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# Modelling impacts of alternative farming management practices on greenhouse gas emissions from a winter wheat–maize rotation system in China

Hu Li [a], Jianjun Qiu [a,*], Ligang Wang [a], Huajun Tang [a], Changsheng Li [b], Eric Van Ranst [c]

[a] Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences (CAAS)/Key Laboratory of Resources Remote Sensing & Digital Agriculture, Ministry of Agriculture, Beijing 100081, China

[b] Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, NH 03824, USA

[c] Department of Geology and Soil Science (WE13), Laboratory of Soil Science, Ghent University, Krijgslaan 281 (S8), B-9000 Ghent, Belgium

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ABSTRACT

Agricultural production plays an important role in affecting atmospheric greenhouse gas concentrations. Field measurements were conducted in Quzhou County, Hebei Province in the North China Plains to quantify carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$) emissions from a winter wheat–maize rotation field, a common cropping system across the Chinese agricultural regions. The observed flux data in conjunction with the local climate, soil and management information were utilized to test a process-based model, Denitrification–Decomposition or DNDC, for its applicability for the cropping system. The validated DNDC was then used for predicting impacts of three management alternatives (i.e., no-till, increased crop residue incorporation and reduced fertilizer application rate) on $CO_2$ and $N_2O$ emissions from the target field. Results from the simulations indicated that (1) $CO_2$ emissions were significantly affected by temperature, initial SOC, tillage method, and quantity and quality of the organic matter added in the soils; (2) increases in temperature, initial SOC, total fertilizer N input, and manure amendment substantially increased $N_2O$ emissions; and (3) temperature, initial SOC, tillage, and quantity and quality of the organic matter added in the soil all had significant effects on global warming. Finally, five 50-year scenarios were simulated with DNDC to predict their long-term impacts on crop yield, soil C dynamics, nitrate leaching losses, and $N_2O$ emissions. The modelled results suggested that implementation of manure amendment or crop residue incorporation instead of increased fertilizer application rates would more efficiently mitigate GHG emissions from the tested agro-ecosystem. The multi-impacts provided a sound basis for comprehensive assessments on the management alternatives.


## 1. Introduction

Emissions of carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$) are major sources of atmospheric greenhouse gases generated from upland agro-ecosystems (Watson et al., 1995). It was estimated that 20% of $CO_2$ and 90% of $N_2O$ in the atmosphere come from agricultural production (Bouwman, 1990). Recently, Greenhouse gas emissions from agriculture accounted for 14% of non-$CO_2$ of total emissions, contributing 84% of total $N_2O$ emissions and 47% of total $CH_4$ emissions (IPCC, 2007). China possesses about 140 million ha of agricultural lands including 110 million ha of upland-crop fields and 30 million ha of paddy rice fields. Based on a former study reported by Li et al. (2003), the Chinese agricultural land emitted about 95 Tg $CO_2$–C, 1.3 Tg $N_2O$–N and 9.2 Tg $CH_4$–C in 1990, among which the upland agro-ecosystems dominated the $CO_2$ and $N_2O$ emissions. Winter wheat–maize rotation is one of the most popular cropping systems in China, which has been adopted across a wide range of climatic zones and geographic regions in the country. The wheat and maize system are both geographically located in the North-eastern region, Huang-huai-hai region, South-western region and many part of the North-western region (Fig. 1). Among the regions, the Huang-huai-hai region is the most important one providing 42.3% of the total national winter wheat–maize production with intensive management by receiving adequate irrigation water and fertilizers (Bureau of Statistics of China, 2007). In the Huang-huai-hai region, 73% of the winter wheat–maize systems possessed well-developed irrigation facilities; and the fertilizer application rates for the cropping system averaged as high as 600 kg N $ha^{-1}$ (Zhong et al., 2006; Liu et al., 2006). Based on the studies reported by many researchers, this kind of intensively managed cropping systems could be an important source of atmospheric $CO_2$ and $N_2O$ (Feng and Yin, 1995; Yan and Shi, 2000; Song et al., 1996; Chen and Hu, 1997; Huang and Chen, 1999; Wang et al., 2004, 2008; Qiu

* Corresponding author. Tel.: +86 10 82106231; fax: +86 10 82106231.
*E-mail addresses:* qiujj@caas.net.cn, lihu0728@163.com (J. Qiu).

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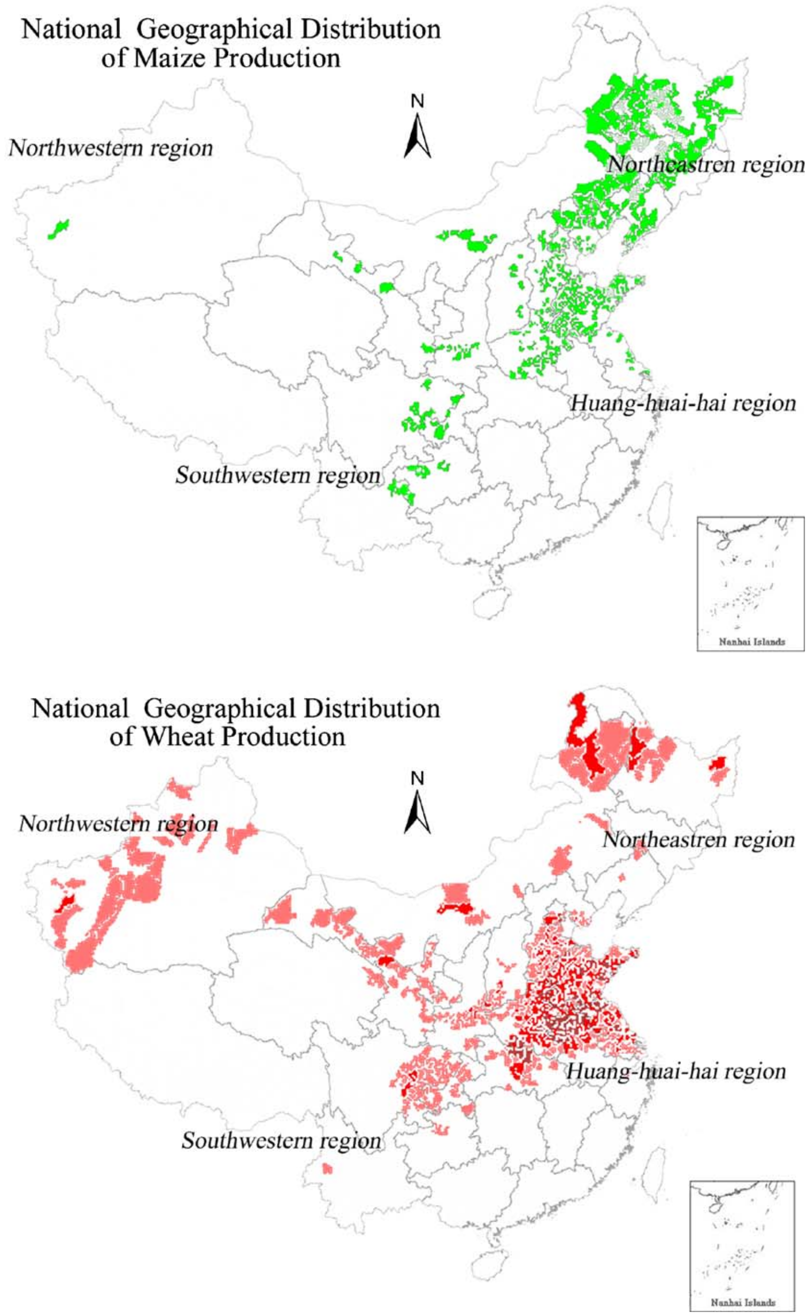


