Nutr Cycl Agroecosyst
https://doi.org/10.1007/s10705-021-10155-4

ORIGINAL ARTICLE

Precipitation and nitrogen application stimulate soil nitrous oxide emission

Huiling Zhang · Qi Deng · Christopher W. Schadt · Melanie A. Mayes · Deqiang Zhang · Dafeng Hui

Received: 27 November 2020 / Accepted: 12 June 2021

Abstract Precipitation and nitrogen (N) fertilization are the two most important drivers for soil nitrous oxide (N_2O) emission. However, the effects of changes in N fertilization and precipitation patterns (i.e., precipitation intensity and frequency) on N_2O emissions in agricultural fields are still unclear. In this study, we simulated soil N_2O emission under different precipitation patterns (6 precipitation intensities, and 12 precipitation frequencies by either merging or splitting precipitation events) and N fertilization rates (low, typical, and high N fertilization) in a cornfield using the DeNitrification-DeComposition model. The model was parameterized and validated using meteorological data and N experimental measurements in Nashville, Tennessee, USA. Results showed that soil water filled pore space (WFPS) and simulated soil N_2O emission increased as precipitation intensity increased. Less frequent but high intensity precipitation treatments reduced the soil WFPS by 25.2% and stimulated soil N_2O emission by 45.3%, while more frequent but low intensity precipitation treatments increased soil WFPS by 9.0% and reduced soil N_2O emission by 23.9%. Compared to typical N fertilization, the sensitivity of soil N_2O emission to precipitation was higher under high N than low N fertilization treatments, and the response ratios were 50.0% and 40.1%, respectively. There was significant interactive effect of precipitation intensity and N fertilization on soil N_2O emission. These findings improved our understanding of precipitation and N impacts on soil N_2O emissions and provided useful knowledge for irrigation and N fertilizer management in agriculture to mitigate greenhouse gas emissions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10705-021-10155-4.

H. Zhang · Q. Deng · D. Zhang
South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China

H. Zhang · D. Hui (✉)
Department of Biological Sciences, Tennessee State University, Nashville, TN 37209, USA
e-mail: dhui@tnstate.edu

H. Zhang
University of Chinese Academy of Sciences, Beijing 10049, China

C. W. Schadt
Biosciences Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA

M. A. Mayes
Environmental Sciences Division and Climate Change Science Institute, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Published online: 22 June 2021

Keywords DNDC model · Precipitation pattern · Nitrogen fertilization · N_2O emission

Introduction

Nitrous oxide (N_2O) is a potent greenhouse gas due to its long residence time in the atmosphere and its strong propensity to deplete ozone. The concentration of atmospheric N_2O was 330.7 ppb in 2018 and is increasing at a rate of 0.81 ppb per year (NOAA 2018; Tian et al. 2020). Although the atmospheric N_2O concentration is much lower than carbon dioxide (CO_2), its global warming potential is 296 times that of CO_2 (Dalal et al. 2003). Thus, a small difference in estimated N_2O emissions can considerably influence the warming potential of the atmosphere. Controlling factors, particularly precipitation and nitrogen (N) fertilization, are the two key drivers for soil N_2O emissions (Dobbie and Smith 2003; Huang et al. 2014; Deng et al. 2016). As a result, projected climate change and anthropogenic activities will influence soil N_2O emission and very likely positively alter global N cycling.

Soil moisture strongly influences N turnover, transference, and emission of soil N_2O (Bollmann and Conrad 1998). There is growing evidence that the global warming has significantly altered the global hydrologic cycle at local, regional, and global scales (Borken and Matzner 2009; Reichstein et al. 2013). The intensity and frequency of precipitation have changed compared to historic climatic norms and include more extreme events with higher precipitation rates and longer duration droughts—trends that are expected to continue into the future (Knutson and Tuleya 2004; IPCC 2014; Knapp et al. 2015). For example, a model based on CMIP5 ensemble showed that the Northern Hemisphere will have more wet extremes and drought will also intensify in the north and central America (Zhan et al. 2020). Previous studies showed that N_2O emission increased with increased precipitation, but most studies focused on the quantity of precipitation instead of precipitation patterns (Wu et al. 2011; Li et al. 2019a). How precipitation patterns involving both intensity and frequency affect soil N_2O emission is still not clear.

Croplands are considered hot spots of soil N_2O emission (Wolf and Russow 2000; Reay et al. 2012; Tian et al. 2016; Deng et al. 2019). A modeling synthesis reported that terrestrial CO_2 uptake is largely offset by CH_4 and N_2O emission (Tian et al. 2016). However, the study notes that the estimation of soil N_2O emission in croplands remains uncertain. The United States is the world's largest corn producer, with 38% of its corn crop exported to other counties in 2018–2019 (NCGA 2019). In addition to its large US area, corn has among the highest mean fertilizer rates thus pointing to its potential for high N_2O emissions and opportunity for mitigation. Although N fertilization increases the availability of soil N and crop yield, recovery of N in crop plants is usually less than 50% worldwide (Fageria and Baligar 2005). A meta-analysis showed soil N_2O emission exhibited a significant positive response to N enrichment in global croplands (+ 105.6%) (Deng et al. 2019). Up to 20–30% of global greenhouse gas emissions may be due to N fertilization (Reay et al. 2012; Tian et al. 2016).

The effects of climate change and N application on soil N_2O emission have been investigated in many field experiments (Zou et al. 2005; Ni et al. 2019). For example, soil N_2O emissions in a Chinese maize field were reduced under deficit irrigation combined with reduced N-fertilizer rate treatment (Ning et al. 2019; Tian et al. 2017). For the wheat–maize rotation system, an improved management practice of water and fertilizer that via changed the fertilization rate, times and timing has the potential to reduce N_2O and emissions (Liu et al. 2011). A study in California grassland showed greater soil moisture corresponded to a much higher emission rate in N addition plots (Aronson et al. 2019). These results indicate that responses of soil N_2O emission could depend on the combinations of soil water availability and N fertilization. However, it is difficult or even impossible to manipulate multiple experimental factors or set many treatment levels for each experimental factor in field experiments (Beier et al. 2012; Li et al. 2019b; Rillig et al. 2019). Most field precipitation experiments only set a few levels of precipitation intensity or frequency. Biogeochemical or ecosystem models have been previously applied to overcome these shortcomings and to assess the effects of climate change or management practices on soil N_2O emissions in agriculture (Deng et al. 2016; Chen et al. 2019; Tian et al. 2020). Based on field experimental results, models can be parameterized and validated to better simulate the direction and magnitude of soil N_2O emission response. With the help of models, a better understanding of soil N_2O emissions resulting from precipitation or irrigation and N fertilization could help reduce N_2O emissions.

The DeNitrification-DeComposition (DNDC) model was designed to simulate soil greenhouse gases emissions in terrestrial ecosystems (Li et al. 1992a, b). Many previous studies have demonstrated that the DNDC model can simulate the dynamics of soil N_2O emission very well (Li et al. 1992b; Giltrap et al. 2010; Zhang et al. 2016; Ingraham and Salas 2019). For example, Giltrap et al. (2010) showed that DNDC model is a useful tool for simulating soil N_2O, CH_4, and CO_2 emissions on a wide range of land-use and agricultural management. Deng et al. (2016) parameterized the DNDC model based on a three-year field experiment in a cornfield in Nashville, TN, and simulated the effects of different agricultural practices on soil N_2O emissions (Deng et al. 2016). Some studies also reported limitations of DNDC model when it was used to simulate daily N_2O emission or to a specific time of emission (Chen et al. 2019; Foltz et al. 2019; Yue et al. 2019). Yue et al. (2019) conducted model comparison of seasonal cumulative N_2O emission across China's cropland and showed that the DNDC underestimated N_2O emissions compared to other three models (DAYCENT, a linear regression model, and IPCC Tier 1 emission factors method). Although there are some limitations, a calibrated and validated DNDC model can reliably simulate soil N_2O emission across a broad range environment conditions (Taft et al. 2019).

In this study, we extended these previous model simulations with different levels of precipitation pattern changes and N fertilization using the previously calibrated DNDC model (Deng et al. 2016). This study builds on these previous studies (Deng et al. 2015, 2016) and further tests how precipitation pattern changes (including 6 levels of intensity and 12 levels of frequency) and N fertilization (3 N levels) would interactively influence soil N_2O emission in the cornfield. The major objectives of this study were: (1) to assess the effects of precipitation intensity and frequency on soil N_2O emission; (2) to simulate the effects of N fertilization on soil N_2O emission; and (3) to quantify the interactive effects of precipitation intensity and frequency, and N fertilization on soil N_2O emission.

Materials and methods

The DNDC model

We used the DNDC model (version 95; http://www.dndc.sr.unh.edu) to simulate and evaluate soil N_2O emissions from the cornfield. The DNDC model was originally developed to simulate soil greenhouse gases including soil N_2O emissions from croplands (Li et al. 1992a, b). This model consists a suite of biogeochemical processes, including decomposition, fermentation, ammonia volatilization, nitrification, and denitrification, and allows computation of the complex transfer and transformations of N in agriculture lands (Li et al. 1992a; Deng et al. 2018). The model includes two major components. The first component, consisting of the soil climate, crop growth and decomposition sub-models, predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles driven by ecological drivers (e.g., climate, soil, vegetation, and anthropogenic activity). The second component, consisting of the nitrification, denitrification and fermentation sub-models, predicts emission of N_2O, CO_2, CH_4, ammonia, nitric oxide, and dinitrogen from the plant-soil systems. Simulated soil N_2O emissions are primarily regulated by soil environment variables, e.g., soil temperature and water-filled pore space (WFSP), and substrate availability (e.g., dissolved organic carbon and inorganic N) (Deng et al. 2016).

