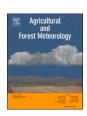
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Distinct driving mechanisms of non-growing season N₂O emissions call for spatial-specific mitigation strategies in the US Midwest

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ABSTRACT

Agricultural N2O emission is a growing concern for climate change. Recent field evidence suggests that nongrowing seasons (NGS) may contribute one-third to half of the annual N₂O emissions, but implications on management adaptations remain unclear. Here we used an advanced process-based model, ecosys, to investigate the magnitude and drivers of NGS N2O emissions from the US Midwest. Results showed that simulated NGS N2O emissions accounted for 6-60% of the annual fluxes under continuous corn systems, peaking in counties with NGS precipitation (P_{NGS}) around 300 mm. Divergent patterns of spatial-temporal correlations between NGS N_2O emissions and environmental variables were shown in the southeast ($P_{NGS} > 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest ($P_{NGS} < 300 \text{ mm}$) and the northwest (300 mm) of the study area by simulations. Causal analysis indicates that more intensive freezing caused by decreased air temperature (T_a) is the dominant driver that leads to NGS N_2O emissions increasing within the southeast of the study area, while increased PNGS and increased Ta cooperatively result in soil moisture decreasing at soil thaws that enhances NGS N2O production within the northwest of the study area. Scenario simulations suggest that annual N_2O emissions in the US Midwest are likely to reduce under climate change primarily due to the reduction of NGS N₂O emissions. Our estimates on monetized social benefits inform the necessity to implement spatial-specific mitigation strategies, i.e. determining fertilizer timing and use of nitrification inhibitors (NI). Spring fertilizer application is more beneficial than fall fertilizer application for most counties, however, the latter can bring extra benefits to some counties in the west of the study area. Introducing NI with either spring or fall applications can greatly increase social benefits by reducing N2O emissions and N leaching. This study addresses possibly effective adaptations by providing seasonal- and spatial-explicit mitigation potentials.

1. Introduction

Nitrous oxide (N_2O) has become a growing threat to climate change due to its much higher global warming potential compared to CO_2 and CH_4 (IPCC6; Forster et al., 2021) and rapid increase in atmospheric concentrations since the 1970s (Prinn et al., 2018; Thompson et al., 2019). As the largest anthropogenic N_2O source, agricultural ecosystems contributed 59–66% of the global direct N_2O emissions in the past four

decades, mainly as a result of fertilizer applications (Tian et al., 2020). N_2O emissions in agricultural soils are characterized by hot spots and hot moments (Krichels and Yang, 2019; Waldo et al., 2019), with peak N_2O pulses observed following rainfall and spring thaw events (Lawrence et al., 2021; Thilakarathna et al., 2020; Wagner-Riddle et al., 2007). However, quantification of N_2O emissions during freeze-thaw periods is inadequate as most observations only cover growing seasons (GS). Limited site-scale observations reported that non-growing season

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(NGS) N₂O emissions can contribute up to 70-90% of annual total emissions in some years (Abalos et al., 2016; Chen et al., 2021; Liu et al., 2019; Kariyapperuma et al., 2012; Wagner-Riddle et al., 2007). In the US Midwest, tall-tower N2O observations suggested that spring thaw and early growing season are two dominant modes in seasonal emission patterns of local croplands that accounted for 30% and 53% of annual emissions, respectively (Griffis et al., 2017). For example, ignoring NGS N₂O emissions will lead to a 35–65% underestimate in annual emissions for seasonally frozen croplands in the North Hemisphere and a 17-28% underestimate for global croplands (Wagner-Riddle et al., 2017). These NGS N2O emissions are highly variable over space and time due to the integrated influence of climatic, soil, and field management conditions (Wagner-Riddle et al., 2017; Shang et al., 2020; Chen et al., 2021), but are poorly characterized at aggregated scales (Lawrence et al., 2021). The effects of fertilizer rate, type, and timing on NGS N₂O emissions are not as well-known as those on GS N₂O emissions (Thies et al., 2020), which hinders optimal agricultural mitigation. Although N-fertilizer rates (Shang et al., 2020) or the usage of nitrification inhibitors (NI) (Chen et al., 2021) are described as less likely to influence the magnitude of NGS N₂O emissions, some field experiments demonstrated that NGS N₂O emissions vary with differences in fertilizer states (i.e. liquid or solid; Kariyapperuma et al., 2012), fertilizer application methods (i.e. broadcast or injected; Adair et al., 2019), and cover crop types (i.e. legume or non-legume; Thomas et al., 2017). Other studies found that interannual weather variations (Baral et al., 2022; Wagner-Riddle et al., 2017) and climate differences (Shang et al., 2020) are in control of NGS N2O emission variability.