**Fig. 1.** The geographical distribution of corn and wheat system in China.

et al., 2009). In fact, emissions of $CO_2$ and $N_2O$ are significantly influenced by environmental factors such as temperature, rainfall and by management practices, etc. For agricultural ecosystems, one of the most cost effective strategies for reducing GHG emissions is through the use of improved management practices (Lal, 2003; Smith et al., 2001), and practices such as adoption of no-tillage, reduction of bare fallow and improving rates of residue returned to fields have frequently proven to be promising for reducing greenhouse gas emissions. However, any management change should accommodate the needs to maintain high crop yields, to conserve diminishing natural resources, and to minimize environmental damage. A demand for predicting effects of the new changes in rice production management in Asia on global atmosphere as well as the local environmental conditions is emerging. Since 2004, field campaigns have been launched to measure both $CO_2$ and $N_2O$ fluxes from a cropland with winter wheat and maize rotated in Quzhou County, Hebei Province within the Huang-huai-hai Plains (Li et al., 2007). The field observations showed clear trends that the management practices, especially fertilizer application rates, had significant effects on both $CO_2$ and $N_2O$ emissions from the soils. This paper reports how we utilized the field data to test a process-based biogeochemistry model, Denitrificaion–Decomposition or DNDC, for its applicability for the winter wheat and maize rotation system and then used the validated model to assess the best management practices for the upland cropping system in China.

## 2. Materials and methods

A one-year experiment was conducted at a field with winter wheat–maize rotation in Quzhou County, Hebei Province in the North China Plains. Soil $CO_2$ and $N_2O$ fluxes were measured, and information of the local climate, soil and farming management practices was collected during the experimental period.

### 2.1. Field site and measurement

The one-year (October 2005–2006) field measurement was conducted at an agricultural experimental station of the Chinese Agricultural University, located in Quzhou County, Huang-huai-hai Plain (36.52N, 115.01E). The site is 40 m above the mean sea level with a typical temperate monsoon climate (warm and wet conditions in summer and cold in winter, yearly mean temperature 13.2 °C, annual precipitation 514.3 mm). About 80% of the precipitation occurs during the period from June to September. Irrigation was applied during the experimental period. The soil of this experimental site can be classified as Cambisol in the Chinese Soil Taxonomy System and Cambisol according to the FAO Taxonomy (FAO/UNESCO, 1974), with bulk density 1.38 g $cm^{-3}$, pH 7.97 and initial soil organic carbon (SOC) content 0.0085 kg C $kg^{-1}$ for the top 20 cm soil profile. Two crops, winter wheat and maize, were planted in rotation within a one-year cycle. Winter wheat was sown on October 9, 2005 and harvested on June 10, 2006, and maize was sown on June 14, 2006 and harvested on October 7, 2006. The soil was tilled once on June 12, 2006 after harvest of the winter wheat. During the winter wheat season, the soil was irrigated with 50 mm of water for three times on December 5, 2005 and March 20 and May 20, 2006. During the maize season, the soil was irrigated with 50 mm once on September 25, 2005. After harvest, 15% of the above-ground maize residue was left in the field and incorporated in the soil with the following tillage (Some of the chemical properties of the maize residue were: total organic C, 12.4%; total N, 0.3%; P, 0.04%; K, 0.38%.). Two treatments, with and without fertilizer application, were implemented during the experimental period to test the impacts of fertilization on $CO_2$ and $N_2O$ fluxes from the agro-ecosystem. Each of the treatments was applied at a plot of 5 m × 11 m. For the treatment with fertilization, 270 kg urea-N $ha^{-1}$ was applied annually, including 90 kg N $ha^{-1}$ applied as basal fertilizer for the winter wheat on October 5, 2005, 90 kg N $ha^{-1}$ as top dressing for the wheat on April 10, 2006, and 90 kg N $ha^{-1}$ for the maize on August 12, 2006. The fertilizer application rates and timing were determined based on the typical practices of the local farmers.

Gas samples were collected with static chamber method basically same as described by other researchers (e.g., Hutchinson and Mosier, 1981; Debnath et al., 1996; Pathak, 2002). Each of the chambers consisted of two parts, the chamber cylinder (30 cm × 30 cm × 60 cm) made of organic glass and the base collar with 5 cm internal diameter fixed in the ground. The collar was inserted at 10 cm depth in the soil and filled with water to make the system air-tight. A ventilator was installed inside the chamber to ensure the internal air mixing (Fig. 2). Two chambers were installed for each treatment as duplicates. A diaphragm pump was used to transport the gas samples at a flow rate of 50 ml $min^{-1}$ to the gas bags made of aluminium (200 ml for each, produced by Dalian GuangMing Special Gas Chemical Research Institute, China) for analysis. Each sampling lasted for 20 min. During each sampling within the closed chamber, a total of 5 samples were taken at an interval of 5 min. Gas fluxes were calculated based on the slope of the gas concentrations in the five samples taken at 0, 5, 10, 15, and 20 min after the chamber closure. The field measurement was conducted once or twice per month during the period from November to March, and once or twice per week during the period from April to October. Daily average $CO_2$ or $N_2O$ fluxes and their standard errors were calculated based on the original data measured in the field.

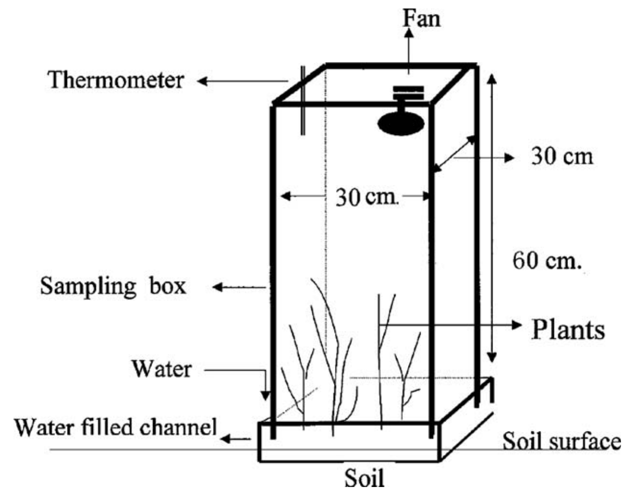


**Fig. 2.** Close chamber system used for collection of gas samples.

Gas samples were analyzed for $CO_2$ and $N_2O$ using GC HP-5890 (produced by HP Company) in the lab within 2–3 days after sampling. $CO_2$ concentrations in the gas samples were determined by GC using a flame ionization detector (FID) and $N_2O$ by GC using a $^{63}$Ni electron capture detector (ECD). The temperature of detectors (FID and ECD) was 350 °C and the temperature of column was 50 °C. The flow rate of carrier gas was 30 $cm^3$ $min^{-1}$. The columns for measuring $CO_2$ and $N_2O$ were packed with Porapak Q (80–100 mesh), and the lengths of the columns were 2 and 3 m respectively. The $CO_2$ or $N_2O$ concentration of each sample was quantified against the concentration of the calibration gas. Further methodology details are given in Li et al. (1997b). The $CO_2$ and $N_2O$ emission fluxes ($F$) were calculated with the equation (e.g., $N_2O$) as follows:

