Summer maize	November 2008–September 2009
Zhangqiu	Winter wheat–Onion	May 2009–June 2010
Shouguang	Greenhouse cucumber	August 2009–December 2009

values of the most sensitive soil factors for each unit. The simulated range was supposed to cover the real flux from the grid cell with a high probability (Li et al., 2004). Many functions embedded in Manure-DNDC or DNDC have been validated by scientists worldwide with encouraging results (Butterbach-Bahl et al., 2004; Smith et al., 2008; Wang et al., 2008; Qiu et al., 2009b; Giltrap et al., 2010). The DNDC family is now used for greenhouse gas mitigation, C sequestration, crop production, non-point source pollution at site and regional scales in North America, Asia, Europe, Oceania, and Africa.

3.2. Model validation tests for cropping systems

Field experiments have been carried out in the Xiaoqinghe watershed since 2008 (Li et al., 2010; Qiu and Wang, 2012). Detailed investigations were conducted at the three crop fields in Zhangqiu, Huantai, and Shouguang Counties within the Xiaoqinghe watershed (Fig. 1). The crop types at the test sites were winter wheat, summer maize, and vegetables (Table 1). Six to eight alternative treatments were implemented at each site. Soil climate, crop biomass, and N leaching loss were measured from 2008 to 2009, and the observed data were used for model tests.

The root mean square error (RMSE) and Nash–Sutcliffe efficiency (NSE) were used to assess quantitatively the goodness-of-fit between the simulated results and measured results (Rykiel, 1996; Smith et al., 1997). Their mathematical expressions are as follows (Nash and Sutcliffe, 1970; Loague and Green, 1991):

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

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (2)$$

where O_i is the observed value, S_i is the simulated value, $\bar{O}$ is the mean of the observed data, and n is the number of samples.

Soil climate, especially temperature and moisture, are key driving factors that affect crop growth and soil biogeochemistry in agricultural ecosystems. The basic requirement for biogeochemical models is accurate simulation of soil temperature and moisture profiles. The modeled daily soil temperatures at 5 cm were consistent with the observed RMSE of 3.02 and NSE of 0.90 (Fig. 3a). The patterns and magnitudes of simulated soil moisture at depths of 10 and 30 cm are consistent with the measured results for the soil samples collected at the corresponding depths (Fig. 3b). The RMSE and NSE values were 0.15 and −0.27 for 10 cm and 0.08 and −0.21 for 30 cm, respectively. Both the measured and modeled moisture data show that the change in soil moisture in the shallow soil layer was more dynamic than in the deep layer.

Crop growth demands water and N from the soil and thus affects soil N dynamics. Crop biomass was measured for the winter wheat and summer maize. The modeled growth curves of wheat and maize are consistent with the observed results (Fig. 3c). However, Manure-DNDC overestimated the growth rate of wheat during winter.

N leaching losses measured at the three experimental sites were compared with the modeled results. The measured data indicated

