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Multifactor effects on the N_2O emissions and yield of potato fields based on the DNDC model

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Abstract: Maintaining or increasing grain yields while also reducing the emissions of field agricultural greenhouse gases is an important objective. To explore the multifactor effects of nitrogen fertilizer on nitrous oxide (N_2O) emissions and the yield of potato fields and to verify the applicability of the DeNitrification-DeComposition (DNDC) model when used to project the N_2O emission load and yield, this research chooses a potato field in Shenyang northeast China from 2017~2019 as the experiment site. The experiment includes four nitrogen levels observed the emission of N_2O by static chamber/gas chromatograph techniques. The results of this study are as follows: (1) DNDC has a good performance regarding the projection of N_2O emissions and yields. The model efficiency index EFs were 0.45~0.88 for N_2O emissions and 0.91, 0.85 and 0.85 for yields from 2017~2019. (2) The annual precipitation, soil organic carbon and soil bulk density had the most significant influence on the accumulated N_2O emissions during the growth period of potato. The annual precipitation, annual average temperature and CO_2 mass concentration had the most significant influences on yield. (3) Under the premise of a normal water supply, sowing potatoes within 5 days after the 5-day sliding average temperature in this area exceeds 10 °C can ensure the temperature required for the normal growth of potatoes and achieve the purpose of maintaining and increasing yield. (4) The application of 94.5 kg·hm^{-2} nitrogen and 15 mm irrigation represented the best results for reducing N_2O emissions while also maintaining the yield in potato fields.

Key words: DNDC model; N_2O; Potato; Sensitivity test; Emission reducing; Yield

1. Introduction

The increasing concentration of greenhouse gases in the atmosphere is an important cause of global warming. The fifth report of the IPCC states that anthropogenic greenhouse gas emissions have a direct impact on global warming (Stocker, *et al.* 2013). N_2O is a potent greenhouse gas with a 120 year atmospheric lifespan and a global warming potential that is 298 times higher than that of CO_2 over a 100 year timescale, and it accounts for approximately 8% of global warming effects (Hu, *et al*., 2016). More than 59% of the anthropogenic N_2O emissions are from agricultural soil (Sanchez-Martín, *et al.*, 2010); therefore, it is necessary to reduce N_2O emissions from agricultural activities.

Numerous studies have shown that farmland N_2O emissions are affected by many factors, such as soil temperature, moisture, and fertilization levels (Barton, *et al.*, 2008; Elmi, *et al.*, 2009). Agehara *et al.* (2005) showed that the soil N_2O emission flux increased along with temperature to a certain soil temperature and usually reached the maximum within the range of 25~35 °C. Soil moisture can affect N_2O emissions by influencing the soil microbial activity, soil REDOX potential and soil aeration (Luo, *et al.*, 2013), and it is generally expressed by the soil water filled pore space (WFPS) in studies of soil moisture content. The relationship between N_2O emission and soil moisture content is parabolic, with N_2O emissions increasing with increasing soil moisture content when the WFPS is less than 75% but decreasing when the WFPS is more than 75% (Kallenbach, *et al.*, 2010). The application of nitrogen fertilizer is the most direct source of nitrogen in farmland soil and has a significant effect on the N_2O emissions from farmland soil. Many researchers have observed and verified that soil N2O emissions increase rapidly with the increase of nitrogen application (Burton, et al., 2008; Zebarth, et al., 2012). Field observations cannot accurately reflect the impact of different management measures on N_2O emissions in farmland due to the high variability of soil N_2O emissions in time and space and the complex relationship between climate and soil (Shang, *et al.*, 2011). Therefore, the emission law of farmland N_2O and its emission reduction potential must be evaluated based on models (Robertson, *et al.*, 2004; Khalil, *et al.*, 2020).

The DeNitrification-DeComposition (DNDC) model is a computer simulation model that describes the biogeochemical processes of carbon and nitrogen in agricultural ecosystems (Li, *et al.*, 1992), and it can be used to simulate the emissions of carbon, nitrogen and other gases in agricultural ecosystems as well as the crop yield, soil carbon sequestration and nitrate leaching, etc. (Giltrap, *et al.*, 2010). The DNDC model is one of the most successful biogeochemical models in the world. Many researchers have independently verified the DNDC model with their own data, indicating that the DNDC model has a good simulation effect on agricultural greenhouse gas emissions, crop yields and other parameters (Li, *et al.*, 2012; Han, *et al.*, 2014). Many studies have shown that N_2O emissions can be affected significantly by environmental factors and farming management by DNDC (Shah, *et al.*, 2020; Deng, *et al.*, 2020). So we can use DNDC for reducing the need for replicated field experiments.

Previous studies on the driving factors underlying farmland N_2O emissions mainly focused on using models to explore grain crops, such as wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and rice (*Oryza sativa*) (Tumer, *et al.*, 2015). However, little research has been done on field studies of N_2O and DNDC simulations in potato(*Solanum tuberosum*) crop systems (Zhang and Niu, 2016). Because potato is one of the most important crops, it is becoming increasingly important to explore the driving factors for the N_2O emissions and yield in potato fields, especially because of the continuous increase of potato planting area in China (Zhang, *et al.*, 2014). We used the DNDC model to study the N_2O emissions and yield driving factors and provided a scientific basis for the formulation of N_2O emission reduction and yield promotion measures in potato fields.

2. Materials and methods

2.1 Study site

This study was conducted from 2017~2019 at the Shenyang Agricultural University Experimental Base (41°49′N，123°33′E) in Shenyang, Liaoning Province, Northeast China. The base is located in a warm temperate sub-humid continental monsoon climate region. The annual average temperature is 8.0 °C, and the average annual precipitation is 716.2 mm (80% of which occurs from June to September). The frost-free period is approximately 145~163 days each year. The soil type is silty loam (clay=15%, loam=51%, and sand=34%), the soil bulk density is 1.297 $g \cdot cm^{-3}$, and the pH is 6.42 on average in 0~20cm depth of the soil, respectively.

2.2 Experimental design

The potato-growing period lasted 88 days in 2017 (from April 28 to July 24), 88 days in 2018 (from April 30 to July 26), and 90 days in 2019 (from April 26 to July 24). The experiment consisted of four different amounts of nitrogen fertilizer (urea) and four treatments in one field: no N fertilizer (N0) (0 $kgN \cdot hm^{-2}$), low fertilizer (N1) (60 $kgN \cdot hm^{-2}$), middle fertilizer (N2) (120 $kgN \cdot hm^{-2}$), and high fertilizer (N3) (180 $kgN \cdot hm^{-2}$). All the treatments were organized in a randomized block design with three replicates (each treatment area was 5 m × 6 m). Potato planting row spacing was 0.5 m, and plant spacing was 0.4 m. Potatoes were planted by ridge planting with a ridge width of 0.5 m, a ridge height of 0.15 m, and a ditch width of 0.5 m. Phosphatic fertilizer (P_2O_5) was applied at 225 $kg \cdot hm^{-2}$, and potassic fertilizer (K_2O) was applied at 75 $kg \cdot hm^{-2}$. The fertilization method included a one-time base fertilizer application before sowing 1 day. The tillage method included plowing to 20 cm before sowing 5 days. No artificial irrigation was performed (rain-fed). Regular artificial weeding (pulling weeds by hand) was performed. The potato cultivar was You Jin, which is an early-maturing variety with a growth period of approximately 90 days. It is currently planted in large areas in Liaoning Province.

