Kaur *et al. Ecological Processes* (2023) 12:17
https://doi.org/10.1186/s13717-023-00429-w

Ecological Processes

RESEARCH **Open Access**

Response patterns of simulated corn yield and soil nitrous oxide emission to precipitation change

Navneet Kaur[1], Dafeng Hui[1*], Daniel M. Riccuito[2], Melanie A. Mayes[2] and Hanqin Tian[3]

Abstract

Background Precipitation plays an important role in crop production and soil greenhouse gas emissions. However, how crop yield and soil nitrous oxide (N_2O) emission respond to precipitation change, particularly with different background precipitations (dry, normal, and wet years), has not been well investigated. In this study, we examined the impacts of precipitation changes on corn yield and soil N_2O emission using a long-term (1981–2020, 40 years) climate dataset as well as seven manipulated precipitation treatments with different background precipitations using the DeNitrification-DeComposition (DNDC) model.

Results Results showed large variations of corn yield and precipitation but small variation of soil N_2O emission among 40 years. Both corn yield and soil N_2O emission showed near linear relationships with precipitation based on the long-term precipitation data, but with different response patters of corn yield and soil N_2O emission to precipitation manipulations. Corn yield showed a positive linear response to precipitation manipulations in the dry year, but no response to increases in precipitation in the normal year, and a trend of decrease in the wet year. The extreme drought treatments reduced corn yield sharply in both normal and wet years. In contrast, soil N_2O emission mostly responded linearly to precipitation manipulations. Decreases in precipitation in the dry year reduced more soil N_2O emission than those in the normal and wet years, while increases in precipitation increased more soil N_2O emission in the normal and wet years than in the dry year.

Conclusions This study revealed different response patterns of corn yield and soil N_2O emission to precipitation and highlights that mitigation strategy for soil N_2O emission reduction should consider different background climate conditions.

Keywords Background precipitation, DNDC model, Precipitation change, Response pattern, Yield, Soil N_2O emission

Background

Due to anthropogenic greenhouse gas emissions, the average surface temperature on Earth is predicted to increase by 1.4–5.8 °C during this century (Houghton et al., 2001; Weltzin et al. 2003). As a result, the patterns of global air circulation and hydrological cycle are likely to change, with more occurrences of severe droughts and floods (Trenberth et al. 2015; Zhan et al. 2020). Such changes in precipitation play an important role in the ecosystem functioning such as plant productivity, crop yield, and greenhouse gas emissions (Bannayan et al. 2011; IPCC 2014; Knapp et al. 2015). Despite a long

---

*Correspondence:
Dafeng Hui
dhui@tnstate.edu
[1] Department of Biological Sciences, Tennessee State University, Nashville, TN 37209, USA
[2] Environmental Sciences Division and Climate Change Science Institute, Oak Ridge National Laboratory, Oak Ridge, TN, USA
[3] Schiller Institute for Integrated Science and Society, Department of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA, USA

history of investigation on the relationship between precipitation and terrestrial ecosystems, it is still not entirely clear how anticipated changes in precipitation affect ecosystem processes like crop yield and greenhouse gas emissions (Weltzin et al. 2003; Knapp et al. 2015; Gao et al. 2022).

Both plant productivity, yield, and soil N_2O emission are significantly influenced by precipitation and soil water conditions (Kennedy et al. 2013; Deng et al. 2015; Plaza-Bonilla et al. 2017). Plant productivity has been linked to precipitation change at both spatial and temporal scales (Wu et al. 2011; Beier et al. 2012; Ye et al. 2018). Crop yield is also found to be significantly correlated to precipitation (Changnon and Holliger 1993; Lobell et al. 2007; Zscheischler et al. 2017; Cammarano et al. 2019). Field measurements, eddy covariance observations, and model simulations all showed that precipitation is the critical factor determining the response of soil N_2O emission (Huang et al. 2014, 2022; Deng et al. 2016; Hossain and Beierkuhnlein 2018; Tian et al. 2020; Zhang et al. 2021; Xie et al. 2022). Knapp et al. (2017) summarized the responses of plant productivity to precipitation change and proposed a conceptual double asymmetric model linking the change of precipitation to productivity. Based on this conceptual model, under the normal precipitation range, plant productivity would increase more to increasing precipitation in comparison to the observed decrease with decreasing precipitation. However, in the event of extreme precipitation, productivity would decrease more dramatically to decreasing precipitation than the increase induced by increasing precipitation (Knapp et al. 2017). The application of the double asymmetrical model to crop yield, soil N_2O emission and precipitation change has not been tested.

To develop and test the response patterns of crop yield and soil N_2O emission to precipitation changes, several approaches have been used. Using long-term datasets, we can group all years into different precipitation categories (i.e., extreme dry, dry, normal, wet, and extreme wet years), and calculate the mean values of ecosystem response variables such as productivity. Response relationships between the mean values of response variable and precipitation can be developed. For example, using 20 years' data of observational and satellite-based datasets of plant productivity in China, Chang et al. (2023) found that productivity mostly showed a positive asymmetry to soil moisture.

Another common approach is conducting field manipulative experiments. By manipulating precipitation intensity and creating different treatment levels, ecosystem responses to precipitation changes can be derived. For example, Deng et al. (2016) conducted a field experiment with five precipitation treatments and showed that switchgrass aboveground net primary productivity (ANPP) responds in a single negative asymmetry model to precipitation change but soil respiration responds strongly to precipitation changes in an "S" curve model. Zhang et al. (2022) also reported a negative asymmetric model for ANPP but a positive asymmetric model for soil respiration in a desert grassland in China. Similarly, Wang et al. (2022) found that global terrestrial ecosystem gross primary productivity responds positively and asymmetrically to precipitation change. One issue with field experiments is that background precipitation may influence overall response patterns (Kukal and Irmak 2018; Song et al. 2019). Responses of soil respiration to temperature and precipitation vary dramatically different background precipitation (local climate) ranges (Wang et al. 2021). ANPP in a desert grassland showed different response patterns in a wet year compared to a dry year (Zhang et al. 2022).

In addition to field measurements, modeling techniques have been used to evaluate how plant productivity, crop yield, and soil N_2O emissions in agricultural ecosystems are affected by climate change (Stehfest and Bouwman 2006; Deng et al. 2016; Ehrhardt et al. 2018; Zhang et al. 2021; Abdalla et al. 2022). The modeling approaches can overcome some shortcomings of field observations such as difficulty in setting many treatment levels and the effects of background precipitation, and modeling can also assess the effects of climate change and management practices (Deng et al. 2016; Tian et al. 2016; Chen et al. 2019). Different ecosystem models have been used for the simulation of N transformations, as well as subsequent responses of soil N_2O emissions to agricultural practices and climate change (Stehfest and Bouwman 2006; Chen et al. 2019; Ehrhardt et al. 2018; Aballa et al. 2022). Specifically, a mechanistic, process-based model DeNitrification-DeComposition (DNDC) has been developed, modified, and extensively applied to calculate the greenhouse gas emissions at both small and large scales in different cropland ecosystems (Li et al. 1992a, b; Giltrap et al. 2010; Zhang et al. 2016; Ingraham and Salas 2019; Cui and Wang 2019). For example, Deng et al. (2016) parameterized the DNDC model based on a 3-year field experiment in a cornfield in Nashville, TN, and simulated the effects of different agricultural practices on soil N_2O emissions. It is feasible to evaluate and forecast the effects of various agricultural management techniques on soil N_2O emissions since the DNDC model takes into account all significant N processes such as nitrification and denitrification and the N_2O transport process (Li et al. 1992a, b; Wang et al. 2021). Variables that affect nitrification and denitrification processes in the model include microbial activity, redox potentials, active organic carbon, ammonium nitrate and nitrogen content and the dynamics of the microbial denitrifier populations (Liu et al. 2011). It is ideal to use the DNDC to test the impacts of climate change on plant and soil greenhouse gas emissions and explore the response patterns and potential mechanisms.