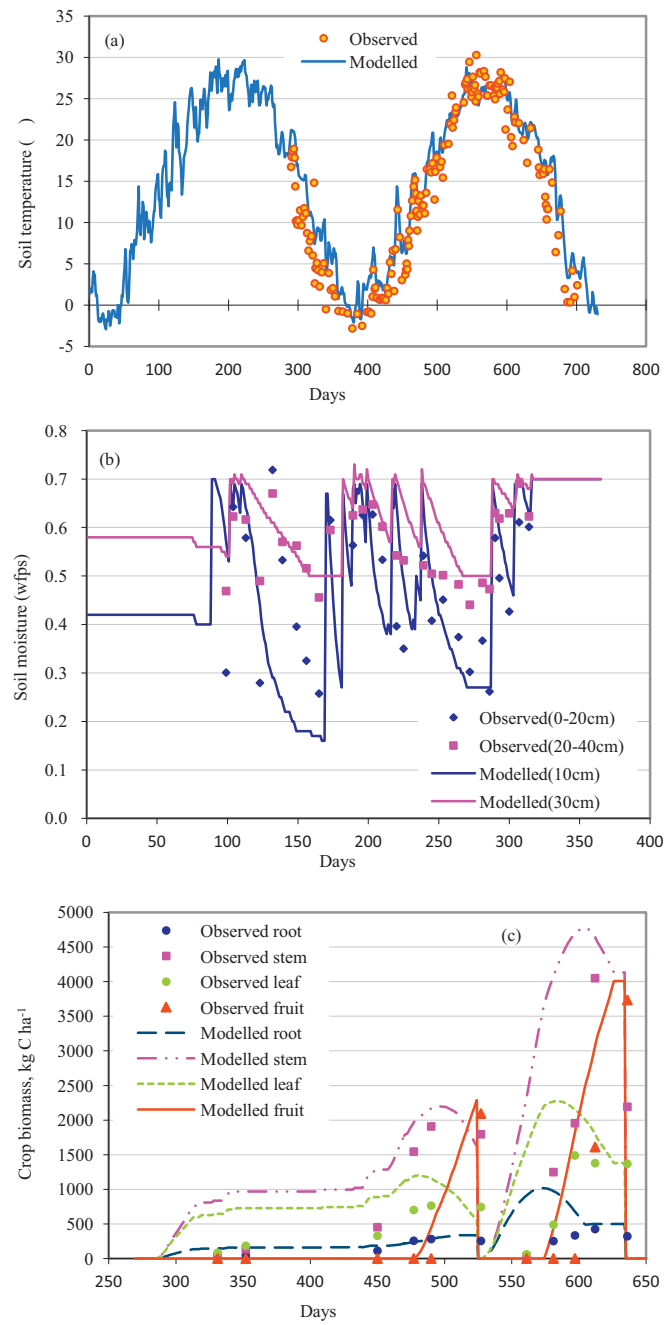

Fig. 3. Comparison between modeled and observed soil temperature of 5 cm (a) soil water content (b) and crop biomass (c) in Huantai.

that nitrate leaching losses occurred during episodes following rainfall or irrigation events (Fig. 4). During the second half of 2009, three leachate samples were collected at the Huantai site on July 15, August 4, and September 8. The modeled N leaching fluxes well matched with the observed results, although the last episode was negligible because of the light rainfall (Fig. 4a). Six leachate samples were collected at the Shouguang site, and the timing and magnitude of the modeled nitrate leaching losses were consistent with the observations (Fig. 4b). Several modeled daily N leaching fluxes in the Zhangqiu site were lower than the observed results but the seasonal flux was comparable with the measured results (Fig. 4c).

The aforementioned cases indicated that the Manure-DNDC is suitable for simulating crop–soil systems for the fields in the target watershed.

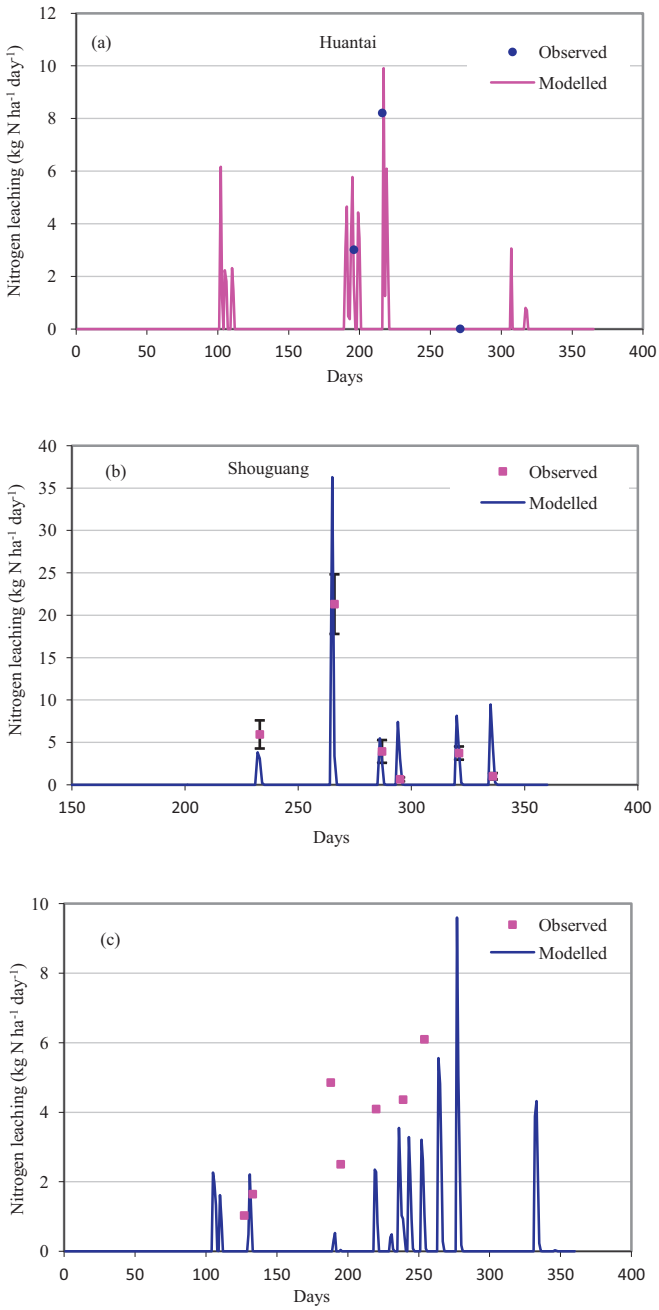

Fig. 4. Comparison between modeled and observed nitrogen leaching in Huantai (a), Shouguang (b), and Zhangqiu (c).

3.3. Model validation tests for livestock operation systems

Livestock operation with manure management is a new part of DNDC with validation tests carried out only in US animal farms (Li et al., 2012). This study is the first to apply the model in Chinese livestock farms. The measurements were conducted at a dairy cow farm in Guangrao County within the Xiaoqinghe watershed (Fig. 1). C and N contents were measured in feed, feces, and urine samples. Greenhouse gases (i.e., CO_2, CH_4, and N_2O) and NH_3 fluxes were also measured. The modeled N data were consistent with the observed results, but the modeled C data in excretion were lower than the measured data (Table 2). The modeled CH_4, NH_3, and respiration CO_2 were comparable with the measured results. The measured N_2O flux was lower than the modeled N_2O flux. This result may be related to the missing N_2O emission episodes during field measurement. Additional tests were conducted to evaluate the applicability of Manure-DNDC for the target area, and the preliminary comparison showed that the model mostly produced acceptable results against the observations (Qiu and Wang, 2012).