Freeze-thaw cycles have significant impacts on NGS N2O emissions through influencing soil temperature, soil moisture, and gas transfer (Koponen and Martikainen, 2004; Risk et al., 2013; Singurindy et al., 2009). Previous studies inferred that greater NGS N2O emissions are associated with greater cumulative freezing-degree days in agricultural soils due to developing soil anaerobiosis under freezing (Wagner-Riddle et al., 2007,2017; Yanai et al., 2011) and increased mineralization of labile C, microbial cytoplasmic release at thaw (Brooks et al., 2005; Finger et al., 2016; Schimel et al., 2007). The freezing-thawing effect can be further complicated by snow cover, which affects soil temperature and hence freezing through insulation and soil moisture through snowmelt (Jia et al., 2021; Ma et al., 2018). Some experimental studies demonstrated that deeper snow cover will increase soil temperature and microbial biomass and consequently lead to increased N cycling rate and N₂O emissions (Jia et al., 2021; Xu et al., 2021). Moreover, freezing-thawing effects can be either enhanced by deeper snow cover because of longer freezing and higher soil moisture at thaw (Chen et al., 2021), or alleviated by deeper snow cover that reduces the freezing intensity and lowers soil mineral nitrogen pool by reducing soil aggregate disruption (Ruan and Robertson, 2017). Those inconsistent facts indicate that freeze-thaw effects are primarily associated with soil temperature and/or soil moisture but have spatial and temporal differences.

Field management is another factor that significantly influences NGS N₂O emissions. It was shown that the magnitude of NGS N₂O emissions is crucially related to fertilizer type, residue management, irrigation regime, and fallow duration (Shang et al., 2020). However, effective management practices that mitigate NGS N2O emissions while not increasing GS N2O emissions nor damaging crop production are understudied. For example, more NGS N2O mitigations are expected for fields under fall applications of N-fertilizer, which potentially leads to high NGS N2O emissions but is prevalent in some regions due to practical and economic considerations (Bierman et al., 2012). Thus, N2O mitigation under fall fertilizer applications probably needs to prioritize NGS consequences. Moreover, effective regional mitigation requires integrative assessment of crop production and environmental impact and optimize agronomic and environmental benefits (Kim et al., 2021). Mitigation hotspots for different practices need to be identified considering the spatial heterogeneity of environmental driving factors and

their complex interactions with management. Modeling studies that enable realistic considerations of management practices will be needed to investigate agricultural climate mitigation at a large scale.

Process-based models (PBMs) that incorporate mechanistic representations of biophysical and biochemical processes in agroecosystems are particularly useful in understanding complex interactions between environmental and management factors on N₂O emissions, which are unlikely to be completely answered by controlled experiments, especially when considering the spatio-temporal variations. PBMs also bring along advantages in assessing mitigation effectiveness under different management practices and climate change (Giltrap et al., 2020; Gurung et al., 2021), thus have been widely used in estimating and predicting N₂O emissions (Fuchs et al., 2020; Tian et al., 2018; Yue et al., 2019). However, hardly any of those models have been proactively utilized to evaluate NGS N₂O emissions and their importance at a regional scale.