Model validation and base meteorological data

Comparing simulated results with experimental measurements was used to verify and validate the model. In brief, the model validation was based on a three-year cornfield experiment conducted at Tennessee State University Agricultural Research and Education Center (latitude 36.12°N, longitude 86.89°W, elevation 127.6 m) in Nashville, TN, USA. The model inputs included meteorological data, soil properties, crop parameters, and farming management practices (Deng et al. 2015, 2016). More detailed description of this no tillage and regular N fertilization study site, field sampling method, and model validation and results were given in Deng et al. (2015, 2016). The local meteorological data during the experiment period were acquired from the weather station (Davis Instruments, Vernon Hills, IL, USA) at the experiment site. The cropland management practices, including planting and harvest, tillage, fertilization, and irrigation, and all of the date and quantity were determined based on the field measurements and operation. The DNDC model was firstly parameterized based on the measured initial soil physical and chemical parameters to simulate daily N_2O emission in the ambient precipitation and typical N fertilization (control_TN) treatment (Deng et al. 2016). Then this parameterized DNDC model was used to simulate daily N_2O emissions for the other 53 treatments.

Experimental design to simulate effects of precipitation intensity and frequency, and N application levels on soil N_2O emission

To simulate the effects of precipitation pattern (i.e., intensity and frequency) change and N fertilization on soil N_2O emission in the cornfield, we set 18 different precipitation patterns including the control treatment and three N fertilization rates. We used the three-year (2012–2014) ambient precipitation (including intensity and frequency) and typical N fertilization by farms as base case scenarios or controls (Deng et al. 2016). The ambient total annual precipitation was 1164, 1394, and 1367 mm in 2012, 2013, and 2014, respectively. Here we can conclude that 2012 was a relatively dry year because the annual precipitation of 2012 was reduced by 15.7% compared to the average value of the other two years. Each of these three years was simulated by altering the precipitation intensity without the change of frequency or by changing of the precipitation frequency without the change of annual total quantity. Overall, the 17 precipitation pattern changes included 5 precipitation intensity changes (2 decreased and 3 increased precipitations) and 12 precipitation frequency changes (7 less frequent precipitations and 5 more frequent precipitations). For precipitation intensity change, we set − 50% (50% decrease in ambient precipitation), − 30% (30% decrease in ambient precipitation), + 30% (30% increase in ambient precipitation), + 50% (50% increase in ambient precipitation), and + 100% (double than the ambient precipitation) without changing the precipitation frequency. For precipitation frequency changes, we maintained the same total amount of precipitation in the years but changed the precipitation frequency by merging or splitting the precipitation events. We considered continuous precipitation days as one event. Less frequent precipitation treatments included M2, M3, …, M8 by merging 2, 3, …, or 8 precipitation events into one large event, respectively. For example, M3 merged precipitation events 1, 2, 3 as event 1, and events 4, 5, 6 as event 2. In the merged treatments, precipitation became less frequent but high intensity (LFHI). S2, S3, …, S6 were more frequent but less intensity (MFLI) precipitation treatments, implemented by splitting one precipitation event to 2, 3, …, or 6 small precipitation events, respectively. For example, we had one precipitation event with four consecutive rainy days, and split it into two precipitation events (S2). We divided four days total precipitation into two even portions. One portion was proportionally allocated to these four days (reduced by half), and another portion was allocated to the middle of the day between the last day of this precipitation event and the first day of the next event. After we split one precipitation into 6 events, the precipitation events almost occurred daily the whole year.

As for N fertilization application treatment, we set three N fertilization rates: TN (typical N fertilization at 118 kg N ha^{-1} yr^{-1}), LN (low N fertilization treatment, half the typical N fertilization at 59 kg N ha^{-1} yr^{-1}), and HN (high N fertilization treatment, + 50% of the typical N fertilization at 177 kg N ha^{-1} yr^{-1}). The LN and HN treatments were within the range of the N fertilizer applied by local farmers to cornfields. Chicken manure (99 kg N ha^{-1} yr^{-1}) was applied to all treatments before the seeds were planted (Deng et al. 2015), and aqueous urea ammonium nitrate was applied twice once on vegetative stage and another one on reproductive stage at the set N application levels accordingly. The detailed fertilization schedule can be found in Table 1.

To assess the interactive effects of precipitation pattern and N fertilization on soil N_2O emission, we ran the DNDC model under the combinations of 18 precipitation pattern changes and three fertilization rates, for a total of 54 simulations. Daily dynamics of soil N_2O emission and emissions through nitrification and denitrification were simulated. Effects of different precipitation patterns and N fertilization and their interactions on soil N_2O emission were detected using the analysis of variation (ANOVA). Multiple comparisons were conducted using Least Square Difference (LSD) method. Data analysis was conducted using

IBM SPSS Statistics 21.0 for Windows (IBM Corp., Armonk, NY, USA).

Results

Effects of precipitation intensity on soil N_2O emission

Results of ANOVA showed that soil mean annual N_2O emission was significantly affected by precipitation intensity and the interaction between intensity and N fertilization ($p < 0.01$; Table 2). Compared to the soil N_2O emission in the ambient precipitation intensity (control), the reduced precipitation intensity treatments (− 50% and − 30%) decreased soil N_2O emission by − 50%, − 33%, respectively, and the three enhanced precipitation intensity treatments (+ 30%, + 50%, + 100%) increased soil N_2O emission by 38%, 67%, and 132%, respectively (Fig. 1a). Simulated soil N_2O emission was more responsive to precipitation change under the high intensity precipitation treatments than the low intensity precipitation (Fig. 1b). There was no significant difference in soil N_2O emission among years ($p > 0.05$, Table 2). The lowest annual mean N_2O emission was in the − 50% precipitation treatment (1.1 kg N ha^{-1} yr^{-1}) and the highest value was in the + 100% precipitation treatment (4.9 kg N ha^{-1} yr^{-1}) (Fig. 1a). The changes of precipitation intensity and N_2O emission were described with polynomial functions (Fig. S1A, R^2 = 0.99). Daily dynamics of soil N_2O emissions simulated using the DNDC model showed pulse responses, particularly during the growing seasons (April to September), and were dramatically enhanced as precipitation intensity increased from − 50% to the control and to + 100% treatments (Fig. S2). The high soil N_2O emission peaks mostly occurred in the growing season for all three years.

Effects of precipitation frequency on soil N_2O emission

We changed the frequency of precipitation events by either merging the 2–8 succeeding precipitation events together (LFHI, denoted as M2 to M8) or splitting one precipitation event into 2–6 precipitation events (MFLI, denoted as S2 to S6) without changing the total amount of precipitation (Fig. 2). The number of precipitation events increased from precipitation frequency treatment M8 to M2, to control, and from S2 to S6 (Fig. 3a). The minimum number of precipitation events of M8 and M7 was an average of 17 times per year across the three years of 2012–2014 (Figs. 3a, S3). The maximum number of precipitation events was S6, averaging to 320 times per year across the three years (Figs. 3a, S3).

Change in precipitation frequency significantly influenced soil N_2O emissions ($p < 0.01$, Table 2). Soil N_2O emission did not vary significantly among the LFHI treatments (M3 to M8) and decreased as precipitation frequency increased from M2 to control, and to S2. Moreover, N_2O emissions did not vary significantly among the S3 to S6 treatments ($p > 0.05$, Fig. S1B). Compared to mean soil N_2O emission over three years under the ambient precipitation (control), simulated soil N_2O emission was increased by + 51%, + 54%, + 51%, 48%, + 40%, + 51%, and + 24% in LFHI treatments (M8, M7, M6, M5, M4, M3, and M2), respectively (Fig. 2b). Soil N_2O emission in the reduced precipitation frequency treatment S2, S3, S4, S5, and S6 was decreased by − 14%, − 17%, − 30%, − 27%, and − 31%, respectively (Fig. 2b). The three years of annual mean soil N_2O emission ranged from 2.6 kg N ha^{-1} yr^{-1} to 3.3 kg N ha^{-1} yr^{-1} under the LFHI treatments (M8-M2) and 1.5 kg N ha^{-1} yr^{-1} to 1.8 kg N ha^{-1} yr^{-1} under the MFLI treatments (Fig. 2a). Soil N_2O emission was higher in the LFHI treatments, and lower in the MFLI

Table 1 Nitrogen fertilization under the different treatments

Treatment	Before seeds planted	Vegetative stage	Reproductive stage
Type	Chicken manure kg N ha^{-1} yr^{-1}	AQUEOUS urea ammonium nitrate kg N ha^{-1} yr^{-1}	Aqueous urea ammonium nitrate kg N ha^{-1} yr^{-1}
LN	99	19.5	39.5
TN	99	39	79
HN	99	58.5	118.5

LN, low N fertilization treatment; TN, typical N fertilization; HN, high N fertilization treatment

Table 2 Summary of three-factor analysis of variance (ANOVA) of year, N fertilization, precipitation pattern (intensity and frequency), and their interactions on soil N_2O emission

Source of variance	*df*	F	P
Year	2	1.148	0.320
N fertilization	2	17.791	**< 0.01**
Precipitation pattern	17		
Intensity	5	99.289	**< 0.01**
Frequency	12	16.272	**< 0.01**
Year*N fertilization	4	0.256	0.905
Year* Precipitation pattern	34	0.077	1.000
N fertilization* Precipitation pattern	34		
N fertilization*intensity	10	2.166	**0.030**
N fertilization*frequency	24	0.284	1.000
N fertilization* Precipitation pattern* Year	68	0.039	1.000

Values in bold represent significant effects with $P < 0.05$

treatments (Fig. 2). MFLI precipitation treatments (S2 to S6) reduced the occurrence of soil N_2O emission peaks (Fig. S3).