Table 2
Comparison between modeled and observed result for manure model (kg d^{-1} head^{-1}).

Item	Modeled C	Observed C	Modeled N	Observed N
Urine	0.15	0.21	0.12	0.11
Feces	1.87	2.44	0.12	0.1
Respiration (CO_2)	1.95	1.98	–	–
CH_4	0.49	0.31	–	–
N_2O	–	–	0.01	0.004
NH_3	–	–	0.05	0.06

4. Spatial database construction

To simulate N transport and transformation in the Xiaoqinghe watershed, we developed a database to store all the input information required for the regional model runs. To create the database, the domain watershed was divided into a number of simulation units, and all the attributes in each subunit were assumed uniform. Town (with an average area of 70 km^2) was selected as the basic unit for the databases. Crop area, fertilization, irrigation, livestock population, manure management, and other data were based on the recorded town information. Each spatial unit was indexed with a unique ID number in the GIS system. The spatial database was composed of a series of text files with ID information, which could be linked to the GIS software. Spatially differentiated attribute data, such as climate, topography, soil properties, crop type and rotation, livestock farm type, and farm management practices were collected to construct the database (Table 3).

Given that SCS and MUSLE function are incorporated in the Manure-DNDC model, topographic data and soil erosion information are essential for the database. Digital elevation model with a resolution of 90 m for the Xiaoqinghe watershed was used for the retrieval of topographic parameters, such as surface slope, slope length, and channel length. The ArcGIS software system was used for data preparation and processing. For the soil data, 17 soil profiles in and around the Xiaoqinghe watershed were obtained from the China Soil Records (The National Soil Survey Office, 1993). Soil

Table 3
GIS file names and main parameters in each file.

File name	Main parameters
Xiaoqinghe_1	ID, Region, Name, Latitude, Climate ID station, N dep, max and min SOC, max and min Clay content, max and min pH, max and min bulk density
Xiaoqinghe_2	Crop area for every cropping system
Xiaoqinghe_3	Fertilizer rate
Xiaoqinghe_4	Percent of crop area irrigated
Xiaoqinghe_5	Planting and harvest dates for each cropping system
Xiaoqinghe_6	Fertilizer application dates
Xiaoqinghe_7	Manure application dates and C/N ratio
Xiaoqinghe_8	Tilling date and depth
Xiaoqinghe_9	Livestock farm number, farm ID, Animal type, Animal heads, Feed rate, Crude protein, Floor area, Storage days, Applied area
Xiaoqinghe_10	CN2, Slope length, Channel length, Manning's roughness coefficient for the channel, Channel slope, Manning's roughness coefficient for the subbasin, Subbasin area, Average annual C factor for the land cover, Support practice factor, Angle of slope, Amount of water in the soil profile at field capacity, Amount of water in the soil profile when completely saturated, Amount of water in the soil profile at wilting point, sand, clay and silt content, Organic carbon content
Xiaoqinghe_11	Fraction of above-ground residue incorporated in soil

Table 4
Parameters related to livestock operation.

Livestock type	Feed-rate (kg DM head^{-1} day^{-1})	Crude-protein (%)	Floor_area (m^2)
Cow	20	16	6
Pig	2.17	17	4
Sheep	3.5	11	4
Poultry	0.15	18	0.1

texture, bulk density, and soil pH were estimated based on the recorded profiles. The soil texture classification system in China differs from that of the US; cubic spline interpolation was used for converting the soil texture. We used the SPAW model to estimate the soil water constant, including the amount of water in the soil profile at field capacity, saturation, and wilting point (Saxton et al., 2006). SOC content was measured in 400 soil samples collected from each town. The hydrologic parameters related to surface runoff and soil erosion were estimated based on land cover and SWAT (input/output file documentation).

Crop type, planted area, fertilizer, and irrigation data were obtained from a statistical yearbook. Thirteen crops were simulated according to the statistical data. Corn and winter wheat were the major crops in the watershed. The other crops include soybean, sorghum, cotton, vegetable, potato, and peanut. Fertilizer rate for different crops in every town was obtained based on crop type, crop area, total fertilizer use, and farming practices in the domain watershed. Planting and harvest dates, tillage, and straw incorporation ratios were set based on field investigation. The rate of manure application in the field was calculated in the model based on livestock population and manure management practice in each unit. Manure was assumed to be uniformly applied to all croplands in each unit. The climate data, including the daily maximum and minimum temperatures and precipitation, were obtained from the meteorological stations located within the watershed.

Livestock type and population information were collected from the statistical data at a town level. Feed rate, crude protein content, floor area, and compost storage duration were estimated based on the field survey. The detailed information is shown in Table 4. Manure management was assumed to be uniform with compost. We used default parameters for compost treatment in the model.