In this study, we extended our previous model exercise to investigate the responses of corn yield and soil N_2O emission using a previously calibrated DNDC model (Deng et al. 2016; Zhang et al. 2021). Two approaches and climate data were used: the natural precipitation variation of a long-term (40-year) precipitation dataset, and a precipitation manipulation of seven levels (from − 50% to + 50% of ambient precipitation). To test the impacts of background precipitation on response patterns, we selected 3 years representing dry, normal, and wet conditions from the long-term precipitation dataset and set precipitation treatments at seven levels for each year. The major objectives of this study were: (1) to explore the coupled response patterns of corn yield and soil N_2O emission to precipitation change using a long-term dataset; (2) to evaluate the impacts of background precipitation on the response patterns of corn yield and soil N_2O emission to precipitation manipulations.

Materials and methods

The DNDC model and model validation

We used the DNDC model (version 95; http://www.dndc.sr.unh.edu) to simulate and evaluate corn yield and soil N_2O emissions. The DNDC model was originally developed to simulate plant growth and greenhouse gases emissions, including soil N_2O emissions, from croplands (Li et al. 1992a, b) and has been widely applied in different terrestrial ecosystems under different agricultural practices and environmental conditions (Uzoma et al. 2015; Deng et al. 2016; Abdalla et al. 2022). This model includes a suite of biogeochemical processes, such as 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; Zhang et al. 2021). There are two major components in the model. 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), and growth of plants under these conditions. 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 plant-soil systems. Simulated crop yield is influenced by precipitation through plant water uptake and growth, and soil N_2O emissions are primarily regulated by soil environmental variables, e.g., soil temperature and water-filled pore space, and substrate availability (e.g., dissolved organic carbon and inorganic N) through denitrification and nitrification processes (Fig. 1).

The model has been parameterized and validated based on a 3-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 (Deng et al. 2015). The model inputs included meteorological data, soil properties, crop parameters, and farming management practices (Deng et al. 2015, 2016; Zhang et al. 2021). Simulated corn yield and soil N_2O emission overall matched well with the field measurements (Additional file 1: Fig. S1, Deng et al. 2016). We also used this validated model and simulated the impacts of precipitation patterns and N application on soil N_2O emission (Zhang et al. 2021). In this study, the same model parameters, including soil properties and plant variables, were used for model runs described below.

Experimental design to simulate the effects of precipitation change on corn yield and soil N_2O emission

Two model simulations/experiments were performed to investigate the response patterns of corn yield and soil N_2O emission to precipitation in this study. In experiment I, we simulated corn yield and soil N_2O emission over 1 year each time with climate data from a long-term climate dataset (40 years, 1981–2020). The dataset was downloaded at NASA POWER CERES/MERRA2 Native Resolution Daily Data website (https://power.larc.nasa.gov/data-access-viewer/) which included daily air temperature and precipitation. Annual precipitation ranged from 926 to 1682 mm during this time period (Fig. 2a). The highest precipitation was recorded in 2020 and the lowest in 2007. Mean average precipitation was 1325.4 mm, range was 793.7 mm, standard deviation was 197.1 mm, and coefficient of variation (CV) was 14.9%. For each model run, we used one of 40 year's climate data between 1981 and 2020 from the long-term climate dataset. All soil properties, cropping and management practices were the same and the only difference was the climate drivers. This way, the changes of simulated corn yield and soil N_2O emission were only caused by climate data. The model was run daily for crop growth and greenhouse gas emissions in 1 year. Corn yield and annual total soil N_2O emission for each year were generated by the model simulation.

In experiment II, we tested the impacts of background precipitation on the response patterns of corn yield and soil N_2O emission to precipitation. We first selected 3 years from 1981 to 2020 that represented a dry year

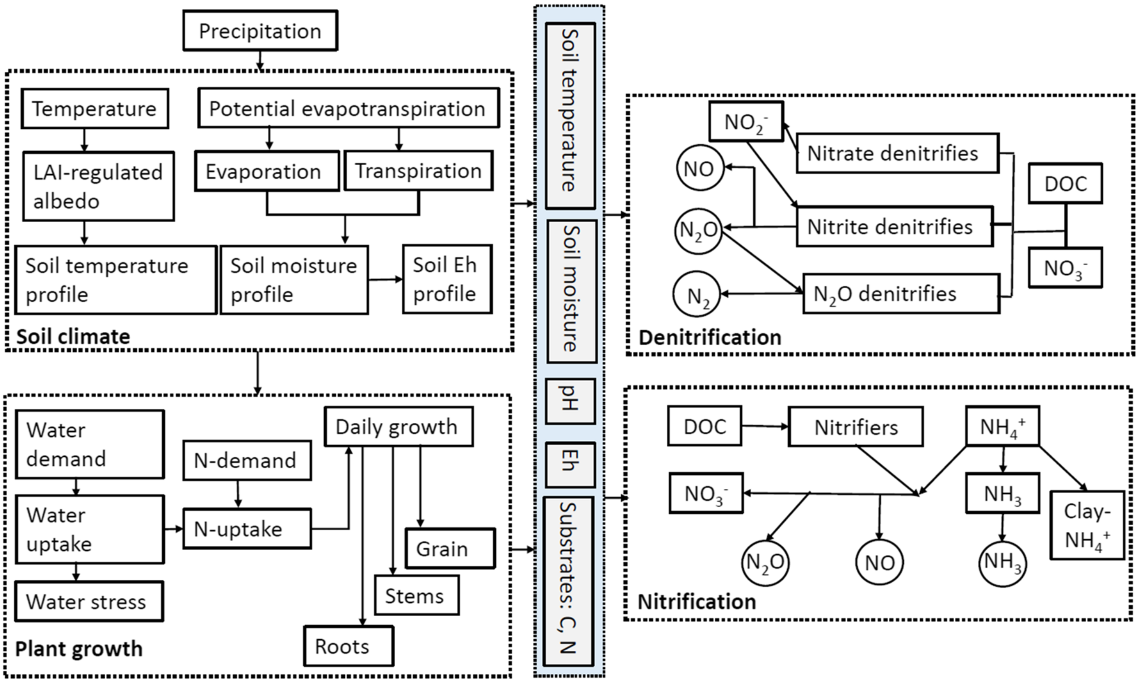

Fig. 1 The impacts of precipitation on plant growth and soil N_2O emission through denitrification and nitrification processes in the DNDC model

(2007), a normal year (1997), and a wet year (2020). These years were chosen based on the annual total precipitation of the years. Year 2007 received the lowest precipitation, and year 2020 received the highest precipitation, and annual total precipitation of year 1997 was closest to the mean annual precipitation of 40 years. Then for each of the three selected years, we manipulated the precipitation intensity and set seven precipitation treatments, including ambient precipitation of the year, − 15%, − 30%, and − 50% of ambient precipitation to represent drought treatments, and + 15%, + 30%, and + 50% of ambient precipitation to represent wet treatments (Additional file 1: Table S1). For example, − 15% precipitation reduction treatment was set by reducing the amount of each precipitation event by 15%, and + 15% precipitation addition treatment was set by adding 15% of precipitation to each precipitation event. Based on 40 years' data, − 30% and + 30% of ambient precipitation were still within the normal range of 40 years' precipitation. The treatments of − 50% and + 50% of ambient precipitation were considered extreme precipitation treatments. The extreme drought treatments were lower than minimum precipitation, but the extreme wet precipitation treatment in the dry background (2007) was still lower than maximum precipitation during 1981–2020 (Additional file 1: Table S1). The model was run for each precipitation treatment, with all other model settings remained the same, for a total of 21 runs.

