Modeling impacts of farming management practices on greenhouse gas emissions in the oasis region of China

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Abstract

Agricultural ecosystems are major sources of greenhouse gas (GHG) emissions, specifically nitrous oxide (N_2O) and carbon dioxide (CO_2). An important method of investigating GHG emissions in agricultural ecosystems is model simulation. Field measurements quantifying N_2O and CO_2 fluxes were taken in a summer maize ecosystem in Zhangye City, Gansu Province, in northwestern China in 2010. Observed N_2O and CO_2 fluxes were used for validating flux predictions by a DeNitrification-DeComposition (DNDC) model. Then sensitivity tests on the validated DNDC model were carried out on three variables: climatic factors, soil properties, and agricultural management. Results indicated that: (1) the factors that N_2O emissions were most sensitive to included nitrogen fertilizer application rate, manure amendment and residue return rate; (2) CO_2 emission increased with increasing manure amendment, residue return rate and initial soil organic carbon (SOC); and (3) net global warming potential (GWP) increased with increasing N fertilizer application rate and decreases with manure amendment, residue return rate and precipitation increase. Simulation of the long-term impact on SOC, N_2O and net GWP emissions over 100 yr of management led to the conclusion that increasing residue return rate is a more efficient method of mitigating GHG emission than increasing fertilizer N application rate in the study area.

1 Introduction

The observed rises in global temperature and global sea level during the past 150 years and the well-documented large-scale melting of snow and glaciers during recent decades are the unequivocal evidence of global warming (Vermeer et al., 2009; Vinnikov et al., 2003; IPCC, 2007a) and the human-induced rise in the greenhouse gases (e.g., CO_2, CH_4, N_2O) are blamed for the warming (IPCC, 2001; IPCC, 2007a). Besides fossil fuel burning, agricultural activities are another major contributor to the rise of these greenhouse gases (Watson et al., 1996). It is estimated that global agricultural emission of CO_2, CH_4 and N_2O account for 20%, 15% and 90% of total human emission, respectively (Bouwman, 1990a; IPCC, 2007a). The contributions of CO_2, CH_4 and N_2O to global warming are 60%, 20% and 6%, respectively (IPCC, 2001; IPCC, 2007a; Oenema et al., 2001). It is thus widely recognized that reducing the agricultural greenhouse gas emissions (GHG) is of great importance in the management of global climate change.

China is an agricultural country with centuries of history of agricultural development. To support the increasingly growing population since the middle of the 20th century, Chinese agricultural area has expanded dramatically, reaching approximately 140 M ha (China statistical yearbook, 2006). The areal expansion has been accompanied with increasingly intensive managements including fertilizer applications. However, these achievements have come with a great cost in exhausting natural resources and in degrading the ecosystems (Huang, 2008a). Although the areal extent of the agricultural lands has been recently decreasing due to acceleration of industrialization and urbanization (Huang, 2008b), fertilizer application has been recently intensified to increase agricultural productivity. An undesired consequence of the intensified application of fertilizer is of course the increase of the agricultural emission of the Greenhouse Gas (FAOSTAT, 2003). Globally speaking, since the industrial revolution the contents of the atmospheric CO_2, CH_4 and N_2O increased 100 ppm, 1000 ppb, 50 ppb, respectively (IPCC, 2007b; Lal, 2004; Mosier et al., 1998). Since the study area of this research is situated in an arid region where soil CH_4 oxidation rate was negligible (Li et al., 2010a), our following discussion thus only focuses on soil N_2O and CO_2 emissions. Soil N_2O comes from two processes in soil: nitrification and denitrification, and these two processes can be affected by climate changes and agricultural activities. For example, the optimal temperature for both nitrification and denitrification is 25-35 ^{o}C (Bouwman, 1990b) and nitrogen fertilizer application increases soil N_2O emission (Chen, 1989; Li, 1993; Wang, 1994; Hou et al., 1998; Chen, 1995). Soil CO_2 emission is also controlled by climate changes and agricultural activities. For example, temperature rising can effectively enhance the soil CO_2 emission (Han, 2007) and nitrogen fertilizer application can stimulate soil CO_2 emission (Liu et al., 2008; Xing, 2006). The above studies were about the individual effects of nitrogen fertilizer or organic fertilizer on the N_2O or CO_2 emissions; however, few studies have considered the associated impact of the two factors (i.e., nitrogen fertilizer and organic fertilizer) on the N_2O and/or CO_2 emissions.

In order to assess the potentials of reducing agricultural N_2O and CO_2 emissions through changing management practices and evaluate the possible responses of agricultural N_2O and CO_2 emissions to different management practices, we utilized the DeNitrification-DeComposition (DNDC) model to simulate soil carbon sequestration potentials and greenhouse gas emissions brought about by different farmland management practices in agroecosystems (Li, 2004a). In the past 20 yr, the DNDC model has proven to be effective in many places around the world, such as North America, Europe, Asia and Oceania (Li et al., 1996; Plant, 1999; Stange et al., 2000; Li, 2000; Zhang et al., 2002; Xu et al., 2003; Cai et al., 2003; Frolking et al., 2004; Grant et al., 2004; Smith et al., 2004; Butterbach-Bahl et al., 2004; Pathak et al., 2005; Jagadeesh Babu et al., 2005; Beheydt et al., 2007; Smith et al., 2010). Application of this model in China began in the late 1990s. The study of Xu et al. (2000, 2001) in Guizhou Province suggested that soil N_2O fluxes can be well simulated by the DNDC model for corn-rape rotation, soybean-winter wheat rotation and fallow fields. A study of soil N_2O emission in soybean fields also lends a strong support to the acceptability of the DNDC model in simulating N_2O emission flux during the soybean growing period (Xie and Li, 2004). The strongest support to the acceptability of DNDC model came from the Quzhou experiment station of China Agricultural University where long-term observational data of soil organic carbon variations with different treatments of fertilization and tillage were consistent with the DNDC modeling results (Wang et al., 2004).

We choose an oasis (i.e., Heihe Oasis) as our study area (Fig. 1) because nearly all of the oases in arid and semi-arid areas of northwestern China are facing serious challenges in developing a sustainable economy and in maintaining health ecosystems. Oases account only for about 4% of the total arid and semi-arid area in China, but they support over 90% of the population of the entire area (Wang, 2010). The objectives of the study are: (1) to evaluate the acceptability of the DNDC model using field-observed data, (2) to test the sensitivity of factors affecting the agricultural GHG, and (3) to assess the possible responses of agricultural N_2O and CO_2 emissions to different management practices. We hope that our study can provide scientific references for optimizing the management practices and for developing sustainable strategies.

2 Materials and methods

A one-year experiment was conducted at a field with summer maize in Zhangye City, Gansu Province, in the Northwestern China. During the experiment, soil CO_2 and N_2O fluxes were measured, and information about local climate, soil and farm management was collected.

2.1 Field site and measurement

Field measurements were conducted during April to October 2010 at an agricultural experimental station run by the Zhangye City Agricultural Science Research Institute. The station is located in an irrigated area within Heihe oasis (38.91° N, 100.36° E) (Fig.1). The elevation of the site is 1560 m. The climate is continental, with an approximate annual mean temperature of 7.0°C, an annual mean rainfall of 127 mm, an annual evaporation of 2345 mm, and 153 frost-free days per year. From April to October, the active accumulated temperature above 5°C is 3223°C. The soil in the experimental field is irrigated desert soil with a bulk density of 1.38 g cm^{-3} and pH of 8.6. The initial soil organic carbon (SOC) content of 0.0138 kg C kg^{-1} for the top 20 cm of the soil profile and the texture of the soil is sandy loam.