5. Result analysis and discussion

Driven by the input data stored in the database, the Manure-DNDC was run for 2 years for each of the 182 towns across the Xiaoqinghe watershed. The modeled daily and annual results of various N pools and fluxes for each town in the second year were recorded for regional assessment.

5.1. N budget at watershed scale

N budget for all the cropping ecosystems in the Xiaoqinghe watershed was calculated based on the simulated data. The total area of the Xiaoqinghe watershed is 13,000 km^2, containing about 6500 km^2 of croplands. In 2008, 184.2 million kg of chemical N fertilizer and 9.2 million kg of N from atmospheric deposition and legume fixation were introduced into the cropland. About 109.1 million kg of N was taken up by crops from the cropland (Fig. 5), including 26.0 million kg of N that was returned back into the soils through crop residue incorporation. A total of 23 million kg of N was brought into the watershed through feed import to support the livestock production. About 66.6 million kg of N contained in urine and feces was applied as manure fertilizer into the cropland, and 35.0 million kg of N remained in the compost pool by the end of the simulated year. During crop growth, livestock breeding, and

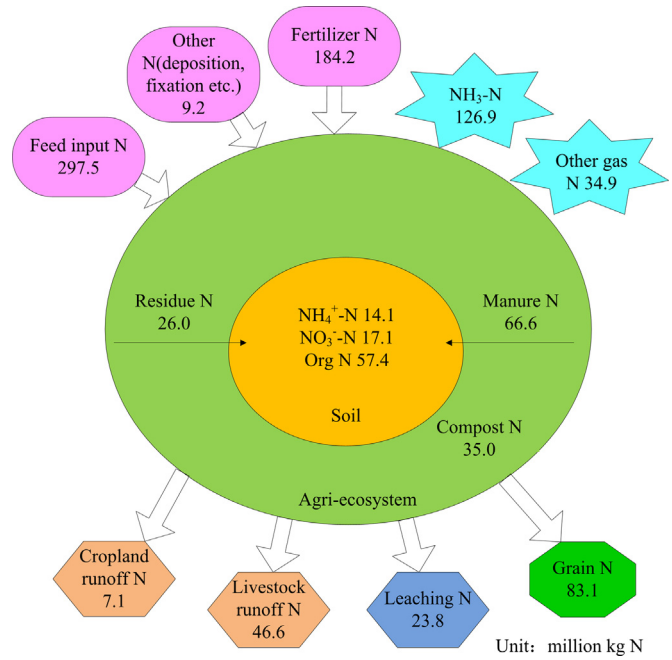

Fig. 5. Nitrogen cycle of agricultural eco-system in the Xiaoqinghe watershed in 2008.

manure storage or treatment, 126.9 million kg of NH_3-N and 34.9 million kg of N from other N gases (e.g., N_2O, NO, and N_2) were released into the atmosphere. N loss through leaching reached 23.8 million kg of N and N loss through soil erosion reached 7.1 million kg of N. N loss through runoff and erosion in livestock farms and manure storage/treatment was 46.6 million kg of N.

5.2. Soil N loss through subsurface leaching flow

N leaching occurs in agricultural land with a number of driving factors including precipitation, irrigation, fertilizer application, and soil properties. The modeled data indicated that 107 towns, which account for 59% of the simulation units, had N leaching rates lower than 10 kg ha^{-1}. A few towns in northern Zhangqiu, as well as southern and eastern Shouguang, suffered heavy N leaching losses. A total of 23 towns had N leaching rates exceeding 50 kg ha^{-1} (Fig. 6a). The N leaching rates were apparently related to precipitation, soil texture, and fertilizer application rates (Fig. 6b).

Fig. 6 shows the comparison between N leaching intensity and fertilizer application rate. About 20% of fertilizer N leached out under fertilizer rates exceeding 400 kg N ha^{-1} (Fig. 7a). N leaching rates varied greatly along the Xiaoqinghe River. A profile through latitude 36.83° N (dashed line in Fig. 1) was made to further analyze the relationship between N leaching and fertilizer rate. The figure shows that almost no N leached when the fertilizer rate was lower than 200 kg ha^{-1} (Fig. 7b). Above the threshold, N leaching loss proportionally increased along with the increase in fertilizer application rate.

Precipitation or irrigation was also a key factor affecting N leaching intensity. Given that more than 60% of the annual precipitation occurred in summer with the most heavy rainfall events observed in July, the soil N leaching loss in July in the simulated year 2008 accounted for 69.52% of the annual N leaching loss (Fig. 8a). The modeled data also indicated that several N residues were left in the soils in the early stage of summer when the winter wheat was mature and the summer corn was still small with less effect to intercept the precipitation.