Effects of N fertilization rate on soil N_2O emission

Nitrogen fertilization had a significant effect on soil N_2O emission ($p < 0.01$, Table2). Linear regression analysis showed that the soil N_2O emission was significantly positively correlated to the N fertilization rate (Fig. 4). Soil N_2O emission was higher in the HN treatment and lower in the LN treatment compared to the TN. Annual mean soil N_2O emissions over the three years was 1.2, 2.1, and 3.2 kg N ha^{-1} yr^{-1} in the LN, control, and HN treatments, respectively (Fig. 4). Soil N_2O emission in the HN treatment was 2.7 times than that in the LN treatment. Soil N_2O emission varied more between years at low N fertilization relative to high N fertilization (Fig. 4a).

Interactive effects of precipitation pattern change and N fertilization on soil N_2O emission

A significant interaction on soil N_2O emission was only found between precipitation intensity and N application ($p = 0.03$, Table 2). The daily soil N_2O emission over the three years showed that soil N_2O emission increased abruptly and reached high peaks at rainy days with N fertilization (Fig. S2). Compared to the mean soil N_2O emission under the control_TN treatment (2.1 kg N ha^{-1} yr^{-1}), the highest soil N_2O emission (increased by 203%) occurred in the + 100% precipitation intensity and the high N fertilization (+ 100%_HN) treatment (Fig. 1). The lowest soil N_2O emission was simulated in the − 50% precipitation and the low N fertilization (− 50%_LN) treatment (0.5 kg N ha^{-1} yr^{-1}), where it was decreased by 75% compared to the control_TN treatment (Fig. 1). The N fertilization with higher intensity precipitations increased soil N_2O emission compared to the lower intensity precipitations. Soil N_2O emission increased nonlinearly with precipitation intensity for all three N fertilization treatments (Fig. 1a). Overall, high intensity precipitation treatments (+ 100%, + 50%, and + 30%) usually generated more soil N_2O emission (higher than 2.5 kg N ha^{-1} yr^{-1} except the + 30%_LN), while the low intensity precipitation treatments (control, − 30% and − 50%) produced less soil N_2O emission (lower than 2.5 kg N ha^{-1} yr^{-1} except the control_HN treatment) (Fig. 1b). We selected this threshold value of 2.5 kg N ha^{-1} yr^{-1} as it could separate all treatments into two groups at the control level mostly (Fig. 1a).

There was no significant interaction between precipitation frequency and N fertilization ($p > 0.05$, Table 2). Soil N_2O emission was not influenced by less frequent treatments (M3-M8) or by more frequent precipitation treatments but reduced from M3 to M2, the control, and S2 (Fig. S1B). Compared to the control_TN treatment, we observed that under the LN and TN treatments, LFHI precipitation increased soil N_2O emission, but MFLI precipitation treatments reduced soil N_2O emission (Fig. 2). However, under the HN treatment, both LFHI and MFLI increased soil N_2O emission compared to the control and TN treatment (Fig. 2b).

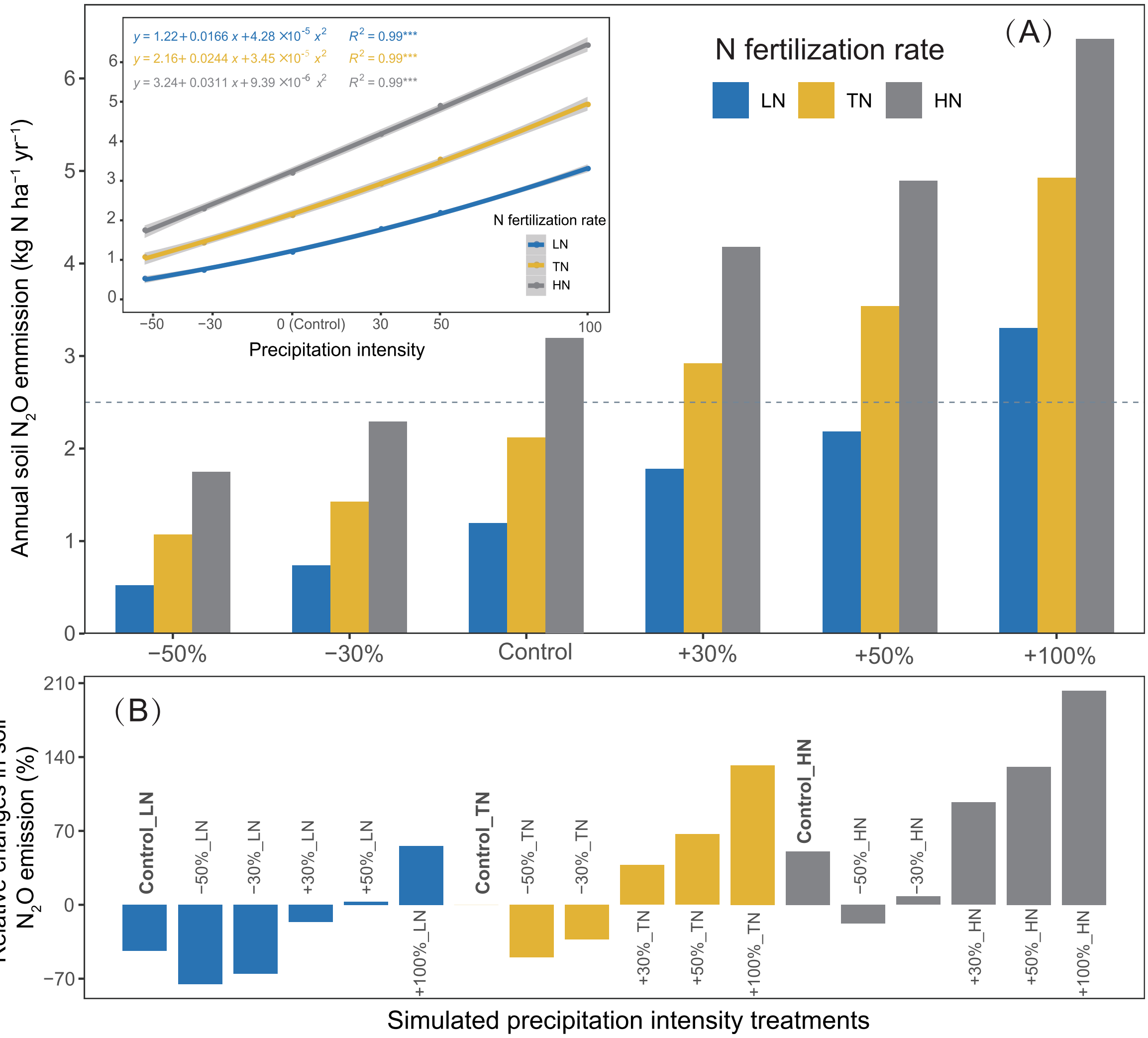

Fig. 1 The interactive effects of precipitation intensity and nitrogen application on annual mean soil N_2O emission over three years (**a**) and relative changes in soil N_2O emission under precipitation intensity treatments (**b**). LN: low nitrogen fertilization; TN: typical nitrogen fertilization; HN: high nitrogen fertilization. − 50%: a 50% decrease in ambient precipitation; − 30%: a 30% decrease in ambient precipitation; control: the ambient precipitation; + 30%: a 30% increase in ambient precipitation; + 50%: a 50% increase in ambient precipitation; + 100%: double the ambient precipitation. Relationships between soil N_2O emission and N application are embedded as inlet and the shaded areas represent 95% confidence intervals (A). Asterisks indicate the level of significance (***$p < 0.001$). The horizontal line indicates that annual N_2O emission is 2.5 kg N ha^{-1} yr^{-1} (**a**). The simulated treatment is denoted as "precipitation pattern_nitrogen level" (**b**)

Discussion

Effects of precipitation intensity on soil N_2O emission

The model predicted that soil N_2O emission increased with increases in precipitation intensity. This phenomenon is prevalent in most terrestrial ecosystems, particularly in forests and grasslands, as revealed in a meta-analysis (Yan et al. 2018). Changes in precipitation intensity directly influence soil moisture conditions that determine soil N_2O emission processes (Attard et al. 2011). Indeed, soil moisture increased with increases in precipitation intensity (Fig. 3b), and annual soil N_2O emissions was increased with an increase in soil moisture in this study (Fig. 6a). Soil moisture is an important factor that strongly influences the processes of nitrification and denitrification