To assess the reliability of model simulation, we conducted an uncertainty analysis of simulated corn yield and soil N_2O emission for the dry, normal, and wet years. Daily precipitation of 1 year was randomly varied (i.e., increased or decreased) by up to 10%, and the model was run for 1000 times for the year. The minimum, maximum, mean, and standard deviation of corn yield and annual total soil N_2O emission of 1000 runs were calculated and compared to the simulated corn yield and soil N_2O emission of the year.

Data analysis

In experiment I, we grouped 40 years' precipitation into seven categories based on the mean annual precipitation (MAP) and percentage changes. The mean MAP of 40 years was 1325.4 mm. The years with precipitations within – 5% and 5% of the mean MAP were considered as normal years. There were three categories for wet years with precipitation rates that are + 5% to + 10% , + 10% to + 20%, and + 20% to + 30% more than the mean MAP. Similarly, the three dry categories included years with precipitation − 5% to − 10%, − 10% to − 20%, and − 20% to − 30% lower than the mean MAP. There was only 1 year (2007) precipitation (926 mm) was smaller than the – 30% of ambient precipitation (927.8 mm) which was included in the – 20% to – 30% category. Mean and standard deviation of precipitation in each category were presented in Additional file 1: Table S2.

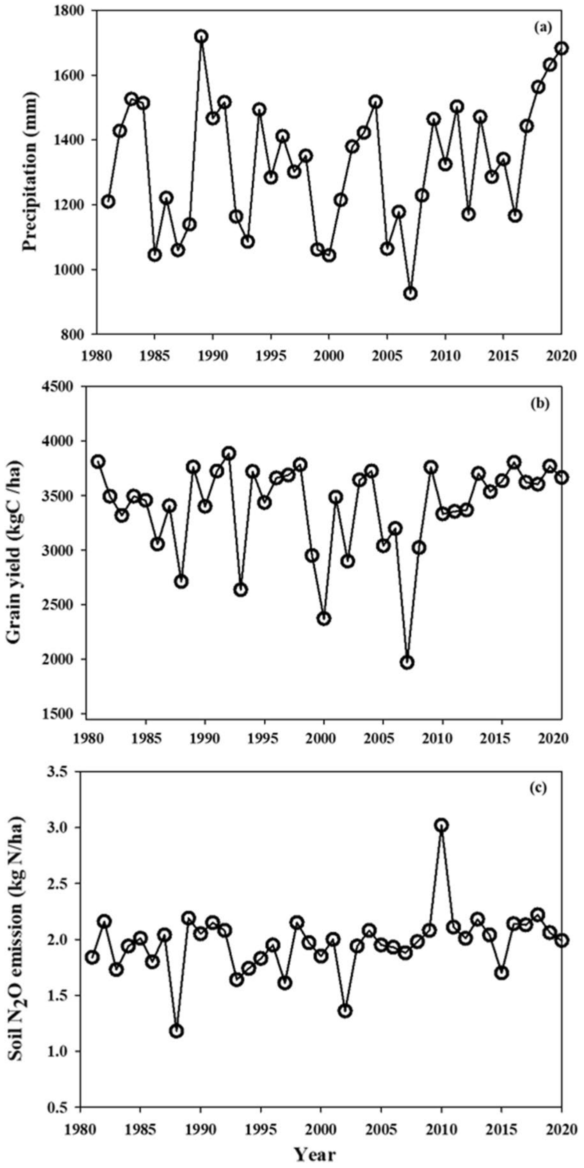

Fig. 2 The variations of precipitation (**a**), simulated corn yield (**b**), and soil N_2O emission (**c**) from 1981 to 2020 using the long-term precipitation dataset

In each category, mean vales of simulated corn yield, and soil N_2O emission among years were also calculated. The effects of precipitation category on corn yield and soil N_2O emission were tested using analysis of variance (ANOVA). Multiple comparisons were conducted using Least Square Difference (LSD) method when the effect was significant. Data analysis was conducted using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). The response patterns of corn yield and soil N_2O emission to precipitation were plotted and relative changes of corn yield and soil N_2O emission to normal years' values were plotted against the relative change of precipitation to precipitation in the normal years.

In experiment II, we first tested the effects of precipitation treatment and year on corn yield and soil N_2O emission using ANOVA and conducted multiple comparisons when the effect was significant. The response patterns of corn yield and soil N_2O emission to precipitation were constructed, and relative changes of corn yield and soil N_2O emission to normal years' values against the relative change of precipitation to precipitation in normal years were plotted for the dry, normal, and wet years.

Results

Means and variations of simulated corn yield, and soil N_2O emission

The corn yield and soil N_2O emission were simulated using the DNDC model based on precipitation from each of the past 40 years (1981–2020). For corn yield, the maximum was 3887.3 kg C/ha recorded with climate in 1992 as compared to only 1970.45 kg C/ha in 2007 for a range of 1916.8 (Fig. 2b). Mean corn yield, standard deviation, and CV were 3398.2 kg C/ha, 425.2 kg C/ha, and 12.5%, respectively. Soil N_2O emission varied from 1.36 kg N/ha in 2002 to 2.22 kg N/ha in 2018 for a range of 1.8 kg N/ha (Fig. 2c). Mean soil N_2O emission, standard deviation, and CV were 1.97 kg N/ha, 0.28 kg N/ha, and 14.1%, respectively.

Response patterns of corn yield to precipitation change

The simulated corn yield increase with precipitation was nearly linear (Fig. 3a). There were significant differences in corn yield among seven precipitation categories (Additional file 1: Table S3). The lowest corn yield was simulated in the − 20% to − 30% category but was not significant different from the − 10% to − 20% category (Additional file 1: Table S4). It was significantly lower than all other categories, and 19.3% lower compared to the normal precipitation category (− 5% to + 5%). The highest yield was simulated in the + 20% to + 30% category but was not significantly different from the + 10% to + 20%, + 5% to + 10%, normal, and − 5% to − 10% categories. It was significantly higher than the − 10% to − 20% and − 20% to − 30% categories. Compared to the normal precipitation (− 5% to 5%) category, up to − 20% or + 20% category did not change corn yield (Additional file 1: Table S4).