$$F = 60 \times 10^{-5}\left[\frac{273}{(273+T)}\right] \times \left(\frac{P}{760}\right)\rho H \times \left(\frac{dc}{dt}\right)$$

where $F$ is the $N_2O$ emissions flux (mg $N_2O$ $m^{-2}$ $h^{-1}$), $\rho$ (g/l) represents $N_2O$ density at 0 °C and 760 mmHg, $T$ (°C) is the mean value of air temperature inside the chamber measured during the closure, $H$ (cm) is the height of chamber headspace, $t$ (min) is time for sampling, $dc/dt$ ($10^{-9}$ $min^{-1}$) is the increase of the $N_2O$ concentration per minute in the closed chamber, $P$ (mmHg) is the air pressure of experimental site. The altitude of the experimental site for this study is very close to that of sea surface, so $P/760 \approx 1$. The measured results were processed with the statistical analysis tools provided by Microsoft Excel software package.

Daily ambient air temperature and precipitation data were collected from the local meteorological station in the experimental station. The air temperature and pressure within the chambers were also recorded during each of gas samplings. Soil moisture at approximately 5 cm depth inside the chamber was measured with the oven drying method. Soil properties, i.e., soil texture, pH, bulk density, and SOC content, were collected from the county-level information in the Agricultural Economic Database (unpublished) of the Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences. The data measured in the field or collected from existing databases were utilized either as input information or as ground truth for the model tests.

### 2.2. The DNDC model

The Denitrification–Decomposition or DNDC model adopted for the study was originally developed for predicting carbon sequestration and trace gas emissions from upland agro-ecosystems (Li et al., 1992, 1994, 1997a). The core of DNDC was built up by integrating a group of biochemical and geochemical reactions

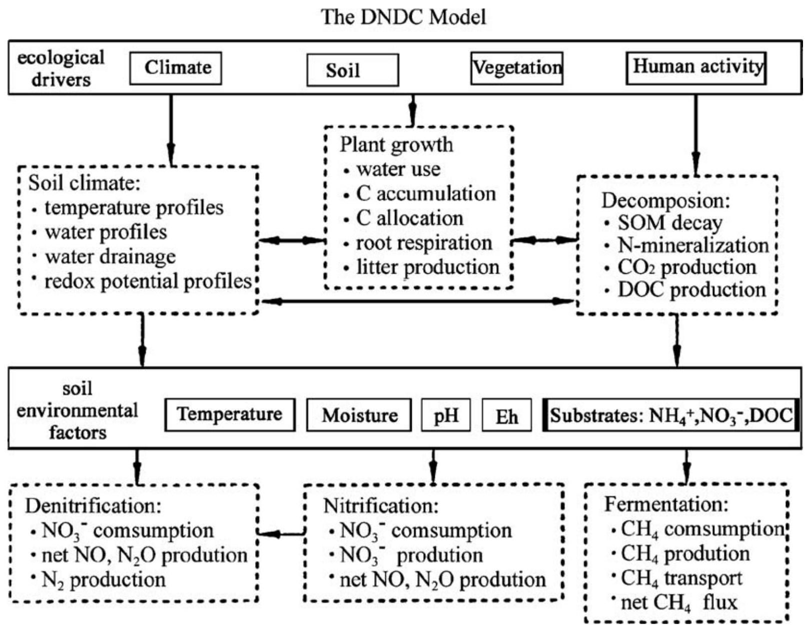


**Fig. 3.** The structure of the DNDC model.

commonly occurring in agro-ecosystems, which govern carbon (C) and nitrogen (N) transport and transformation in the plant–soil systems. DNDC consists of six sub-models for simulating soil climate, plant growth, decomposition, nitrification, denitrification and fermentation, respectively (Fig. 3). DNDC predicts soil organic carbon dynamics mainly by quantifying the SOC gain from crop litter and/or manure incorporation as well as the SOC loss through decomposition. DNDC simulates plant growth by tracking photosynthesis, respiration, water and N demand, C allocation, crop yield, and litter production. The modelled litter (roots and aboveground residue) production is one of the major factors controlling the C dynamics during the simulations. As soon as the modelled litter is incorporated in the simulated soil profile, DNDC will partition the litter into three soil litter pools, namely very labile litter, labile litter and resistant litter, based on the C/N ratio of the bulk litter. Each of the litter pools has a specific decomposition rate though subject to temperature, moisture and N availability in the soil profile. During the decomposition of litter, part of the litter C is consumed as the energy source by the soil microbes and hence becomes $CO_2$; and part of the litter C is turned into the microbial biomass. After death of the microbes, the microbial remains will become humads (i.e., active humus) to undergo further decomposition. During the decomposition processes, the N bound in the organic compounds is released into the soil in the form of ammonium. Ammonium can be oxidized into nitrate through nitrification. Ammonium or nitrate can be utilized by the soil nitrifiers or denitrifiers to produce $N_2O$ through nitrification or denitrification, respectively. Under deeply anaerobic conditions, soil methanogens will be activated to produce $CH_4$ based on the soil substrate (e.g., DOC or $CO_2$) concentrations. The above-described processes have been embedded in DNDC to simulate the processes of decomposition, nitrification, denitrification and fermentation, which dominate $CO_2$, $N_2O$ and $CH_4$ emissions from the soils. A relatively complete set of farming management practices such as tillage, fertilization, manure amendment, irrigation, flooding, grazing etc. have been parameterized in DNDC to regulate their impacts on soil environmental factors (e.g., temperature, moisture, pH, redox potential and substrate concentration gradients). Two classical equations, the Nernst Equation and the Michaelis–Menton Equation, have been adopted in DNDC to bridge between the soil environmental factors and the biogeochemical reactions. DNDC tracks the soil redox potential evolution and calculates productions and consumptions of $CO_2$, $N_2O$ and $CH_4$ sequentially for both upland and wetland ecosystems (see details in Li et al., 1992, 2004; Li, 2007). In DNDC, DOC concentration is calculated based on the SOC decomposition rate and used to control $N_2O$ or $CH_4$ production by fuelling the relevant microbial activities in conjunction with other substrates (e.g., ammonium, nitrate, hydrogen). By precisely simulating the soil microbial activities, DNDC links C sequestration to $N_2O$ or $CH_4$ emissions. During the past decade, DNDC has been tested and used by a number of researchers worldwide with promising results (Smith et al., 1997, 2002; Butterbach-Bahl et al., 2001; Brown et al., 2002; Cai et al., 2003; Saggar et al., 2003; Grant et al., 2004; Kiese et al., 2005; Pathak et al., 2005; Qiu et al., 2005; Jagadeesh Babu et al., 2006; Beheydt et al., 2007; Wang et al., 2008). The model is currently applied for greenhouse gas inventory or mitigation in North America, Europe, Asia and Oceania.