Summer maize was the main crop in the area. It was sown on 28 April 2010 and harvested on 3 October 2010 with a sowing rate of 50 kg ha^{-1}. The experiment included four treatments: (1) M (manures at 2000 kg C ha^{-1}); (2) N (nitrogen applied as urea at 300 kg N ha^{-1}); (3) MN (manures at 2000 kg C ha^{-1} and nitrogen applied as urea at 300 kg N ha^{-1}); and (4) B (neither fertilizer nor manure). The experiment was a randomized block design with three replications. That is, 12 plots were used and each plot was 4 m × 8 m. All of the treatments had the same K fertilizer, P fertilizer, tillage and irrigation. The animal manure was applied as a basic fertilizer to the soil on 28 April 2010. Urea application was conducted three times: 28 April (planting), 18 June (jointing stage) and 26 July (silking stage), with a mass ratio of 2:2:1. During the growing season, the field was irrigated 4 times: 18 June, 26 July, 6 August, and 26 August. After the harvest, 15% of the above-ground maize residue was left in the field and later incorporated into the soil during the subsequent tillage.

Gas samples were collected using the closed-chamber method. Each of the chambers consisted of two parts, one is the chamber cylinder (30 cm × 50 cm × 70 cm) made of organic glass, and the other one is the base collar with 5 cm internal diameter. The base collars for gas collection chambers were installed in each plot 24 h before the sampling. One base collar was installed in each one of the 12 plots. Permanent boardwalks were set before the cropping season to minimize soil disturbance during gas sampling. The gas sampling started at 9:00 AM and ended at 11:00 AM (local time). Each sampling lasted for 20 minutes and 5 samples were taken at an interval of 5 minutes during each sampling. The field measurement was conducted once per week from April to May, twice or more per week from June to August, and again once per week from September to October. The N_2O concentration of gas samples was measured using a GC Agilent 7890 equipped with a ^{63}Ni electron capture detector (ECD) in the laboratory within 2-3 days after sampling. The column for measuring N_2O was packed with Porapak Q (80-100 mesh), and the length of the column was 3 m. The temperature of ECD was 350 ℃ and the temperature of column was 55 ℃. The flow rate of carrier gas was 30 ml min^{-1}. The N_2O concentration of each sample was quantified against the concentration of the calibration gas. The N_2O emission flux (F) was calculated with the equation as follows (Li et al., 2010a):

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

where F is the N_2O emissions flux (mg N_2O m^{-2} h^{-1}), ρ (g l^{-1}) represents N_2O density at 0 ℃ and 760 mmHg, T (℃) 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 the 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.

Soil CO_2 flux in the field was determined with open-type soil carbon flux monitoring instrumentation of LI-8100 (LI-COR, Lincoln, NE, USA). Three steel collars were installed for each treatment as duplicates. That is, one steel collar was installed in each one of the 12 plots. To avoid short-term fluctuation in the respiratory rate of soil caused by human disturbance, we inserted all of the steel collars into the soil, with a 5 cm wall exposed above the soil surface for installing the monitoring chamber, and cleared the litter and the newly-germinated weeds in the steel collars 24 h before measurement (Zhang, 2008). Each measurement was commenced at 9:00 AM and ended at 11:00 AM (local time). The field measurement was conducted twice or three times per month during May, August and September, and twice or more per week from June to July.

2.2 The DNDC model

To assess the impacts of climate change and human activities on ecosystems, biogeochemicalcycles become foci of recent scientific research and a need for developing a mathematical descriptions or model has thus been pressing to quantitatively evaluate the combined influence of various factors (e.g. climate, soil, vegetation and human activity). The DNDC model, a biogeochemical model, was developed to meet this need (Li, 2001).

2.2.1 Model introduction

Denitrification and decomposition are the main chemical reactions that bring nitrogen and carbon in soil into the atmosphere. These two reactions change the soil fertility while releasing CO_2, N_2O and CH_4 to the atmosphere. The model consists of six sub-models: soil climate, crop growth, decomposition, nitrification, denitrification and fermentation. The functional equations of the six sub-models are primarily derived from basic physical, chemical and biological theories or from empirical relationships based on observed data. The detailed model structure can be seen in Li et al. (1992).

2.2.2 Model simulation

To simulate tracer gas emissions for a specific site, the DNDC model requires a number of input parameters, including climate conditions, soil properties and agricultural management practices. The basic meteorological data (e.g., daily maximum temperature, daily minimum temperature, daily precipitation, air pressure) were acquired from the China Meteorological Data Sharing Service Network (http://cdc.cma.gov.cn/). The initial physical and chemical properties of the soil (e.g., SOC, bulk density, pH, clay content) were acquired from conventional field sampling and laboratory analysis. The agricultural management practices (e.g., tillage, fertilization, and irrigation) were determined by the experimental design.

The DNDC model can simulate the major GHG emission fluxes of N_2O, CO_2 and CH_4, crop yields, carbon/nitrogen content in soil and plants, and soil temperature and humidity in different levels of a soil profile. Observed values were compared with simulation values to evaluate the accuracy of modeling results.

The purpose of sensitivity tests is to find those factors that have a major impact on the variables of interest and to quantify the degree of sensitivity. Baseline scenarios were dictated by local climate, soil properties and agricultural management practices. Alternative scenarios were constructed by changing the values of a single input factor while keeping all other input parameters constant. According to the research by Xing and Shen (1998), eight variables were included for sensitivity test and they were mean annual temperature, annual precipitation, soil texture, SOC, pH, residue incorporation, and N fertilizer and organic manure application. The annual mean temperature and annual precipitation in the baseline scenario were acquired from the China Meteorological Data Sharing Service Network (http://cdc.cma.gov.cn/). Soil physical and chemical properties were acquired from the Institute of Soil Science, Chinese Academy of Sciences, where they were compiled from the second national soil survey during 1979–1994 covering all counties. Farm management data come from household surveys. In the sensitivity test, we adopted the same strategies of nitrogen fertilizer and animal manure applications as in the experimental study.

A 100-yr simulation was conducted with the DNDC model to study the greenhouse gas emissions under different scenarios in the oasis summer maize system. The purpose was to identify practices that might reduce greenhouse gas emissions while soil potentials for reasonable productivity were elevated.

The global warming potential (GWP) is an estimate of the degree of contribution to global warming from a given amount of greenhouse gas. It is on a relative scale that compares the effect of the gas in question to that of the same mass of CO_2. The GWP is calculated using the following equation (Li et al., 2004b):

$$GWP_i = CO_{2i}/12 \times 44 + N_2O_i/28 \times 44 \times 298 + CH_{4i}/12 \times 16 \times 25$$

where GWP_i (kg CO_2 ha^{-1} yr^{-1}) is the global warming potential induced by scenario i; CO_{2i}, N_2O_i and CH_{4i} are the CO_2 flux (kg C ha^{-1} yr^{-1}), the N_2O flux (kg N ha^{-1} yr^{-1}) and the CH_4 flux (kg C ha^{-1} yr^{-1}), respectively, induced by scenario i. For this research, which focused on an arid region, the CH_4 oxidation rate was negligible in comparison with the CO_2 and N_2O fluxes from the agricultural soil (Li et al., 2010a).