2.3 Method of analyzing the samples

N_2O emission fluxes were observed using the static chamber-gas chromatography method and manual sampling (Mapanda *et al.*, 2011). The static chamber size was 60 mm× 50 mm× 45 mm. The static chambers were set on ridges included plants within the chamber in the middle of each experimental plot after basal fertilizer and before sowing. Gas samples were measured daily five days after fertilization and then once a week at other times. If rain occurred, gas samples would be measured 1 more time after the rain day. When the N_2O emission fluxes were measured, the soil moisture (by the oven-drying method), air temperature (by thermometer) and soil temperature (by soil thermometer) at 0, 10 and 20 cm were synchronously measured. Each sampling time was at 09:00-11:00, and the gas sample amount was 80-100 ml and extracted using an air pump. Gas samples were analyzed using an Agilent 7890A gas chromatograph (Agilent Technologies, USA), and the daily N_2O emission fluxes were calculated using a linear regression analysis according to the following equation:

$$\text{Flux} = \rho \times V \times \Delta C \times 273 / A \times \Delta t \times \ (273 + T) \quad (1)$$

where flux is the gas exchange flux of N_2O (μg m^{-2} h^{-1}), ρ is the gas density (mg m^{-2}), V is volume of the static chamber box (m^3), A is the bottom area of the box (m^2), ΔC is the gas concentration difference, Δt is the time interval (h), and T is the temperature (°C). A negative gas exchange flux means that the observed system absorbs gas from the atmosphere, while a positive flux means the system is discharging gas into the atmosphere.

2.4 DNDC Model

2.4.1 Initial conditions

The DNDC model is version 9.5, and it consists of two parts: the climate, crop growth, and soil conditions that convert main drivers (e.g., climate, soil properties, vegetation, and anthropogenic activity) to soil environmental factors (e.g., temperature, moisture, pH, redox potential, and substrate concentration gradients) and the nitrification, denitrification, and fermentation submodels that simulate C and N transformations mediated by the soil microbial activities (Deng, *et al.*, 2011). To correct the model, some parameters that are not consistent with the actual field growth in the local area are modified so that the actual model parameters in the applied area are determined. The input parameters were as follows: latitude and longitude (41°49′N and 123°33′E); maximum daily temperature (℃), minimum daily temperature (℃), daily precipitation (mm), daily mean wind speed ($m \cdot s^{-1}$), and relative humidity (%), which were provided by the Shenyang Meteorological Bureau; soil type (silty loam); pH (6.42); field capacity (0.25 $g \cdot g^{-1}$); soil bulk density (1.297 $g \cdot cm^{-3}$); organic matter content of the topsoil (0~10 cm) (12.48 $g \cdot kg^{-1}$); average mass concentration of N in precipitation (3.26 $mg \cdot L^{-1}$); and average concentration of CO_2 in the atmosphere (400 $mg \cdot m^{-3}$), which were determined according to local actual production conditions, test sample analyses as well as relevant literature (Raymundo, *et al.*, 2017). The adjusted potato-related parameters were as follows: optimum potato yield (25000 $kg \cdot hm^{-2}$); potato growth cumulative temperature (1300℃); potato biomass allocation ratio (Grain: Leaf: Stem: Root was 0.60:0.20:0.18:0.02); and water requirement (400 $kg \cdot kg^{-1}$ dry matter).

2.4.2 Model test method

Three statistical indexes, the coefficient of determination (R^2), average error (E) and model efficiency index (EF), were used for the quantitative comparisons.

$$R^2 = \left(\frac{\sum_{i=1}^{n} \left(S_i - \overline{S_i}\right)\left(M_i - \overline{M_i}\right)}{\sqrt{\sum_{i=1}^{n} \left(S_i - \overline{S_i}\right)^2 \sum_{i=1}^{n} \left(M_i - \overline{M_i}\right)^2}} \right)^2 \qquad (2)$$

$$E = \frac{\sum_{i=1}^{n} (S_i - M_i)}{n} \qquad (3)$$

$$EF = 1 - \frac{\sum_{i=1}^{n} (S_i - M_i)^2}{\sum_{i=1}^{n} (S_i - \overline{M})^2} \qquad (4)$$

where S_i and M_i are the simulated and observed values, respectively; $\overline{M_i}$ and $\overline{S_i}$ are their averages, respectively; and *n* is the number of observations. The closer R^2 is to 1, the better the model fits. The average error E represents the average of the error between the observed value and the simulated value. The larger the absolute value of E, the larger the average error. When the average error E is > 0, the observed value is less than the simulated value, and when E is <0, the observed value is greater. When EF is 0~1, it is the larger the value, the greater the correlation between the observed value and the simulated value. When EF is <0, the observed value is extremely uncorrelated with the simulated value (Yang, *et al.*，2014).

2.4.3 Sensitivity analysis method

Table 1 Background values and test values of the sensitivity test indexes.

Factors	Parameters	Baseline	Alternative range
Meteorological factors	Annual precipitation /mm	716.2	859.4, 787.8, 716.2, 644.6, 573.0
	Annual average temperature/℃	8.0	10.0, 9.0, 8.0, 7.0, 8.0
	CO_2 mass concentration/(mg·m^{-3})	400	440, 420, 400, 380, 360
	Nitrogen deposition(by N)/(mg·L^{-1})	3.26	3.912, 3.586, 3.912, 3.26, 2.934, 2.608
Soil factors	Soil organic carbon/(g·g^{-1})	0.01248	0.01498, 0.01373, 0.01248, 0.01123, 0.00998
	Soil pH	6.42	5.136, 5.778, 6.42, 7.062, 7.704
	Soil capacity/(g·cm^{-3})	1.297	1.556, 1.427, 1.297, 1.167, 1.038
Field management	Nitrogen application/(kg·hm^{-2})	120	240, 180, 120, 60, 0

factor

In the sensitivity analysis, the numerical input of one of the influencing factors in the DNDC model is changed within a certain range while keeping the other influencing factors unchanged to obtain the change law of the output value. Multi-year averages and actual local production conditions were selected as the baseline data. Different impact factors were set to simulate the N_2O emissions and yield from the potato field (Table 1). The sensitivity index S (Walker, *et al*., 2000) was used to study the effect of these factors on the yield of potato field N_2O emissions. The calculation formula of S was as follows:

$$S = ((O_2 - O_1) / O_{avg}) / ((I_2 - I_1) / I_{avg}) \qquad (5)$$

where S is sensitivity index; I_1 and I_2 are the minimum and maximum values of the input parameters, respectively; $O_1$and O_2 are the minimum and maximum values of the output parameters, respectively; I_{avg} is the average of the input parameters; and O_{avg} is the average of the output parameters. The larger the absolute value of S, the greater the influence of the input parameters on the output and the stronger the correlation between them. S> 0 indicates a positive correlation between the input parameter and the output, and S <0 indicates a negative correlation.

SPSS 17.0 and Excel 2010 software were used for the analysis of variance (ANOVA) and linear regression analysis in this study. The meteorological data required for the test were provided by the Shenyang Meteorological Bureau.

3. Results

3.1 Ancillary data

The daily average temperatures in the growing periods of 2017, 2018 and 2019 were 20.2 °C, 19.9 °C and 19.4 °C, respectively, and the amount of precipitation in the growing periods was 222.4 mm, 212.0 mm and 286.7 mm, respectively (Fig. 1).

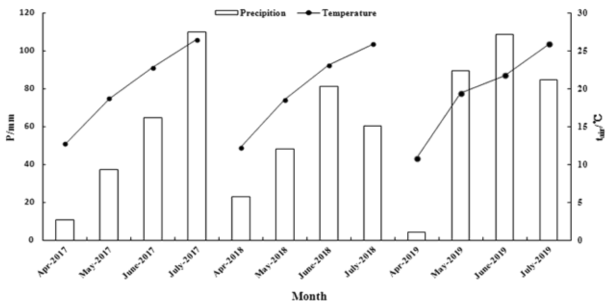

Fig. 1 Monthly average air temperature (t_{air}) and monthly precipitation (P) in the experiment field during the experiment stage.