Here we used an advanced PBM, ecosys, to estimate the NGS N2O emissions in croplands in the US Midwest during 2001-2020. Seasonally explicit N2O emissions were quantified at the county level to address three scientific questions in this study: (i) How much do NGS N2O emissions contribute to annual N2O emissions in the study area? We quantified the magnitude and variations of NGS N2O emissions from corn fields in each county across the Midwest. (ii) What are the key environmental drivers in the spatial and temporal variabilities of GS and NGS N2O emissions? We used PCMCI (Peter and Clark momentary conditional independence), a novel data-driven causal inference method (Runge et al., 2019), to better understand the complex and time-lagged interactions among multiple variables of interest. (iii) What are the spatial-explicit mitigation potentials of different field strategies in the context of climate change? To answer this question, we simulated the responses of N2O emissions to fertilizer timing, with and without NI under different climate scenarios. County-level social benefits under alternative N-fertilizer practices were synthesized upon the cost-benefit of yield, N2O emissions, N leaching, and change in soil organic carbon (△SOC), to assess agronomic sustainability in the study area and identify regional hotspots for mitigation. With these evaluations, we aim to clarify the magnitude and drivers of NGS N2O emissions in this world-leading agricultural region and provide science-informed mitigation recommendations on combating climate change and environmental pollution.

2. Material and methods

2.1. Ecosys and model validation

Ecosys is a mechanistic ecosystem model that has been widely used in various ecosystems (Grant et al., 2009, 2011; Mekonnen et al., 2019). It is developed on primary biophysical and biochemical principles and formulated with coupled energy, water, carbon, and nutrient cycles in the soil-plant-atmosphere continuum (Mekonnen et al., 2019). With model representations of major agricultural managements, including fertilization, tillage, irrigation, and drainage, ecosys has been extensively validated via laboratory and in-situ observations regarding energy, water, carbon, and nutrient dynamics (Grant and Nalder, 2000; Grant et al., 2010, 2020a). Robust simulations of those processes are important to constrain N2O emissions driven by soil carbon and nitrogen transformations through processes of microbial respirations, which are influenced by soil energy and water statuses. Particularly, the ability of ecosys to simulate responses of agricultural N2O emissions to soil temperature (Grant and Pattey, 2008), N-fertilizer type (Mezbahuddin et al., 2020) and rate (Grant et al., 2006), and the use of NI (Grant et al., 2020b) have been demonstrated.

Rather than using simple empirical relationships, *ecosys* implements a comprehensive and mechanistic approach to simulate soil N_2O evolution from basic kinetics of microbial respiration that is interactively controlled by temperature, water, mineral nutrient, and O_2 (Grant and Pattey, 2008). N_2O is a product during both nitrification and

denitrification by two groups of microbial populations, including autotrophic nitrifiers and heterotrophic denitrifiers. Nitrifier respiration (nitrification) in ecosys is assumed to use NH3 as the energy source and CO₂ as substrate (Grant et al., 2016). When O₂ availability fails to meet O₂ demand, nitrifiers will use NO₂ as alternative electron acceptors to meet electron demand and generate N2O. The N2O evolution via denitrifier respiration is built upon the kinetics that the demand of acceptors for electrons unmet by O2 will be met by NO3, NO2 and N2O sequentially, with NO2, N2O as intermediate products and N2 as the final product (Grant and Pattey 2003; Grant et al., 2006). The produced N2O undergoes volatilization-dissolution between aqueous and gaseous forms, and is transferred by diffusion-convection-dispersion driven by concentration gradients in different soil layers and between the soil surface and the atmosphere. Diffusivity for gaseous N₂O and dispersivity for aqueous N₂O are calculated from air-filled porosity and water-filled porosity, respectively (Grant et al., 2016). Nitrification inhibitors are assumed to reduce specific rates of NH₄ oxidation by nitrifiers. The inhibition efficiency is initialized to 1 (i.e. complete inhibition) at the time of application and then degrades by each time step as a function of soil temperature and a degradation constant (Grant et al., 2020b).