3 Results and discussion

Field observations provided the primary data of greenhouse gas emissions in a specific environment and were utilized for model validation first. They were then extrapolated through sensitivity analysis and long-term prediction with the validated model.

3.1 Model validation

To simulate daily N_2O and CO_2 fluxes from the summer maize field, the DNDC model was run with the following input data: (1) local meteorological data (e.g. maximum and minimum air temperatures and precipitation) in 2010; (2) soil physical and chemical properties (e.g. SOC, soil bulk density, pH, soil clay content); and (3) agricultural management information (e.g. crop type, planting and harvest dates, tillage, fertilization and irrigation), which has already been detailed in Section 2.1. Figure 2 and 3 show that there was a significant correlation between modeled and observed daily N_2O and CO_2 emission fluxes under conditions of four different fertilizing, the ranging from 0.62 to 0.82 for N_2O and from 0.70 to 0.78 for CO_2, and the relative deviations were about 45% for N_2O and 25% for CO_2. This relative high correlation suggests that the N_2O and CO_2 emissions can be well modeled by DNDC. The relationship between observed and modeled the nitrate (NO_3^-) for the top 10 cm of the soil profile in summer maize fields are shown in Figure 4, and the relative deviations were about 40%. The results further supported the acceptability of the DNDC model.

DNDC-modeled daily N_2O is in the form of peak emissions. It mainly comes from both nitrification and denitrification at daily (dry period) and hourly (rainfall period) time steps. The model captured the main peak emissions of N_2O, which well matched with field observations in discharge time. The peak emissions of N_2O mainly occurred after fertilization and irrigation or during soil freezing and thawing.

The modeled and observed CO_2 fluxes included autotrophic respiration by plant roots and heterotrophic respiration by soil microorganisms. The observed and modeled daily CO_2 emission rates had the similar seasonal patterns for four different treatments (Fig. 3). That is, the observed and the modeled CO_2 fluxes increased in the spring, reached their highest values in the summer, and then decreased rapidly in the autumn. Results indicated that there was a significant positive correlation between CO_2 flux and air temperature. When the daily mean temperature was greater than 0°C, the coefficients of determination (R^2) between modeled CO_2 fluxes and temperature were 0.47, 0.47, 0.47 and 0.51, respectively (Fig. 5). The model results showed that autotrophic respiration of plant roots is the main source of soil CO_2 emission during the maize growing season (table 1), especially during the vegetative growth stage (Li et al., 2010b; Moyes et al., 2010).

Table 2 indicated the N_2O and CO_2 fluxes, the crop yield, the annual SOC and the net GWP values obtained with the DNDC model under four different management scenarios. The results demonstrated that when the crop yield was high, the net GWP under the MN treatment was much smaller than it was under the N treatment. Statistical tests suggested that there was a significant N_2O and CO_2 concentration difference between experiments with and without fertilizer application ($P \leq 0.01$), which indicated that more N_2O and CO_2 were generated in experiments with fertilizer application than in the control. This was a result caused by fertilizer application, not by errors in sampling and measurement.

3.2 Sensitivity tests

Three sets of variables considered in sensitivity test are climatic factors, soil properties and agricultural management. The ranges of all variable factors were based on the field survey. The DNDC model was run with different scenarios regarding the climatic factors, soil properties and management practices (Table 3).

In the DNDC model, CO_2 flux includes photosynthesis, plant autotrophic respiration, microorganism heterotrophic respiration, and dissolved organic carbon (DOC) leaching.

3.2.1 Climate effects

The results of the sensitivity tests showed that temperature and precipitation have significant effects on N_2O and CO_2 emissions (Fig. 6). Many studies have shown that N_2O and CO_2 fluxes have significant positive correlations with air temperature or soil temperature if soil moisture is not a limiting factor (Han et al., 2007; Yamulki et al., 1997). However, in this study the sensitivity tests indicated that the N_2O flux decreased and the CO_2 flux increased with an increase of temperature at the study site. There are two major reasons for decreased N_2O emission at higher temperatures: one is decreased soil nitrogen concentration due to inhibition of vegetation at high temperatures; the other is inhibition of soil mineralization due to decreased water content at high temperatures. The CO_2 flux increased due to the increased decomposition rate of organic matter caused by higher microbial activity, which increased with temperature.

The impacts of precipitation change on gas emissions were mainly due to changes in soil moisture. Model simulations showed that when the precipitation changed from 80% to 120%

of the baseline value, the annual N_2O emissions decreased from 3.61 to 3.54 kg N ha^{-1} yr^{-1} and the CO_2 emissions increased from 380 to 412 kg C ha^{-1} yr^{-1}. Increased precipitation stimulated denitrification, which was the main process of N_2O production, but with the extension of hypoxia, denitrification could produce more N_2 than N_2O. There are three main driving factors that control the production process: soil redox potential (Eh), DOC concentration and available N (i.e. ammonium or nitrate). When the environmental conditions change, these driving factors will also change. If any one factor becomes a restrictive factor, N_2O flux will be reduced. The relationship between soil moisture and CO_2 emission is more complicated. When soil moisture is lower than the field capacity, CO_2 flux increases with precipitation; when soil moisture ranges between the field capacity and the wilting point, there is no significant correlation between precipitation and CO_2 flux; when soil moisture is higher than the field capacity, the diffusion of oxygen in the soil is restrained, as is autotrophic and heterotrophic respiration, and CO_2 flux decreases with increasing precipitation (Davidson et al., 1998; Lavigne et al., 2004; Chen et al., 2004; Reichstein et al., 2003). In the DNDC model, Li et al. (2006) used a recession curve to describe the drainage after rainfall.

3.2.2 Impacts of soil properties

Based on the analysis of sensitivity tests on the soil properties, N_2O emission is most sensitive to SOC factor (Fig. 6). As initial SOC increased from 0.5% to 2%, N_2O emission increased from 3.11 kg N ha^{-1} yr^{-1} to 4.43 kg N ha^{-1} yr^{-1}, which is identical to the result of Jagadeesh Babu et al.(2006), and the range of change covered the range of N_2O flux change caused by the change of other soil factors. Within the DNDC model, dissolved organic carbon (DOC) is the only energy source for the entire denitrification process. Higher SOC generates more DOC, which in turns drives denitrification until the final product N_2 is produced. Soil texture is determined mainly by the ratios of sand, silt and clay. The influence of soil clay content on N_2O emission is mainly through its effect on soil hydraulic characteristics and soil aeration. Soil aeration gradually deceases as soil texture changes from sand to clay. When soil moisture is high, more N_2O will be produced in fine-textured soil. In this situation, an anaerobic environment is formed, and denitrification becomes the major factor determining N_2O emission (Bollmann and Conrad, 1998). Because soil in arid areas is usually alkaline, the pH range set in the sensitivity tests was 7.3–9.4, which was intended to represent normal soil conditions in the Zhangye Region. N_2O flux decreased when pH was increasing (Fig. 6). It is commonly agreed that soil denitrification is not directly controlled by pH, but it is indirectly influenced by it because effective carbon control by pH is required for microbial denitrifiers, a decrease in which will lead to a decrease in denitrification (Koskinen and Keeney, 1982). It is generally agreed that the optimal pH for denitrifying bacteria is 6–8 and that their total pH range of activity is 3.5–11.2 (Chen, 1989).