3.2 N_2O emission flux and yield with different nitrogen levels in the potato field

As shown in Fig. 2, the emission flux of the N3 treatment was significantly higher than that of other treatments, and the emission of CK was the lowest. The average N_2O emission rates of the CK, N0, N1, N2, and N3 treatments were 4.75 $\mu g \cdot m^{-2} \cdot h^{-1}$, 9.97 $\mu g \cdot m^{-2} \cdot h^{-1}$, 21.99 $\mu g \cdot m^{-2} \cdot h^{-1}$, 45.83 $\mu g \cdot m^{-2} \cdot h^{-1}$ and 77.05 $\mu g \cdot m^{-2} \cdot h^{-1}$ in 2017, respectively; 6.39 $\mu g \cdot m^{-2} \cdot h^{-1}$, 7.70 $\mu g \cdot m^{-2} \cdot h^{-1}$, 10.48 $\mu g \cdot m^{-2} \cdot h^{-1}$, 21.29 $\mu g \cdot m^{-2} \cdot h^{-1}$ and 35.27 $\mu g \cdot m^{-2} \cdot h^{-1}$ in 2018, respectively; and 10.92 $\mu g \cdot m^{-2} \cdot h^{-1}$, 11.83 $\mu g \cdot m^{-2} \cdot h^{-1}$, 19.43 $\mu g \cdot m^{-2} \cdot h^{-1}$, 25.45 $\mu g \cdot m^{-2} \cdot h^{-1}$ and 39.72 $\mu g \cdot m^{-2} \cdot h^{-1}$ in 2019, respectively. The N_2O emission flux of soil showed a significant increasing trend as the nitrogen application rate increased. The trends and fluctuations of N_2O emissions in all treatments were basically consistent, which indicated that nitrogen application would not lead to the changes in the emission trend but only affected the amount of soil N_2O emissions.

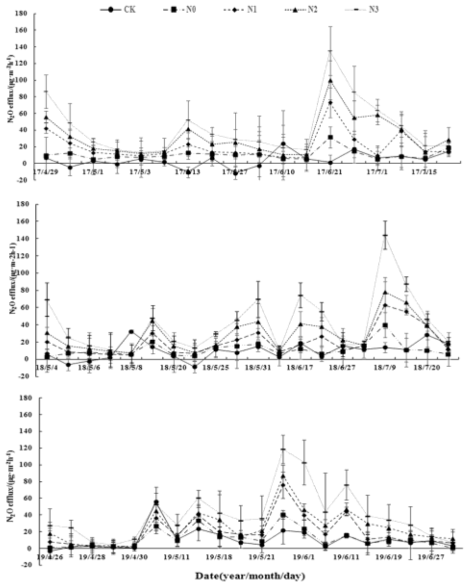

Fig. 2 N_2O emissions from the potato field under different nitrogen application levels from 2017 to 2019

As shown in Fig. 3, the potato yield of different treatments showed basically the same rule in three years. That is, the treatment without nitrogen fertilizer was significantly lower than that of other treatments. Moreover, it was found that the yield did not increase continuously with the increase of nitrogen application rate. Excessive application of nitrogen fertilizer would decrease the yield to some extent.

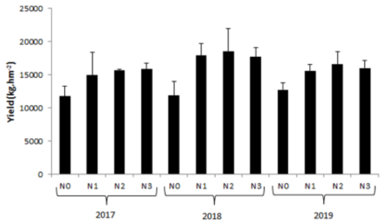

Fig. 3 Yield of potato from 2017 to 2019

3.3 DNDC model calibration and validation

Table 2 Fitting indexes of N_2O emissions and yield for the DNDC model

Year	Treatment	R^2	P	E	EF
2017	N0	0.92	0.000	-1.17	0.88
	N1	0.88	0.000	4.90	0.85
	N2	0.74	0.000	1.98	0.73
	N3	0.62	0.000	-19.79	0.45
	Yield/(kg·hm^{-2})	0.97	0.017	-403.82	0.91
2018	N0	0.87	0.000	-0.89	0.80
	N1	0.84	0.000	6.31	0.63
	N2	0.87	0.000	6.35	0.64
	N3	0.90	0.000	-0.78	0.83
	Yield/(kg·hm^{-2})	0.95	0.027	761.58	0.85
2019	N0	0.76	0.000	5.43	0.58
	N1	0.88	0.000	9.36	0.63
	N2	0.83	0.000	11.24	0.56
	N3	0.81	0.000	4.37	0.66
	Yield/(kg·hm^{-2})	0.92	0.040	52.29	0.85

Note: the number of N_2O emissions and yield observations were 18 and 4 in 2017, 20 and 4 in 2018, 20 and 4 in 2019, respectively.

The data in 2017 and 2018 were used for DNDC model tuning, and the data in 2019 were used for DNDC model validation. In general, the simulation of the N_2O emission effect for the low nitrogen treatment was better than that of the high nitrogen treatment in Table.2. The average efficiency index EF of the N_2O emissions and yield simulation models were 0.69 (P<0.01) and 0.87 (P<0.01) in 2017~2019, which indicated that DNDC model had a good simulation effect on both the N_2O emissions and yield of the potato field as shown in Fig. 4.

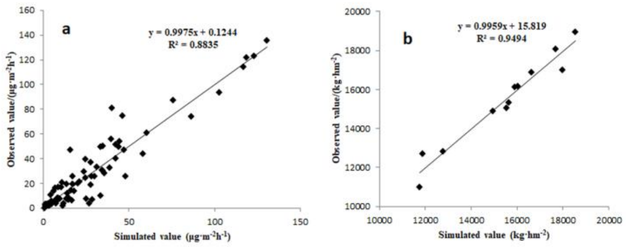

Fig. 4 Comparison of simulated and observed values about N_2O emissions (a) and yield (b)

3.4Sensitivity analysis of the driving factors for N_2O emissions and yield in the potato field

Table 3 Results of the sensitivity analysis by the DCNC model

Factors	Index	Ranges and results of the sensitivity test					Sensitivity index
Meteorological factors	Annual precipitation/mm	-20%	-10%	B(0%)	10%	20%	
	Accumulated N_2O emission during the growth period/($kg \cdot hm^{-2}$)	0.663	0.802	0.972	1.185	1.429	1.894
	Yield/($kg \cdot hm^{-2}$)	17012.5	18512.5	20025	21300	22775	0.723
	Annual average temperature/°C	-2	-1	B(0)	1	2	
	Accumulated N_2O emission during the growth period/($kg \cdot hm^{-2}$)	0.905	0.941	0.972	1.010	1.071	0.405
	Yield/($kg \cdot hm^{-2}$)	20050	20300	20025	18025	16050	-0.508
	CO_2 mass concentration/($mg \cdot m^{-3}$)	360	380	B(400)	420	440	
	Accumulated N_2O emission during the growth period/($kg \cdot hm^{-2}$)	0.993	0.978	0.972	0.961	0.969	-0.123
	Yield/($kg \cdot hm^{-2}$)	17687.5	18875	20025	21400	22912.5	1.295
	Nitrogen deposition (by N)/($mg \cdot L^{-1}$)	2.608	2.934	B(3.26)	3.586	3.912	
	Accumulated N_2O emission during the growth period/($kg \cdot hm^{-2}$)	0.962	0.969	0.972	0.975	0.979	0.043
	Yield/($kg \cdot hm^{-2}$)	20050	20000	20025	20062.5	20037.5	-0.015
Soil factors	Soil organic carbon/($g \cdot g^{-1}$)	-20%	-10%	B(0%)	10%	20%	
	Accumulated N_2O emission	0.779	0.872	0.972	1.076	1.191	1.052

	during the growth period/(kg·hm^{-2})						
	Yield/(kg·hm^{-2})	20075	20025	20025	20037.5	20062.5	-0.002
	soil pH	-20%	-10%	B(0%)	10%	20%	
	Accumulated N_2O emission during the growth period/(kg·hm^{-2})	0.717	0.875	0.972	0.844	0.614	0.319
	Yield/(kg·hm^{-2})	20012.5	20062.5	20025	20000	19950	-0.008
	Soil capacity/(g·cm^{-3})	-20%	-10%	B(0%)	10%	20%	
	Accumulated N_2O emission during the growth period/(kg·hm^{-2})	0.773	0.866	0.972	1.080	1.216	1.129
	Yield/(kg·hm^{-2})	20000	20025	20025	19950	20025	0.003
Field management factors	Nitrogen applications/(kg·hm^{-2})	0	60	B(120)	180	240	
	Accumulated N_2O emission during the growth period/(kg·hm^{-2})	0.214	0.771	0.972	1.144	1.315	0.624
	Yield/(kg·hm^{-2})	17012.5	20025	20025	20000	19937.5	0.045

