Multifactor effects on the N$_2$O emissions and yield of potato fields based on the DNDC model

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Received: 3 August 2021 / Accepted: 18 November 2021 / Published online: 29 November 2021
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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$_2$O) emissions and the yield of potato fields and to verify the applicability of the denitrification–decomposition (DNDC) model when used to project the N$_2$O emission load and yield, this research chooses a potato field in Shenyang northeast China from 2017 to 2019 as the experiment site. The experiment includes four nitrogen levels observing the emission of N$_2$O 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$_2$O emissions and yields. The model efficiency index $EF_s$ were $0.45 \sim 0.88$ for N$_2$O emissions and 0.91, 0.85, and 0.85 for yields from 2017 to 2019. (2) The annual precipitation, soil organic carbon, and soil bulk density had the most significant influence on the accumulated N$_2$O emissions during the growth period of potatoes. 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$^\circ$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$_2$O emissions while also maintaining the yield in potato fields.

Keywords DNDC model · N$_2$O · Potato · Sensitivity test · Emission reducing · Yield

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$_2$O 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$_2$O emissions are from agricultural soil (Sanchez-Martín et al. 2010); therefore, it is necessary to reduce N$_2$O emissions from agricultural activities.

Numerous studies have shown that farmland N$_2$O emissions are affected by many factors, such as soil temperature, moisture, and fertilization levels (Barton et al. 2008; Elmi et al. 2009). Agehara and Warncke (2005) showed that the soil N$_2$O 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$_2$O emissions by influencing the soil microbial activity, soil REDOX potential, and soil aeration (Luo et al. 2013). The application of nitrogen fertilizer is the most direct source of nitrogen in farmland soil and has a significant effect on the N$_2$O emissions from farmland soil. Many researchers have observed and verified that soil N$_2$O 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$_2$O emissions in farmland due to the high variability of soil N$_2$O emissions in time and space and the complex relationship between climate and soil (Shang et al. 2011). Therefore, the emission law of farmland N$_2$O and its emission reduction potential must be evaluated based on models (Robertson 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). 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$_2$O 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$_2$O emissions mainly focused on using models to explore grain crops, such as wheat (Triticum aestivum L.), maize (Zea mays L.), and rice (Oryza sativa) (Turner et al. 2015). However, little research has been done on field studies of N$_2$O and DNDC simulations in potato (Solanum tuberosum) crop systems (Zhang and Niu 2016). The potato is one of the primary crops in China. The planting area and total yield of potatoes in China are the first in the world, accounting for about 30% of the total planting area and 25% of the total output of the world (Wang et al. 2019). The N$_2$O emission factors (EFs) of potatoes are about 15 ~ 40% higher than that of maize and wheat (Gao et al. 2013; Shang et al. 2019). It indicates that there is more N$_2$O emission of potato than other primary crops in dry farmland under the same nitrogen application rate. It is of great significance to study the law of N$_2$O emission with the expansion of potato planting intensity in the future (Zhang and Hu 2014). We used the DNDC model to study the N$_2$O emissions and yield driving factors and provided a scientific basis for the formulation of N$_2$O emission reduction and yield promotion measures in potato fields.

### Materials and methods

#### Study site

This study was conducted from 2017 to 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·cm$^{-3}$, and the pH is 6.42 on average in 0 ~ 20 cm depth of the soil, respectively.

#### 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·hm$^{-2}$), low fertilizer (N1) (60 kgN·hm$^{-2}$), middle fertilizer (N2) (120 kgN·hm$^{-2}$), and high fertilizer (N3) (180 kgN·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$_2$O$_5$) was applied at 225 kg·hm$^{-2}$, and potassic fertilizer (K$_2$O) was applied at 75 kg·hm$^{-2}$. The fertilization method included a one-time base fertilizer application before sowing for 1 day. The tillage method included plowing to 20 cm before sowing for 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.

#### Method of analyzing the samples

N$_2$O 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 $\text{N}_2\text{O}$ emission fluxes were measured, the soil moisture (by the oven-drying method), air temperature (by thermometer), and soil temperature (by soil thermometer) at 0 cm, 10 cm, 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 $\text{N}_2\text{O}$ emission fluxes were calculated using a linear regression analysis according to the following equation:

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

where flux is the gas exchange flux of $\text{N}_2\text{O}$ ($\mu g \text{ m}^{-2} \text{h}^{-1}$), $\rho$ is the gas density (mg m$^{-2}$), $V$ is the volume of the static chamber box (m$^3$), $A$ is the bottom area of the box (m$^2$), $\Delta C$ is the gas concentration difference, $\Delta t$ 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.