Baiyunhu Town, which exhibited high N leaching intensity, was selected for further analysis (Fig. 8b). The total N leaching

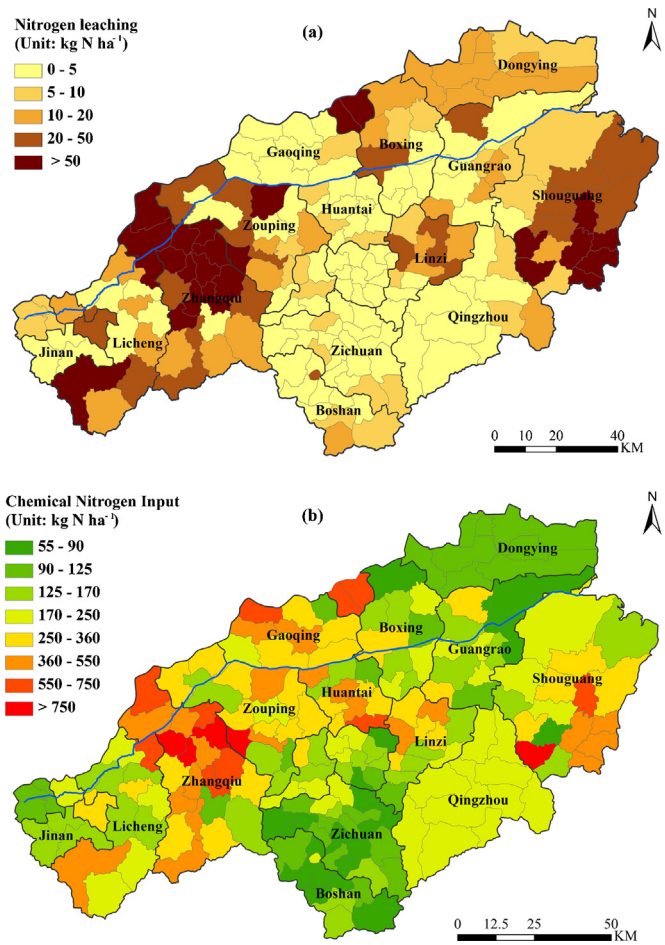

Fig. 6. Distribution of nitrogen leaching (a) and chemical nitrogen fertilizer input (b) in cropland in the Xiaoqinghe watershed.

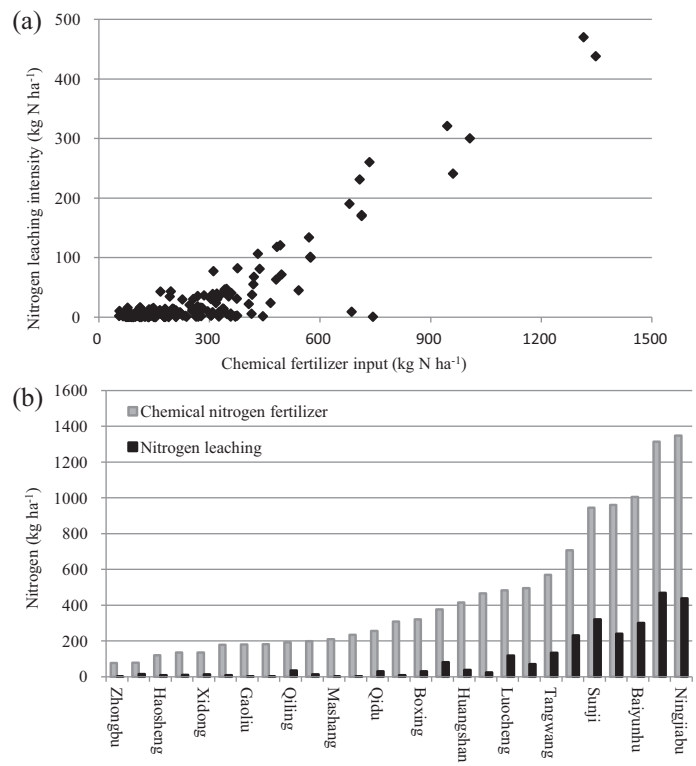

Fig. 7. Relationship between nitrogen leaching and fertilizer input in cropland for all the towns (a) and typical towns (b).

load of Baiyunhu with 2431 ha of cropland was 961.35 t with 94.08% occurred in July. The annual precipitation was 784.6 mm with 317 mm occurred in July. The comparison between N leaching rate and rainfall at a daily time step indicated no linear correlation between N leaching loss and precipitation. For example, the rainfall event on July 8 contributed 70.27 mm of precipitation and caused a N leaching load of 7.31 t of N for the town with a rate of 3.01 kg ha^{-1}. On July 18, a heavy rainstorm brought 104.43 mm of water to the arable land that caused 749.69 t of N loss by leaching, which accounted for 80% of the annual total N leaching load.

5.3. Soil N loss due to surface runoff and soil erosion

N losses through surface runoff and soil erosion mainly occurred as dissolved nitrate and organic N in the SOM or adsorbed on clay minerals. Soil erosion is a serious problem in the watershed because of intensive rainfalls in summer. The modeled surface runoff flow was 50–60 mm for 2008. The total sediment yield in the watershed was 6.96 million t for 2008, which is equivalent to 10.67 t of soil eroded from 1 h of arable land.

The total N losses through surface runoff and erosion in the Xiaoqinghe watershed in 2008 were 53.7 million kg of N, including 7.1 million kg from arable land and 46.6 million kg from livestock operation systems (Table 5). The eroded N (82.38%) was in the form of organic N. Dissolved N losses mainly occurred in livestock operation systems and accounted for 17.01% of the total N losses.