To simulate trace gas emissions for a specific site, DNDC requires a number of input parameters including daily meteorological data (maximum and minimum temperatures, precipitation), soil properties (SOC content, clay content, pH and bulk density) and farming management measures (tillage, fertilization, manure amendment, irrigation, and crop rotation). Any change in either the natural conditions or the farming management practices will simultaneously alter several soil environmental factors including temperature, moisture, Eh, pH, and substrate concentration gradients; and the altered environmental factors will simultaneously and collectively affect a series of biochemical or geochemical reactions such as elemental mechanical movement, oxidation and reduction, dissolution and crystallization, adsorption and dissimilation, complexation and decomplexation, assimilation and dissimilation, etc., which finally determine $CO_2$ and $N_2O$ emissions from the modelled ecosystems. More information about the concepts or mathematics of the model can be found in former publications (e.g., Li et al., 1992, 1996, 2007). The DNDC model is available via the Internet (http://www.dndc.sr.unh.edu).

### *2.3. Integration of field data and model*

The field data from experiment were integrated with DNDC through three phases. At first, a part of the field data was utilized for model validation, through which the applicability of DNDC for the maize–wheat rotation system in China was tested. During the validation tests, the local daily weather data, soil properties and actual farming practices (e.g., tillage, fertilization, irrigation etc.) were used to drive DNDC to simulate the crop growth, litter incorporation, SOC turnover, N leaching and trace gas emissions for the target ecosystem; and the modelled crop yields as well as the fluxes of $CO_2$ and $N_2O$ were compared with the field observations. After the tests, the validated DNDC was utilized for a sensitivity test. DNDC was run for the same site but with varied climate, soil and management conditions. The purpose of the sensitivity test was to identify the most sensitive factors that could most effectively mitigate the greenhouse gas emissions from the target ecosystem. Finally, 50-year scenarios were designed by varying the identified most sensitive factors to quantify their long-term impacts on greenhouse gas emissions from the winter wheat–maize rotation systems in China. The modelled $CO_2$ and $N_2O$ data were assessed by means of the concept of global warming potential (GWP). Since each of the management alternatives could simultaneously affect $CO_2$, $N_2O$ and $CH_4$ fluxes, a net effect of the scenario on global warming need to be quantified. For this study, the net impact was defined to be the sum of the warming forces of all greenhouse gases (GHGs) based on 100-year global warming potentials. According to the IPCC method (2007), the GHGs can be compared based on the effectiveness of each of GHGs for trapping heat in the atmosphere (Pathak et al., 2005). When the GWP value for $CO_2$ is taken as 1, the GWP for $CH_4$ (based on a 100-year time horizon) is 23, while that for $N_2O$ is 296. The GWP of each of the management scenarios was calculated using the following equation (Li et al., 2004):

$$\mathrm{GWP} = \frac{\mathrm{CO}_{2i}}{12 \times 44} + \frac{\mathrm{N_2O}_i}{28 \times 44 \times 296} + \frac{\mathrm{CH}_{4i}}{12 \times 16 \times 23},$$

where $\mathrm{GWP}_i$ (kg $CO_2$ equivalent $ha^{-1}$ $y^{-1}$) is the global warming potential induced by scenario $i$; $CO_{2i}$, $N_2O_i$, and $CH_{4i}$ are $CO_2$ flux (kg C $ha^{-1}$ $y^{-1}$), $N_2O$ flux (kg N $ha^{-1}$ $y^{-1}$), and $CH_4$ flux (kg C $ha^{-1}$ $y^{-1}$), respectively, induced by scenario $i$. For this study focusing on the upland ecosystem, there was no $CH_4$ emission, and the $CH_4$ oxidation rate was negligible in comparison with the $CO_2$ or $N_2O$ fluxes from the soil.

## 3. Results and discussions

For the measurement-model fused study, the field experiments provided the first hand of information about the GHGs emissions with relevant environmental conditions, and the field observations were utilized for the model validation first and then extrapolated through the sensitivity analysis as well as long-term predictions with the validated model.

### 3.1. Measured $CO_2$ and $N_2O$ fluxes

Daily $CO_2$ and $N_2O$ fluxes from the winter wheat–maize rotated field with and without fertilizer application in Quzhou County, Hebei province were measured with static chamber method during the period from October of 2005 to October of 2006. The $CO_2$ fluxes observed at the plots ranged from 8.8 to 56.9 kg C $ha^{-1}$ $d^{-1}$ with standard errors of 4.2 and 22.9 kg C $ha^{-1}$ $d^{-1}$, respectively, for the winter wheat season; and from 14.0 to 61.8 kg C $ha^{-1}$ $d^{-1}$ with standard errors of 3.2 and 40.0 kg C $ha^{-1}$ $d^{-1}$, respectively, for the maize season (Fig. 4a). In comparison with the fertilized plot, the unfertilized plot emitted less $CO_2$ (8.3–37.9 kg C $ha^{-1}$ $d^{-1}$ for winter wheat and 10.2–34.3 kg C $ha^{-1}$ $d^{-1}$ for maize). There was a clear seasonal pattern of $CO_2$ emissions during the experimental period. The daily $CO_2$ fluxes in the summer were higher than that in the winter (Fig. 4a). The maximum $CO_2$ fluxes occurred following the tillage in June of 2006. The results observed in the experiment were comparable with that reported by other researchers. The daily $CO_2$ flux range (9–62 kg C $ha^{-1}$ $d^{-1}$) from our site were in agreement with that (24–57 kg C $ha^{-1}$ $d^{-1}$) reported by Song et al. (1996) for a winter wheat field in Hebei Province. Chen and Hu (1997) reported that application of urea increased $CO_2$ emissions at a wheat field that matched our observations.

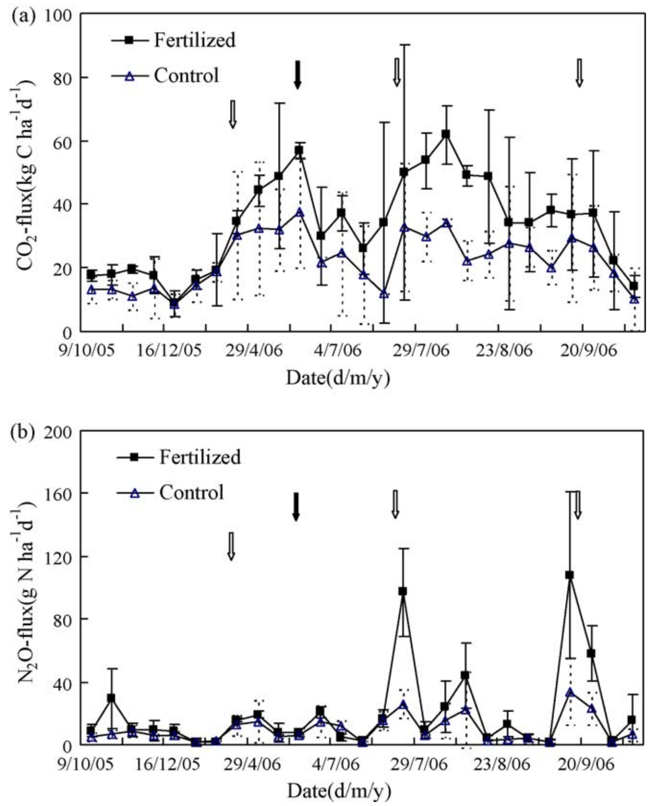


**Fig. 4.** Observed daily emissions of $CO_2$ and $N_2O$ during a whole period for the winter wheat and summer maize growth (arrow: time of fertilizer application and tillage; error bars are standard errors for 3 repetitions).