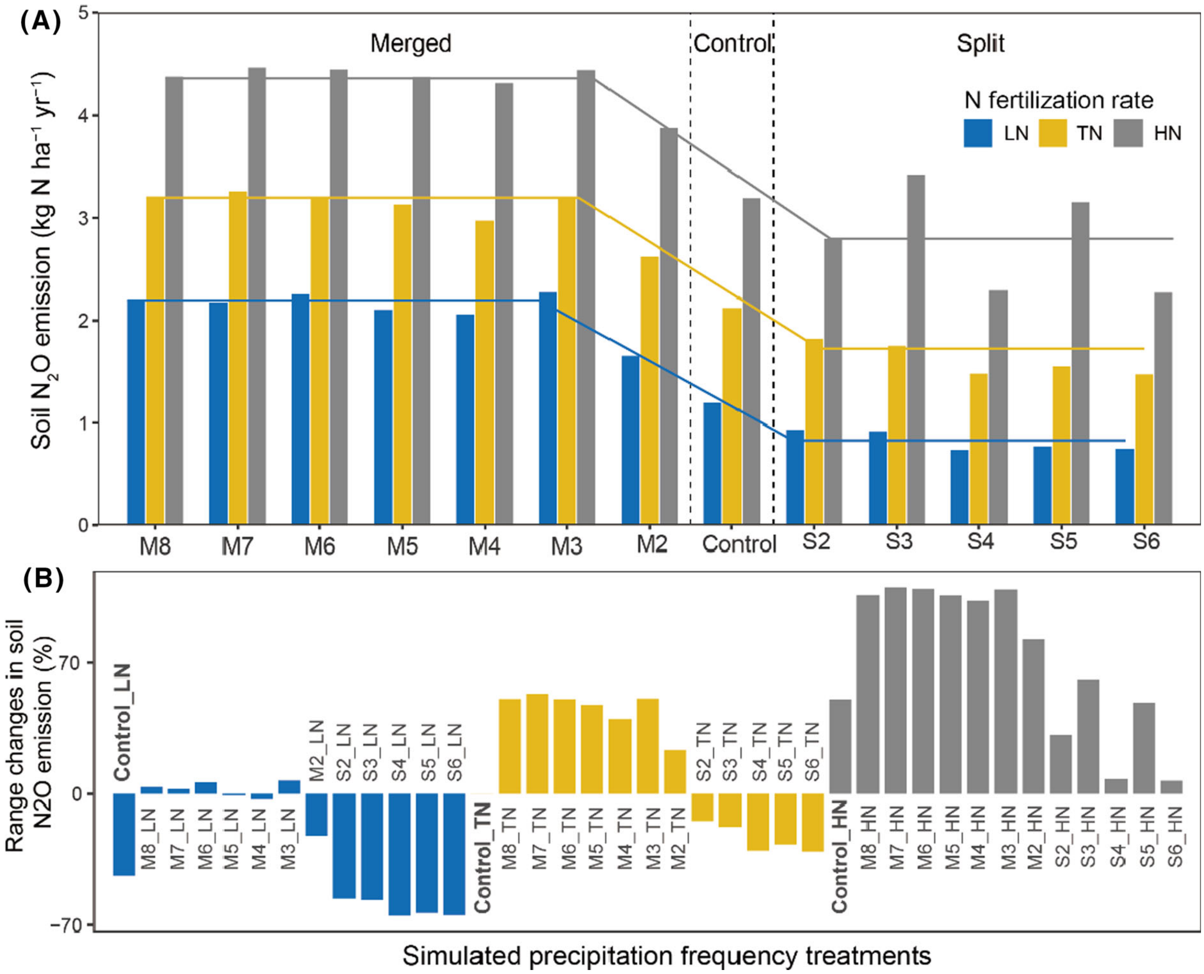

Fig. 2 The interactive effects of precipitation frequency and N application on N_2O emission (**a**) and relative changes in soil N_2O emission under precipitation frequency treatments (**b**). LN: low N fertilization; TN: typical N fertilization; HN: high N fertilization. Mn: merged n precipitation events into one event; Sn: spilt one precipitation event into n events; Control: the ambient precipitation. Lines are trend lines of soil N_2O emission changes with precipitation frequency treatments (**a**). The simulated treatment is denoted as "precipitation pattern_nitrogen level"; Mn: merged n precipitation events into one event; Sn: spilt one precipitation event into n events (**b**)

(Bremner 1997; Wrage et al. 2001; Rochette et al. 2010). Both annual soil nitrification and denitrification rates were enhanced with the increases in precipitation intensity (Fig. 5a, b). Soil nitrification dominates the total soil N_2O emission, while denitrification has more potential than nitrification in producing more soil N_2O emission under anaerobic and saturated conditions (Wolf and Russow 2000; Mathieu et al. 2006). A previous study also showed that under an anaerobic condition with more precipitation, the fraction of N_2O loss from enhanced denitrification can be 10 times larger than that in the nitrification process (Xu et al. 2019). Compared to the control, in our study, soil N_2O emission, nitrification, and denitrification under the + 100% precipitation treatment increased by 132%, 7%, and 221%, respectively (Figs. 1b, 5a, b). Under the high precipitation intensity condition, the increased soil moisture and an anaerobic environment would stimulate the decomposition of organic matter and contribute to the process of denitrification (Chen et al. 2013), allowing simultaneous nitrification and denitrification (Butterbach-Bahl et al. 2013). The nonlinear and asymmetric response of soil N_2O emissions to soil moisture and precipitation intensity treatments (Fig. 6c) showed the soil N_2O emission was more responsive to increased precipitation than

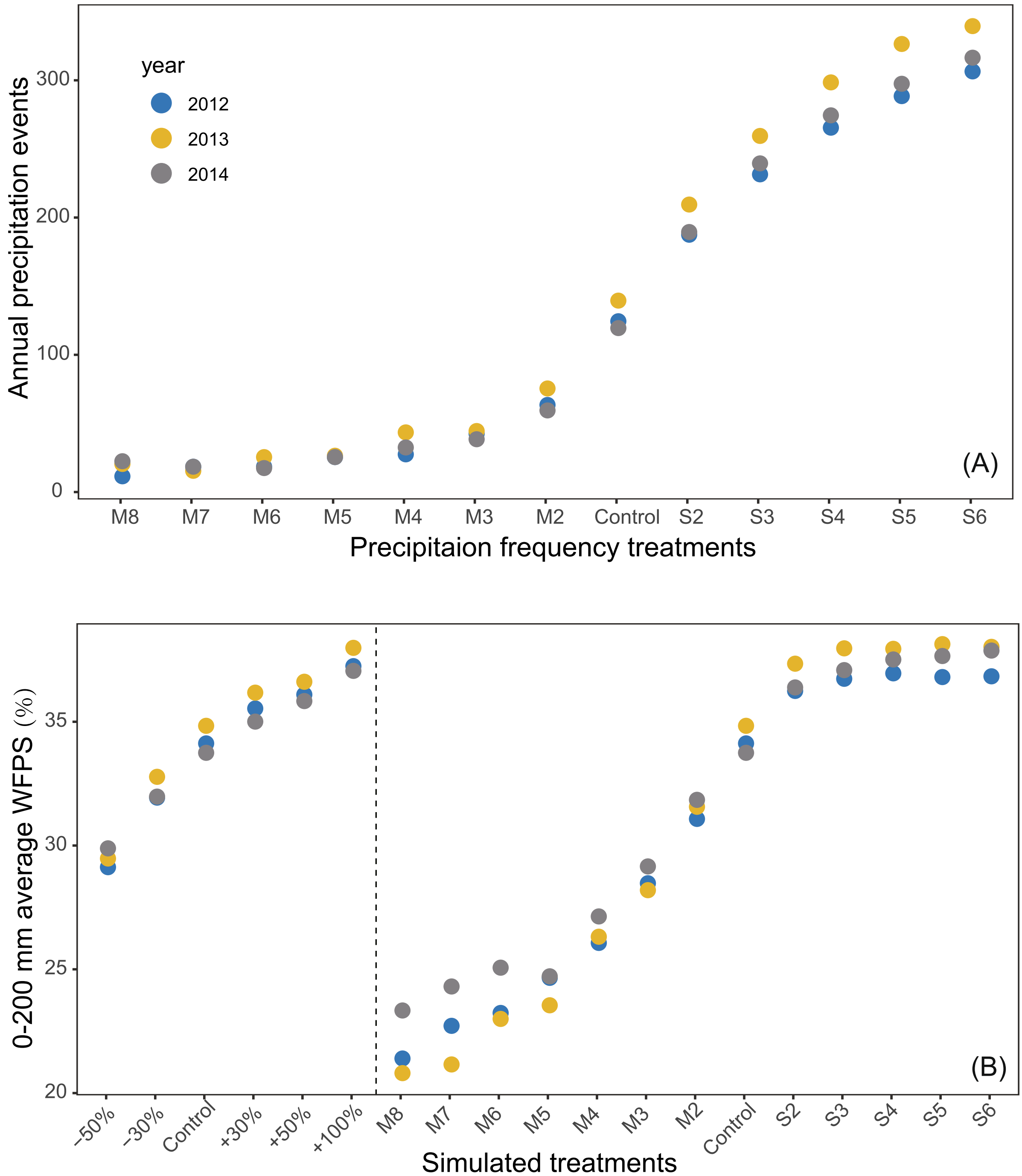

Fig. 3 The precipitation events under different simulated precipitation frequency treatments (**a**), the soil average WFPS (%) under different simulated precipitation treatments (**b**) among different years. − 50%: a 50% decrease in ambient precipitation; − 30%: a 30% decrease in ambient precipitation; control: the ambient precipitation; + 30%: a 30% increase in ambient precipitation; + 50%: a 50% increase in ambient precipitation; + 100%: double the ambient precipitation. Mn: merged n precipitation events into one event; Sn: spilt one precipitation event into n events; control: the ambient precipitation; WFPS: water-filled porosity