In the U.S. Midwest, ecosys has been calibrated and validated for

carbon dynamics including gross primary productivity (GPP), ecosystem respiration (Reco), net ecosystem exchange of CO2 (NEE, NEE=Reco -GPP), and leaf area index (LAI) at field-scale and regional-scale (Li et al., 2022; Qin et al., 2021; Zhou et al., 2021). Incorporating these processes, we further conducted site-scale model validations for soil temperature (T_s), soil water content (SWC), and N₂O flux. Four agricultural sites (Ne1–3, Ro5) from the AmeriFlux network (https://ameriflux.lbl.gov/) were used to evaluate the model performances on simulating GPP, R_{eco}, NEE, and T_s and SWC at a soil depth of 10 cm (Table S1). Validations of energy, water, and carbon variables ensure reliable simulations of the biophysical environment that is related to N2O production. Three sites (ARL, NWR, and BRD) with weekly/biweekly N2O observations covering growing seasons (static chambers were used) and one site (KBS) with daily N₂O observations during winters (automated chambers were used) were used to validate the simulation of N2O fluxes (Table S1). Model performances in NGS on snow depth and soil temperature were evaluated along with N2O flux at KBS during the winters of 2010-2013. Moreover, we collected 38 site-year estimates of cumulative N2O emissions and 92 site-year corn yield observations at sites with or without NI (Table S2), and additional 70 site-year estimates of cumulative N2O emissions and corn yield observations from sites not

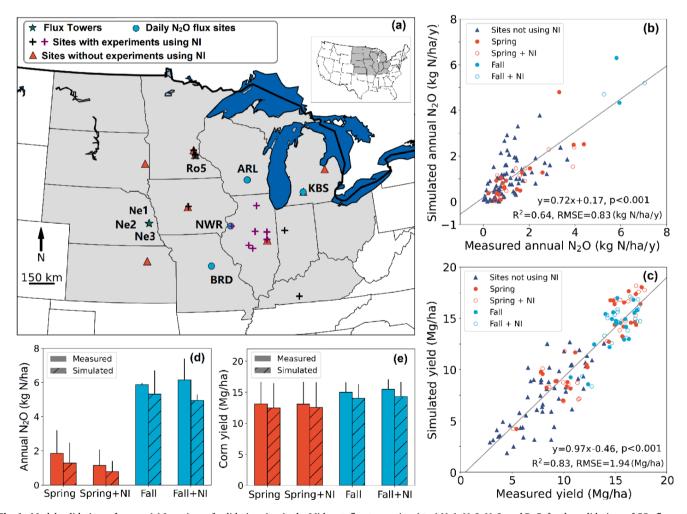


Fig. 1. Model validations of ecosys. (a) Locations of validation sites in the Midwest: flux tower sites (star) Ne1, Ne2, Ne3, and Ro5, for the validations of CO_2 flux, soil temperature, and soil moisture; sites ARL, NWR, BRD, and KBS (circle) for the validation of N_2O flux; sites not using nitrification inhibitors (NI) in 8 states (triangle) and sites with controlled experiments using NI in five states (cross) for the validation of cumulative N_2O emission and corn yield (purple cross denotes that the site only has corn yield data). The upper right map shows the study area in the contiguous US. Comparison of simulated and measured (b) annual cumulative N_2O emissions and (c) corn yield at sites with controlled experiments of with vs. without NI, and the mean + std of the simulated and measured (d) annual cumulative N_2O emissions and (e) corn yield. Spring and Fall indicate the fertilizer timing and NI indicates the use of NI. Gray lines indicate fitted linear regression and the error bar indicates the standard deviation of observations or simulations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

using NI to benchmark the model performance on quantifying annual N_2O emissions (Fig. 1a). This dataset results in 108 site-year estimates of cumulative N_2O emissions across eight Midwestern states. In this study, soil information from Gridded Soil Survey Geographic Database (gSSURGO, Soil Survey Staff 2021) was used to drive the model simulations (i.e., bulk density (BD), field capacity (FC), wilting point (WP), soil texture, saturated hydraulic conductivity (KSat), soil organic carbon (SOC), pH, and cation exchange capacity (CEC)). Five meteorological variables for driving the model including air temperature (T_a), precipitation (P), relative humidity (H), wind speed (WS), and net solar radiation (R_n) were derived from the NLDAS-2 dataset (Xia et al., 2012a, 2012b), except for the four AmeriFlux sites, where local observations were available.