Note: B means the baseline in Table 1.

The sensitivity testing identified changes in the different driving factors (Table 3), and the following results were obtained.

Meteorological factors. (1) The cumulative N_2O emissions and yield of the potato field during the growth period showed an increasing trend with the increase of annual precipitation. The cumulative N_2O emissions and yield during the growing period of the potato field increased by 21.2% and 7.6% on average for every 10% increase in annual precipitation, respectively. The sensitivity indexes were 1.894 and 0.723, which indicated high sensitivity. (2) The cumulative N_2O emissions increased with the increase of average annual temperature during the growth period in the potato field by 4.3% on average for every 1 ℃ increase in annual temperature. The sensitivity index was 0.405. However, the yield decreased with the increase of annual temperature under the management of potato field in this region by an average of 5.3% for every 1 ℃ increase in annual temperature. The sensitivity index was -0.508. (3) The cumulative change of N_2O emissions during the growing period of the potato field was small with the change of the atmospheric CO_2 mass concentration in the range of 360~440 mg·m^{-3} and decreased by an average of 0.6% for every 20 mg·m^{-3} increase in CO_2 mass concentration in the atmosphere. The sensitivity index was only -0.123. With the increase of CO_2 concentration in the atmosphere, the potato yield increased by an average of 6.7% for every 20 mg·m^{-3} increase in CO_2 mass concentration in the atmosphere. The sensitivity index was 1.295. (4) The cumulative change of N_2O emissions during the growing period of the potato field was small with the change of nitrogen deposition in the range of 2.608~3.912 mg·L^{-1}. The cumulative N_2O emissions and yield during the growing period of potato field increase by only by 0.4% and 0.02% on average for every 10% change of nitrogen deposition, and the sensitivity indexes were only 0.043 and -0.015, respectively.

Soil factors. (1) The cumulative N_2O emissions in the potato field during the growth period showed a significant increasing trend as the soil organic carbon (SOC) content increased. The emission increased by 11.2% on average for every 10% of SOC, and the sensitivity index was 1.052. However, as the organic carbon content in the soil gradually increased between 0.00998 and 0.01498 g·g^{-1}, the potato yield remained almost unchanged, and the sensitivity index was only -0.002. (2) The cumulative N_2O emissions and yield in the potato field showed an obvious trend of initially increasing and then decreasing with the increase of soil pH during the growth period. The highest cumulative N_2O emissions and yields were in neutral soil, and they decreased in acidic and alkaline soils, and the sensitivity indexes were 0.319 and -0.008. (3) Soil bulk density was positively correlated with the cumulative N_2O emissions in the potato field during the growth period. The cumulative N_2O emission increased by 12.1% on average for every 10% of soil bulk density, and the sensitivity index was 1.129. The change of yield was small with the change of soil bulk density in the range of 1.038~1.556 g·cm^{-3}, and the sensitivity index was only 0.003.

Field management factors. The nitrogen application rate was positively correlated with the cumulative N_2O emissions in the potato field during the growth period. The cumulative N_2O emissions increased by 79.7% on average for every 60 kg·hm^{-2} nitrogen application, and the sensitivity index was 0.624. The results showed that nitrogen application significantly promoted N_2O emissions in the potato field and the nitrogen application rate and potato yield showed a parabolic trend. The yield increased as the nitrogen application increased from low nitrogen levels, whereas excessive nitrogen application tended to reduce the yield. The sensitivity index was 0.045.

4. Discussion

4.1 Effects of meteorological factors, soil factors and field management factors on the cumulative N_2O emissions and yield in the potato field

Meteorological factors. (1) Precipitation could significantly affect the dynamic changes of soil moisture, change the soil moisture content, and then affect the N_2O emissions and yields. The N_2O emissions and yield of the potato field were very sensitive to the soil water content in this study, which has been verified by many research studies (Reyes-Cabrera, *et al*., 2016; Banerjee, *et al*., 2016). (2) Air temperature affected the soil N_2O emissions and yields by affecting the soil temperature. The soil microbial activity and N_2O emission rate during denitrification and nitrification increased as the soil temperature increased in a certain range. Therefore, the soil N_2O emission flux is usually positively correlated with soil temperature (Xu, *et al*., 2017). There was a negative correlation between potato yield and average annual temperature in this region in this study because potato prefers cooler temperatures (Pulatov, *et al*., 2015). The late sowing of potatoes in this experiment provided a basis for us to explore the early sowing date of potatoes in this region (In section 4.3). (3) The cumulative change of N_2O emissions during the growing period of potato was small with changes in the atmospheric CO_2 mass concentration in this study, which was similar to the results of other studies (Dijkstra, *et al*., 2012; Lam, *et al*., 2012). As the basic raw material of photosynthesis, the increase of CO_2 concentrations in the atmosphere can affect the photosynthesis of C3 plants and potatoes in two aspects: competition for the Rubisco binding sites to increase the rate of carboxylation and increasing the photosynthesis reaction substrate by inhibiting photorespiration, thereby increasing the net photosynthetic rate (McGrath and Lobell, 2013). The photosynthetic capacity of C3 plants can increase by 10% to 15% with the increase of CO_2 concentrations, thereby increasing the yield (Kou, *et al*., 2008). (4) The ecological effect of nitrogen deposition in the atmosphere has attracted increasing attention in recent years. Nitrogen input through atmospheric deposition can increase the primary productivity and biomass of nitrogen-deficient ecosystems (Matson, *et al*., 2002). However, nitrogen inputs do not play a significant nutritional role in nitrogen-saturated ecosystems (Magill, *et al*., 2000). The baseline scenario in this study is nitrogen-saturated for the potato field ecosystem, and the nitrogen that enters the soil via nitrogen deposition is very small compared to the nitrogen content of the potato field ecosystem. Therefore, the cumulative N_2O emissions and yields of the potato field were not significantly changed with nitrogen deposition during the growing period.