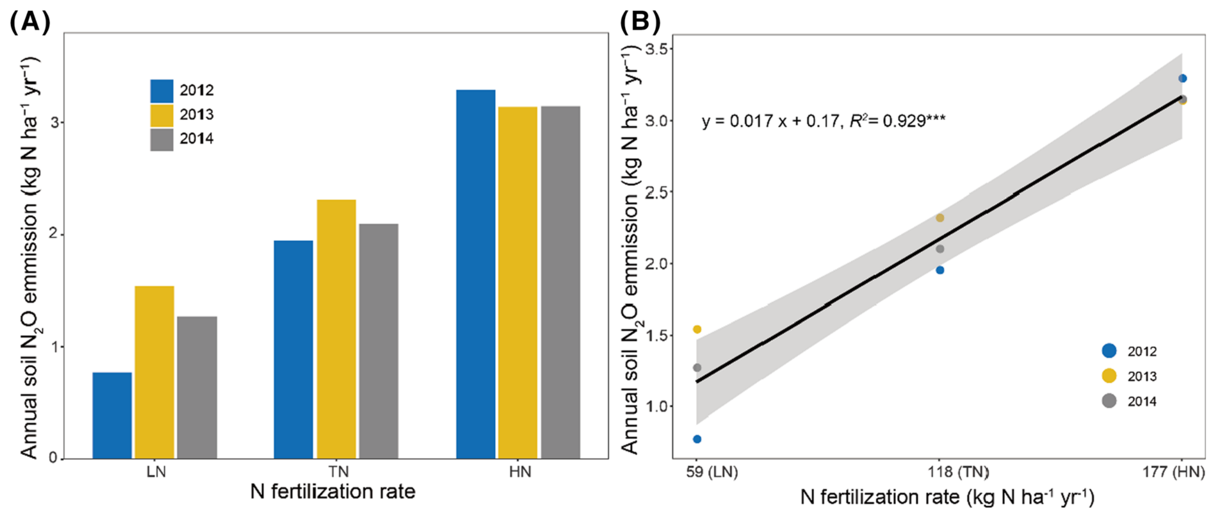

Fig. 4 The annual soil N_2O emission under different fertilizer application from 2012 to 2014 (**a**). Relationships between soil N_2O emission and nitrogen fertilization (**b**). The shaded areas represent 95% confidence intervals. LN: low nitrogen fertilization; TN: typical nitrogen fertilization; HN: high nitrogen fertilization. Asterisks indicate the level of significance (***$p < 0.001$)

that to decreased precipitation. Similar patterns were shown for plant productivity and ecosystem carbon fluxes (Wu et al. 2011). These were due to simultaneous increases in both nitrification and denitrification with high intensity precipitation.

Effects of precipitation frequency on soil N_2O emission

In this study, the LFHI treatments reduced precipitation events, increased precipitation intensity and soil moisture for each event, as a result, soil N_2O emission was higher than the control (Figs. 2, S3). The MFLI treatments showed opposite effects on these variables. Furthermore, soil moisture increased nonlinearly with precipitation intensity and number of precipitation events (Figs. 3, 6a). As the total amount of precipitation was the same for all precipitation frequency treatments, MFLI precipitation treatments increased soil moisture, but reduced soil N_2O emission. In a previous study, Liang et al. (2016) showed that soil N_2O emission declined as drying-rewetting cycles increased, similar to our result. However, the relationship of soil N_2O emission and soil moisture under the precipitation frequency treatments was quite different from that under the precipitation intensity treatments. Decreasing soil N_2O emissions with increases in soil moisture in this study (Fig. 6d) were contradictory to the finding of Fentabil et al. (2016) who found that more frequent irrigation increased soil N_2O emission in an orchard. The inconsistencies could be caused by the differences in the amount of water added in precipitation or irrigation treatments or the difference in ecosystems. As the same amount of precipitation was added, precipitation frequency treatments had less effects on soil annual N leaching, compared to precipitation intensity treatments (Fig. 5d). The soil N loss through surface runoff was also similar under all precipitation frequency treatments (Fig. 5c). Thus, the decreased soil N_2O emission in the MFLI treatments could be due to the obvious decrease in soil denitrification (Fig. 5b).

Precipitation interval or drought duration could influence substrate supply and microbial activities and affect soil N_2O emission (Xiang et al. 2008; Borken and Matzner 2009). Rapid soil microbial response to frequent rewetting events and concomitant greater moisture availability often resulted in instantaneous C and N mineralization, followed by shifts in C/N of microbially available substrate, and enhanced potentially available N (Austin et al. 2004; Butterly et al. 2011; Lopez-Sangil et al. 2018). During the drought periods, the hydration and lysis of dead microbial cells would increase substrate availability (Fierer and Schimel 2002; Borken and Matzner 2009). The additional mineralization increased the release of N

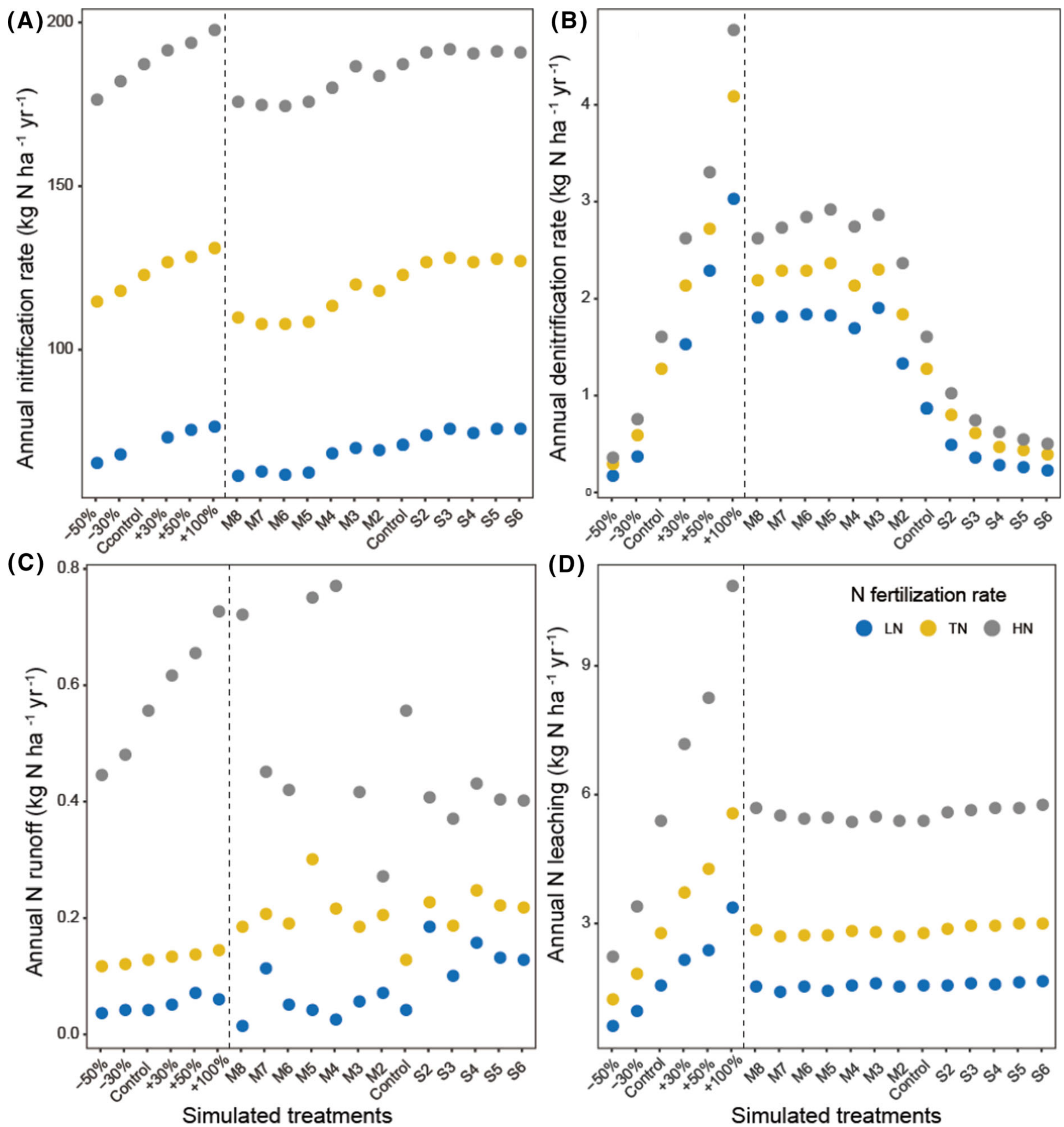

Fig. 5 Dynamic of annual nitrification rate (**a**), annual denitrification rate (**b**), annual N runoff (**c**, annual soil N loss through surface runoff), and annual N leaching (**d**, annual soil N loss through subsurface leaching) under different nitrogen fertilization rate among different simulated precipitation treatments. − 50%: a 50% decrease in ambient precipitation; − 30%: a 30% decrease in ambient precipitation; control: the ambient precipitation; + 30%: a 30% increase in ambient precipitation; + 50%: a 50% increase in ambient precipitation; + 100%: double the ambient precipitation. Mn: merged n precipitation events into one event; Sn: spilt one precipitation event into n events; control: the ambient precipitation

from soils. Meanwhile, frequent rewetting events might cause the breakage of soil macroaggregates and expose physically protected organic matter that was difficult for microorganisms to reach, and more available substrate will be supplied to microorganisms (Denef et al. 2001). In this study, we found that the LFHI treatments enhanced the denitrification process