From the sensitivity tests, it can be seen that there was a significant positive correlation between SOC and CO_2 emission rate (Fig. 6). When the initial SOC content increased from 0.5% to 2%, CO_2 emission was increased by 229%. Because the initial SOC is the determining material basis of CO_2 production by microbial decomposition, it is essential to soil respiration (Sikora and McCoy, 1990). Bazzaz and Willians (1991) predicted that the CO_2 emission rate increases with SOC content. In this study, CO_2 flux is 215, 607 and 506 kg C ha^{-1} yr^{-1}, as soil texture is sand, loam and clay, respectively, as SOC decomposition inhibited by SOC absorption of clay mineral.

3.2.3 Impacts of management options

Results from the sensitivity tests indicated that the N_2O and CO_2 emissions were most sensitive to N fertilizer and manure amendment (Fig. 6). Increasing manure amendment from 2000 to 4000 kg C ha^{-1} yr^{-1} increased annual N_2O and CO_2 emission rates from 4.51 to 5.42 kg N ha^{-1} yr^{-1} and from 1113 to 1843 kg C ha^{-1} yr^{-1}. These increases occurred because manure amendment or return of crop residue to the soil could increase the SOC content and because of the positive correlation between SOC and the emissions of N_2O and CO_2 (Smith et al., 1997). Application of N fertilizer to agricultural soil affected the N_2O emission rate, and the magnitude of this effect mainly depended on the nitrogen utilization efficiency of the plants. N fertilizer increased the substrate concentrations (NO_3^-, NH_4^+) of nitrification and denitrification, which in turn promoted the production of N_2O, yielding the observed linear increase in N_2O emission with increasing N fertilizer (Gregorich et al., 2005). Excess of N fertilizer could significantly promote N_2O emission (Hou and Chen, 1998; Dobbie et al, 1999). There is a complex interaction between N fertilizer application and CO_2 emission rate (Kowalenko et al., 1978; Paustian et al., 1990; Jacinthe et al., 2002). In our analysis, the CO_2 flux increased when N fertilizer application rate increased; however, when the N fertilizer application rate reached a certain value (250 kg N ha^{-1} yr^{-1}), the rate of increase of the CO_2 flux decreased. One reason for this phenomenon could be a decrease in nitrogen utilization efficiency followed by a slowdown of biomass accumulation and a decrease in autotrophic respiration rate when N fertilizer application rate reaches a certain value. The other reason is that N fertilizer applied to the soil will reduce the C/N ratio, initially promoting microbial decomposition of SOC and increasing the CO_2 emission rate, but the CO_2 emission rate will decrease when the DOC consumption is excessive and there is no supplementation.

3.3 Long-term impacts of management practices

The one-year sensitivity tests identified the factors to which the N_2O and CO_2 fluxes were most sensitive on a short time scale in the Hexi oasis summer maize ecosystem. For the same soil C and N accumulation and consumption, the results of the DNDC model simulation may show a difference between a long time sequence (100 yr) and a short time sequence (1 yr). To test the long-term impacts, four long-term (100 yr) alternative management scenarios were constructed: (1) a fertilizer application rate of 450 kg N ha^{-1} yr^{-1}, which is typical of agricultural production in this region, (2) a N fertilizer application rate of 200 kg N ha^{-1} yr^{-1}, (3) an increase in the crop incorporation rate from the baseline (15%) to 90%, and (4) an increase in manure amendment rate from the baseline (0) to 2000 kg C ha^{-1} yr^{-1}. The rest of the model's driving variables (climate, soil and farm management) were kept constant with the observed values and household survey data. The DNDC model was run for 100 yr with each of the scenarios with the climate data of 2010.

3.3.1 Long-term impacts on SOC

When the N fertilizer application rate was 1.5 times higher or 2/3 lower than the baseline scenarios, the SOC content decreased by 0.14% or increased by 0.60%, respectively. When the rate of crop residue incorporation or manure amendment was increased from 15% to 90% or 2000 kg C ha^{-1} yr^{-1} was added to the soil, the SOC content increased by 42% or 31%, respectively. Long-term simulation results showed that the increase of N fertilization rate alone was not effective in increasing the SOC content. The residue return rate and the manure amendment rate were the key factors governing the SOC content, and there was a positive correlation between them (Fig. 7).

3.3.2 Long-term impacts on N_2O fluxes

Compared with the baseline scenario, the simulation results explained that elevated manure amendment and N fertilizer application rates both increased the N_2O flux; decreased N fertilizer application rate decreased the N_2O flux. This was because the manure amendment increased SOC content, which provided more nitrification and denitrification substrate to stimulate the production of N_2O. An increased N fertilizer application rate could cause rapid increase of NO_3^- and NH_4^+ in soil, thus promoting nitrification and denitrification; conversely, a decreased N fertilizer application rate could inhibit nitrification and denitrification. Returning straw to the soil reduces N_2O emission, perhaps because the high C/N ratio in the straw could accelerate biological nitrogen fixation and reduce nitrogen loss by denitrification. During straw decomposition, allelopathic substances that inhibit denitrification might be produced (Wang et al., 2006) (Fig. 8).

3.3.3 Long-term changes in net greenhouse gas emissions

The influence of different management practices on global warming was evaluated by calculating net GWP for the four scenarios. Figure 9 shows a rapid increase of net GWP in all four scenarios in the first 35 yr, and then it tends to level off. In comparison with the baseline results, larger amounts of N fertilizer use and manure amendment increases net GWP; smaller amounts of N fertilizer use decreases net GWP. Net GWP from the high residue return rate and the baseline rate are nearly equal after 40 yr. In general, increasing residue return rate would be a more effective measure than other scenarios for reducing net GWP emission.

4 Conclusions

Because agricultural ecosystems are one of the major sources of GHG emissions, reduction of GHG emissions in various agricultural management systems is a current focus of research. Assessing the impacts of various management practices on different crops and soil types through the explicit use of experimental data becomes very difficult. Biogeochemical models, such as the DNDC model, thus play an important role in such research. In the present study, N_2O and CO_2 emissions from agricultural soils were measured in a summer maize field in Zhangye City, China, in 2010. The effectiveness of the DNDC model was assessed by comparison with the field measurements. Sensitivity tests indicated that: (1) the most important factors governing N_2O emissions were N fertilizer application rate, manure amendment and residue return rate; (2) CO_2 emissions increased with manure amendment, residue return and initial SOC; and (3) net GWP decreased with increasing manure amendment, residue return rate and precipitation and increased with N fertilizer application rate. During the simulated 100 yr, the DNDC model predicted four scenarios of long-term impacts on SOC, N_2O and net GWP emissions. The results suggested that a high residue return rate was the most effective practice for maintaining sustainable development of agriculture in the study area.

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Table 1. Modeled soil CO_2 flux with autotrophic respiration by plant roots and heterotrophic respiration by soil microorganisms

Treatment	Root-respiration kg C ha^{-1} yr^{-1}	Soil-heterotrophic-respiration kg C ha^{-1} yr^{-1}
M	3416	1524
N	4654	939
MN	4635	1751
B	595	359

M was a traditional agricultural fertilization mode when there was no chemical fertilizer provided; N was a fertilization mode with high input and intensive agriculture; MN was a fertilization mode recommended by local experts; B was a controlled trial.