**DNDC model**

**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 (°C), minimum daily temperature (°C), daily precipitation (mm), daily mean wind speed (m·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·g$^{-1}$); soil bulk density (1.297 g·cm$^{-3}$); organic matter content of the topsoil (0 ~ 10 cm) (12.48 g·kg$^{-1}$); average mass concentration of N in precipitation (3.26 mg·L$^{-1}$); and average concentration of CO$_2$ in the atmosphere (400 mg·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 (25,000 kg·hm$^{-2}$); potato growth cumulative temperature (1300°C); potato biomass allocation ratio (Grain: Leaf: Stem: Root was 0.60:0.20:0.18:0.02); and water requirement (400 kg·kg$^{-1}$ dry matter) (Ludwig et al. 2011).

**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.

$$R^2 = \frac{\sum_{i=1}^{n} (S_i - \bar{S_i})(M_i - \bar{M_i})^2}{\sqrt{\sum_{i=1}^{n} (S_i - \bar{S_i})^2 \sum_{i=1}^{n} (M_i - \bar{M_i})^2}}$$  \hspace{1cm} (2)

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

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

where $S_i$ and $M_i$ are the simulated and observed values, respectively; $\bar{M_i}$ and $\bar{S_i}$ 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).

**Sensitivity analysis method**

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 $\text{N}_2\text{O}$ 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:

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

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.

### Results

#### DNDC model calibration and validation

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 the DNDC model had a good simulation effect on both the $N_2O$ emissions and yield of the potato field, as shown in Fig. 1.

#### $N_2O$ emission flux and yield with different nitrogen levels in different climates in the potato field

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. 2).

As shown in Fig. 3, the emission flux of the N3 treatment was significantly higher than that of other treatments, and the emission of CK was the lowest. 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.

As shown in Fig. 4, 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

### 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 (°C)                 | 8.0      | 10.0, 9.0, 8.0, 7.0, 8.0         |
|                        | CO₂ 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 factor| Nitrogen application (kg·hm⁻²)                  | 120      | 240, 180, 120, 60, 0             |

### 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  |

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.
application of nitrogen fertilizer would decrease the yield to some extent.

**Effects of optimized fertilization and irrigation on yield and N$_2$O emissions**

In this study, we used the DNDC model to simulate the change of potato yield and N$_2$O emissions with different nitrogen application rates. The yields all showed a parabolic trend (the trend was consistent with the experimental results) 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$_2$O emissions and yield.

The different irrigation amounts were set to simulate the changes in N$_2$O emissions and yields (Table 3). Table 3 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 mm, 10 mm, 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 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, 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$_2$O emissions still increased rapidly. Compared with 15 mm irrigation, the cumulative N$_2$O emissions increased by 11.1%, 19.3%, 28.1%, 37.9%, 44.9%, 54.7%, and 62.7%. The yield-scaled N$_2$O 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$_2$O intensity of 5 mm, 10 mm, 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$_2$O intensity rapidly. Compared with 15 mm irrigation, the yield-scaled N$_2$O intensity of 20 mm, 25 mm, 30 mm, 35 mm, 40 mm, 45 mm, 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$_2$O intensity while maintaining yield. The results indicate that
a nitrogen application amount of 94.5 kg·hm⁻² and an irrigation amount of 15 mm are the optimal values for reducing N₂O emissions from potato fields under the premise of maintaining yield in the conventional farming systems used in the study area.

**Study on the effects of seeding date regulation**

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 ($y = -6.18x^2 + 278.38x + 11,024.0, R^2 = 0.84, P < 0.01$, where $x$ 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 5-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 5-day sliding average temperature stabilized through 10°C, and April 5th and 6th were the 4th and 5th days.

The same phenomenon was 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.

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 2nd). An obvious phenomenon was observed in which 5-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 5-day sliding average temperature stabilized through 10°C, and April 10th and 2nd were the 3rd and 2nd days.

**Sensitivity analysis of the driving factors for N₂O emissions and yield in the potato field**

The sensitivity testing identified changes in the different driving factors (Table 4), and the following results were obtained.
Meteorological factors. (1) The cumulative N₂O emissions and yield of the potato field during the growth period showed an increasing trend with the increase of annual precipitation. The cumulative N₂O 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, which indicated high sensitivity. (2) The cumulative N₂O 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 °C 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 °C increase in annual temperature. (3) The cumulative change of N₂O emissions during the growing period of the potato field was small with the change of the atmospheric CO₂ 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 CO₂ mass concentration in the atmosphere. With the increase of CO₂ concentration in the atmosphere, the potato yield increased by an average of 6.7% for every 20 mg·m⁻³ increase in CO₂ mass concentration in the atmosphere. (4) The cumulative change of N₂O 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 N₂O emissions and yield during the growing period of potato field increase by only 0.4% and 0.02% on average for every 10% change of nitrogen deposition, respectively.