Soil factors. (1) Soils with higher organic carbon contained more dissolved organic carbon (DOC), which increases substrates for soil nitrification and denitrification and enhances nitrification and denitrification, which in turn increased soil N_2O emissions (Li, *et al*., 2010). The results showed that the potato yield barely changed as the soil organic carbon content increased, which was possibly due to stress from the water supply. (2) Soil pH affects nitrification and denitrification by affecting the activity of nitrification and denitrification bacteria and changing the rate of nitrification and denitrification and the final product ratio. The highest N_2O emissions were in neutral soil and they decreased under low or high pH (Čuhel, *et al*., 2010), which was consistent with this study. Potato has relatively loose requirements for soil pH and can grow normally when planted with soil pH between 5 and 7.5 (Agbede, 2010). In this study, the pH value was basically within this range; therefore, the change of pH value had no significant effect on the potato yield. (3) Bulk density is an important physical property of soil that can reflect the porosity, tightness and fertility of soil. Soil bulk density affects soil N_2O emission fluxes by affecting the soil permeability and water diffusion rate. The bulk density reflects the degree of soil compactness. Under the condition of a similar soil texture, a decrease of bulk density indicates that the soil compactness is low and there are more aeration pores. However, under the condition of a constant soil moisture content, the diffusion rate of soil moisture decreases as the soil bulk density increases (Logsdon, *et al*., 2004). Decreased soil bulk density increases the soil aeration and oxygen content, thereby reducing the number of anaerobic bacteria, which inhibits denitrification and reduces N_2O emissions (Cavigelli, *et al*., 2001; Balaine, *et al.*, 2016).

In reality, the influence effectiveness of different factors are very different, such as soil moisture and temperature can directly change the microbial activity and the diffusion rate of soil gas into the atmosphere, and then thus affecting the emissions of N_2O (Lan, *et al.*, 2018; Cui and Wang, *et al.*, 2019). This part is planned to be combined with experimental data and models to carry out a deeper discussion in the future research.

Field management factors. The application of nitrogen fertilizer has an obvious effect on N2O emissions as the most direct nitrogen source. The excessive use of nitrogen fertilization was the primary reasons for the increase in N_2O emissions from the farmland (Yang, *et al.*, 2017). Soil N_2O emissions increased rapidly with the increase of nitrogen application, which has been observed and verified by many researchers (Zebarth, *et al*., 2012; Wang, *et al*., 2017). Excessive application of nitrogen fertilizer not only did not increase the yield but also tended to decrease the yield, which has also been reflected in other crops (Vanlauwe, *et al*., 2011; Hou, *et al*., 2012),and it was also consistent with the results of our experiments.

4.2 Study on the earlier sowing date based on the potato yield increase

In the sensitivity study of the DNDC model, a negative correlation was found between potato yield and average annual temperature, which indicated that lowering the temperature could increase the potato yield. In other words, potato could be sown at an earlier date. Taking 2017 as an example, potato production showed a significant decline only if the sowing date was advanced while the other conditions remained unchanged (P<0.05), which was mainly because the earlier sowing date corresponded to lower precipitation. Precipitation had a limiting effect on potato growth. When the sowing date was 5, 10, 15, 20, 25 and 30 days earlier, the precipitation during the growing period decreased by 18.2%, 32.3%, 39.4%, 46.9% and 50.9%, respectively. However, in the DNDC model simulation, when the 2017 potato growth period precipitation (211.7 mm) was held constant (the rainfall days advanced according to the sowing date), the yield showed a parabolic trend (y=-6.18x^2+278.38x+11024.0, R^2=0.84, P<0.01; x is the number of days in the earlier sowing date and y is the yield) with the earlier sowing dates. The number of days at the parabolic apex was 22.5, meaning that the potato sowing date in 2017 should be 22.5 days earlier than April 28th (sowing on April 5th and April 6th) because the temperature conditions can meet the potato growth requirements. Moreover, the five day sliding average temperature on April 2nd was 10.54 °C, and after April 2nd, it was higher than 10 °C, while before April 2nd, it was lower than 10 °C. Therefore, April 2nd was the first day of 2017 when the five day sliding average temperature stabilized through 10 °C, and April 5th and 6th were the 4th and 5th days.

The same phenomenon observed in 2018 and 2019, and the potato yield did not increase as expected and showed a downward trend by simply advancing the sowing date. Under constant rainfall (212.0 mm and 286.7 mm) during the potato growth period in 2018 and 2019, the potato yield also showed a parabolic trend with the earlier sowing date (2018: y=-4.45x^2+178.46x+17802.12, R^2=0.86, P<0.01; 2019: y = -6.30x^2 + 306.21x + 15852.05, R^2 = 0.90, P<0.01). The number of days in 2018 and 2019 at the parabolic apex were 20.0 and 24.3. Therefore, the potato sowing date in 2018 should be 20.0 days earlier than April 30th (sowing on April 10th), and the potato sowing date in 2019 should be 20.0 days earlier than April 26th (sowing on April 2th). An obvious phenomenon was observed in which five day sliding average temperature was higher than 10 °C after April 8th in 2018 and April 1st in 2019 and lower than 10 °C after these dates. That is, April 8th in 2018 and April 1st in 2019 were the first days when the five day sliding average temperature stabilized through 10 °C, and April 10th and 2nd were the 3rd and 2nd days.

In Northeast China, potato could be seeded after the five day sliding average temperature passes through 10 °C (Li, *et al.*, 2018). However, combining the yield simulation and actual production shows that the temperature is stabilized through sowing within 5 days after increasing to 10 °C to achieve the purpose of increasing the yield under the premise of maintaining a normal water supply (such as by proper irrigation). Potato prefers cooler temperatures, and research on advancing potato sowing date is of positive significance to the improvement of potato yield under global warming (Stocker, *et al.*, 2013).

4.3 Effects of optimized nitrogen application and irrigation on N_2O emissions and yield

The sensitivity analysis showed that both the cumulative N_2O emissions and yield were significantly affected during the potato growth period, and the controllable impact factors in actual production were the water supply and nitrogen application. In Section 4.2, it was mentioned that the earlier sowing date can increase the yield under the condition of ensuring the water supply. However, in actual production, the water supply does not rely solely on precipitation but is mainly achieved through irrigation. Therefore, this study took 2019 as an example and used the DNDC model to advance the sowing date to April 2 to study the effect of irrigation on the cumulative N_2O emissions and yields under the condition of optimized nitrogen application.

In this study, we used the DNDC model to simulate the change of potato yield with different nitrogen application rates. The yields all showed a parabolic trend with increases in the nitrogen application rate in 2017, 2018 and 2019 (P<0.05). The nitrogen application rates at the parabolic apex were 91.1 kg·hm^{-2}, 98.7 kg·hm^{-2} and 93.6 kg·hm^{-2} in 2017, 2018 and 2019, respectively. We took the average value of 94.5 kg·hm^{-2} as the nitrogen application rate based on the optimal nitrogen application for increasing yield and the conventional irrigation time of local farmers (approximately 45 days after sowing) to study the effects of these factors on the N_2O emissions and yield.

Table 4 N_2O emissions and yield under different irrigation volumes with the optimum nitrogen application level (94.5 kg·hm^{-2}) for the potato field

Irrigation volume per unit area/mm	Accumulated emission in growth period/(kgN·hm^{-2})	Yield/kg·hm^{-2}	Yield-scaled N_2O intensity/(gN·kg^{-1})
0	0.415	15075.0	0.028
5	0.447	16537.5	0.027
10	0.476	17987.5	0.026
15	0.523	19325.0	0.027
20	0.581	19212.5	0.030
25	0.624	19525.0	0.032
30	0.670	19725.0	0.034
35	0.721	19112.5	0.038
40	0.758	19712.5	0.038
45	0.809	19062.5	0.042
50	0.851	19062.5	0.045