Table 2. Modeled N_2O and CO_2 fluxes, crop yields, SOC values and net GWP under four different treatments of summer maize in the field

	M	N	MN	B
N_2O (kg N ha^{-1} yr^{-1})	0.31	3.6	4.57	0.1
CO_2 (kg C ha^{-1} yr^{-1})	4940.17	5592.85	6386.35	953.82
Crop yield (kg C ha^{-1} yr^{-1})	1484	2303	2301	293
SOC 0–20cm (kg C kg^{-1})	0.0141	0.0138	0.0142	0.0135
Net GWP (kg CO_2-equivalent ha^{-1})	-6722	-2084	-6331	346

M was a traditional agricultural fertilization mode when there was no chemical fertilizer provided; N was a fertilization mode with high input and intensive agriculture; MN was a fertilization mode recommended by local experts; B was a controlled trial.

1 Table 3. Baseline values for sensitivity tests.

Parameter	Baseline	Range tested
Annual mean temperature (°C)	9.14	Decrease by 2°C and 4°C and increase by 2°C and 4°C
Total annual precipitation (mm)	163.8	Decrease by 10% and 20% and increase by 10% and 20%
Soil texture	Sandy loam	Sand, loamy sand, loam, clay
SOC content (%)	1.38	0.5, 0.75, 1.0, 1.5, 1.75, 2.0
Soil pH	8.7	7.3, 8, 9.4
Total fertilizer N input (kg N ha^{-1} yr^{-1})	300	200, 250, 350, 400, 450
Manure amendment (kg C ha^{-1} yr^{-1})	0	2000, 4000
Residue incorporation (%)	15	0, 50, 90