Responses of soil N_2O emission to precipitation change

Result of ANOVA showed that there was no significant difference in soil N_2O emission among the seven precipitation categories (Additional file 1: Table S3). This could be caused by the large variations of soil N_2O emission within each category, particularly in the

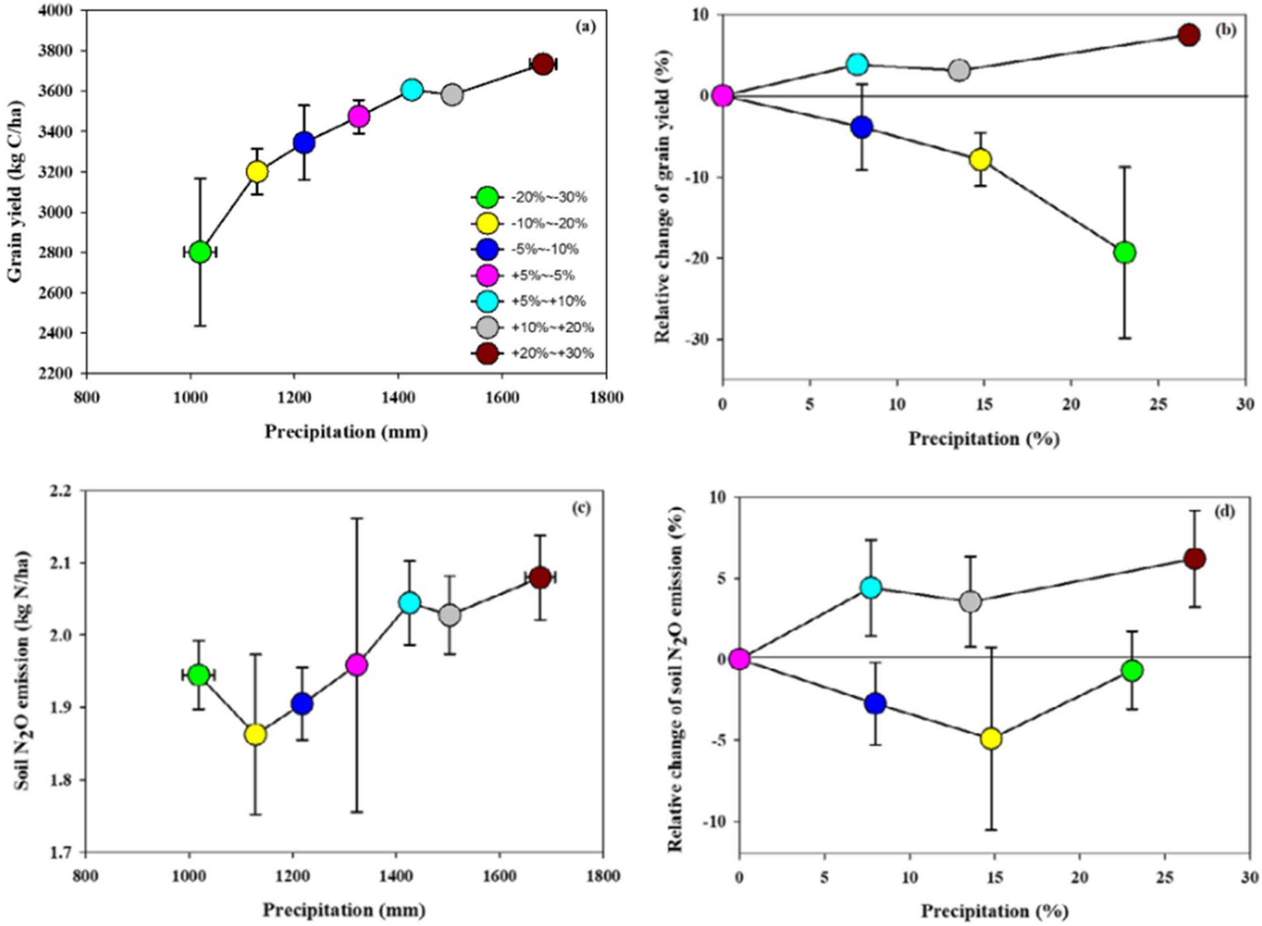

Fig. 3 The responses of corn yield (**a**, **b**) and soil N_2O emission (**c**, **d**) to precipitation change based on the long-term (40 years, 1981–2020) precipitation dataset. Color symbols indicated different precipitation categories

− 5% to + 5% and − 10% to − 20% categories (Fig. 3c). The large variations also indicated that not just annual total precipitation, but the timing of precipitation could influence soil N_2O emission, and soil N_2O emission could be very different even the annual total precipitations were similar. Soil N_2O emission in the highest dry (− 20% to − 30%) category showed a trend of increase which was caused by high soil N_2O emission simulated in 2 of 4 years (Fig. 3d). The potential causes and impact of precipitation timing on soil N_2O emission could have significant impacts on soil N_2O emission (Zhang et al. 2021).

Across seven precipitation categories, soil N_2O emission showed a trend of linear increase with precipitation (Fig. 3c, d). Except for the soil N_2O emission in the highest dry category, soil N_2O emission generally responded to precipitation followed a near symmetric response model (Fig. 3d).

Responses of corn yield to precipitation treatments in the dry, normal, and wet years

We tested the effects of precipitation treatments and background precipitation (dry, normal, and wet years) on corn yield using ANOVA. Results showed there were significant effects of precipitation treatment on corn yield, and corn yield varied among dry, normal, and wet years. Across the three background precipitation years, the mean corn yield in the – 50% treatment was significantly lower than any other treatments (Additional file 1: Table S5). It was 45.1% lower than the ambient treatment. The difference in corn yield between the − 30% and ambient precipitations was not significant (Additional file 1: Table S6). The + 50% treatment had the highest yield, but was not significantly different with the + 30%, + 15%, ambient, and even − 15% treatment. Among the background precipitation (years), corn yield in the dry year (2007) was significantly lower than in the