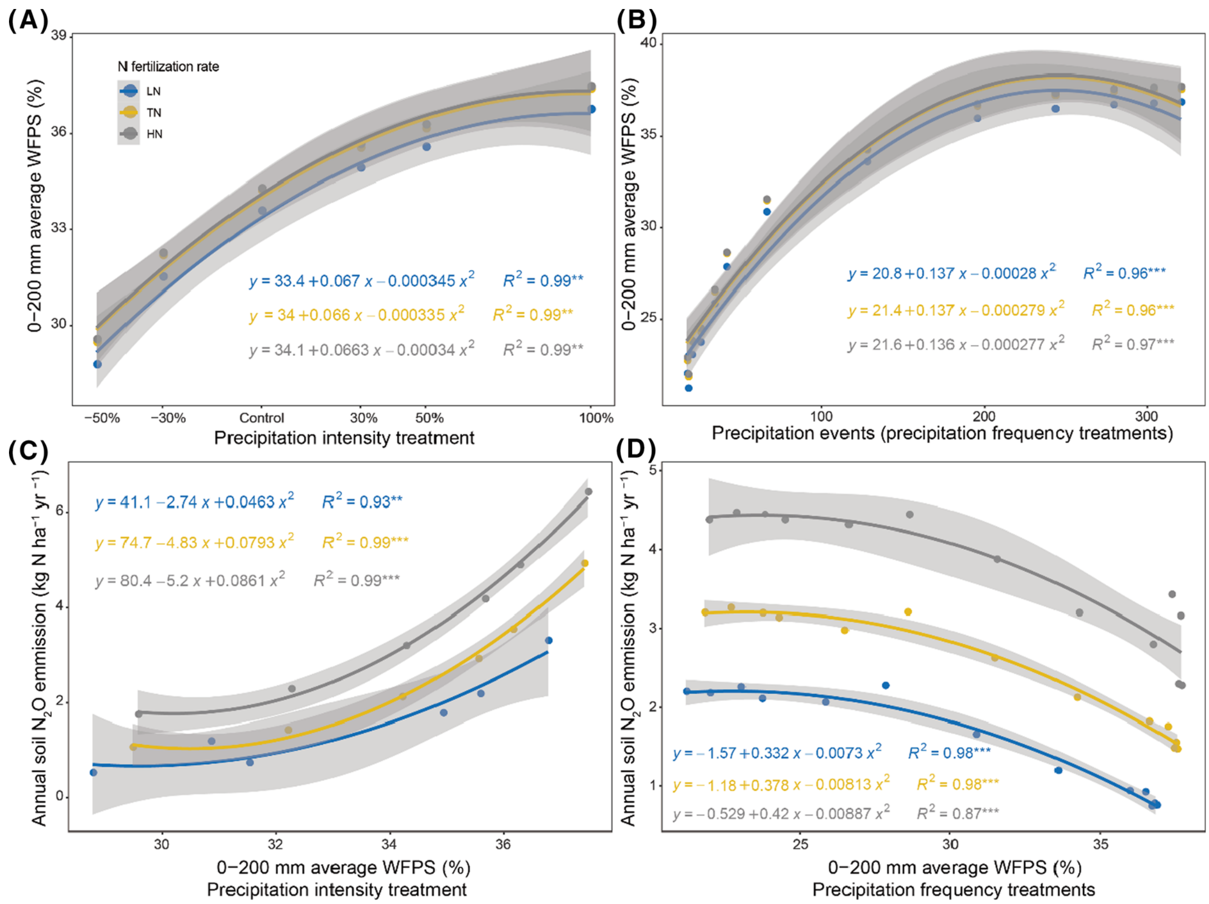

Fig. 6 The relationship between soil average WFPS (%) and simulated precipitation treatments (**a**, **b**), and the relationship between soil average WFPS (%) and annual soil N_2O emission under different nitrogen fertilization rate (**c**, **d**). − 50%: a 50% decrease in ambient precipitation; − 30%: a 30% decrease in ambient precipitation; control: the ambient precipitation; + 30%: a 30% increase in ambient precipitation; + 50%: a 50% increase in ambient precipitation; + 100%: double the ambient precipitation. Mn: merged n precipitation events into one event; Sn: spilt one precipitation event into n events; control: the ambient precipitation; WFPS: water-filled porosity. Asterisks indicate the level of significance (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$)

(Fig. 5b). As a result, an immediate pulse in soil N_2O emission could be produced (Fig. S3).

Effects of N fertilization on soil N_2O emission

Soil N_2O emission increased with N application (Bouwman et al. 2002; Charles et al. 2017; Wang et al. 2018; Volpi et al. 2019). This was mainly because the N is the substrate for microorganisms related to soil nitrification and denitrification processes. Indeed, we found that nitrification and denitrification were enhanced by N application, particularly soil nitrification (Fig. 5b). Nitrogen leaching and N runoff were also increased, especially when exceeded N fertilization was applied.

Regarding the relationship between soil N_2O emission and N application, both linear (e.g., Albanito et al. 2017) and nonlinear (Kim et al. 2013; Shcherbak et al. 2014; Ning et al. 2019) relationships have been reported. In this study, there were good linear relationships between N_2O emission and N fertilization rate ($p < 0.05$, Fig. 4). We also found that annual variation was larger under the LN treatment than the TN and HN treatments (Fig. 4a). Soil N_2O emission was lower in the dry year (2012), probably due to lower nitrification as soil nitrifiers could be more limited by lower soil moisture (Brown et al. 2012).

The changes of soil N_2O emission between the HN and LN fertilization varied from 104.2% in 2013 to 327.7% in 2012 (Fig. 4a). It indicated that soil N_2O emission was more sensitive to N availability in a dry year. However, these results should be interpreted with caution, since we only tested three N application levels, as one of the main objectives in this study was to test the responses of the soil N_2O emission to precipitation pattern changes under different N application levels. Further studies need to be conducted with multiple N applications to develop their relationships.

Interactive effects of precipitation pattern change and N fertilization on soil N_2O emission

In this study, increased precipitation intensity with N fertilization generally increased soil N_2O emission (Fig. 1). Soil N_2O emission increased with precipitation intensity treatments from dry to wet years under all N fertilization treatments, but soil N_2O emission was stimulated more under the higher N fertilization than the typical and the low N fertilization treatments (Fig. 1a). The lowest soil N_2O emission under the − 50% and LN treatment was caused by low nitrification and denitrification (Fig. 5a, b). The higher sensitivity of soil N_2O emission to precipitation intensity was mostly caused by the stronger increases in soil denitrification under the high precipitation intensity (Fig. 5b). Under the control, − 30% and − 50% treatments, soil N_2O emission was lower than 2.5 kg N ha^{-1} yr^{-1} for all N fertilization treatments except the HN with the control, and under the other precipitation intensity treatments, soil N_2O emission was higher than 2.5 kg N ha^{-1} yr^{-1} except the LN with + 30% and + 50% treatments. These results indicated that water availability was a more important factor in reducing soil N_2O emission in the field. The highest soil N_2O emission occurred in the HN with + 100% precipitation treatment, due to both high soil nitrification and denitrification under this condition (Fig. 1b).

In this study, we found no significant interaction of precipitation frequency and N fertilization on soil N_2O emission. We observed different soil N_2O emission patterns with precipitation frequency treatments, but the responses were similar under different N fertilization treatments (Fig. 2a). As precipitation frequency decreased and intensity increased, soil nitrification was enhanced, but denitrification was mostly reduced, resulting in no significant differences among the MFLI treatments or among the LFHI treatments, for all N fertilization levels.

The timings of N fertilization and precipitation/irrigation could also influence responses of soil N_2O emission. Applying N fertilizer on or after a rainy day produced the highest peak of soil N_2O emission (Fig. S3), as more substrate and water availability simultaneously stimulated soil microbial activities. We also found that the annual soil N_2O emission was unexpectedly increased in the S3 and S5 precipitation treatments under the HN treatment (Fig. 2a). The higher annual N_2O emission might be due to the soil N_2O emission peaks in November (Fig. S3). Higher soil N_2O emission corresponded to higher precipitation events, but the emissions occurred always during or soon after the precipitation. When drought was followed by large precipitation, increased soil moisture would likely enhance soil N_2O emission in periodic pulses (Aronson et al. 2019). The effects of N fertilization and precipitation on soil N_2O emission were additive especially in the dry years (Zhang et al. 2017). In this study, the HN treatment greatly increased soil N_2O emission and showed the greatest changes in 2012, a relatively dry year (Fig. 4a).

Conclusions

Based on 54 simulations of soil N_2O emission in a cornfield over three years using the DNDC model, we investigated the main and interactive effects of precipitation pattern (intensity and frequency) change and N fertilization. Less frequent but high intensity precipitation stimulated soil N_2O emission, particularly under the high nitrogen application. Similar results could be found in croplands and grasslands with similar climate conditions and agricultural practices. However, soil N_2O emission in a changing environment is unlikely affected by a single factor. Understanding the interactive effects of precipitation patterns, N fertilization, and the timing of management practices provides insights regarding timing and intensity of irrigation and fertilization, and improves water and N use efficiencies in agriculture. Although we have qualitatively estimated the response of N_2O emission to many scenarios, the changing of precipitation events to global warming may be more complex than we expected. It implies that we should study the interaction between precipitation intensity and frequency rather than these two factors individually. More field experiments with combined precipitation pattern changes and N fertilization are needed to confirm the interactive effects of precipitation pattern and N application in croplands observed here.