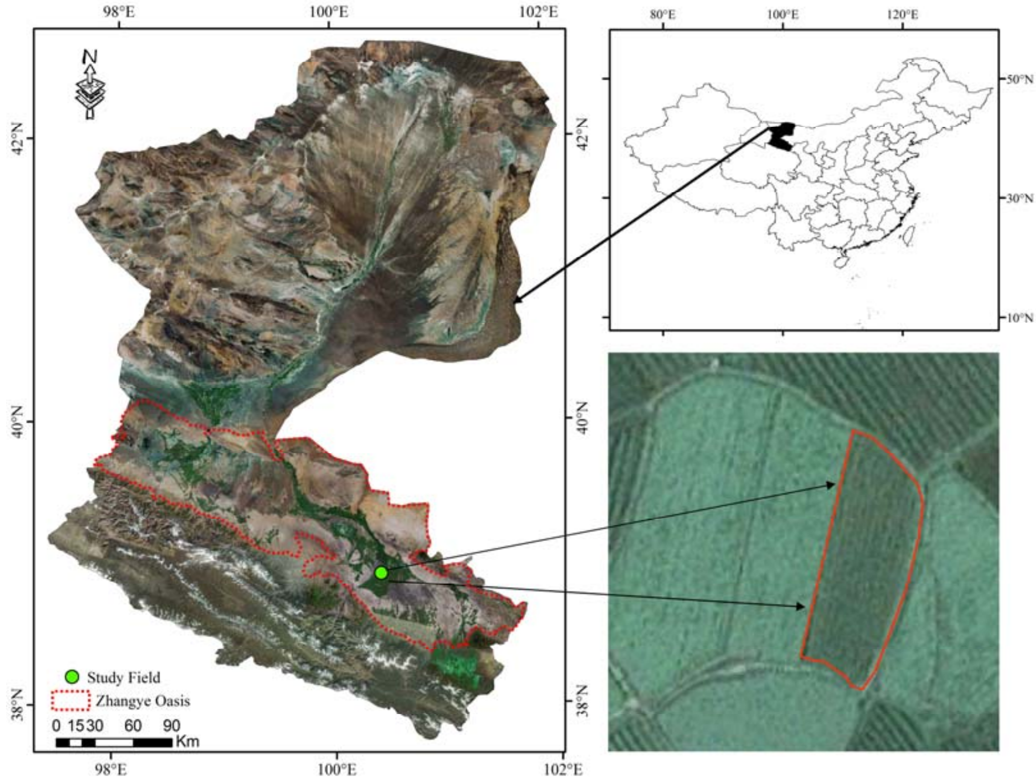

Fig. 1. Location of the Heihe River Basin and study field

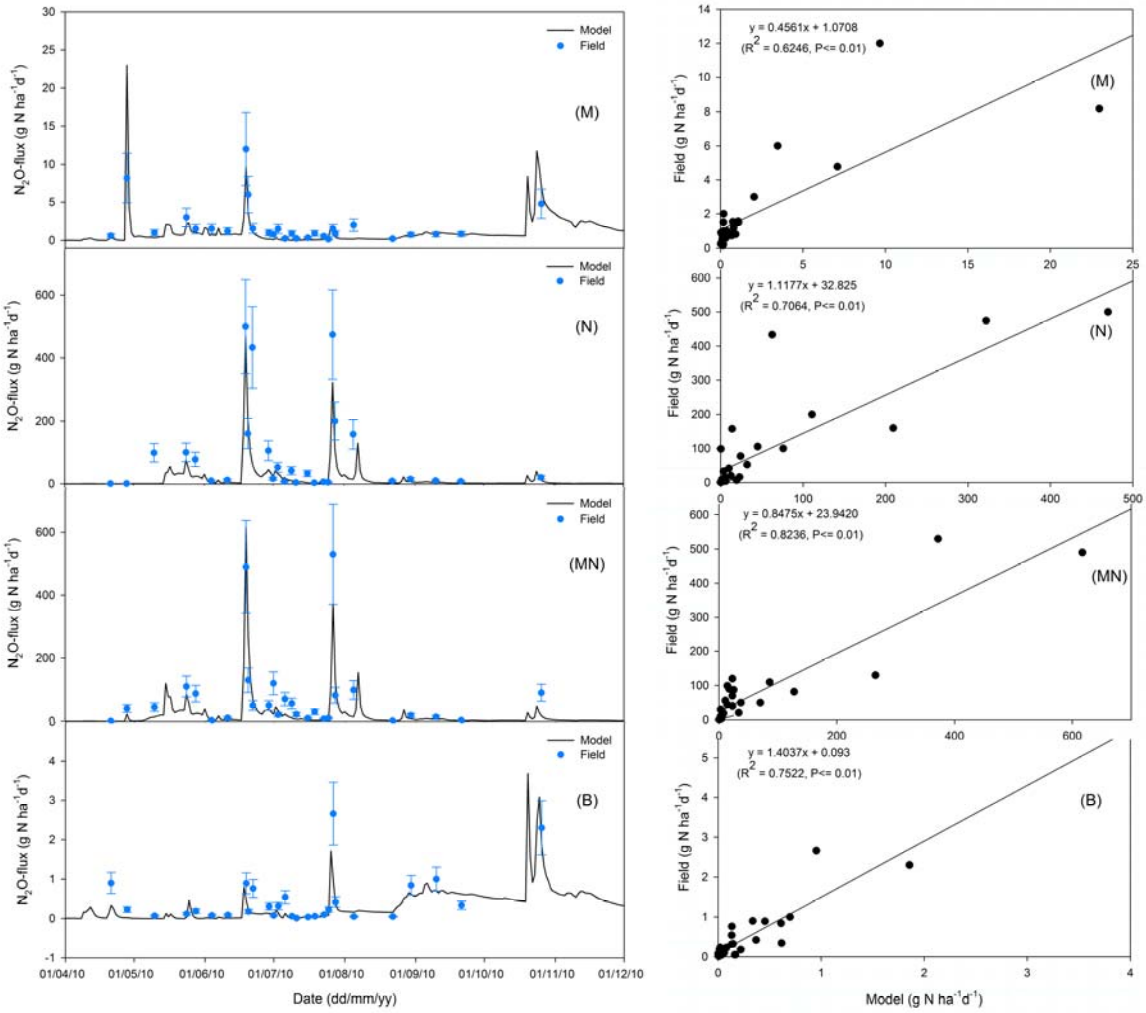

Fig. 2. Comparison of observed and modeled N_2O emissions in summer maize fields

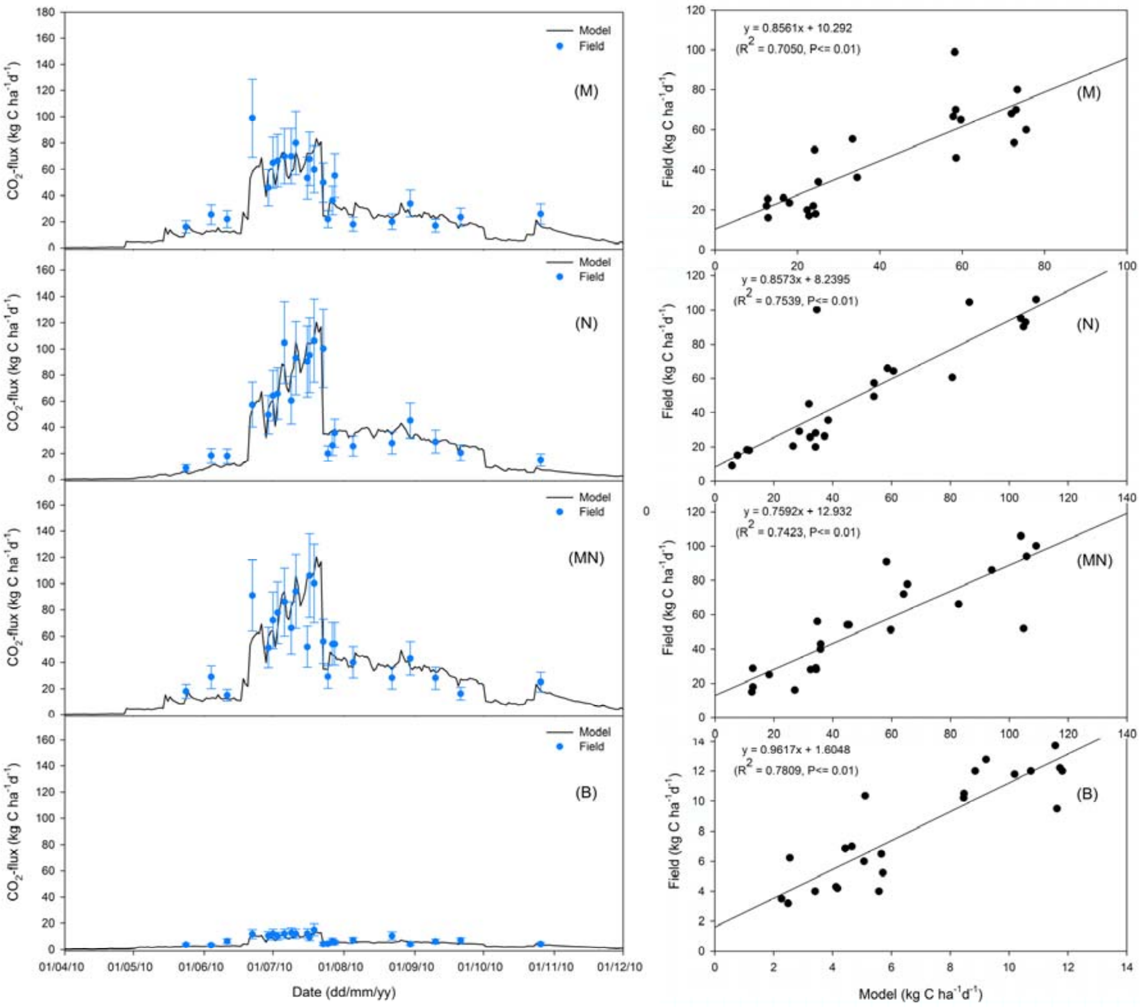

Fig. 3. Comparison of observed and modeled CO_2 emissions in summer maize fields

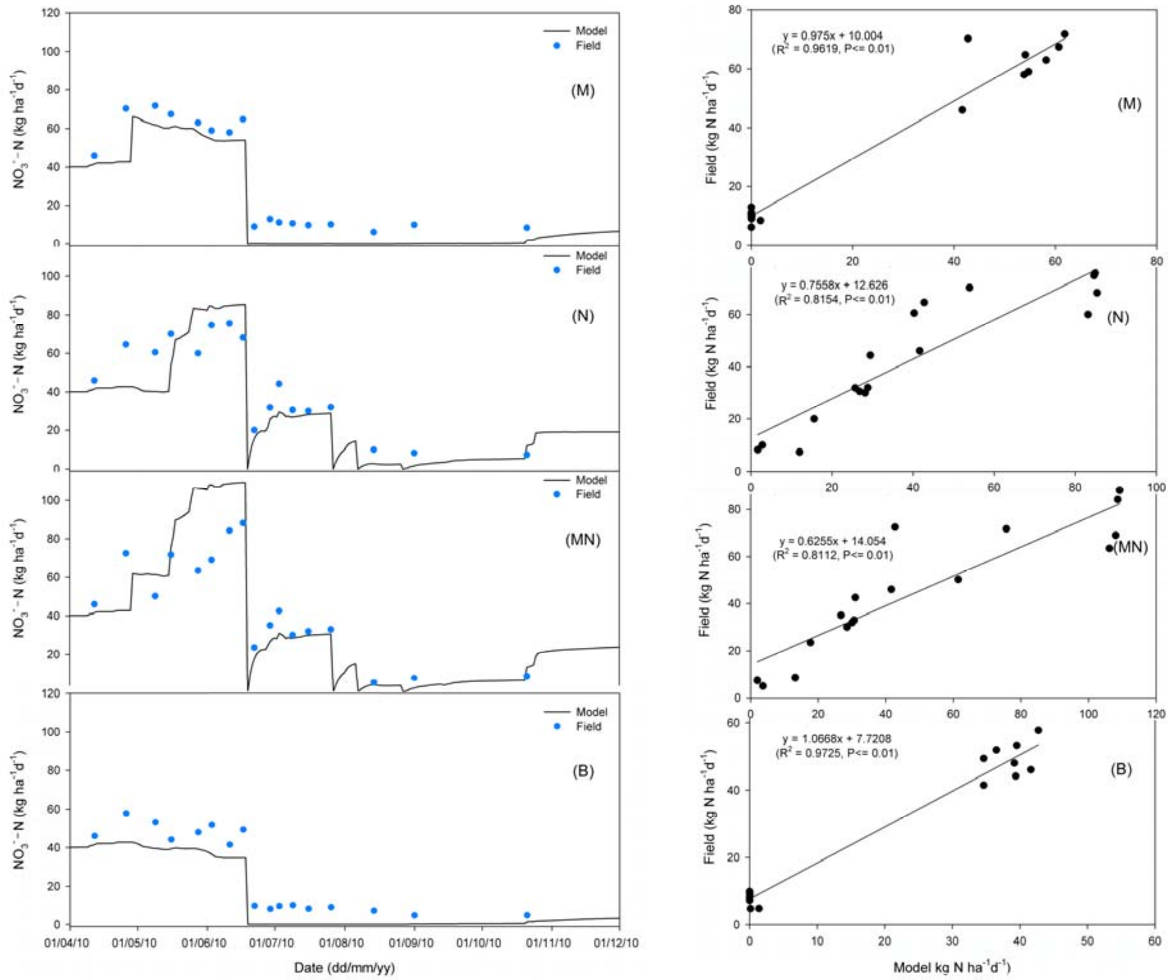

Fig. 4. Comparison of observed and modeled the nitrate (NO_3^-) for the top 10 cm of the soil profile in summer maize fields