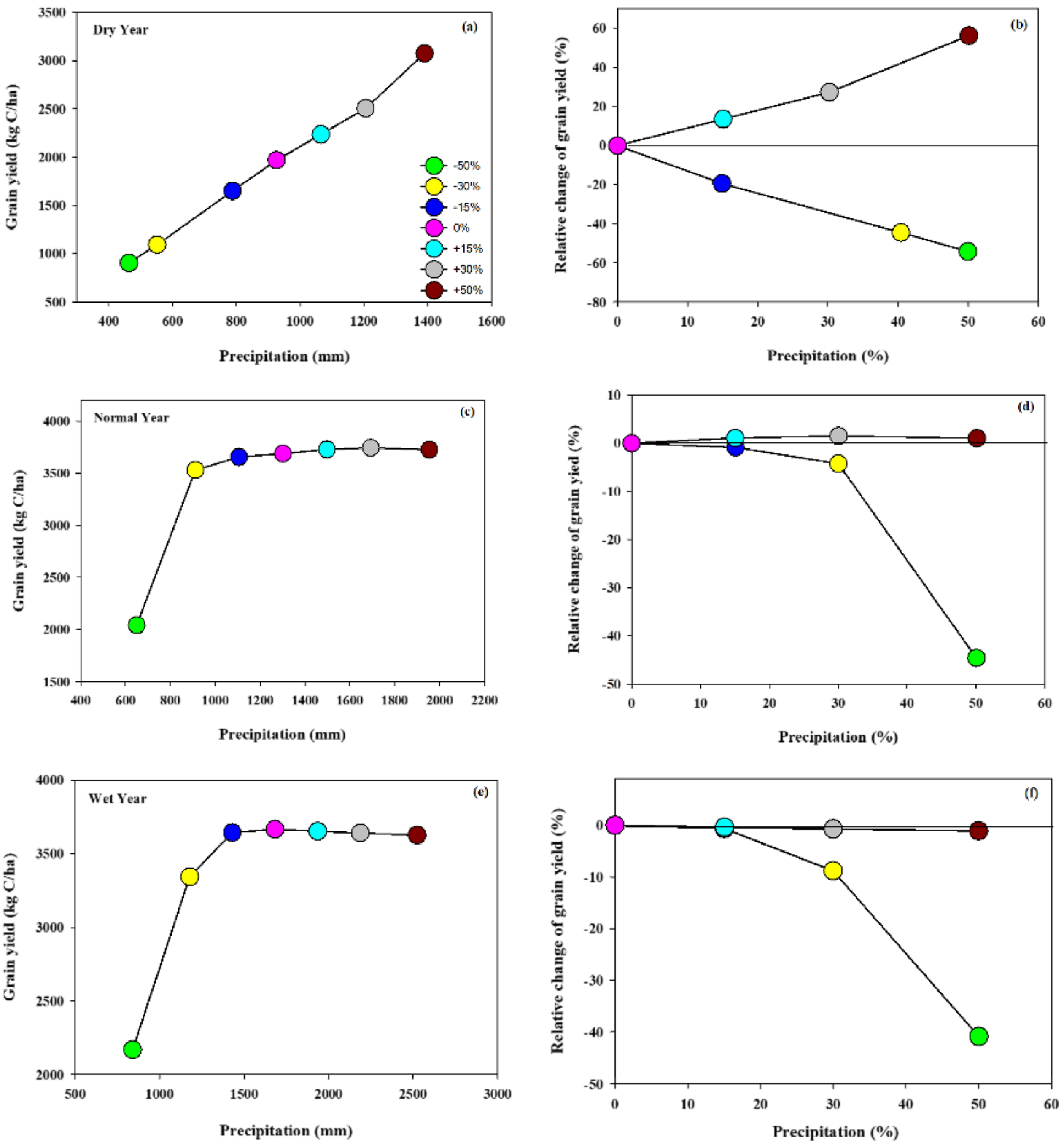

Fig. 4 The responses of corn yield to precipitation treatments in the dry (**a**, **b**), normal (**c**, **d**), and wet (**e**, **f**) years. Color symbols indicated different precipitation treatments

normal (2020) and wet (1997) years and there was no significant difference between the normal and wet years (Additional file 1: Table S6).

The response pattern of corn yield to precipitation varied dramatically among different background precipitation. In the dry year, corn yield increased linearly with precipitation, showing a symmetric response (Fig. 4a, b). In the normal year, corn yield did not change much from light drought treatment (− 15%) to extreme wet treatments (+50%), showing a single negative asymmetrical response associated only with the strongest drought (Fig. 4c, d). However, in the wet year, adding more precipitation showed a trend of decrease in corn yield (Fig. 4e, f). Drought treatments, particularly the extreme drought treatment (– 50%), dramatically reduced corn yield (Fig. 4; Additional file 1: Table S6).

Uncertainty analysis showed that simulated corn yields of 1000 runs had small ranges, and mean corn yields slightly differed from the corn yield simulated in the dry, normal, and wet years, but the differences were less than 1% (Additional file 1: Table S7). Smaller variations of simulated soil N_2O emission were found for all 3 years, and the mean soil N_2O emissions of 1000 runs were the same as the soil N_2O emissions in the 3 years. Our results indicated that model simulations were relatively stable and reliable.

Responses of soil N_2O emission to precipitation treatments in the dry, normal, and wet years

We tested the effects of precipitation treatments and background precipitation (dry, normal, and wet years) and their interaction on soil N_2O emission using ANOVA. Results showed that both precipitation treatments and background precipitation significantly influenced soil N_2O emission, but no interaction was found between them. The lowest soil N_2O emission occurred in the − 50% treatment, significantly lower all other treatments except the − 30% treatment (Additional file 1: Table S5). Soil N_2O emission was reduced by 21.3% in the − 50% treatment compared to the ambient precipitation treatment (Additional file 1: Table S6). The highest soil N_2O emission was simulated in the + 50% treatment, but there was no significant difference compared to the ambient and up to the + 30% treatments. It was only significantly higher than drought (− 15% to − 50%) treatments. Soil N_2O emissions in the nominal precipitation range (from − 30% to + 30%) were not significantly different from the ambient precipitation. Among the three background precipitation years, there were significant differences in soil N_2O emission. Soil N_2O emission in the wet year was significantly higher than in the normal year which was significantly higher than in the dry year (Additional file 1: Table S6).

Similar response patterns of soil N_2O emission to precipitation were shown in the dry, normal, and wet years (Fig. 5). Overall, soil N_2O emission responded to precipitation following a single negative asymmetrical model where drought treatments reduced more soil N_2O emission more than increased by the wet treatments. But magnitude varied among the background precipitations. The decreases in precipitation in the dry year reduced more soil N_2O emission than those in normal and wet years, particularly for the − 30% treatment (Fig. 5). Increases in precipitation increased more soil N_2O emission in the wet and normal years than in the dry year, especially the + 50% treatment.

Discussion

Response pattern of corn yield to precipitation change

The findings of this study indicated that corn yield was directly influenced by annual precipitation and almost linearly increased with increases in precipitation (Fig. 3). This result was consistent with several previous studies (Payero et al. 2006; Daryanto et al. 2016; Xu et al. 2021). For example, Payero et al. (2006) reported that crop yield increases linearly with seasonal irrigation. But other studies also found different response patterns. In one study in the US, Xu et al. (2021) found that corn yield of 28.6% counties linearly increases with precipitation, but 30.4% counties show no relationship between yield and precipitation, and 40.3% counties show inverse-U-shaped relationship. Klocke et al. (2011) found that the relationship of relative corn yield and irrigation follows a curvilinear model. The different responses could be caused by the balance between crop water demand and supply, and whether optimal precipitation supply is satisfied (Xu et al. 2021). In dry conditions when precipitation is below optimal precipitation, corn yield would show a linear response to precipitation. Indeed, corn yield had a nearly linear increase in this study based on the long-term precipitation dataset. The decrease in the yield was seen to be more noticeable as compared to the increase in the corn yield when precipitation was high (Fig. 3a, b). The precipitation response of yield illustrates the combined impact of several physiological and environmental processes of crop development and yield production and their reactions to precipitation (Xu et al. 2021). Climate factors like precipitation can affect nutrient availability in the soil, plant nutrient uptake, and therefore corn yield. An increase in precipitation could reduce water stress and increase yield under drier or hotter conditions when precipitation is below the optimal levels (Asghari and Hanson 1984). Corn is sensitive to drought and low precipitation conditions during the growing seasons could remarkably reduce the crop's development and yield production (Daryanto et al. 2016), resulting a single asymmetric response.

Response patterns of soil N_2O emission to precipitation change

Variations in precipitation have an impact on soil N dynamics, microbial activity, and the corresponding soil N_2O emission (Tian et al. 2017; Zhang et al. 2021). The results from model simulation showed that soil N_2O emissions generally increased with an increase in precipitation (Fig. 3c, d). Similar results were found in Zhang et al. (2021), Miller et al. (2022), and Li et al.