Soil factors. (1) The cumulative N₂O 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. However, as the organic carbon content

| Factors | Index | Ranges and results of the sensitivity test | Sensitivity index |
|---------|-------|------------------------------------------|-------------------|
| Meteorological factors | Annual precipitation (mm) | −20% −10% B(0%) 10% 20% | 1.894 |
| | Accumulated N₂O emission during the growth period (kg·hm⁻²) | 0.663 0.802 0.972 1.185 1.429 | 1.429 |
| | Yield (kg·hm⁻²) | 17,012.5 18,512.5 20,025 21,300 22,775 | 0.723 |
| | Annual average temperature (°C) | −2 −1 B(0) 1 2 | 0.405 |
| | Accumulated N₂O emission during the growth period (kg·hm⁻²) | 0.905 0.941 0.972 1.010 1.071 | 0.405 |
| | Yield (kg·hm⁻²) | 20,050 20,300 20,025 18,025 16,050 | −0.508 |
| | CO₂ mass concentration (mg·m⁻³) | 360 380 B(400) 420 440 | 1.295 |
| | Accumulated N₂O emission during the growth period (kg·hm⁻²) | 0.993 0.978 0.972 0.961 0.969 | −0.123 |
| | Yield (kg·hm⁻²) | 17,687.5 18,875 20,025 21,400 22,912.5 | 1.295 |
| | Nitrogen deposition (by N) (mg·L⁻¹) | 2.608 2.934 B(3.26) 3.586 3.912 | 0.319 |
| | Accumulated N₂O emission during the growth period (kg·hm⁻²) | 0.962 0.969 0.972 0.975 0.979 | 0.043 |
| | Yield (kg·hm⁻²) | 20,050 20,000 20,025 20,062.5 20,037.5 | −0.008 |
| | Soil organic carbon (g·g⁻¹) | −20% −10% B(0%) 10% 20% | 1.052 |
| | Accumulated N₂O emission during the growth period (kg·hm⁻²) | 0.779 0.872 0.972 1.076 1.191 | 1.052 |
| | Yield (kg·hm⁻²) | 20,075 20,025 20,025 20,037.5 20,062.5 | −0.002 |
| | soil pH | −20% −10% B(0%) 10% 20% | 0.319 |
| | Accumulated N₂O emission during the growth period (kg·hm⁻²) | 0.717 0.875 0.972 0.844 0.614 | 0.043 |
| | Yield (kg·hm⁻²) | 20,012.5 20,062.5 20,025 20,000 19,950 | −0.008 |
| | Soil capacity (g·cm⁻³) | −20% −10% B(0%) 10% 20% | 0.043 |
| | Accumulated N₂O emission during the growth period (kg·hm⁻²) | 0.773 0.866 0.972 1.080 1.216 | 0.043 |
| | Yield (kg·hm⁻²) | 20,000 20,025 20,025 19,950 20,025 | 0.003 |
| | Field management factors | Nitrogen applications (kg·hm⁻²) | 0 60 B(120) 180 240 | 0.003 |
| | Accumulated N₂O emission during the growth period (kg·hm⁻²) | 0.214 0.771 0.972 1.144 1.315 | 0.624 |
| | Yield (kg·hm⁻²) | 17,012.5 20,025 20,025 20,000 19,937.5 | 0.045 |

B means the baseline in Table 1
in the soil gradually increased between 0.00998 g·g⁻¹ and 0.01498 g·g⁻¹, the potato yield remained almost unchanged.

(2) The cumulative N₂O 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 N₂O emissions and yields were in neutral soil, and they decreased in acidic and alkaline soils.

(3) Soil bulk density was positively correlated with the cumulative N₂O emissions in the potato field during the growth period. The cumulative N₂O emission increased by 12.1% on average for every 10% of soil bulk density. The change of yield was small with the change of soil bulk density in the range of 1.038 – 1.556 g·cm⁻³.

Field management factors. The nitrogen application rate was positively correlated with the cumulative N₂O emissions in the potato field during the growth period. The cumulative N₂O emissions increased by 79.7% on average for every 60 kg-hm⁻² nitrogen application. The results showed that nitrogen application significantly promoted N₂O 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.

Discussion

The sensitivity analysis showed that both the cumulative N₂O emissions and yield were significantly changed in different impact factors, and the controllable impact factors in actual production were the water supply (precipitation and irrigation) and nitrogen application. Precipitation and irrigation could significantly affect the dynamic changes of soil moisture, change the soil moisture content, and then affect the N₂O emissions and yields. The N₂O 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). 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 reason for the increase in N₂O emissions from the farmland (Yang et al. 2017). Soil N₂O 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.