Fig. 4b shows episodic emissions of $N_2O$ from the experimental field. High picks of $N_2O$ fluxes were measured following the fertilizer applications. The maximum $N_2O$ fluxes were measured at the fertilized plot on July 16 and September 17, 2006 when the soil was warm and N-fertilizer was just applied (Fig. 4b). In contrast, low $N_2O$ fluxes were measured during the winter months of 2005–2006 when the soil was dry and cold. The observed daily $N_2O$ emission rates ranged between 0.0 and 20.8 g N $ha^{-1}$ $d^{-1}$ with standard errors ranged 0.0 and 18.8 g N $ha^{-1}$ $d^{-1}$, respectively for the winter wheat season; and between 0.0 and 108.1 g N $ha^{-1}$ $d^{-1}$ with standard errors of 0.0 and 52.9 g N $ha^{-1}$ $d^{-1}$, respectively for the maize season. In comparison with the fertilized plot, the unfertilized plot had lower $N_2O$ emission rates ranging between 0.0 and 34.0 g N $ha^{-1}$ $d^{-1}$. The relationship between $N_2O$ fluxes and fertilizer application observed in the study was in agreement with other observations in China (Zheng and Wang, 1997). However, our field measurements indicated that fertilizer application was not the only factor determining $N_2O$ fluxes. For example, the fertilizer application in April of 2006 did not stimulate $N_2O$ emissions as much as other applications implemented in the summer time. The low soil temperature in the April inherently depressed $N_2O$ emissions.

Annual emission rates of $CO_2$ and $N_2O$ were estimated by interpolating the measured datasets with monthly or weekly intervals. The annual $CO_2$ and $N_2O$ emission rates were 9623.9 kg C $ha^{-1}$ $y^{-1}$ and 4.9 kg N $ha^{-1}$ $y^{-1}$ for the fertilized plot, and 6590.4 kg C ha$^{-1}$ y$^{-1}$ and 2.3 kg N ha$^{-1}$ y$^{-1}$ for the unfertilized plot, respectively. The estimates could have high uncertainties due to the method of interpolation, especially for $N_2O$ that is characterized with episodic emissions.

### *3.2. Model validation*

The measured $CO_2$ and $N_2O$ fluxes as well as other local information of weather, soil and farming management were utilized to test DNDC for its applicability for the winter wheat–maize rotation system. DNDC was run with the local weather data (i.e., air maximum and minimum temperatures and precipitation) of 2005 and 2006, soil properties (i.e., texture, bulk density, SOC content and pH), and farming management practices (i.e., crop type and rotation, planting and harvest dates, tillage, fertilization, and irrigation) as described in Section 2.1 (Field Site and Measurement). In the simulations, maize was planted on June 6 and harvested on October 12 for 2005 and 2006, and winter wheat planted on October 14, 2005 and harvested on June 9, 2006. The soil was tilled to 20 cm on June 10 in 2005 and 2006. 15% of above-ground crop residue was left in the field after harvest and incorporated into the soil by tillage. The field was irrigated with 50 mm of water on March 20, May 20, September 25 and December 5 for 2005 and 2006. Two fertilizer application rates, full fertilization with 270 kg N ha$^{-1}$ applied annually (FS) and no fertilizer used (US), were simulated to match the field fertilizing practices.

Fig. 5a and b shows the modelled $CO_2$ emission fluxes in comparison with observations. The modelled $CO_2$ fluxes showed a strong correlation with observations. The field observed and simulated daily $CO_2$ emission rates showed similar seasonal patterns for both FS and US. Along with the change in temperature, both modelled and observed $CO_2$ fluxes increased in the spring and decreased rapidly in the autumn. The modelled soil $CO_2$ fluxes came from both the crop root autotrophic respiration and the soil microbial heterotrophic respiration. The modelled data indicated that the relationship between $CO_2$ and temperature was governed by not only the SOC decomposition rates but also the plant root respiration rates. During the period of the crop growth, especially in the vegetative stage, the root respiration accounted about 50% of the total soil $CO_2$ emissions. The modelled $CO_2$ fluxes were mostly located within the standard deviations of the measured $CO_2$ fluxes. The linear regression of all simulated and observed mean $CO_2$ emission rates resulted in $r^2$ values 0.88 and 0.73 for FS and US, respectively.

The simulations fairly captured the magnitudes and patterns of the observed $N_2O$ emissions for both FS and US (Fig. 5c and d). DNDC quantifies $N_2O$ fluxes by simulating both nitrification and denitrification rates at daily and hourly time steps, respectively. The simulated data indicated that the modelled background emissions of $N_2O$ were mostly from nitrification; and the episodic peak fluxes were dominated by denitrification. Several of the modelled high peaks of $N_2O$ emissions were induced by the N-fertilizer applications or irrigation. However, DNDC underestimated $N_2O$ emissions for the winter period from November 2005 to March 2006. The discrepancy could result from insufficient description of the impact of soil freezing and thawing on $N_2O$ production. In general, in comparison with observations, DNDC predicted more $N_2O$ flux peaks which were not observed in the field. The overall correlation between observed and simulated daily $N_2O$ fluxes was acceptable for FS and US ($r^2$ = 0.71 and 0.60, respectively). Given the inherently complex processes involved in the $N_2O$ production/consumption in the field, the modelled results were encouraging.

Total measured annual emissions of $CO_2$ during the winter wheat and summer maize growing season were 10,623.9 and 7482.4 kg C ha$^{-1}$ y$^{-1}$ for the fertilized plot and the unfertilized plot, respectively, while the simulated emissions were 8668.7 and 6590.3 kg C ha$^{-1}$ y$^{-1}$, respectively. The discrepancies between simulated and observed annual fluxes were less than 20% of the field annual fluxes. The measured annual $N_2O$ emission rates for the two treatments were 4.85 and 2.25 kg N ha$^{-1}$ y$^{-1}$, respectively,