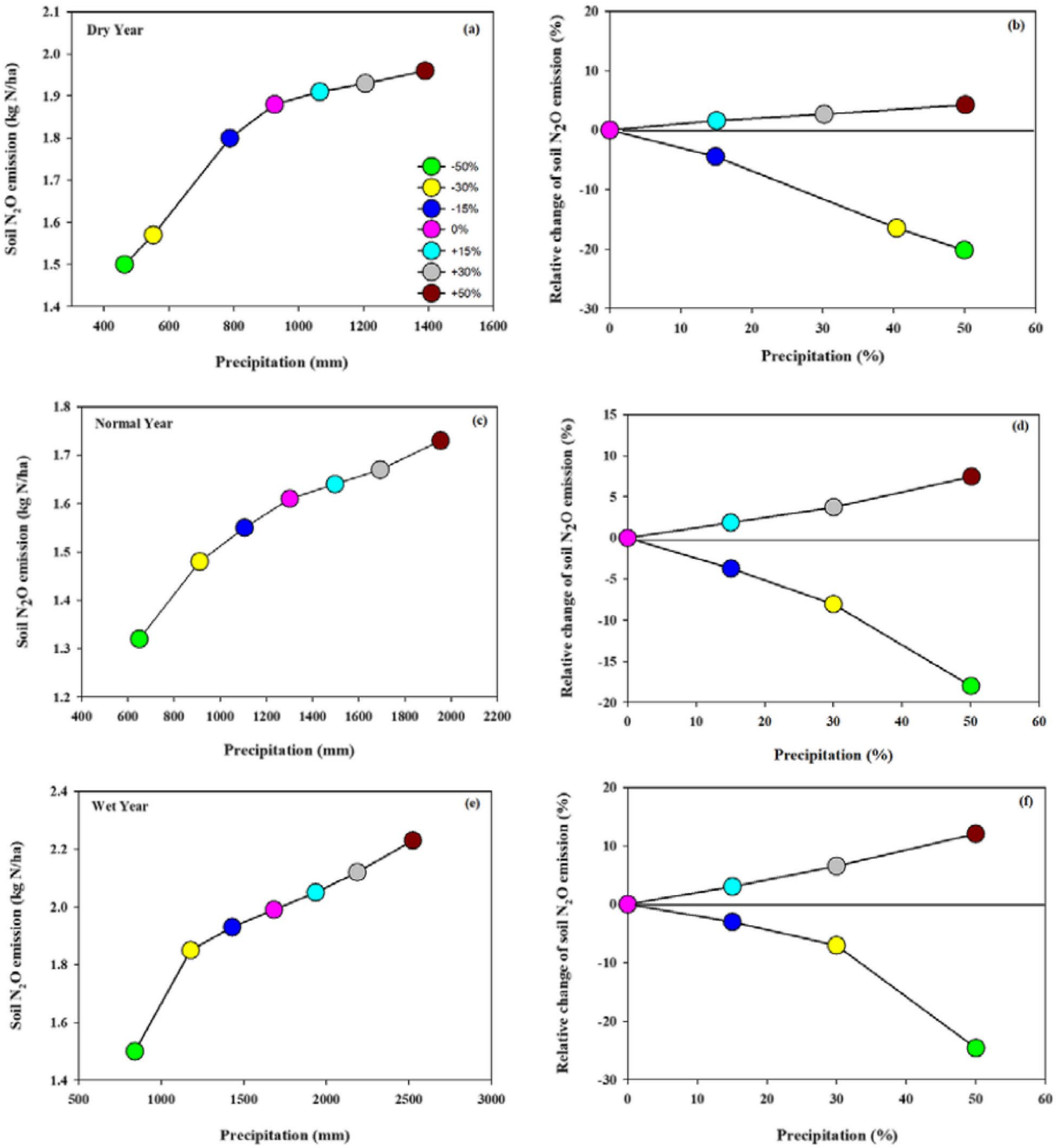

Fig. 5 The responses of soil N_2O emission to precipitation treatments in the dry (**a**, **b**), normal (**c**, **d**), and wet (**e**, **f**) years. Color symbols indicated different precipitation treatments

(2019). Changes in precipitation have a direct impact on soil moisture, which controls soil N_2O emission. The processes of nitrification and denitrification are significantly influenced by soil moisture. While denitrification has a greater potential than nitrification to increase soil N_2O emission in anaerobic and saturated conditions, soil nitrification still accounts for most of the soil N_2O emission overall (Zhang et al. 2021). In contrast to the accompanying positive effect, such as an increase in C and N substrate inputs and favorable aerobic environments for nitrifiers, soil N_2O emission was more impacted by the negative effects induced by precipitation decrease, such as the suppression of microorganism activities, a decline in N mineralization, and an unfavorable aerobic environment for denitrifiers, therefore affecting the process of denitrification (Shi et al. 2012; Larsen et al. 2011). In this study, we found that denitrification process played a key role in soil N_2O emission, as strong linear regressions were found between soil N_2O emission and denitrification rate using both the long-term dataset and manipulated precipitation (Fig. 6). It is also generally recognized that the substrates for the soil nitrification and denitrification processes are soil NH_4^+-N and NO_3^--N (Yue et al. 2019). Changes in precipitation have been proven to have a significant impact on soil NH_4^+-N and NO_3^--N concentrations. Indeed, in this study, soil NH_4^+-N showed a linear relationship with precipitation (NH_4^+-N = − 0.5219 + 0.0017 × Precipitation, $R^2 = 0.56^{**}$). We found a small increase in soil N_2O emission when precipitation was the lowest during the 40 years of this study. The higher soil N_2O emission in the most drought category was probably caused by precipitation timing (Zhang et al. 2021). The linear and near symmetric response of soil N_2O emissions to precipitation change using the 40-year precipitation dataset showed the soil N_2O emission responded similarly to precipitation increase and decrease within normal precipitation range.

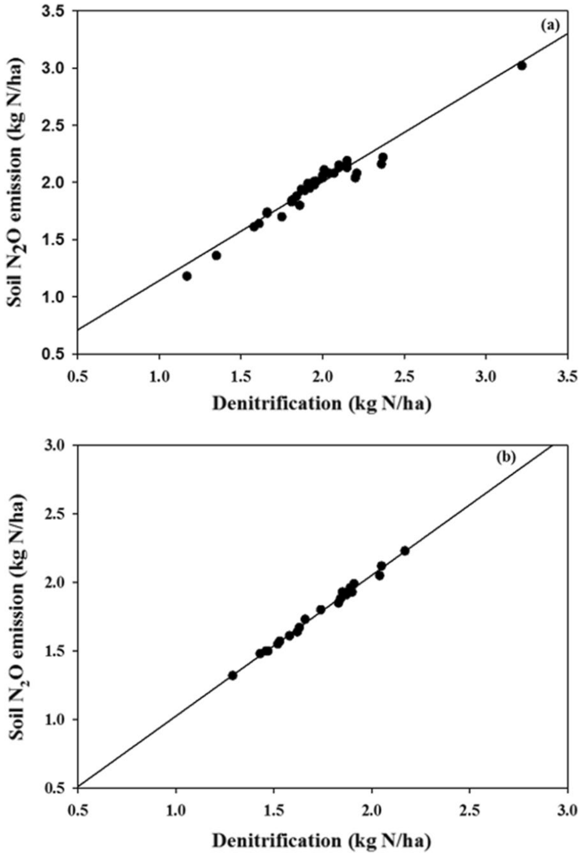

Fig. 6 The relationship between soil N_2O emission and denitrification rate based on the long-term dataset (**a**) and under different precipitation treatments (**b**)

Response patterns of corn yield to precipitation change in the dry, normal, and wet years

One interesting finding was that the response of corn yield to precipitation varied with background precipitation conditions (Fig. 4). The linear response of crop yield to precipitation treatments under the dry year was similar to the response pattern above with the long-term precipitation dataset (Fig. 4a, b). Corn yield increased with increases in precipitation and decreased with decreases in precipitation. Corn is a diclinous monoecious plant, and under droughts, flower development could be negatively influenced, resulting in the reduction of corn yield during limited water availability (Daryanto et al. 2016). Under normal background precipitation, corn yield did not change much with precipitation increase treatments, probably due to that the requirement of soil moisture by plants was satisfied and extra precipitation addition did not stimulate plant growth and grain production (Fig. 4c, d). Under this condition, water is not a major limiting factor for crop growth (Xu et al. 2021). Only extreme drought treatment dramatically reduced the corn yield. In the wet year, corn yield tended to decrease under the precipitation increase treatments (Fig. 4e, f). Reduced corn yield during the high precipitation intervals is caused by excessive moisture that created water stress to crop growth. Excessive precipitation during the sowing period can prevent soil aeration and increase disease pressure by interfering with growth and grain yield (Huang et al. 2015). The drought treatments, particularly the extreme drought, still remarkably reduced corn yield. As a result, a nonlinear and asymmetric response of corn yield to precipitation was observed under normal and wet conditions.