2.2. County-level simulations

To quantify the regional N2O variability, we conducted county-level simulations across 13 US Midwestern states (ND, SD, NE, KS, MN, IA, MO, WI, IL, IN, MI, OH, and KY). Weather information was generated from NLDAS-2, which has a 0.125 $^{\circ}$ spatial resolution, for each county at its geometric centroid (air temperature and precipitation are shown in Fig. S1). For each county, the top five cropland soil map units with the largest areas in gSSURGO were used to generate five soil profiles. The outputs of five simulations conducted separately using the five soil profiles were area-weighted to represent the model simulation for a county. The simulation period was set as 2000–2020 following 20 years of spin-up (1980–1999) under rainfed continuous corn systems. Planting dates at the state level from USDA National Agricultural Statistics Service (NASS) were linearly interpolated to the county level and applied in the simulations. Corn-specific N-fertilizer inputs at the county level (Fig. S1) were obtained from the product developed by Xia et al. (2021), whose estimation was based on the Nutrient use Geographic Information System (NuGIS, Fixen et al., 2012). The same rate of N-fertilizer was assumed to be applied (injected at 10 cm depth with 0.76 m row space) each year on the planting day during the simulation period since state-level N-inputs were relatively stable after 2000. N-fertilizer type was set as the commonly used urea-ammonium nitrate (UAN), which contains 25%, 25%, and 50% of the total nitrogen coming from ammonium, nitrate, and urea, respectively. For statistical purposes, the NGS of a year was considered from November 1st of last year to April 30th of the current year, and May 1st-October 31st was taken as the GS.

For the baseline county-level simulation above, N-fertilizer was assumed to be applied in spring on the same day as planting. To further investigate the effect of fertilizer timing, we compared the baseline simulation (spring application) with three other fertilizer scenarios: fall application, spring application with NI, and fall application with NI. Eight climate-management scenarios were developed based on the combination of two fertilization timings (spring and fall) and four hypothesized climatic conditions: moderate warmer and wetter (MWW, annual $T+1\,^{\circ}\mathrm{C}$, annual $P+\mathrm{std}$), moderate warmer and drier (MWD, annual $T+1\,^{\circ}\mathrm{C}$, annual $P-\mathrm{std}$), intense warming and wetter (IWW, annual $T+2\,^{\circ}\mathrm{C}$, annual $P-\mathrm{std}$), and intense warming and drier (IWD, annual $T+2\,^{\circ}\mathrm{C}$, annual $P-\mathrm{std}$). The experiment design resulted in 12 scenarios in total (Table S3).

The method to calculate social benefits was adapted from Kim et al. (2021) with the adjustment that we added for non-fertilizer costs (including estimates on pesticides, seed, drying, storage, crop insurance, power, overhead, and land costs). Social benefit (SB) is estimated with the following equation:

 $SB = yield \times (P_{yield} \cdot C_{non\text{-}fert}) \cdot N_{fert} \times C_{fert} + (GHG_{N2O} + GHG_{\triangle SOC}) \times C_{GHG} \cdot N \text{ leaching} \times C_{leaching} \text{ where } P_{yield} \text{ is corn price ($/t) and } C_{non-fert} \text{ is the non-fertilizer cost in corn production ($/t); } N_{fert} \text{ is } N\text{-}fertilizer \text{ rate and } C_{fert} \text{ is fertilizer price ($/kg N); } GHG_{N2O} \text{ and } GHG_{\triangle SOC} \text{ are } N_2O \text{ emissions and } \Delta SOC \text{ converted to } CO_2 \text{ equivalent (} CO_2\text{e)} \text{ greenhouse gas } (GHG) \text{ emissions (} t CO_2\text{e}/ha/y), \text{ respectively; } N \text{ leaching is nitrogen leaching attached to groundwater discharge and runoff (kg N/ha/y);}$

 C_{GHG} and $C_{leaching}$ are social costs of GHG emissions (\$/t CO₂e) and N leaching (\$/kg N). Corn price and non-fertilizer costs scaled by yield were set to 170 \$/t and 135 \$/t as in 2020 (Schnitkey et al., 2021). The fertilizer price was set to 1.15 \$/kg N (Kim et al., 2021). N₂O emission was converted into 265 times $CO_{2}e$ based on its global warming potential for a time horizon of 100 years (IPCC5; Pachauri et al., 2014). The price of CO_{2} was set to \$50/t according to the Interagency Working Group's central estimate (IWG, 2016; Revesz et al., 2017). The cost for N leaching was estimated at 2.44 \$/kg N based on damage cost from groundwater N loading (Sobota et al., 2015). The density of social benefit was estimated as quantity per ha, and county-level social benefits were obtained by multiplying corn production acres from the USDA census data in 2017 (USDA, 2017).