In Northeast China, the potato could be seeded after the five days 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). Air temperature affected the soil N₂O emissions and yields by affecting the soil temperature. The soil microbial activity and N₂O emission rate during denitrification and nitrification increased as the soil temperature increased in a certain range. Therefore, the soil N₂O 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 research on advancing potato sowing date is of positive significance to the improvement of potato yield under global warming (Stocker et al. 2013).

In addition to the above factors affecting yield and emissions, other factors in the sensitive analysis also have varying degrees of influence. The cumulative change of N₂O emissions during the growing period of potato was small with changes in the atmospheric CO₂ 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 CO₂ concentrations in the atmosphere can affect the photosynthesis of C3 plants and potatoes (McGrath and Lobell 2013). The photosynthetic capacity of C3 plants can increase by 10 to 15% with the increase of CO₂ concentrations, thereby increasing the yield (Kou et al. 2008). 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 N₂O emissions and yields of the potato field were not significantly changed with nitrogen deposition during the growing period.

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 N₂O 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. 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 N₂O 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. Bulk density is an important physical property of soil that can reflect the porosity, tightness, and fertility of the soil. Soil bulk density affects soil N₂O 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 and Karlen 2004). Decreased soil bulk density increases the soil aeration and oxygen content, thereby reducing the number of anaerobic bacteria, which inhibits denitrification and reduces N₂O emissions (Cavigelli and Robertson 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 N₂O (Lan et al. 2018; Cui and Wang 2019). This part is planned to be combined with experimental data and models to carry out a deeper discussion in future research.

There was a special phenomenon in this study by taking the N1 treatment in 2018 as an example (in Fig. 5). The soil N₂O 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 precipitations of 7.3 mm, 2.5 mm, 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.

Since farmland N₂O emissions have great temporal and spatial variability, which is related to the three factors controlling the production of N₂O (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 N₂O emission based on this (Li 2016). Taking N1 nitrogen application level treatment as an example, the DNDC model simulation showed that Eh was 764.3 mV at 10 cm of soil on July 7th, 2018. There was no obvious N₂O 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 the DNDC model. There was an obvious emission peak of N₂O. DNDC model is based on the 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
7 of 2018 was 3.5 h and 0.75 h, respectively. The actual Tp was converted into Wp by \( Tp = \frac{Wp}{Ip} \), and input into the DNDC model. The DNDC model was able to accurately simulate the \( \text{N}_2\text{O} \) 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 the daily intensity of precipitation and time of precipitation should be considered in the DNDC model. This is to accurately simulate the \( \text{N}_2\text{O} \) emission characteristics of low and long time of precipitation.

Conclusions

Based on a 3-year experiment in a potato field, the effects of multiple factors on \( \text{N}_2\text{O} \) emissions and yield have been discussed in this paper using the DNDC model, which had a good simulation effect on \( \text{N}_2\text{O} \) emission and yield in the potato field. The simulation effect of the DNDC model was better for \( \text{N}_2\text{O} \) emissions. The simulation of the \( \text{N}_2\text{O} \) 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 to 0.88 for \( \text{N}_2\text{O} \) emissions 0.91, 0.85, and 0.85 for yield from 2017 to 2019. The annual precipitation, soil organic carbon, and soil bulk density had the most significant influence on the accumulated \( \text{N}_2\text{O} \) 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 \( \text{CO}_2 \) 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 \( \text{CO}_2 \) 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·hm\(^{-2}\) and the irrigation amount of 15 mm represented the optimal values for reducing \( \text{N}_2\text{O} \) emissions from the potato field under the premise of maintaining yield in the conventional farming systems of the study area.

Acknowledgements This research was funded by the National Key Research and Development Program of China (2019YFD1002204), the National Natural Science Foundation of China (32001409), and the Science and technology research project of Liaoning Provincial Department of Education (LSQN201711). The authors would like to extend their thanks and appreciation to the staff at the College of Agronomy, Shenyang Agricultural University, for assisting in all experiments.

Author contribution Conceptualization: L.W. and X.G.; methodology: L.W. and M.J.; software: K.Z. and K.G.; validation: L.W. and L.L.; formal analysis: L.W., K.Z., and K.G.; investigation: L.W., K.Z., K.G., T.Z., and X.Y.; resources: L.W. and X.G.; data curation: L.W.; writing—original draft preparation: L.W.; writing—review and editing: L.W.; supervision: X.G.; project administration: X.G. All authors have read and agreed to the published version of the manuscript.

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

Declarations

Ethics approval Not applicable.

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

Conflict for publication Not applicable.

Conflict of interest The authors declare no competing interests.