Response patterns of soil N_2O emission to precipitation change in the dry, normal, and wet years

Interestingly, similar response patterns of soil N_2O emission to precipitation were found under the dry, normal, and wet conditions (Fig. 5). In general, nonlinear and single asymmetrical responses of soil N_2O emission to precipitation was revealed in this study. The response pattern was also similar to that using the long-term precipitation dataset. High intensity of rainfall affects the soil N_2O emissions by increasing the water content in soil and hence providing conditions favoring the process of denitrification. In addition, high precipitation could lead to the breakdown of soil macroaggregates, exposing physically protected organic matter that was difficult for microorganisms to access, and providing more readily available substrate to microbes, therefore, increasing the microbial activity (Zhang et al. 2021). In the model, the increase in soil moisture significantly enhanced the soil denitrification rate and soil available carbon content and therefore promoted soil N_2O emission. A linear relationship between soil N_2O emission and nitrification was found across all precipitation treatments and background precipitations in this study ($N_2O = -0.0032 + 1.0278 \times$ Denitrification, $r^2 = 0.99^{**}$; Fig. 6b). A decline of soil N_2O emission was noticed when the precipitation was low. There is a reduction in solute transport and a high risk of soil microbial motility due to excessive desiccation during low soil moisture conditions (Beare et al. 2009; Shi et al. 2012). Soil microbial biomass C and N, the number of certain microorganisms, and soil N_2O emission rates are found to be dramatically reduced during drought conditions (Shi et al. 2012; Hartmann et al. 2013; Homyak et al. 2017).

Conclusions

Simulating corn yield and soil N_2O emission under different precipitation intensities based on a long-term precipitation dataset and manipulated precipitation treatments using the DNDC model, we demonstrated that the response pattern of corn yield to precipitation varied with background precipitation. Corn yield nearly linearly increased with precipitation based on long-term simulations and in the dry year, showed little response to increases in precipitation in the normal and wet years, and decreased in drought treatments. In contrast, soil N_2O emission mostly linearly increased with precipitation under different background precipitation conditions. However, soil N_2O emission was reduced more with decreases in precipitation in the dry year compared to the normal and wet years, and soil N_2O emission was increased more with increases in precipitation in the wet and normal years than the dry year. This study demonstrated the important role of background precipitation and suggested that background conditions should be considered when developing the response patterns of certain variables to precipitation change.

Abbreviations

ANPP	Aboveground net primary productivity
MAP	Mean annual precipitation
N_2O	Nitrous oxide

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13717-023-00429-w.

Additional file 1. Figure S1. Comparison between model simulated and field observed N_2O emissions at the growing season over 3 years in a cornfield using the DNDC model. **Table S1**. Mean and range of precipitation of seven precipitation categories based on averaged mean annual precipitation (1325.4 mm) and percentage changes based on average precipitation over the 40 years (1981–2020) in a long-term climate dataset. **Table S2**. Annual total precipitations (mm) of different precipitation treatments in different background precipitations (years) in the experiment II. **Table S3**. ANOVA of the effects of precipitation category on corn yield and soil N_2O emission based on a long-term climate dataset. **Table S4**. Multiple comparison of yield and soil N_2O emission among seven precipitation categories based on a long-term climate dataset. **Table S5**. ANOVA of the effects of background precipitation (year), precipitation treatment, and their interaction on corn yield and soil N_2O emission. **Table S6**. Multiple comparison of yield and soil N_2O emission among seven precipitation treatments and three background precipitations (years). **Table S7**. Uncertainty analysis of simulated corn yield and soil N_2O emissions in the dry, normal, and wet years.

Acknowledgements

This research was supported by the Department of Energy (DOE) RDPP project, National Science Foundation (NSF) MRI and EiR projects, U.S. Department of Agriculture (USDA) projects, and Tennessee State University (TSU) RSP Seed grant. MAM was financially supported by the U.S. 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. We thank the editors and two anonymous reviewers for their constructive comments and suggestions.

Author contributions

DH developed the ideas for this manuscript. NK and DH conducted the model runs and data analysis, and drafted the manuscript. All authors contributed to the writing of the manuscript. All authors read and approved the final manuscript.

Funding

This research was supported by the Department of Energy (DOE) RDPP project, National Science Foundation (NSF) MRI and EiR projects, U.S. Department of Agriculture (USDA) projects, and Tennessee State University (TSU) RSP Seed Grant. MAM was financially supported by the U.S. DOE Office of Biological and Environmental Research through the Terrestrial Ecosystem Science Scientific Focus Area at Oak Ridge National Laboratory (ORNL).

Availability of data and materials

The datasets generated and analyzed during the current study are available in the figshare repository at https://doi.org/10.6084/m9.figshare.22335598.v1.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

The authors consent to publish the data included in this draft.

Competing interests

The authors declare that they have no competing interests.

Received: 7 December 2022 Accepted: 21 March 2023

References

Abdalla M, Song X, Ju X, Smith P (2022) Evaluation of the DNDC model to estimate soil parameters, crop yield and nitrous oxide emissions for alternative long-term multi-cropping systems in the north China plain. Agronomy 12(1):109

Asghari M, Hanson RG (1984) Nitrogen, climate, and previous crop effect on corn yield and grain N. Agron J 76(4):536–542

Bannayan M, Sadeghi S, Sanjani S, Mohamadian A, Aghaalikhani M (2011) Effects of precipitation and temperature on crop production variability in northeast Iran. Int J Biometeorol 55(3):387–401

Beare MH, Gregorich EG, St-Georges P (2009) Compaction effects on CO_2 and N_2O production during drying and rewetting of soil. Soil Biol Biochem 41(3):611–621

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(8):899–911

Cammarano D, Hawes C, Squire G, Holland J, Rivington M, Murgia T, Roggero PP, Fontana F, Casa R, Ronga D (2019) Rainfall and temperature impacts on barley (*Hordeum vulgare* L.) yield and malting quality in Scotland. Field Crops Res 241:107559

Chang Q, He H, Ren X, Zhang L, Feng L, Lv Y, Zhang M, Xu Q, Liu W, Zhang Y, Wang T (2023) Soil moisture drives the spatiotemporal patterns of asymmetry in vegetation productivity responses across China. Sci Total Environ 855:158819

Changnon SA, Hollinger SE (1993) The potential use of summer rainfall enhancement in Illinois. Part I: a field experiment to define responses of crop yields to increased rainfall. J Appl Meteorol Climatol 32(3):445–454

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

Cui G, Wang J (2019) Improving the DNDC biogeochemistry model to simulate soil temperature and emissions of nitrous oxide and carbon dioxide in cold regions. Sci Total Environ 687:61–70