Acknowledgements This research was partially supported by the National Science Foundation (NSF) TIP (1623085), MRI (1919897), and EiR (1900885, 2000058) projects. We gratefully acknowledge financial support from China Scholarship Council (CSC: 201804910689) to HZ, and the Oak Ridge National Laboratory/Oak Ridge Associated Universities HBCU/MEI Faculty Summer Research Program to DH. DZ was supported by National Natural Science Foundation of China (41773088). MAM was financially supported by the U.S. Department of Energy (DOE) Office of Biological and Environmental Research through the Terrestrial Ecosystem Science Scientific Focus Area at Oak Ridge National Laboratory (ORNL). ORNL is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the U.S. DOE.

References

Albanito F, Lebender U, Cornulier T, Sapkota TB, Brentrup F, Stirling C, Hillier J (2017) Direct nitrous oxide emissions from tropical and sub-tropical agricultural systems-a review and modelling of emission factors. Sci Rep 7:44235. https://doi.org/10.1038/srep44235

Aronson EL, Goulden ML, Allison SD (2019) Greenhouse gas fluxes under drought and nitrogen addition in a Southern California grassland. Soil Biol Biochem 131:19–27. https://doi.org/10.1016/j.soilbio.2018.12.010

Attard E, Recous S, Chabbi A, De Berranger C, Guillaumaud N, Labreuche J, Philippot L, Schmid B, Le Roux X (2011) Soil environmental conditions rather than denitrifier abundance and diversity drive potential denitrification after changes in land uses. Global Change Biol 17:1975–1989. https://doi.org/10.1111/j.1365-2486.2010.02340.x

Austin AT, Yahdjian L, Stark JM, Belnap J, Porporato A, Norton U, Ravetta DA, Schaeffer SM (2004) Water pulses and biogeochemical cycles in arid and semiarid ecosystems. Oecologia 141:221–235. https://doi.org/10.1007/s00442-004-1519-1

Beier C, Beierkuhnlein C, Wohlgemuth T, Penuelas J, Emmett B, Körner C, de Boeck H, Christensen JH, Leuzinger S, Janssens IA, Hansen K (2012) Precipitation manipulation experiments - challenges and recommendations for the future. Ecol Lett 15:899–911. https://doi.org/10.1111/j.1461-0248.2012.01793.x

Bollmann A, Conrad R (1998) Influence of O_2 availability on NO and N_2O release by nitrification and denitrification in soils. Global Change Biol 4:387–396. https://doi.org/10.1046/j.1365-2486.1998.00161.x

Borken W, Matzner E (2009) Reappraisal of drying and wetting effects on C and N mineralization and fluxes in soils. Global Change Biol 15:808–824. https://doi.org/10.1111/j.1365-2486.2008.01681.x

Bouwman AF, Boumans LJM, Batjes NH (2002) Emissions of N_2O and NO from fertilized fields: summary of available measurement data. Global Biogeochem Cycles. https://doi.org/10.1029/2001gb001811

Bremner JM (1997) Sources of nitrous oxide in soils. Nutr Cycl Agroecosyst 49:7–16. https://doi.org/10.1023/a:1009798022569

Brown JR, Blankinship JC, Niboyet A, van Groenigen KJ, Dijkstra P, Le Roux X, Leadley PW, Hungate BA (2012) Effects of multiple global change treatments on soil N_2O fluxes. Biogeochemistry 109:85–100. https://doi.org/10.1007/s10533-011-9655-2

Butterbach-Bahl K, Baggs EM, Dannenmann M, Kiese R, Zechmeister-Boltenstern S (2013) Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philos Trans R Soc B Biol Sci. https://doi.org/10.1098/rstb.2013.0122

Butterly CR, McNeill AM, Baldock JA, Marschner P (2011) Rapid changes in carbon and phosphorus after rewetting of dry soil. Biol Fertility Soils 47:41–50. https://doi.org/10.1007/s00374-010-0500-x

Charles A, Rochette P, Whalen JK, Angers DA, Chantigny MH, Bertrand N (2017) Global nitrous oxide emission factors from agricultural soils after addition of organic amendments: A meta-analysis. Agric Ecosyst Environ 236:88–98. https://doi.org/10.1016/j.agee.2016.11.021

Chen W, Zheng X, Chen Q, Wolf B, Butterbach-Bahl K, Brueggemann N, Lin S (2013) Effects of increasing precipitation and nitrogen deposition on CH_4 and N_2O fluxes and ecosystem respiration in a degraded steppe in Inner Mongolia, China. Geoderma 192:335–340. https://doi.org/10.1016/j.geoderma.2012.08.018

Chen H, Li L, Luo X, Li Y, Liu D, Zhao Y, Feng H, Deng J (2019) Modeling impacts of mulching and climate change on crop production and N_2O emission in the Loess Plateau of China. Agric for Meteorol 268:86–97. https://doi.org/10.1016/j.agrformet.2019.01.002

Dalal RC, Wang WJ, Robertson GP, Parton WJ (2003) Nitrous oxide emission from Australian agricultural lands and mitigation options: a review. Aust J Soil Res 41:165–195. https://doi.org/10.1071/sr02064

Denef K, Six J, Paustian K, Merckx R (2001) Importance of macroaggregate dynamics in controlling soil carbon stabilization: short-term effects of physical disturbance induced by dry–wet cycles. Soil Biol Biochem 33:2145–2153. https://doi.org/10.1016/S0038-0717(01)00153-5

Deng Q, Hui D, Wang J, Lwuozo S, Yu C, Jima T, Smart D, Reddy C, Dennis S (2015) Corn yield and soil nitrous oxide emission under different fertilizer and soil management: a three-year field experiment in middle tennessee. PLoS ONE. https://doi.org/10.1371/journal.pone.0125406

Deng Q, Hui D, Wang J, Yu CL, Li C, Reddy KC, Dennis S (2016) Assessing the impacts of tillage and fertilization management on nitrous oxide emissions in a cornfield using the DNDC model. J Geophys Res-Biogeosci 121:337–349. https://doi.org/10.1002/2015jg003239

Deng J, Guo L, Salas W, Ingraham P, Charrier-Klobas JG, Frolking S, Li C (2018) Changes in irrigation practices likely mitigate nitrous oxide emissions from California cropland. Global Biogeochem Cycles 32:1514–1527. https://doi.org/10.1029/2018gb005961

Deng L, Huang C, Dong-Gill K, Shangguan Z, Wang K, Song X, Peng C (2019) Soil GHG fluxes are altered by N deposition: New data indicate lower N stimulation of the N_2O flux and greater stimulation of the calculated C pools. Global Change Biol. https://doi.org/10.1111/gcb.14970

Dobbie KE, Smith KA (2003) Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. Global Change Biol 9:204–218. https://doi.org/10.1046/j.1365-2486.2003.00563.x

Fageria NK, Baligar VC (2005) Enhancing nitrogen use efficiency in crop plants. In: Sparks DL (ed) Advances in Agronomy, vol 88. Elsevier Academic Press Inc, San Diego, USA, pp 97–185. https://doi.org/10.1016/S0065-2113(05)88004-6

Fentabil MM, Nichol CF, Jones MD, Neilsen GH, Neilsen D, Hannam KD (2016) Effect of drip irrigation frequency, nitrogen rate and mulching on nitrous oxide emissions in a semi-arid climate: An assessment across two years in an apple orchard. Agric Ecosyst Environ 235:242–252. https://doi.org/10.1016/j.agee.2016.09.033

Fierer N, Schimel JP (2002) Effects of drying-rewetting frequency on soil carbon and nitrogen transformations. Soil Biol Biochem 34:777–787. https://doi.org/10.1016/s0038-0717(02)00007-x

Foltz ME, Zilles JL, Koloutsou-Vakakis S (2019) Prediction of N_2O emissions under different field management practices and climate conditions. Sci Total Environ 646:872–879. https://doi.org/10.1016/j.scitotenv.2018.07.364

Giltrap DL, Li C, Saggar S (2010) DNDC: a process-based model of greenhouse gas fluxes from agricultural soils. Agric Ecosyst Environ 136:292–300. https://doi.org/10.1016/j.agee.2009.06.014

Huang H, Wang J, Hui D, Miller DR, Bhattarai S, Dennis S, Smart D, Sammis T, Reddy KC (2014) Nitrous oxide emissions from a commercial cornfield (*Zea mays*) measured using the eddy covariance technique. Atmos Chem Phys 14:12839–12854. https://doi.org/10.5194/acp-14-12839-2014

Ingraham PA, Salas WA (2019) Assessing nitrous oxide and nitrate leaching mitigation potential in US corn crop systems using the DNDC model. Agric Syst 175:79–87. https://doi.org/10.1016/j.agsy.2019.05.005

IPCC (2014) Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)] Geneva, Switzerland, p 151

Kim D-G, Hernandez-Ramirez G, Giltrap D (2013) Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: a meta-analysis. Agric Ecosyst Environ 168:53–65. https://doi.org/10.1016/j.agee.2012.02.021

Knapp AK, Hoover DL, Wilcox KR, Avolio ML, Koerner SE, La Pierre KJ, Loik ME, Luo YQ, Sala OE, Smith MD (2015) Characterizing differences in precipitation regimes of extreme wet and dry years: implications for climate change experiments. Global Change Biol 21:2624–2633. https://doi.org/10.1111/gcb.12888

Knutson TR, Tuleya RE (2004) Impact of CO_2-induced warming on simulated hurricane intensity and precipitation: sensitivity to the choice of climate model and convective parameterization. J Clim 17:3477–3495. https://doi.org/10.1175/1520-0442(2004)017%3c3477:iocwos%3e2.0.co;2