The results indicated that N losses related to livestock manure through runoff and erosion were greater than the synthetic fertilizer-oriented N losses for the studied watershed. The modeled maps of N loadings driven by surface runoff and soil erosion across the watershed clearly showed that the high livestock-induced N loadings (>100 kg ha^{-1}) occurred in 31 towns distributed across the watershed and the high farmland-induced N loadings were modeled in the upstream counties (Fig. 9).

5.4. N budget comparison with other regions of China

N surplus is a common problem in China. The N budget study in Huimin, Shandong Province showed that the N surplus of wheat–maize rotation was 349 kg ha^{-1} and that from plastic greenhouse vegetable was 3227 kg ha^{-1} (Kou et al., 2005). The N surplus in the aforementioned study included NH_3 volatilization, denitrification, leaching, and excess N in the soil. According to the previously mentioned method, the N surplus in the arable land of Xiaoqinghe watershed was 398.11 kg ha^{-1} in 2008, which is comparable with the aforementioned result. Studies in Jiaxing, Zhejiang Province showed that the agricultural N surplus exceeded 100 kg ha^{-1} from 1991 to 1997 and decreased in 1998, with an average of 53.87–100.73 kg ha^{-1} (Li and Zhang, 2009). A N balance study in a typical watershed in the hilly area of central Sichuan Basin indicated that the N surplus of agro-ecosystem in the watershed was 66.8 kg ha^{-1} (Zhu et al., 2006). Replacing synthetic fertilizer with manure fertilizer moderated the N surplus effect in croplands.

Table 5
Source and major forms of nitrogen losses from runoff and soil erosion.

Source	Form	Loss (t N)	Percent
Arable land	Organic Nitrogen	6739.84	12.56
	Ammonium	162.30	0.30
	Nitrate	162.99	0.30
Animal system	Organic Nitrogen	37,452.26	69.82
	Inorganic Nitrogen	9126.30	17.01

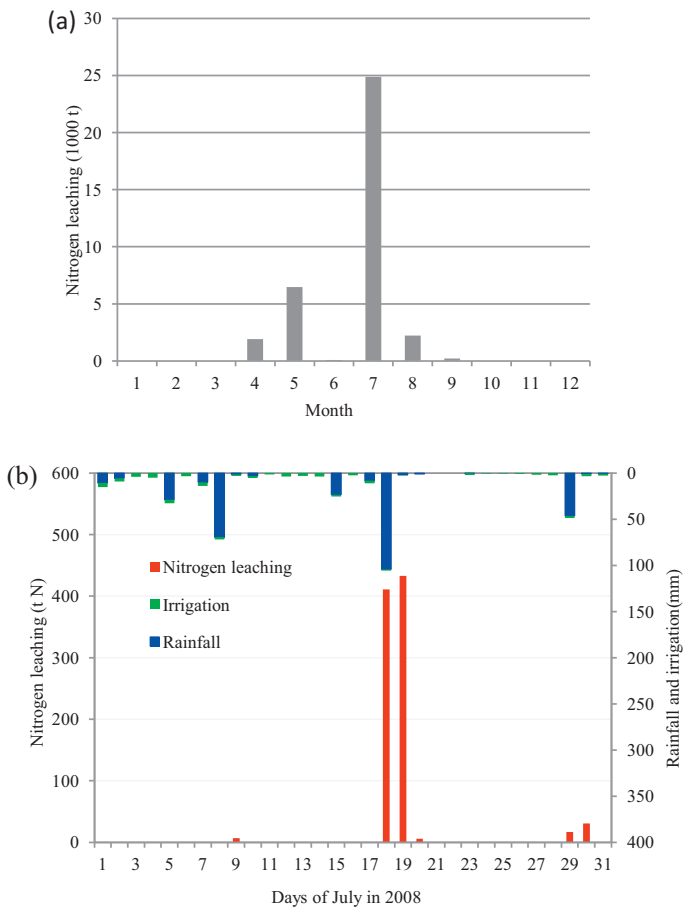

Fig. 8. Modeled monthly nitrogen leaching loading rates in the Xiaoqinghe watershed (a) and relationship between nitrogen leaching and rainfall plus irrigation in Baiyuhu town of Zhangqiu county (b).