2.3. Causal analysis

With the results of county-level simulations, we first tested linear correlations between NGS $\rm N_2O$ emission and environmental variables. To better understand the underlying relationships in NGS, we introduced a novel data-driven causal inference method, PCMCI (Peter and Clark momentary conditional independence, Runge et al., 2019), for discovering and quantifying the causal interdependencies. PCMCI has advantages in the identification of common drivers and time-lagged links among variables in complex ecosystems (Runge et al., 2019).

We used different climate and soil variables in the causal analysis, including four climatic variables ($T_{a,NGS},\ P_{NGS},\ snowfall$ (SWF), and snow depth (SWD)) and seven soil variables ($T_{s,NGS}$ at 5 cm depth, SWC $_{NGS}$ at 5 cm depth, soil ice content at 5 cm depth (SIC $_{NGS}$), SWC $_{NGS}+SIC_{NGS}$, soil aqueous O_2 concentration at 5 cm depth ($O_{2,NGS}$), soil N_2O concentration at 5 cm depth ($N_2O_{soil,NGS}$) and soil N_2O flux ($N_2O_{flux,NGS}$)). T_a (°C) was calculated as the monthly mean and P (mm) was calculated as monthly accumulation. SWF (mm) was filtered as monthly cumulative precipitation when $T_a<0$ °C. Monthly means of SWD (mm), T_s (°C), SWC (m³/m³), SIC (m³/m³), O_2 (g $O_2/m³$), N_2O_{soil} (g N/m³), and monthly cumulative N_2O_{flux} (g N/m²/month) were calculated from the model outputs of county-level simulations. These variables were selected based on the results of correlation detections between N_2O emission and environmental variables.

In this study, PCMCI tests based on partial correlation were adopted to perform two steps of causal analysis: (1) detecting the interdependencies among climatic variables and three soil variables: SWC, SIC, and T_s; and (2) detecting the interdependencies among soil variables and N₂O_{flux}. This step division assumes that climatic variables directly influence soil temperature and soil moisture (SWC, SIC, and T_s), and these variables work as drivers of other soil attributes. Considering the spatial difference shown in correlations results, cumulative freezingdegree days (CFD) was used as an indicator to outline two regions for the causal analysis: the northwest region, which showed negative correlations between CFD and NGS N2O; and the southeast region, which showed positive correlations. The causal interdependencies among climatic drivers, soil variables, and N2O emissions were detected separately for the two regions. The magnitude of the causal effect between any two variables was described using link strength (-1 to 1), and the effect size of a pathway was calculated by multiplying all associated link strengths from a climatic driver to N₂O_{flux}, with positive/negative values indicating positive/negative overall impacts.

3. Results

3.1. Site-scale model validations

The simulated and observed daily N_2O fluxes showed good consistency in magnitude and seasonal pattern (Fig. S2). It captured major peaks of N_2O pulses that occurred in spring thaw periods or fertilization periods, for example, the thaw emissions in March and peak emissions in July at ARL1, 2011 (Fig. S2a). However, the variation in replicate

measurements suggests that there are larger uncertainties with peak N_2O pulses. Model validations at KBS specifically demonstrated the performances of $\it ecosys$ on simulating snow depth (SWD, RMSE = $53{\text -}67$ mm), soil temperature (T_s , RMSE = $1.2{\text -}1.8\,^{\circ}C$), and NGS N_2O flux (RMSE = $0.005{\text -}0.024$ kg N/ha/d) during the winters of $2010{\text -}2013$ (Fig. S3). Only small N_2O fluxes were observed and simulated at KBS and spring thaw periods were not covered in the observations (Fig. S3), which limited the model capacity to perfectly capture N_2O dynamics in some periods due to large uncertainties existing in both observations and model forcing. The model-data comparisons at the four flux tower sites showed that $\it ecosys$ can well capture the dynamics of long-term GPP, R_{eco} , NEE, T_s at 10 cm depth, SWC at 10 cm depth (Fig. S4, Table S4).