The different irrigation amounts were set to simulate the changes of N_2O emissions and yields (Table 4). Table 4 shows that when the irrigation amount was less than 15 mm, the yield increased rapidly as the irrigation amount increased. Compared with 0 mm irrigation, the yield under 5, 10 and 15 mm irrigation increased by 9.7%, 19.3% and 28.2%, respectively. Continuing to increase the irrigation amount would increase the yield slowly when the irrigation amount was more than 15 mm. Compared with 15 mm irrigation, the yield of 20, 25, 30, 35, 40, 45 and 50 mm irrigation increased by -0.6%, 1.0%, 2.1%, -1.1%, 2.0%, -1.4% and -1.4%, respectively. However, the cumulative N_2O emissions still increased rapidly. Compared with 15 mm irrigation, the cumulative N_2O emissions increased by 11.1%, 19.3%, 28.1%, 37.9%, 44.9%, 54.7% and 62.7%. The yield-scaled N_2O intensity did not change significantly with the increase of irrigation amount when the irrigation amount was less than 15 mm. Compared with 0 mm irrigation, the yield-scaled N_2O intensity of 5, 10 and 15 mm irrigation increased by -3.6%, -7.1% and -3.6%, respectively. Continuing to increase the irrigation amount would increase the yield-scaled N_2O intensity rapidly. Compared with 15 mm irrigation, the yield-scaled N_2O intensity of 20, 25, 30, 35, 40, 45 and 50 mm irrigation increased by 11.1%, 18.5%, 25.9%, 40.7%, 40.7%, 55.6% and 66.7%, respectively. Therefore, 15 mm irrigation was retained for the minimum yield-scaled N_2O intensity while maintaining yield. The results indicate that a nitrogen application amount of 94.5 $kg\cdot hm^{-2}$ and an irrigation amount of 15 mm are the optimal values for reducing N_2O emissions from potato fields under the premise of maintaining yield in the conventional farming systems used in the study area.

4.4 Suggestions for DNDC model improvement

There was a special phenomenon in this study by taking the N1 treatment in 2018 as an example (In Fig 5). The soil N_2O emission of observing showed a small peak on July 7 and July 9, 2018, but the DNDC model did not simulate the emission peak(In Fig 6a). We found that there were precipitation of 7.3, 2.5 and 5.7 mm in the first three days of July 9, 2018, respectively. Therefore, we guessed that this phenomenon may be due to the model's not obvious response to low precipitation for several consecutive days.

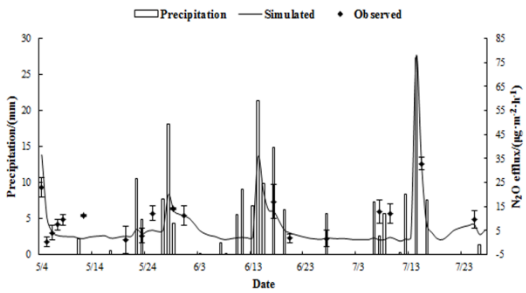

Fig. 5 The simulation and observing of N_2O emission and precipitation in N1 treatment in 2018

Since farmland N_2O emissions have great temporal and spatial variability, which is related to the three factors controlling the production of N_2O (Eh in the soil (oxidation-reduction potential of the soil environment), Dissolved organic carbon (DOC), and available nitrogen (ammonium nitrogen, nitrate nitrogen)). Observations from around the world indicate that annual N2O emissions in most places are integrated by a small number of emission peaks, and the DNDC model simulates the peak N_2O emission based on this(Li, 2016). Taking N1 nitrogen application level treatment as an example, DNDC model simulation showed that Eh was 764.3mV at 10cm of soil on July 7th, 2018. There was no obvious N_2O emission peak in the simulated values. However, a rainfall on July 14 was 27.3 mm, and Eh of the soil 10 cm was 421.4 mV simulated by DNDC model. There was an obvious emission peak of N_2O. DNDC model is based on

Nengst equation to calculate the simulated soil Eh. When there is rainfall, soil Eh decreases, and the extent of the decrease is related to the duration of rainfall. The longer the duration of rainfall, the more soil Eh decreases. Moreover, a certain threshold value is assigned to the Eh of the soil at the beginning of N_2O emission (if the initial nitrate nitrogen concentration in the soil is 0.00357 mol•L^{-1}, Eh is 460 mV at the beginning of N_2O emission). In the DNDC model, intensity of precipitation (Ip) is defined as a fixed value, that is, 0.5 cm per hour (Ip=0.5 cm•h^{-1}). Then, according to the whole precipitation (Wp, cm•d^{-1}) provid by meteorological data, the time of precipitation (Tp, h) is defined as: Tp=Wp/Ip (Li, 2016).

However, the Ip is not a fixed value. So the Tp cannot be simply calculated with Tp=Wp/Ip. The precipitation was 7.3mm and 2.5mm on July 6 and July 7 of 2018, respectively. According to the Tp=Wp/Ip formula, the Tp of these two days was only 1.46h and 0.5h in the simulation of DNDC, respectively. However, in fact, the Tp on July 6 and 7 of 2018 was 3.5h and 0.75h, respectively. The actual Tp was converted into Wp by Tp=Wp/Ip, and input into the DNDC model. The DNDC model was able to accurately simulate the N_2O emission peak on 6 July 2018 (In Fig 6b). This practice of converting the actual Tp into Wp input into the model according to the formula applied in the model has increased the actual Wp, but this attempt had achieved more accurate simulation results. It shows that the optional input items of the input module of daily intensity of precipitation and time of precipitation should be considered in the DNDC model. This is to accurately simulate the N_2O emission characteristics of low and longtime of precipitation.

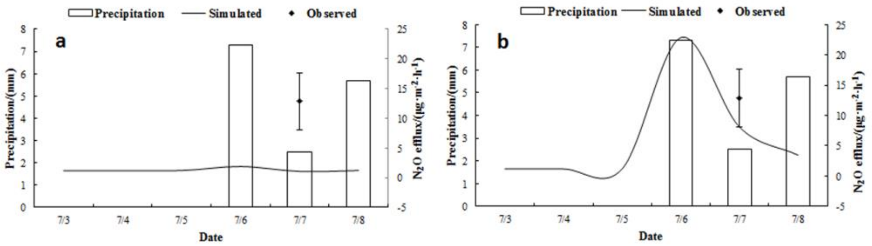

Fig. 6 The simulation of N_2O emission before and after improvement and observing of N_2O emission and precipitation in N1 treatment in 2018

5. Conclusions

Based on a 3-year experiment in a potato field, the effects of multiple factors on N_2O emissions and yield have been discussed in this paper using the DNDC model, which had a good simulation effect on N_2O emission and yield in the potato field. The simulation effect of the DNDC model was better for N_2O emissions. The simulation of the N_2O emission effect in the low nitrogen treatment was better than that of the high nitrogen treatment. The model efficiency indexes EFs were from 0.45~0.88 for N_2O emissions 0.91, 0.85 and 0.85 for yield from 2017~2019. The annual precipitation, soil organic carbon and soil bulk density had the most significant influence on the accumulated N_2O

emissions during the growth period of potato, and the sensitivity index values were 1.894, 1.052 and 1.129, respectively. Positive correlations were observed between those factors and emissions. The annual precipitation, annual average temperature and CO_2 mass concentration had the most significant influence on yield, and the sensitivity index values were 0.723, -0.508 and 1.295, respectively. Positive correlations were observed between the CO_2 mass concentration and annual precipitation and the yield while a negative correlation was observed between the annual average temperature and the yield. By combining the DNDC simulation and actual production, the temperature is stabilized by sowing potato crops within 5 days after reaching 10 °C to achieve increased yield while maintaining a normal water supply. The nitrogen application amount of 94.5 $kg \cdot hm^{-2}$ and the irrigation amount of 15 mm represented the optimal values for reducing N_2O emissions from the potato field under the premise of maintaining yield in the conventional farming systems of the study area.

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Consent to participate:I am free to contact any of the people involved in the research to seek further clarification and information.

Consent for publication: Not applicable.

Availability of data and materials: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

Agbede, T. (2010) Tillage and fertilizer effects on some soil properties, leaf nutrient concentrations, growth and sweet potato yield on an Alfisol in southwestern Nigeria. *Soil Till Res*, *110* (1), 25-32. https://doi.org/10.1016/j.still.2010.