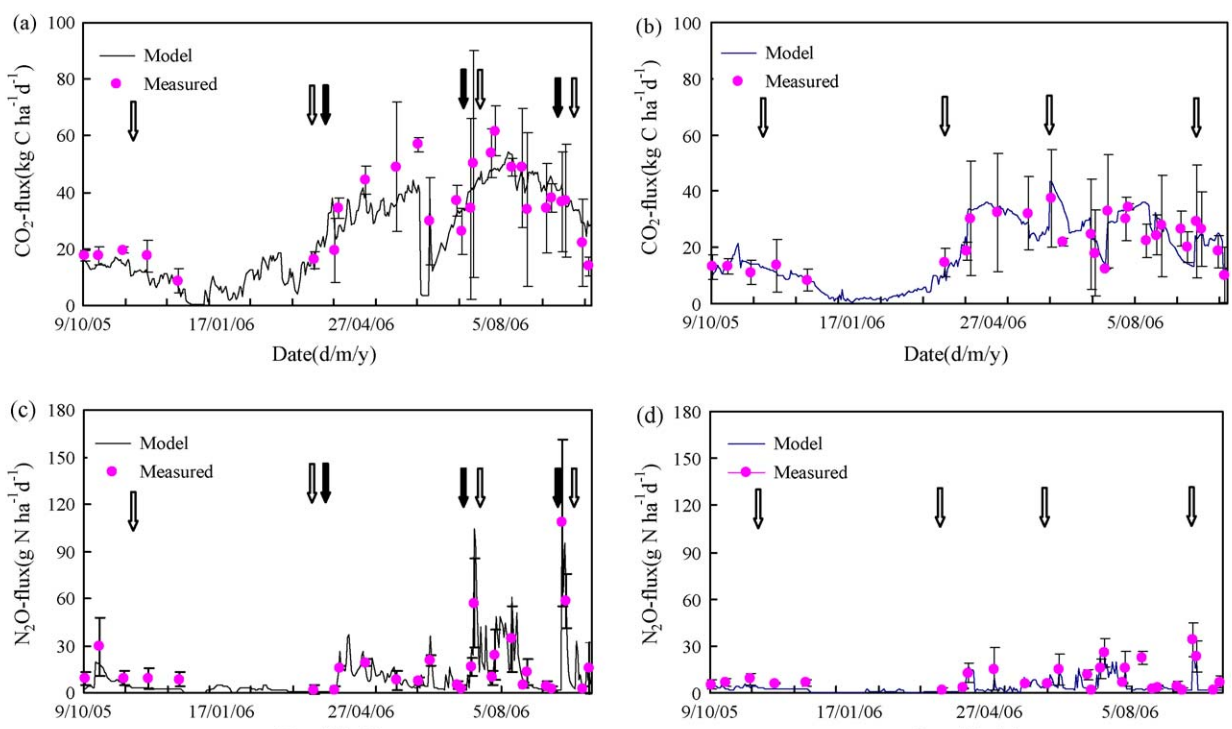


**Fig. 5.** Comparison of observed (filled circles) and simulated (solid line) of $CO_2$ and $N_2O$ emissions in wheat/maize rotation fields: (a) and (c) the control treatment and (b) and (d) the fertilized treatment (Filled arrow: time of fertilization; open arrow: time of irrigation; dashed error bars are standard deviations for 3 repetition.)

while the simulated emissions were 3.38 and 1.28 kg N $ha^{-1}$ $y^{-1}$, respectively. The relative deviations between the observed and modelled $N_2O$ fluxes were about 45% with an absolute difference of 1–1.5 kg N $ha^{-1}$ $y^{-1}$. The discrepancy on the $N_2O$ emissions could be related to the interpolation approach converting the observed daily $N_2O$ fluxes to an annual total. Overall, it was encouraging to see how DNDC predicted the magnitudes and patterns of $CO_2$ and $N_2O$ emissions for the winter wheat–maize rotation system in China though discrepancies existed in some cases.

### 3.3. Sensitivity tests

Sensitivity tests were conducted to check the general behaviour of the DNDC model for the specific cropping system. Though a great amount of observations on GHG emissions from croplands have been reported worldwide, few of field measurements have tested impacts of variations of a complete set of the drivers (e.g., climate, soil properties and farming management measures) on GHG emissions. Financial cost, time consuming and man-power demand inhibited the experiments. However, it is essential for mitigating GHG emissions to identify the sensitivities for the major GHG drivers, which could vary greatly in space and time. In the study, DNDC was run with a one-year baseline scenario that was composed based on the actual climate, soil and management conditions in the winter wheat–maize in Quzhou County in 2006. The sensitivity tests were conducted by varying a single input factor in the range, which was commonly observed in the local farmland within the county scope, while keeping all other input parameters constant as in the baseline scenario. The details of the baseline and alternative scenarios are listed in Tables 1 and 2. DNDC was run with each of the scenarios to produce an annual flux of $CO_2$ or $N_2O$ for the tested site. The sensitivity order of the drivers was determined by comparison the annual $CO_2$ or $N_2O$ fluxes induced by varying each of the drivers.

#### 3.3.1. Net $CO_2$ emissions

DNDC simulates several C fluxes occurring at the interface between the atmosphere and terrestrial ecosystems. The modelled C fluxes include photosynthesis, plant autotrophic respiration, soil microbial heterotrophic respiration, and dissolved organic carbon (DOC) leaching. In this sensitivity assessment, we adopted annual change in SOC (dSOC) content as the net $CO_2$ emissions from soil to the atmosphere. Model results showed the great impacts on dSOC of varied climatic conditions and soil properties. Increase in the air temperature by 4 °C from the baseline increased SOC loss rate from 300 to 700 kg C $ha^{-1}$ $y^{-1}$ driven by the elevated SOC decomposition rate. Lower precipitation led to lower SOC accumulation rates due to the reduced production of crop biomass including litter driven by the water stress. Shifting soil texture from the baseline, loam, to clay altered the field from a source (230 kg C $ha^{-1}$ $y^{-1}$) to a sink (−640 kg C $ha^{-1}$ $y^{-1}$) of atmospheric $CO_2$ as clay minerals adsorb SOC and hence protect it from decomposition. An increase in the initial SOC from baseline 1% to 2% elevated SOC decomposition rate, and hence led to more $CO_2$ emitted. Conversely, a decrease in the initial SOC content from 1% to 0.25% converted the soil from a source (231 kg C $ha^{-1}$ $y^{-1}$) to a sink (−1104 kg C $ha^{-1}$ $y^{-1}$) of atmospheric $CO_2$. $CO_2$ emissions were affected by not only the natural factors but also farming management practices including tillage, fertilizer application rate and splits, straw amendment and crop residue incorporation rate. Among the tested management practices, tillage, straw amendment, and crop residue incorporation showed notable impacts on the annual net $CO_2$ emissions. When change in tillage from the baseline conventional tillage to no-till, the soil switched from a source to a sink of atmospheric $CO_2$ (231 kg C $ha^{-1}$ $y^{-1}$ vs. −2339 kg C $ha^{-1}$ $y^{-1}$). Increasing straw amendment or crop residue incorporation rate elevated SOC accumulation rates due to the direct addition of organic matter. The simulated data indicated that an increase in percentage of crop residue incorporated from 15% (baseline) to 100% reduced net $CO_2$ emission rate from 231 to −2953 kg C $ha^{-1}$ $y^{-1}$.

**Table 2**
Fertilizer application dates used in the model simulations (the numbers in parentheses stand for fertilizer application rate).

| Number of fertilizer application | Fertilizer application dates |
|---|---|
| (1) (270 kg N $ha^{-1}$) | 10 April |
| (2) (135 kg N $ha^{-1}$) | 10 April, 12 August |
| (3) (90 kg N $ha^{-1}$) | 10 April, 12 August, 5 October |
| (4) (67.5 kg N $ha^{-1}$) | 10 April, 15 July, 12 August, 5 October |
| (5) (54 kg N $ha^{-1}$) | 10 April, 13 June, 15 July, 12 August, 5 October |

#### 3.3.2. $N_2O$ emissions

Results from the sensitivity tests indicated that, among the tested natural factors (i.e., temperature, precipitation, Soil texture, SOC content and soil pH), the SOC content showed the greatest impact on $N_2O$ fluxes. When SOC increased from 0.25% to 2%, the annual $N_2O$ emission rate increased from <1 to 22 kg N $ha^{-1}$ $y^{-1}$. The modelled data indicated that higher SOC produced more DOC and inorganic N (i.e., ammonium and nitrate) through decomposition that led to higher rates of nitrification and denitrification, the two processes producing $N_2O$. In comparison with SOC, other natural factors such as temperature, precipitation, soil texture or pH had relatively moderate effects on $N_2O$ emissions for the tested site. For example, increasing the rainfall by 20% did not affect $N_2O$ emissions very much. The modelled data indicated that higher precipitation induced higher rates of nitrate leaching that competed denitrification reaction. Among the tested farming management practices,