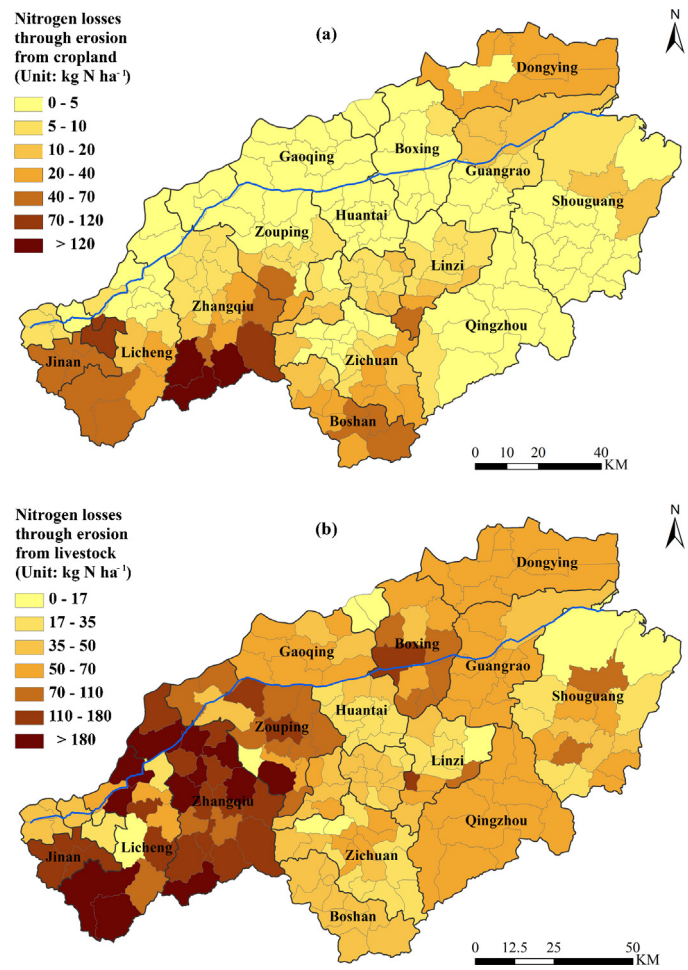

Fig. 9. Distribution of nitrogen losses through runoff and soil erosion from cropland (a) and livestock (b) in the Xiaoqinghe watershed.

6. Evaluation of modeled results at watershed scale

When models validated are applied for regions, uncertainty is produced because of the generalization of the input parameters (Qiu et al., 2009a, 2011). Census and other published data for the Xiaoqinghe watershed were collected to evaluate the modeled crop yield, surface runoff flow, soil erosion, and N loading rates.

6.1. Crop yield

Winter wheat–maize rotation dominated the cropping systems in the Xiaoqinghe watershed. Actual yield data were collected from the census of each county and used to compare with the modeled yields. The modeled yield of wheat and that of maize was comparable to that in the census data with $R^2 = 0.84$ for wheat and maize across the 182 counties for 2008 (Fig. 10). Discrepancies were observed for some counties because the actual factors affecting crop yield were greater than the input factors of the model.

6.2. Surface runoff flow

The hydrologic records for Xiaoqinghe showed that the annual average runoff flow for 1956–1986 was 1.13 billion m^3, which is equivalent to 107.6 mm water (Tian et al., 1991). However, climate change and the increase in water consumptions of the agricultural and industrial sectors decreased the surface runoff flow to 0.4 billion m^3 in 1998 and 0.15 billion m^3 in 2002 (Ma et al., 2004).

The present study simulated the surface runoff flow for 2008. The average precipitation in the Xiaoqinghe watershed during this year was 728.15 mm with maximum of 889.00 mm in Zhangqiu County and minimum of 516.80 mm in Gaoqing County. Our modeled surface runoff flow was 0.16 billion m^3, which was comparable to the hydrological record at 0.15 billion m^3. The runoff coefficient of the watershed based on the hydrologic monitoring data was about 0.1 in 1996–1999 (Hui et al., 2005). Our modeled runoff coefficient was 0.07, which is slightly lower than the statistical data. The difference could be attributed to the modeled land use. In this study, we simulated only arable land, which inherently represented flat or gentle slope topography that differs from the adopted basis of the hydrologic monitoring system.

6.3. N loading

Soil N loading to water systems through surface runoff and soil erosion in the target watershed has been increasingly serious over the past two decades. A formal study indicated that 4926 t of soil was lost because of erosion in Xiaoqinghe (Tian et al., 1991). Chen et al. (2003) calculated the N loading rates at the Chahe Hydrological Station within the Xiaoqinghe watershed from 1996 to 1999 using the hydrologic method. Their results showed that the non-point source inorganic N loading increased from 4.1 million kg of N in 1996 to 12.1 million kg of N in 1999. Gao et al. (2010a) evaluated the effects of agricultural non-point resources on water environment in Shandong Province using the equivalent standard pollution method. Their results showed that chemical fertilizer use and livestock production were contributed most to the regional N loading.