Li C, Frolking S, Frolking TA (1992a) A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. J Geophys Res Atmospheres 97:9759–9776. https://doi.org/10.1029/92jd00509

Li C, Frolking S, Frolking TA (1992b) A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model applications. J Geophys Res Atmospheres 97:9777–9783. https://doi.org/10.1029/92jd00510

Li L, Zheng Z, Biederman JA, Xu C, Xu Z, Che R, Wang Y, Cui X, Hao Y (2019a) Ecological responses to heavy rainfall depend on seasonal timing and multi-year recurrence. New Phytol 223:647–660. https://doi.org/10.1111/nph.15832

Li L, Zheng Z, Wang W, Biederman JA, Xu X, Ran Q, Quan R, Xu C, Zhang B, Wang F, Zhou S, Cui L, Che R, Hao Y, Cui X, Xu Z, Wang Y (2019b) Terrestrial N_2O emissions and related functional genes under climate change: a global meta-analysis. Global Change Biol. https://doi.org/10.1111/gcb.14847

Liang J, Qi X, Souza L, Luo Y (2016) Processes regulating progressive nitrogen limitation under elevated carbon dioxide: a meta-analysis. Biogeosciences 13:2689–2699. https://doi.org/10.5194/bg-13-2689-2016

Liu C, Wang K, Meng S, Zheng X, Zhou Z, Han S, Chen D, Yang Z (2011) Effects of irrigation, fertilization and crop straw management on nitrous oxide and nitric oxide emissions from a wheat-maize rotation field in northern China. Agric Ecosyst Environ 140:226–233. https://doi.org/10.1016/j.agee.2010.12.009

Lopez-Sangil L, Hartley IP, Rovira P, Casals P, Sayer EJ (2018) Drying and rewetting conditions differentially affect the mineralization of fresh plant litter and extant soil organic matter. Soil Biol Biochem 124:81–89. https://doi.org/10.1016/j.soilbio.2018.06.001

Mathieu O, Henault C, Leveque J, Baujard E, Milloux MJ, Andreux F (2006) Quantifying the contribution of nitrification and denitrification to the nitrous oxide flux using N-15 tracers. Environ Pollut 144:933–940. https://doi.org/10.1016/j.envpol.2006.02.005

NCGA (2019) World of Corn 2019. https://doi.org/worldofcorn.com/pdf/WOC-2019.pdf. Accessed 1 Dec 2019

Ni X, Liao S, Wu F, Groffman PM (2019) Short-term precipitation pulses stimulate soil CO_2 emission but do not alter CH_4 and N_2O fluxes in a northern hardwood forest. Soil Biol Biochem 130:8–11. https://doi.org/10.1016/j.soilbio.2018.11.021

Ning D, Qin A, Duan A, Xiao J, Zhang J, Liu Z, Liu Z, Zhang B, Liu Z (2019) Deficit irrigation combined with reduced N-fertilizer rate can mitigate the high nitrous oxide emissions from Chinese drip-fertigated maize field. Glob Ecol Conserv. https://doi.org/10.1016/j.gecco.2019.e00803

NOAA (2018) Trends in atmospheric nitrous oxide. Global monitoring laboratory. NOAA's Earth System Research Laboratories. https://www.esrl.noaa.gov/gmd/ccgg/trends_n2o/.Accessed 1 Dec 2019

Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, Dentener F, Crutzen PJ (2012) Global agriculture and nitrous oxide emissions. Nat Climate Change 2:410–416. https://doi.org/10.1038/nclimate1458

Reichstein M, Bahn M, Ciais P, Frank D, Mahecha MD, Seneviratne SI, Zscheischler J, Beer C, Buchmann N, Frank DC, Papale D, Rammig A, Smith P, Thonicke K, van der Velde M, Vicca S, Walz A, Wattenbach M (2013) Climate extremes and the carbon cycle. Nature 500:287–295. https://doi.org/10.1038/nature12350

Rillig MC, Ryo M, Lehmann A, Aguilar-Trigueros CA, Buchert S, Wulf A, Iwasaki A, Roy J, Yang G (2019) The role of multiple global change factors in driving soil functions and microbial biodiversity. Science 366:886–890. https://doi.org/10.1126/science.aay2832

Rochette P, Tremblay N, Fallon E, Angers DA, Chantigny MH, MacDonald JD, Bertrand N, Parent LÉ (2010) N_2O emissions from an irrigated and non-irrigated organic soil in eastern Canada as influenced by N fertilizer addition. Eur J Soil Sci 61:186–196. https://doi.org/10.1111/j.1365-2389.2009.01222.x

Shcherbak I, Millar N, Robertson GP (2014) Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen. Proc Natl Acad Sci USA 111:9199–9204. https://doi.org/10.1073/pnas.1322434111

Taft HE, Cross PA, Hastings A, Yeluripati J, Jones DL (2019) Estimating greenhouse gases emissions from horticultural peat soils using a DNDC modelling approach. J Environ Manag 233:681–694. https://doi.org/10.1016/j.jenvman.2018.11.113

Tian H, Lu C, Ciais P, Michalak AM, Canadell JG, Saikawa E, Huntzinger DN, Gurney KR, Sitch S, Zhang B, Yang J, Bousquet P, Bruhwiler L, Chen G, Dlugokencky E, Friedlingstein P, Melillo J, Pan S, Poulter B, Prinn R, Saunois M, Schwalm CR, Wofsy SC (2016) The terrestrial biosphere as a net source of greenhouse gases to the atmosphere. Nature 531:225–228. https://doi.org/10.1038/nature16946

Tian D, Zhang YY, Mu YJ, Zhou YZ, Zhang CL, Liu JF (2017) The effect of drip irrigation and drip fertigation on N2O and NO emissions, water saving and grain yields in a maize field in the North China. Plain Sci Total Environ 575:1034–1040. https://doi.org/10.1016/j.scitotenv.2016.09.166

Tian H, Xu R, Canadell JG, Thompson RL, Winiwarter W, Suntharalingam P, Davidson EA, Ciais P, Jackson RB, Janssens-Maenhout G, Prather MJ (2020) A comprehensive quantification of global nitrous oxide sources and sinks. Nature 586(7828):248–256

Volpi I, Ragaglini G, Di Nasso NNO, Bonari E, Bosco S (2019) Soil N2O emissions in Mediterranean arable crops as affected by reduced tillage and N rate. Nutrient Cycl Agroecosyst. https://doi.org/10.1007/s10705-019-10032-1

Wang J, Chadwick DR, Cheng Y, Yan X (2018) Global analysis of agricultural soil denitrification in response to fertilizer nitrogen. Sci Total Environ 616:908–917. https://doi.org/10.1016/j.scitotenv.2017.10.229

Wolf I, Russow R (2000) Different pathways of formation of N_2O, N_2 and NO in black earth soil. Soil Biol Biochem 32:229–239. https://doi.org/10.1016/s0038-0717(99)00151-0

Wrage N, Velthof GL, van Beusichem ML, Oenema O (2001) Role of nitrifier denitrification in the production of nitrous oxide. Soil Biol Biochem 33:1723–1732. https://doi.org/10.1016/s0038-0717(01)00096-7

Wu Z, Dijkstra P, Koch GW, Penuelas J, Hungate BA (2011) Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation. Global Change Biol 17:927–942. https://doi.org/10.1111/j.1365-2486.2010.02302.x

Xiang SR, Doyle A, Holden PA, Schimel JP (2008) Drying and rewetting effects on C and N mineralization and microbial activity in surface and subsurface California grassland soils. Soil Biol Biochem 40:2281–2289. https://doi.org/10.1016/j.soilbio.2008.05.004

Xu R, Wang Y, Wang Y, Niu H, Liu Y, Zhuang Q (2019) Estimating N_2O emissions from soils under natural vegetation in China. Plant Soil 434:271–287. https://doi.org/10.1007/s11104-018-3856-6

Yan G, Mu C, Xing Y, Wang Q (2018) Responses and mechanisms of soil greenhouse gas fluxes to changes in precipitation intensity and duration: a meta-analysis for a global perspective Can. J Soil Sci 98:591–603. https://doi.org/10.1139/cjss-2018-0002

Yue Q, Cheng K, Ogle S, Hillier J, Smith P, Abdalla M, Ledo A, Sun J, Pan G (2019) Evaluation of four modelling approaches to estimate nitrous oxide emissions in China's cropland. Sci Total Environ 652:1279–1289. https://doi.org/10.1016/j.scitotenv.2018.10.336

Zhan W, He XG, Sheffield J, Wood EF (2020) Projected seasonal changes in large-scale global precipitation and temperature extremes based on the CMIP5 ensemble. J Clim 33:5651–5671. https://doi.org/10.1175/jcli-d-19-0311.1

Zhang Y, Niu H, Wang S, Xu K, Wang R (2016) Application of the DNDC model to estimate N_2O emissions under different types of irrigation in vineyards in Ningxia, China. Agric Water Manage 163:295–304. https://doi.org/10.1016/j.agwat.2015.10.006

Zhang LH, Hou LY, Guo DF, Li LH, Xu XF (2017) Interactive impacts of nitrogen input and water amendment on growing season fluxes of CO_2, CH_4, and N_2O in a semiarid grassland, Northern China. Sci Total Environ 578:523–534. https://doi.org/10.1016/j.scitotenv.2016.10.219

Zou JW, Huang Y, Jiang JY, Zheng XH, Sass RL (2005) A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. Global Biogeochem Cycles. https://doi.org/10.1029/2004gb002401