The measured and simulated annual cumulative N₂O emissions (R² = 0.64, RMSE=0.89 kg N/ha/y) and corn yield ($R^2 = 0.83$, RMSE=1.91 Mg/ha) showed similar ranges and good consistency (Fig. 1b and c). The mean standard deviation in the observations (std) suggests that uncertainties associated with estimates of cumulative N2O emissions (std = 0.69 kg N/ha/y) and measurements of corn yield ($\overline{\text{std}} = 1.43 \text{ Mg/ha}$) are close to the level of model errors. These performances are comparable to similar studies in cropping systems of North America using DayCent ($R^2 = 0.74$ for cumulative N₂O; $R^2 = 0.66$ for yield; n = 21) (Del Grosso et al., 2005) and DLEM ($R^2 = 0.52$, n = 85) (Lu et al., 2022), and a study in north China where two PBMs showed R^2 of 0.30 and 0.31 for cumulative N₂O emissions and R² of 0.52 and 0.59 for corn yield (Yue et al., 2019). At the site scale, studies showed that ensemble estimation of several PBMs can reduce the model bias and uncertainty (Gaillard et al., 2018; Fuchs et al., 2020). Both measurements and simulations showed that using NI slightly increased mean corn yield while the observed effects on mean N2O emissions were inconsistent between spring application and fall application (Fig. 1d and e).

3.2. Spatio-temporal pattern of N_2O emissions and the drivers

Large spatial and interannual variations in annual, GS, and NGS N_2O emissions were modeled in the county-level simulations for 2001–2020 across the Midwest (Fig. S5). Annual mean N_2O emissions ranged from 0.50 to 8.91 kg N/ha/y in different counties, with an average mean of 3.18 kg N/ha/y and std of 1.02 kg N/ha/y overall (Fig. S5a, b). GS and NGS N_2O emissions accounted for 74% (2.35 kg N/ha/y) and 26% (0.83 kg N/ha/y) of the averaged mean, respectively (Fig. S4c and e). Both GS and NGS N_2O emissions showed large interannual variations over all counties with a mean std of 0.83 kg N/ha/y in GS and 0.64 kg N/ha/y in NGS (Fig. S5d, f). Hotspots of NGS N_2O emissions were in eastern Minnesota, eastern Iowa, and Wisconsin (Fig. S5e), not overlapping with those of GS N_2O emissions located in Nebraska, Kansas, Minnesota, Iowa, and Missouri (Fig. S5c). The contribution of NGS N_2O emissions to annual N_2O emissions ranged from 6 to 60% in different counties (Fig. 2a), and a regional mean of 13% to 38% in different years (Fig. 2b).

GS and NGS N2O emissions showed different correlations with environmental variables. Yearly GS N2O emissions had significant positive correlations with PGS in 50% of all counties, indicating interannual variations of GS N2O emissions were driven by precipitation (Fig. S6). Spatial variations of GS N2O emissions can be well explained by N-fertilizer rate (Nrate) and soil inorganic nitrogen (SIN), with significant positive correlations (r > 0.35, p < 0.001) shown with the two variables (Fig. S7). However, NGS N₂O emissions showed divergent patterns in the southeast and the northwest of the Midwest regarding both interannual and spatial variations. P_{NGS}, T_{a,NGS}, T_{s,NGS}, and CFD were used to explain the interannual variations of NGS N_2O emissions, where P_{NGS} of 300 mm was found to be an approximate threshold for divergence (Fig. 2c-f). In the humid southeast ($P_{NGS} > 300 \ mm$), interannual NGS N₂O emissions had significant negative correlations with P_{NGS} , $T_{a,NGS}$, $T_{s,NGS}$ in 32%, 14%, and 38% of 637 counties, respectively, and significant positive correlations with CFD in 38% of those counties (Fig. 2c-f). In the arid

northwest (P_{NGS} < 300 mm), interannual NGS N_2O emissions showed significant positive correlations with P_{NGS} and $T_{a,NGS}$ in 47% and 23%, respectively, and negative ones with CFD in 36% of 538 counties (Fig. 2c-f). Overall, CFD significantly explained the interannual variation of NGS N_2O emissions in 38% of all counties in the study area (Fig. 2f), more than any other environmental variable.