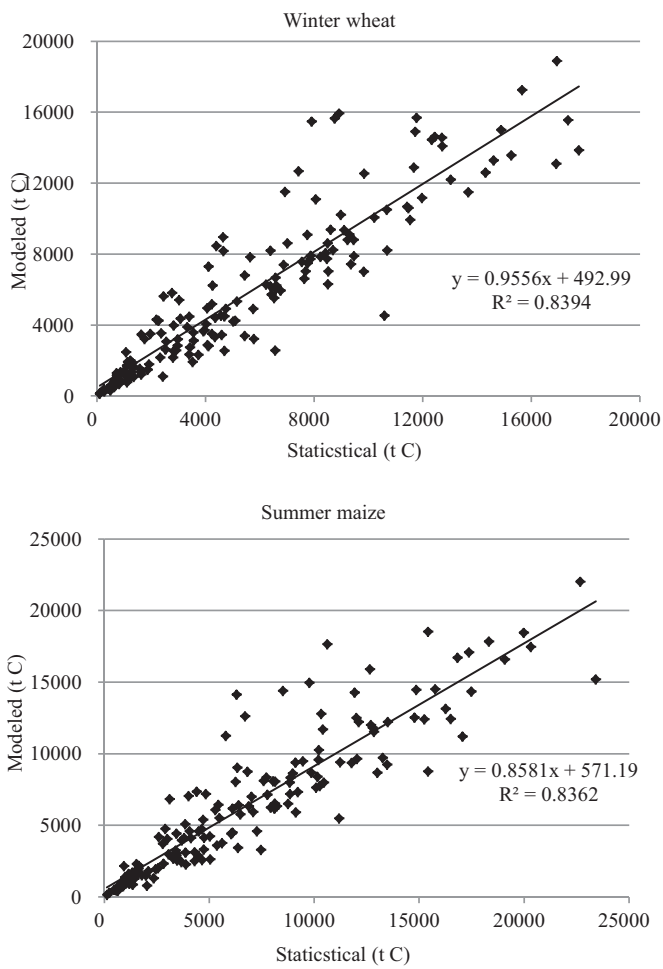

Fig. 10. Comparison between modeled and statistical yield for winter wheat and summer maize.

The total N load rate was 672.7 million kg for the entire province in 2006; and livestock manure, chemical fertilizer, and municipal sewage accounted for 49.3%, 42.6%, and 8.1% of the total nutrient loads, respectively. In this study, our data indicated that 60.16% of the leaching- and erosion-induced N load in the Xiaoqinghe watershed came from livestock manure storage or treatment. Our result was slightly higher than that of Gao et al. (2010b). Based on the data from Gao et al. (2010b), the N load was 55.8 million kg for Xiaoqinghe, assuming the pollution load was uniform across the province. We calculated the N load rate as 77.4 million kg of N for the watershed in 2008, which is in close agreement with those by Gao et al. The Manure-DNDC model produced higher N loadings because the Xiaoqinghe watershed has the most intensive management for both cropping and livestock systems in Shandong Province.

N leaching in arable land is a major reason for underground water pollution. N loss by surface runoff and soil erosion was one of the main causes of surface water pollution. Based on the modeled results, the N lost through leaching and erosion in the agricultural land of the Xiaoqinghe watershed in 2008 were 36.42 kg ha^{-1} and 10.82 kg ha^{-1}, respectively. During the process of animal breeding and manure management, 46.6 million kg N was eroded. The observations in Tangwang, Jinan showed that N leaching during the wheat growth period was 14.89 kg N ha^{-1} in 2008 (Li et al., 2009). An in situ field experiment with a lysimeter indicated that the leaching loss of soil N in maize field was mainly in NO_3^- form. The accumulative leaching loss of NO_3^- N in the growth period of maize was 12.90–46.53 kg ha^{-1} (Li et al., 2008). Considering the whole winter wheat–summer maize rotation, the aforementioned results were comparable to the modeled result in this study. Rainfall, irrigation, and fertilizer amount were the key factors affecting N leaching in cropland.

7. Conclusion

Contemporary agriculture is faced by the challenge of nutrient management. On one hand, large amounts of nutrient-rich manure are treated as waste that pollutes the environment. On the other hand, the cropping systems receive excess synthetic fertilizer to support food and feed production. One of the reasons that hampered the nutrient complementation between cropping and livestock systems is the lack of quantitative tools for precisely describing the nutrient cycles across the agricultural systems. This study attempted to fill this need. Manure-DNDC, a process-based model, was used to analyze a watershed where both croplands and livestock farms existed. We quantified the major N fluxes entering and exiting the domain watershed by simulating N exchange between the crop fields and the livestock farms.

The modeled results indicated that about 184 million kg of N is annually applied as synthetic fertilizer in the 652,881 ha of croplands. A total of 297 million kg of N is introduced as feed into the 728 livestock farms, and 9.2 million kg of N came from atmospheric deposition in the Xiaoqinghe watershed in 2008. The cropland soils received about 260 million kg of N, of which only 25.6% (67 million kg of N) came from manure amendment. The entire watershed released 127 million kg of NH_3-N into the air, including 42% from the croplands and 58% from livestock farms. Other N gases such as N_2O, NO, and N_2 were released into the atmosphere at a rate of 35 million kg of N per year. The N loads into surface water from livestock farms was 47 million kg of N and that from crop fields was 7 million kg of N. About 24 million kg of nitrate-N was leached from the cropping systems, which could be loaded to both surface water and groundwater. Some of the modeled results were compared with the measured data with encouraging results.

The Xiaoqinghe watershed had 2.87 million pigs, 0.67 million cows, 0.94 million sheep, and 71.38 million poultry in 2008. They produced 224 million kg of manure-N per year. Under current management conditions, only 30% of livestock waste N is applied to the crop fields in the Xiaoqinghe watershed. Increasing it to 80% will save 112 million kg of N of synthetic fertilizer, which accounts for 61% of the current fertilizer use in the watershed. Manure fertilizer releases N or other nutrients through decomposition, which should increase the nutrient use efficiency. Manure applications increase soil C sequestration and improve soil thermohydraulic properties. The result from the Xiaoqinghe study indicates the huge potential for improving nutrient complementation between cropping and livestock systems is possible. This win–win strategy should enhance the sustainability of Chinese agriculture.

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