**Table 1**
Values of driver parameters varied for sensitivity tests.

| Parameter | Baseline | Range tested |
|---|---|---|
| Environmental factors | | |
| Annual mean temperature (°C) | 14.3 | Decrease by 2 °C and 4 °C and increase by 2 °C and 4 °C |
| Precipitation (cm) | 33.82 | Decrease by 20% and increase by 20% |
| Soil texture | Loam | Loamy sand, sandy loam, clay loam, and clay |
| SOC content | 1% | 0.25%, 0.5%, 1.5%, 2% |
| Soil pH | 7.5 | 6.5 and 8.5 |
| Management alternatives | | |
| Tillage | Tilling 20 cm | Tilling 10 cm and no-tillage |
| Total fertilizer N input (kg N $ha^{-1}$ $y^{-1}$) | 270 | 210, 150, 90 |
| Number of fertilizer applications | 3 | 1, 2, 4, 5 |
| Fertilizer application dates | 5 October, 10 April, 12 August | See Table 2 |
| Manure (straw) amendment | 0 | Additional 2000 and 4000 kg manure-C/ha |
| Residue incorporation | 15% | 0% and 90% |

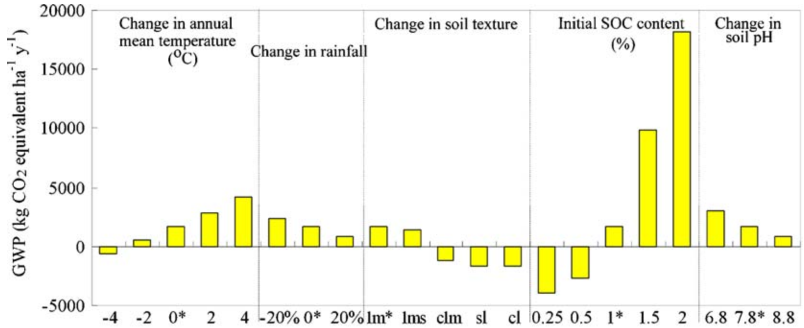


**Fig. 6.** Sensitivity of GWP to environment factors including temperature, precipitation, soil texture, SOC content and soil pH. The alternative climate/soil conditions, with asterisks, are baseline conditions. The soil texture 'lm', 'lms', 'clm', 'sl', 'cl' respectively stand for 'loam', 'loamy sand', 'clay loam', 'sand loam', 'clay'.

fertilizer application rate showed almost linear effect on $N_2O$ emissions. Increase in fertilizer application rate from 90 to 270 kg N ha$^{-1}$ increased $N_2O$ emission rate from 0.7 to 1.8 kg N ha$^{-1}$ y$^{-1}$. In the tests, conventional tillage with a tilling depth 20 cm elevated $N_2O$ emissions. The simulated results indicated that the soil disturbance with tillage increased the soil aeration and decomposition rate that led to more substrates (e.g., DOC, ammonium, nitrate etc.) released into the soil to stimulate nitrification and denitrification. Splitting the annual fertilizer into two or more applications did not show significant effect on $N_2O$ emissions. Adding organic material to the soil, e.g., crop straw and manure, can significantly increase $N_2O$ emissions that would in a large degree offset the C benefit. However, sensitivity tests showed that elevating the rate of crop residue incorporation from 15% to 100% resulted in 22% less $N_2O$ emitted. It was likely that the addition of organic carbon would result in insufficient oxygen supply and reduce the activity of autotrophic nitrification bacteria, and impact $N_2O$ emissions. In addition, some studies also revealed that decayed crop straw may produce chemical compounds which can significantly reduce $N_2O$ emissions from the soil (Zhou and Huang, 2002).

### 3.3.3. Net greenhouse gas emissions

Since each of the environmental management factors could simultaneously affect $CO_2$ and $N_2O$ emissions, a net effect on global warming need to be assessed for each scenario based on the global warming potential calculation. For the tested upland agro-ecosystem, since the modelled $CH_4$ oxidation fluxes were low (<0.5 kg C ha$^{-1}$ y$^{-1}$), we calculated GWP by ignoring the $CH_4$ effect. The calculated GWP values for all the tested scenarios are shown in Figs. 6 and 7. The results indicated that, among all environmental factors, change in initial SOC content had the greatest effect on GWP. Among the tested management factors, N-fertilizer application rate, tillage, straw amendment and residue incorporation showed significant effects on GWP. It implies that changes in these management practices could effectively mitigate the net effect of the agro-ecosystem on global warming.

## 3.4. Long-term impacts of management practices

The above-described one-year sensitivity tests indicated that $CO_2$ or $N_2O$ emissions were sensitively affected by certain natural or management factors. However, the long-term consequence of varying the natural or management factors could differ from the shout-term results due to the accumulative effects of C and N in the soils. To test the long-term impacts, we set 4 long-term (50 years) alternative management scenarios by (1) decreasing the fertilizer application rate from the baseline (270 kg ha$^{-1}$) to 150 kg ha$^{-1}$, (2) increasing the fertilizer application rate to 360 kg ha$^{-1}$, a level commonly found in the intensively managed farmland in the region, (3) increasing the crop residue incorporation rate from the baseline (15%) to 100%, and (4) increasing straw amendment rate from 0 (baseline) to 2000 kg straw-C ha$^{-1}$. Except the above-listed alternatives, other factors (e.g., climate, soil and management) were kept same as the actual conditions at the maize–wheat field in Quzhou County. The climate data of 2006 were repeatedly utilized for the 50 years. DNDC was run for 50 years with each of the scenarios, and the modelled annual fluxes of $CO_2$ and $N_2O$ were recorded for assessment.

### 3.4.1. Long-term impacts on SOC

Crop residue and straw are the main sources for the soil organic matter. The modelled results indicated that (1) under the baseline scenario which had only 15% of crop residue returned to the field, the SOC content at the site gradually decreased during the simulated 50 years; (2) when the rate of crop residue incorporation was increased from 15% to 100% or 2000 kg straw-C ha$^{-1}$ was added to the soil, the SOC content increased by 30% or 15%, respectively; (3) the sole increase in fertilizer application rate did

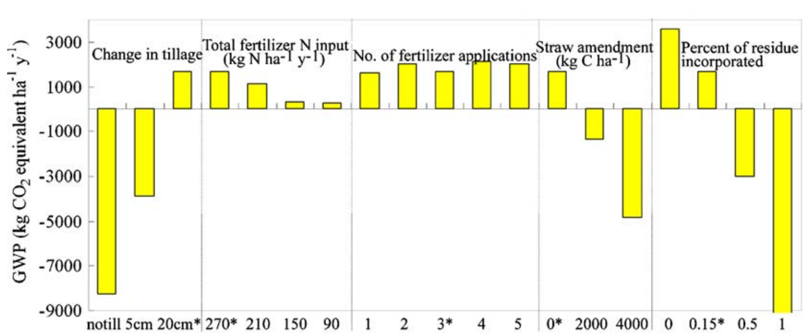


**Fig. 7.** Sensitivity of GWP to alternative management practices including tillage, fertilizer application, number of fertilizer application, straw amendment, and percent of residue incorporated. The alternative climate/soil conditions, with asterisks, are baseline conditions.