06.003
Agehara, S.; Warncke, D.(2005) Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. *Soil Sci Soc Am J*, *69* (6), 1844-1855. https://doi.org/10.2136/sssaj2004.0361
Balaine N , Clough T J , Beare M H , Thomas S M, Meenken E D. (2016) Soil gas diffusivity controls NO and N Emissions and their ratio. *Soil Sci Soc Am J, 80(3)*:529. https://doi.org/10.2136/sssaj2015.09.0350
Banerjee, S.; Helgason, B.; Wang, L.; Winsley, T.; Ferrari, B. C.; Siciliano, S. D.(2016) Legacy effects of soil moisture on microbial community structure and N_2O emissions. *Soil Biol. Biochem.*, *95*, 40-50. https://doi.org/ 10.1016/j.soilbio.2015.12.004
Barton, L.; Kiese, R.; Gatter, D.; BUTTERBACH-BAHL, K.; Buck, R.; Hinz, C.; Murphy, D. V.(2008) Nitrous oxide emissions from a cropped soil in a semi-arid climate. *Glob. Change Biol.*, *14* (1), 177-192. https://doi.org/10.1111/j.1365-2486.2007.01474.x
Burton, D.; Zebarth, B.; Gillam, K.; MacLeod, J. (2008) Effect of split application of fertilizer nitrogen on N_2O emissions from potatoes. *Can J Soil Sci*, *88* (2), 229-239. https://doi.org/10.4141/CJSS06007
Cavigelli, M.; Robertson, G. (2001) Role of denitrifier diversity in rates of nitrous oxide consumption in a terrestrial ecosystem. *Soil Biol. Biochem.*, *33* (3), 297-310. https://doi.org/10.1016/S0038-0717(00)00141-3
Čuhel, J.; Šimek, M.; Laughlin, R. J.; Bru, D.; Chèneby, D.; Watson, C. J.; Philippot, L. (2010) Insights into the effect of soil pH on N_2O and N_2 emissions and denitrifier community size and activity. *Appl. Environ. Microbiol.*, *76* (6), 1870-1878. https://doi.org/10.1128/AEM.02484-09
Cui, G., Wang, J. (2019) Improving the DNDC biogeochemistry model to simulate soil temperature and emissions of nitrous oxide and carbon dioxide in cold regions. *Sci. Total Environ.*,687, 61-70. https://doi.org/10.1016/j.scitotenv. 2019.06.054
Deng, J.; Zhu, B.; Zhou, Z.; Zheng, X.; Li, C.; Wang, T.; Tang, J. (2011) Modeling nitrogen loadings from agricultural soils in southwest China with modified DNDC. *J. Geophys. Res.-Biogeosci.*, *116* (G2). https://doi.org/ 10.1029/2010JG001609
Deng, M., Hou, M., Zhang, Q., Bellingrath-kimura, S. D. (2020) Critical livestock densities and manure management for the typical paddy rice and corn cropping systems in an intensive livestock watershed, Japan. *Agr Syst*, 177. https://doi.org/10.1016/j.agsy.2019.102722
Dijkstra, F. A.; Prior, S. A.; Runion, G. B.; Torbert, H. A.; Tian, H.; Lu, C.; Venterea, R. T. (2012) Effects of elevated carbon dioxide and increased temperature on methane and nitrous oxide fluxes: evidence from field experiments. *Front. Ecol. Environ.*, *10* (10), 520-527. https://doi.org/10.2307/41811865
Elmi, A.; Mehdi, B.; Chandra, M.; Dam, R.; Smith, D. (2009) Long-term effect of conventional and no-tillage production systems on nitrous oxide fluxes from corn (Zea mays L.) field in Southwestern Quebec. *Am. J. Environ. Sci.*, *5* (3), 238-246. https://doi.org/10.3844/ajessp.2009.238.246
Giltrap, D. L.; Li, C.; Saggar, S. (2010) DNDC: A process-based model of greenhouse gas fluxes from agricultural soils. *Agric. Ecosyst. Environ.*, *136* (3-4), 292-300. https://doi.org/10.1016/j.agee.2009.06.014
Han, J.; Jia, Z.; Wu, W.; Li, C.; Han, Q.; Zhang, J. (2014) Modeling impacts of film mulching on rainfed crop yield in Northern China with DNDC. *Field Crop Res*, *155*, 202-212. https://doi.org/10.1016/j.fcr.2013.09.004
Hou, P.; Gao, Q.; Xie, R.; Li, S.; Meng, Q.; Kirkby, E. A.; Römheld, V.; Müller, T.; Zhang, F.; Cui, Z. (2012) Grain yields in relation to N requirement: Optimizing nitrogen management for spring maize grown in China. *Field Crop Res*, *129*, 1-6. https://doi.org/10.1016/j.fcr.2012.01.006
Hu, M.; Chen, D.; Dahlgren, R. A. (2016) Modeling nitrous oxide emission from rivers: a global assessment. *Glob. Change Biol.*, *22* (11), 3566-3582. https://doi.org/10.1111/gcb.13351
Kallenbach, C. M.; Rolston, D. E.; Horwath, W. R. (2010) Cover cropping affects soil N_2O and CO_2 emissions differently depending on type of irrigation. *Agr Ecosyst Environ*, *137* (3-4), 251-260. https://doi.org/10.1016/

j.agee.2010.02.010
Khalil, M. I., Fornara, D. A., Osborne, B. (2020) Simulation and validation of long-term changes in soil organic carbon under permanent grassland using the DNDC model. *Geoderma*, 361. https://doi.org/10.1016/j.geoderma.2019. 114014
Kou, T.; Zhu, J.; Xie, Z.; Liu, G.; Zeng, Q. (2008) Effect of elevated atmospheric CO_2 concentration and level of nitrogen fertilizer on root respiration and biomass of winter wheat. *Chin. J. Plant Ecol*, *32*, 922-931. https://doi.org/10.3724/SP.J.1005.2008.01083
Lam, S. K.; Chen, D.; Norton, R.; Armstrong, R.; Mosier, A. R. (2012) Nitrogen dynamics in grain crop and legume pasture systems under elevated atmospheric carbon dioxide concentration: A meta-analysis. *Glob. Change Biol.*, *18* (9), 2853-2859. https://doi.org/10.1111/j.1365-2486.2012.02758.x
Lan, T., Suter, H., Liu, R., Yuan, S., Chen, D. (2018) Effects of nitrification inhibitors on gross N nitrification rate, ammonia oxidizers, and N_2O production under different temperatures in two pasture soils. *Environ. Sci. Pollut*. Res. 25, 28344–28354. https://doi.org/10.1007/s11356-018-2873-6
Li, C.; Frolking, S.; Frolking, T. A. (1992) A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. *J. Geophys. Res.-Atmos.*, *97* (D9), 9759-9776. https://doi.org/10.1029/92JD00510
Li, C.; Salas, W.; Zhang, R.; Krauter, C.; Rotz, A.; Mitloehner, F. (2012) Manure-DNDC: a biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. *Nutr Cycl Agroecosys*, *93* (2), 163-200. https://doi.org/10.1007/s10705-012-9507-z
LI C., (2016) Biogeochemistry: scientific fundamentals and modeling approach[M]. Beijing: Tsing Hua University Press.
Li, H.; Qiu, J.; Wang, L.; Tang, H.; Li, C.; Van Ranst, E. (2010) Modelling impacts of alternative farming management practices on greenhouse gas emissions from a winter wheat–maize rotation system in China. *Agric. Ecosyst. Environ.*, *135* (1-2), 24-33. https://doi.org/10.1016/j.agee.2009.08.003
Li, Q.; Li, H.; Zhang, L.; Zhang, S.; Chen, Y. (2018) Mulching improves yield and water-use efficiency of potato cropping in China: A meta-analysis. *Field Crop Res*, *221*, 50-60. https://doi.org/10.1016/j.fcr.2018.02.017
Logsdon, S. D.; Karlen, D. L. (2004) Bulk density as a soil quality indicator during conversion to no-tillage. *Soil Till Res*, *78* (2), 143-149. https://doi.org/10.1016/j.still.2004.02.003
Luo, G.; Kiese, R.; Wolf, B.; Butterbach-Bahl, K. (2013) Effects of soil temperature and moisture on methane uptakes and nitrous oxide emissions across three different ecosystem types. *Biogeosciences*, *10* (1), 3205-3219. https://doi.org/10.5194/bg-10-3205-2013
Magill, A. H.; Aber, J. D.; Berntson, G. M.; McDowell, W. H.; Nadelhoffer, K. J.; Melillo, J. M.; Steudler, P. (2000) Long-term nitrogen additions and nitrogen saturation in two temperate forests. *Ecosystems*, *3* (3), 238-253. https://doi.org/10.1007/s100210000023
Mapanda F , Wuta M , Nyamangara J , Rees R M. (2011) Effects of organic and mineral fertilizer nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe. *Plant Soil*, *343*(1-2):67-81. https://doi.org/10.1007/s11104-011-0753-7
Matson, P.; Lohse, K. A.; Hall, S. J. (2002) The globalization of nitrogen deposition: consequences for terrestrial ecosystems. *Ambio*, 113-119. https://doi.org/10.1639/0044-7447(2002)031[0113:TGONDC]2.0.CO;2
McGrath, J. M.; Lobell, D. B. (2013) Regional disparities in the CO_2 fertilization effect and implications for crop yields. *Environ. Res. Lett.*, *8* (1), 014054. https://doi.org/10.1088/1748-9326/8/1/014054
Pulatov, B.; Linderson, M.-L.; Hall, K.; Jönsson, A. M. (2015) Modeling climate change impact on potato crop phenology, and risk of frost damage and heat stress in northern Europe. *Agr Forest Meteorol*, *214*, 281-292. https://doi.org/10.1016/j.agrformet.2015.08.266
Raymundo, R.; Asseng, S.; Prassad, R.; Kleinwechter, U.; Concha, J.; Condori, B.; Bowen, W.; Wolf, J.; Olesen, J. E.;