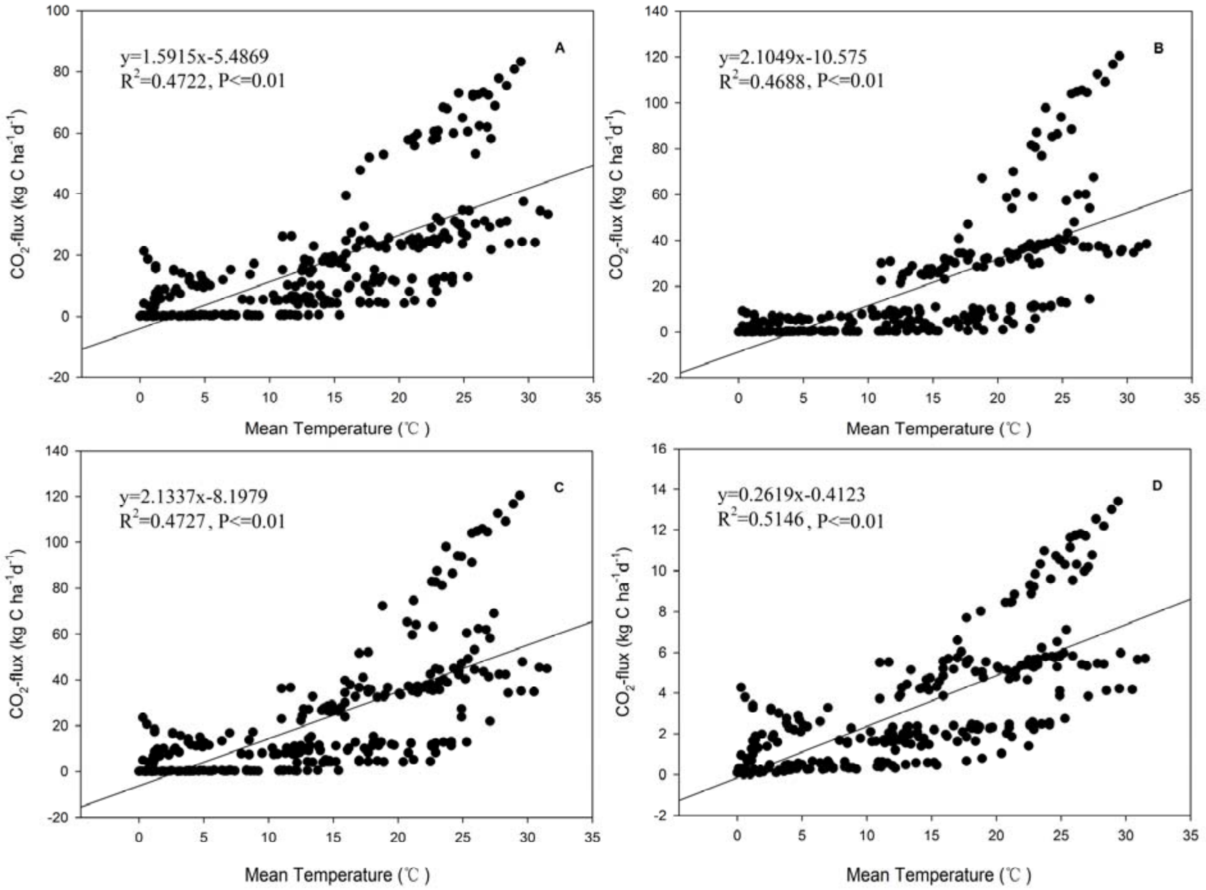

Fig. 5. The relationship between CO_2 emissions and the daily mean temperature greater than 0 ℃

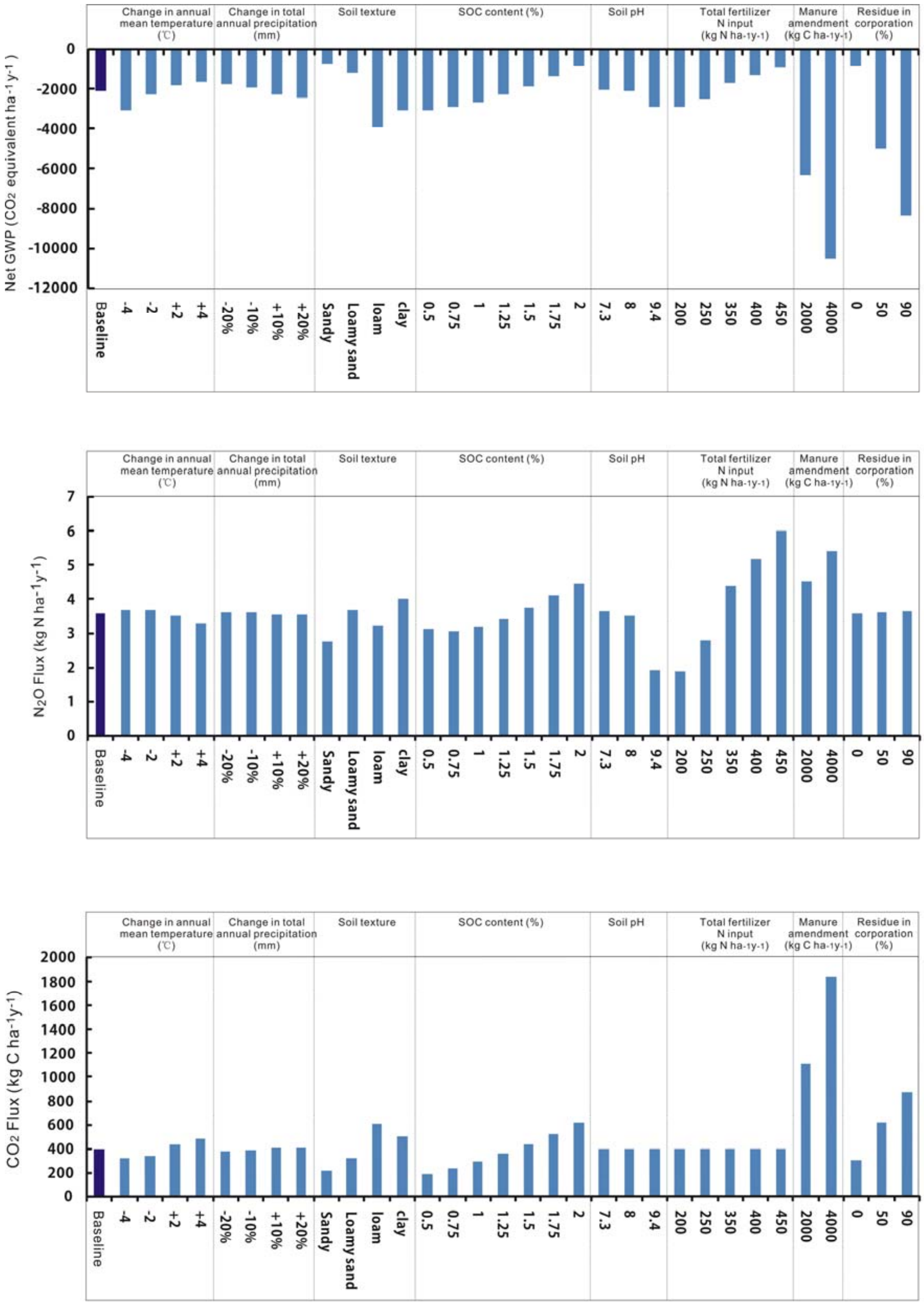

Fig. 6. Sensitivity of net GWP, N_2O flux and CO_2 flux to change of each of the following factors: climate, soil and management