**Table 3**
Impacts of management scenarios on annual mean crop yield, soil fertility, N leaching, and GHGs emission during 50-year model simulation.

| | Fertilizer applied 150 kg N $ha^{-1}$ $y^{-1}$ | Fertilizer applied 360 kg N $ha^{-1}$ $y^{-1}$ | Manure applied 2000 kg C $ha^{-1}$ $y^{-1}$ | Residue returned 100% | Baseline |
|---|---|---|---|---|---|
| SOC change (kg C $ha^{-1}$ $y^{-1}$) | 27,696 | 30,321 | 40,088 | 43,962 | 29,934 |
| Yield (kg C $ha^{-1}$ $y^{-1}$) | 3246 | 3724 | 3732 | 3735 | 3730 |
| $N_2O$ (kg N $ha^{-1}$ $y^{-1}$) | 0.7 | 2.0 | 3.0 | 1.8 | 1.1 |
| GWP (kg $CO_2$ equivalent $ha^{-1}$ $y^{-1}$) | 1267 | 1496 | 904 | −91 | 1183 |
| N leaching loss (kg N $ha^{-1}$ $y^{-1}$) | 2.2 | 8.6 | 8.4 | 8.5 | 7.3 |

not improve the SOC loss very much; and (4) the decrease in fertilizer application rate accelerated the SOC loss by reducing the crop biomass production (Fig. 8).

### *3.4.2. Long-term impacts on $N_2O$ fluxes*

In comparison with the baseline, the modelled results indicated that manure amendment and elevated residue incorporation both increased SOC content that provided more substrates to stimulate $N_2O$ emissions through nitrification and denitrification in the soil. The increase in fertilizer application rate elevated $N_2O$ emissions; and the decrease in fertilizer application rate reduced $N_2O$ emissions (Fig. 9).

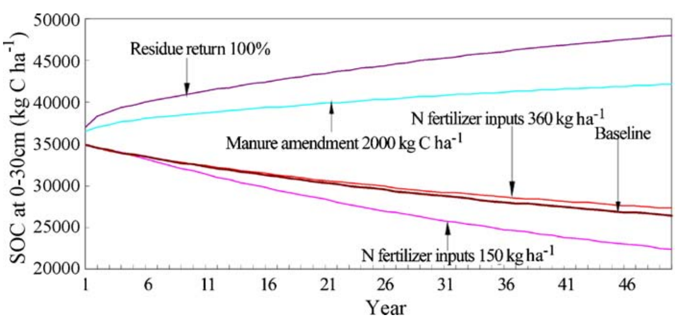


**Fig. 8.** Impacts of management practices on long-term SOC dynamics.

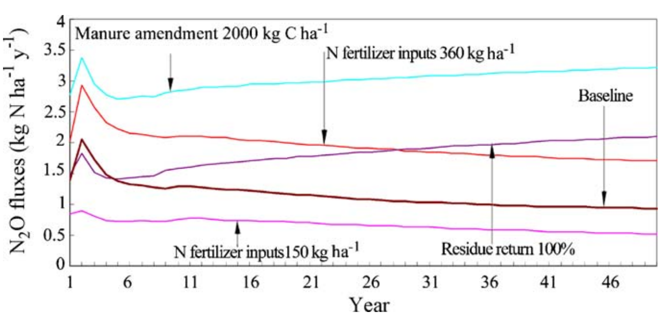


**Fig. 9.** Impacts of management practices on long-term $N_2O$ fluxes.

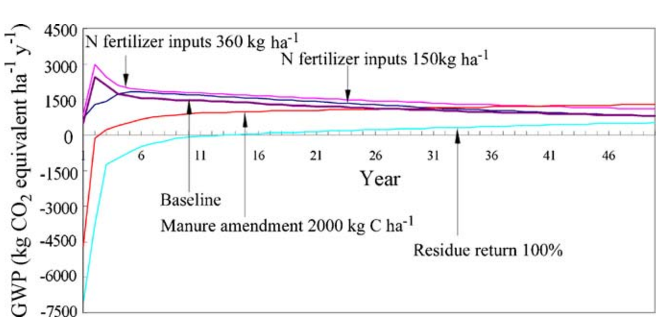


**Fig. 10.** Modeled impacts of management practices on long-term net greenhouse gas emissions.

### *3.4.3. Long-term changes in net greenhouse gas emissions*

We examined long-term impacts of the baseline and 4 alternative management scenarios on global warming by calculating their GWP values. During the first about 15 years, the 5 scenarios had different impacts on the field GWP; both high crop residue incorporation and straw amendment reduced GWP in comparison with the baseline. However, along with the time prolonged, only the high crop residue incorporation maintained the benefit. The results implied that the effects of the tested management alternatives on $CO_2$ and $N_2O$ could offset each other regarding the global warming mitigation (Fig. 10).

As a summary, Table 3 shows the 50-year mean annual SOC changes, crop yields, $N_2O$ emissions, GWP values, and nitrogen leaching losses specified with the baseline and alternative management scenarios.

In comparison with the baseline results, increase in fertilizer application rate elevated soil C content but resulted in a higher GWP value and N leaching loss. Increase in manure application rate and crop residue incorporation both had positive impacts on mitigating the global warming though the two practices led to a litter increase in N leaching loss due to increase in the soil N supply. In general, the modelled results suggested that implementation of manure amendment or crop residue incorporation instead of increased fertilizer application rates would more efficiently mitigate GHG emissions from the tested agro-ecosystem. Although the results reported in this paper were only for a specific site, the general trends resulted from the study could be applicable to other locations.

## 4. Conclusions

Agricultural systems are significant GHG sources. As a large agricultural country, China has the responsibility to mitigate greenhouse gas emissions from agricultural production. Because the GHG emissions from agro-ecosystems are affected by many environmental factors as well as management practices, researchers need special tools to tackle the complex systems. Biogeochemistry-oriented, process-based models such as DNDC could play a key role in GHG inventory and mitigation. In this study, we tested DNDC against our observations, and then applied the model for interpreting, integrating and extrapolating the field observations. By comparing the modelled results on $CO_2$ and $N_2O$ emissions against observations for the wheat–maize rotated field in Quzhou County, the applicability of DNDC for this kind of cropping system was confirmed. The sensitivity tests conducted with DNDC provided detailed information about how the environmental or management factors affected $CO_2$ and $N_2O$ emissions. The results indicated that (1) $CO_2$ emissions were significantly affected by temperature, initial SOC, tillage method, and quantity and quality of the organic matter added in the soils; (2) increases in temperature, initial SOC, total fertilizer N input, and manure amendment substantially increased $N_2O$ emissions; and (3) temperature, initial SOC, tillage, and quantity and quality of the organic matter added in the soil all had significant effects on global warming. Finally, five 50-year scenarios were simulated with DNDC to predict their long-term impacts on crop yield, soil C dynamics, nitrate leaching losses, and $N_2O$ emissions. The multi-impacts provided a sound basis for comprehensive assessments on the management alternatives. In general, DNDC proved a decent model through the validations, sensitivity tests and long-term predictions conducted in the study. This kind of modelling tools should play an important role in not only environmental impacts but also agricultural production for a wide range of agro-ecosystems in China.

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