Dong, Q. (2017) Performance of the SUBSTOR-potato model across contrasting growing conditions. *Field Crop Res*, *202*, 57-76. https://doi.org/10.1016/j.fcr.2016.04.012

Reyes-Cabrera, J.; Zotarelli, L.; Dukes, M. D.; Rowland, D. L.; Sargent, S. A. (2016) Soil moisture distribution under drip irrigation and seepage for potato production. *Agr Water Manage*, *169*, 183-192. https://doi.org/ 10.1016/ j.agwat.2016.03.001

Robertson, G. P. 2004. Abatement of nitrous oxide, methane, and the other non-CO_2 greenhouse gases: The need for a systems approach. Pages 493-506 in C. B. Field and M. R. Raupach, eds. The Global Carbon Cycle. Island Press, Washington, DC, USA.

Sanchez-Martín, L.; Meijide, A.; Garcia-Torres, L.; Vallejo, A. (2010) Combination of drip irrigation and organic fertilizer for mitigating emissions of nitrogen oxides in semiarid climate. *Agric. Ecosyst. Environ.*, *137* (1-2), 99-107. https://doi.org/10.1016/j.agee.2010.01.006

Shah, S. H., Li, Y., Wang, J., Collins, A. L. (2020) Optimizing farmyard manure and cattle slurry applications for intensively managed grasslands based on UK-DNDC model simulations. *Sci. Total Environ.*, 714. https://doi.org/ 10.1016/j.scitotenv.2020.136672

Shang, Q.; Yang, X.; Gao, C.; Wu, P.; Liu, J.; Xu, Y.; Shen, Q.; Zou, J.; Guo, S. (2011) Net annual global warming potential and greenhouse gas intensity in Chinese double rice-cropping systems: a 3-year field measurement in long-term fertilizer experiments. *Glob. Change Biol.*, *17* (6), 2196-2210. https://doi.org/ 10.1111/j.1365-2486. 2010.02374.x

Stocker, T. F.; Qin, D.; Plattner, G.-K.; Tignor, M.; Allen, S. K.; Boschung, J.; Nauels, A.; Xia, Y.; Bex, V.; Midgley, P. M. (2013) Climate change 2013: The physical science basis. *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*, *1535*. https://doi.org/10.1007/BF00524943

Turner, P. A.; Griffis, T. J.; Lee, X.; Baker, J. M.; Venterea, R. T.; Wood, J. D. (2015) Indirect nitrous oxide emissions from streams within the US Corn Belt scale with stream order. *Proc. Natl Acad. Sci. USA*, *112* (32), 9839-9843. https://doi.org/10.1073/pnas.1503598112

Vanlauwe, B.; Kihara, J.; Chivenge, P.; Pypers, P.; Coe, R.; Six, J. (2011) Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil*, *339* (1-2), 35-50. https://doi.org/10.1007/s11104-010-0462-7

Walker, S.; Mitchell, J.; Hirschi, M.; Johnsen, K. (2000) Sensitivity analysis of the root zone water quality model. *T Asae*, *43* (4), 841. https://doi.org/10.13031/2013.2978

Wang, L.; Wang, C.; Pan, Z.; Xu, H.; Gao, L.; Zhao, P.; Dong, Z.; Zhang, J.; Cui, G.; Wang, S.; Han, G.; Zhao, H. (2017) N_2O emission characteristics and its affecting factors in rain-fed potato fields in Wuchuan County, China. *Int J Biometeorol*, *61* (5), 911-919. https://doi.org/10.1007/s00484-016-1271-3

Xu, X.; Liu, X.; Li, Y.; Ran, Y.; Liu, Y.; Zhang, Q.; Li, Z.; He, Y.; Xu, J.; Di, H. (2017) High temperatures inhibited the growth of soil bacteria and archaea but not that of fungi and altered nitrous oxide production mechanisms from different nitrogen sources in an acidic soil. *Soil Biol. Biochem.*, *107*, 168-179. https://doi.org/ 10.1016/j.soilbio. 2017.01.003

Yang, J.; Yang, J.; Liu, S.; Hoogenboom, G. (2014) An evaluation of the statistical methods for testing the performance of crop models with observed data. *Agr Syst*, *127*, 81-89. https://doi.org/10.1016/j.agsy.2014.01.008

Yang, Y., Meng, T., Qian, X., Zhang, J., Cai, Z. (2017) Evidence for nitrification ability controlling nitrogen use efficiency and N losses via denitrification in paddy soils. *Biol. Fertil.Soils 53*, 349-356. https://doi.org/ 10.1007/ s00374-017-1185-1

Zebarth, B. J.; Snowdon, E.; Burton, D. L.; Goyer, C.; Dowbenko, R. (2012) Controlled release fertilizer product effects on potato crop response and nitrous oxide emissions under rain-fed production on a medium-textured soil. *Can J Soil Sci*, *92* (5), 759-769. https://doi.org/10.4141/cjss2012-008

Zhang, X.; Hu, D. (2014) Overcoming successive bottlenecks: The evolution of a potato cluster in China. *World Dev.*, *63*, 102-112. https://doi.org/10.1016/j.worlddev.2013.10.003

Zhang, Y. and Niu, H., 2016. The development of the DNDC plant growth sub-model and the application of DNDC in agriculture: a review. *Agric. Ecosyst. Environ., 230*, 271-282. https://doi.org/10.1016/j.agee.2016.06.017