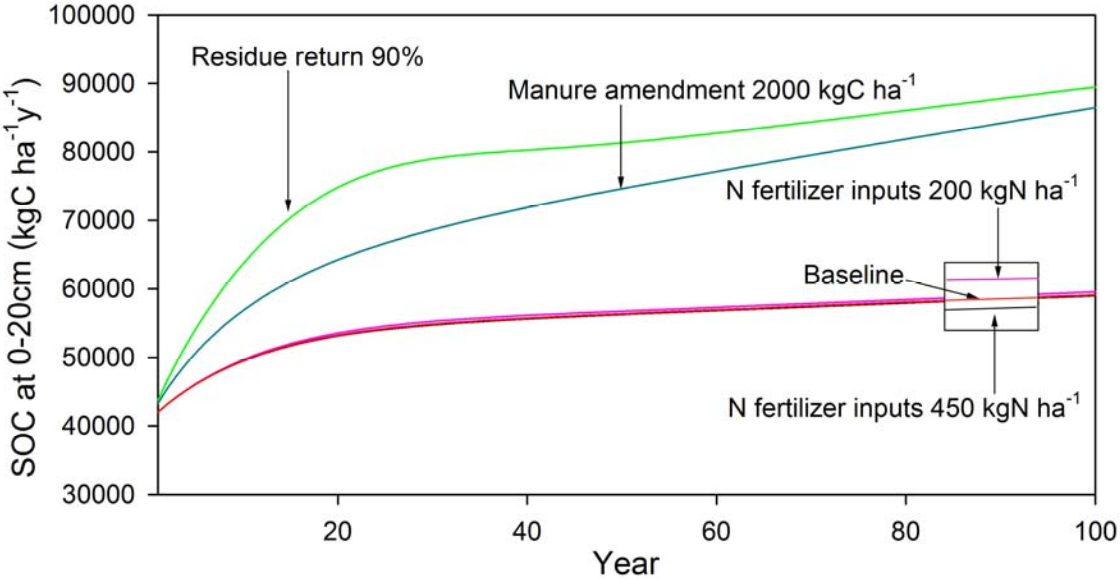

Fig. 7. Influence of management practices on long-term SOC content

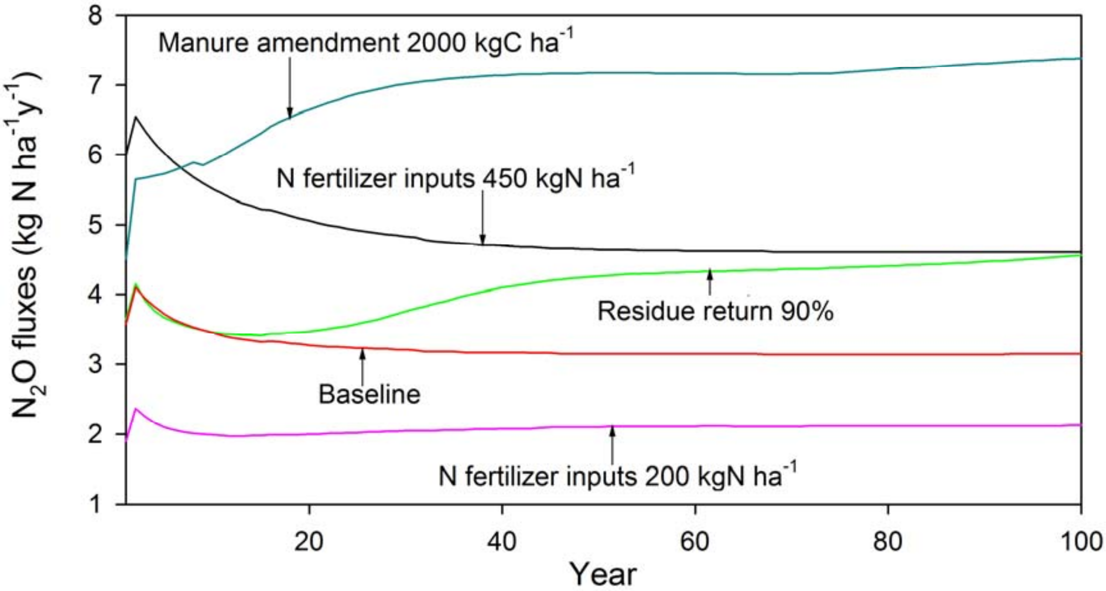

Fig. 8. Influence of management practices on long-term N_2O fluxes

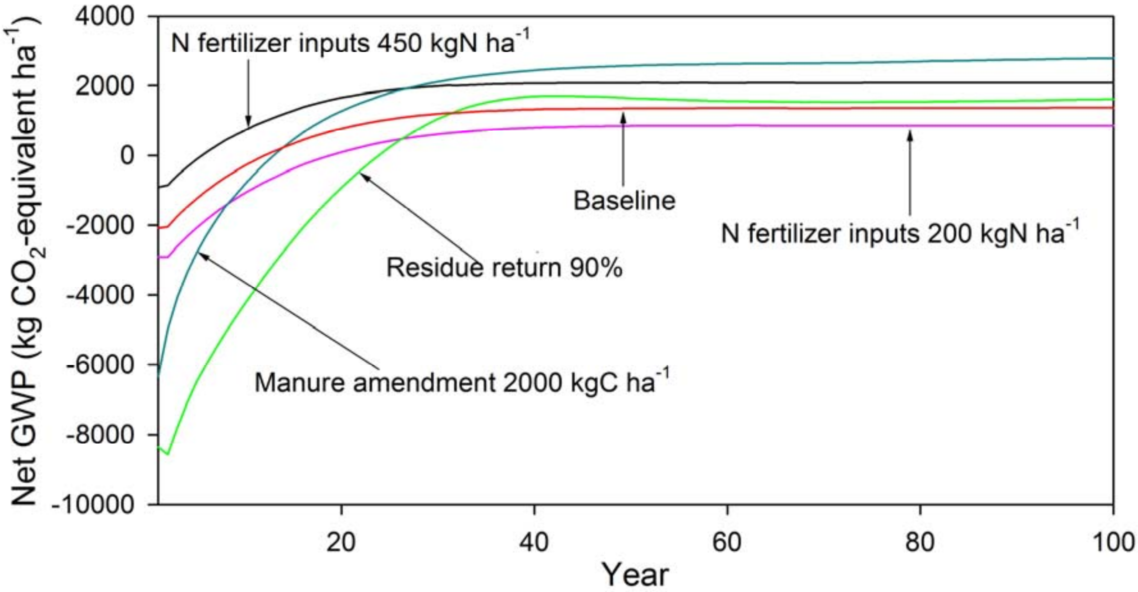

Fig. 9. Influence of management practices on long-term net GWP