Daryanto S, Wang L, Jacinthe PA (2016) Global synthesis of drought effects on maize and wheat production. PLoS ONE 11(5):e0156362

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 10:e0125406. 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

Ehrhardt F, Soussana JF, Bellocchi G, Grace P, McAuliffe R, Recous S, Sándor R, Smith P, Snow V, de Antoni MM, Basso B (2018) Assessing uncertainties in crop and pasture ensemble model simulations of productivity and N_2O emissions. Glob Change Biol 24(2):e603–e616

Gao Z, Wang C, Zhao J, Wang K, Shang M, Qin Y, Bo X, Chen F, Chu Q (2022) Adopting different irrigation and nitrogen management based on precipitation year types balances winter wheat yields and greenhouse gas emissions. Field Crop Res 280:108484

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

Hartmann AA, Barnard RL, Marhan S, Niklaus PA (2013) Effects of drought and N-fertilization on N cycling in two grassland soils. Oecologia 171(3):705–717

Homyak PM, Allison SD, Huxman TE, Goulden ML, Treseder KK (2017) Effects of drought manipulation on soil nitrogen cycling: a meta-analysis. J Geophys Res Biogeosci 122(12):3260–3272

Hossain ML, Beierkuhnlein C (2018) Enhanced aboveground biomass by increased precipitation in a central European grassland. Ecol Process 7:37

Houghton JT, Ding YDJG, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) (2001). Climate Change 2001—The Scientific Basis. Cambridge University Press

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

Huang C, Duiker SW, Deng L, Fang C, Zeng W (2015) Influence of precipitation on maize yield in the Eastern United States. Sustainability 7(5):5996–6010

Huang Y, Ciais P, Boucher O, Wang Y, Tian H, Zhou F, Chang J, Li Z, Goll DS, Langenfelds R, Shi H (2022) Increasing sensitivity of terrestrial nitrous oxide emissions to precipitation variations. Environ Res Climate 1:025010

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, 151

Kennedy TL, Suddick EC, Six J (2013) Reduced nitrous oxide emissions and increased yields in California tomato cropping systems under drip irrigation and fertigation. Agr Ecosyst Environ 170:16–27

Klocke NL, Currie RS, Tomsicek DJ, Koehn J (2011) Corn yield response to deficit irrigation. Trans ASABE 54(3):931–940

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

Knapp AK, Ciais P, Smith MD (2017) Reconciling inconsistencies in precipitation–productivity relationships: implications for climate change. New Phytol 214(1):41–47

Kukal MS, Irmak S (2018) Climate-driven crop yield and yield variability and climate change impacts on the U.S great plains agricultural production. Sci Rep 8:1–18

Larsen KS, Andresen LC, Beier C, Jonasson S, Albert KR, Ambus PER, Arndal MF, Carter MS, Christensen S, Holmstrup M, Ibrom A (2011) Reduced N cycling in response to elevated CO_2, warming, and drought in a Danish heathland: synthesizing results of the CLIMAITE project after two years of treatments. Glob Change Biol 17(5):1884–1899

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 Atmos 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 Atmos 97:9777–9783. https://doi.org/10.1029/92jd00510

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

Lobell DB, Cahill KN, Field CB (2007) Historical effects of temperature and precipitation on California crop yields. Clim Change 81(2):187–203

Miller LT, Griffis TJ, Erickson MD, Turner PA, Deventer MJ, Chen Z, Yu Z, Venterea RT, Baker JM, Frie AL (2022) Response of nitrous oxide emissions to individual rain events and future changes in precipitation. J Environ Qual 51(3):312–324

Payero JO, Melvin SR, Irmak S, Tarkalson D (2006) Yield response of corn to deficit irrigation in a semiarid climate. Agric Water Manag 84(1–2):101–112

Plaza-Bonilla D, Léonard J, Peyrard C, Mary B, Justes E (2017) Precipitation gradient and crop management affect N_2O emissions: simulation of mitigation strategies in rainfed Mediterranean conditions. Agr Ecosyst Environ 238:89–103

Shi F, Chen H, Chen H, Wu Y, Wu N (2012) The combined effects of warming and drying suppress CO_2 and N_2O emission rates in an alpine meadow of the eastern Tibetan Plateau. Ecol Res 27(4):725–733

Song J, Wan S, Piao S, Knapp AK, Classen AT, Vicca S, Ciais P, Hovenden MJ, Leuzinger S, Beier C, Kardol P (2019) A meta-analysis of 1,119 manipulative experiments on terrestrial carbon-cycling responses to global change. Nat Ecol Evol 3(9):1309–1320

Stehfest E, Bouwman L (2006) N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutr Cycl Agroecosyst 74(3):207–228

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 N_2O and NO emissions, water saving and corn 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
Trenberth KE, Fasullo JT, Shepherd TG (2015) Attribution of climate extreme events. Nat Clim Chang 5(8):725–730
Uzoma KC, Smith W, Grant B, Desjardins RL, Gao X, Hanis K, Tenuta M, Goglio P, Li C (2015) Assessing the effects of agricultural management on nitrous oxide emissions using flux measurements and the DNDC model. Agr Ecosyst Environ 206:71–83
Wang C, Amon B, Schulz K, Mehdi B (2021) Factors that influence nitrous oxide emissions from agricultural soils as well as their representation in simulation models: a review. Agronomy 11(4):770
Wang Y, Xiao J, Li X, Niu S (2022) Global evidence on the asymmetric response of gross primary productivity to interannual precipitation changes. Sci Total Environ 814:152786
Weltzin JF, Loik ME, Schwinning S, Williams DG, Fay PA, Haddad BM, Harte J, Huxman TE, Knapp AK, Lin G, Pockman WT (2003) Assessing the response of terrestrial ecosystems to potential changes in precipitation. Bioscience 53(10):941–952
Wu Z, Dijkstra P, Koch GW, Peñuelas J, Hungate BA (2011) Responses of terrestrial ecosystems to temperature and precipitation change: a meta-analysis of experimental manipulation. Glob Change Biol 17(2):927–942
Xie Y, Zhang M, Xiao W, Zhao J, Huang W, Zhang Z, Hu Y, Qin Z, Jia L, Pu Y, Chu H (2022) Nitrous oxide flux observed with tall-tower eddy covariance over a heterogeneous rice cultivation landscape. Sci Total Environ 810:152210
Xu R, Li Y, Guan K, Zhao L, Peng B, Miao C, Fu B (2021) Divergent responses of maize yield to precipitation in the United States. Environ Res Lett 17(1):014016
Ye JS, Pei JY, Fang C (2018) Under which climate and soil conditions the plant productivity–precipitation relationship is linear or nonlinear? Sci Total Environ 616:1174–1180
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
Zhan W, He X, Sheffield J, Wood EF (2020) Projected seasonal changes in large-scale global precipitation and temperature extremes based on the CMIP5 ensemble. J Clim 33(13):5651–5671
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 H, Deng Q, Schadt CW, Mayes MA, Zhang D, Hui D (2021) Precipitation and nitrogen application stimulate soil nitrous oxide emission. Nutr Cycl Agroecosyst 120(3):363–378
Zhang L, Wang J, Zhao R, Guo Y, Hao L (2022) Aboveground net primary productivity and soil respiration display different responses to precipitation changes in desert grassland. J Plant Ecol 15(1):57–70
Zscheischler J, Orth R, Seneviratne SI (2017) Bivariate return periods of temperature and precipitation explain a large fraction of European crop yields. Biogeosciences 14(13):3309–3320

Publisher's Note