The spatial-divergent pattern between above and below P_{NGS} of 300 mm was also found in the ratio of NGS to annual N_2O emissions (Fig. 3). For arid counties with $P_{NGS} < 300$ mm, NGS/annual N_2O ratio had a significant positive correlation with P_{NGS} (r=0.57, p<0.001; Fig. 3a), and a negative one with CFD (r=-0.37, p<0.001; Fig. 3f); while for humid counties with $P_{NGS} > 300$ mm, a significant negative correlation with P_{NGS} (r=-0.69, p<0.001; Fig. 3a) and a significant positive one with CFD (r=0.67, p<0.001; Fig. 3f) were found. Unlike in the GS, N_{rate} and SIN didn't show strong correlations (|r|<0.3) with NGS N_2O emissions (Fig. 3j, k). Mean snow depth (SWD) and snow cover duration (SCD) both showed (Fig. 3g, h) significant positive correlations with NGS N_2O emissions, indicating the important role of snow cover in influencing NGS N_2O production via the regulation of soil moisture and soil temperature.

3.3. Causal relationships between key drivers and NGS N₂O emissions

We used the causal inference method, PCMCI, to further clarify the spatial-divergent pattern of environmental drivers to NGS N₂O emissions in the southeast and the northwest regions. Three climatic drivers, $T_{a,NGS},\, P_{NGS},\, \text{and SWF}$ were detected for the causal effects on NGS N₂O flux through other climatic and soil variables including SWD, $T_{s,NGS},\, \text{SWC}_{NGS},\, \text{SIC}_{NGS},\, \text{O}_{2,NGS},\, \text{and N}_{2}\text{O}_{\text{soil},NGS}.\, \text{In the northwest,}\,\, T_{a,NGS}\, \text{(effect size}=0.005)\,\, \text{and}\,\, P_{NGS}\, (0.005)\,\, \text{showed comparable positive effects on N}_{2}\text{O}_{\text{flux},NGS}\,\, \text{that are stronger than the effect of SWF}\, (0.001),\,\, \text{indicating their cooperative influence on NGS N}_{2}\text{O}\,\, \text{emissions}\,\, \text{(Fig. 4a-c)}.\,\, \text{In the southeast,}\,\, T_{a,NGS}\,\, \text{showed}\,\, \text{a dominating negative effect on N}_{2}\text{O}_{\text{flux},NGS}\,\, \text{(effect size}=-0.088)\,\, \text{compared with the other two drivers,}\,\, P_{NGS}\, (-0.011)\,\, \text{and SWF}\,\, (0.012)\,\, \text{(Fig. 4d-f)}.\,\, \text{The effect significance should not be compared across the northwest and the southeast since the causal analyses for the two regions were conducted separately.}$

In the northwest region, the causal relationship of P_{NGS} and $N_2O_{flux,NGS}$ showed a single positive pathway via sequential interdependencies with SWC_{NGS}, $O_{2,NGS}$, and $N_2O_{soil,NGS}$ (Fig. 4a). Higher P_{NGS} can be a decisive factor that results in higher NGS N_2O emissions via increasing SWC before soil freezing and at soil thaw. The causal effects of $T_{a,NGS}$ on $N_2O_{flux,NGS}$ consisted of three positive pathways and two negative pathways (Fig. 4b), with the dominant pathways being positive via influences on SWC $_{NGS}$, $O_{2,NGS}$ and $N_2O_{soil,NGS}$ similarly. Higher $T_{a,NGS}$ probably drives earlier and faster snowmelt which leads to increased SWC and N_2O production. The lagged causal relationship (e.g. between $N_2O_{soil,NGS}$ and $N_2O_{flux,NGS}$) indicates that the effect requires a longer time to be detected. It suggests that the thawing effect dominates in this region, with higher P_{NGS} and higher $T_{a,NGS}$ leading to increased $N_2O_{soil,NGS}$ via increasing SWC.

In the southeast region, $T_{a,NGS}$ showed dominating casual effects on N_2O_{flux} through two negative pathways (Fig. 4e), one via controls of $T_{s,NGS}$ and then $SWC_{NGS}+SIC_{NGS}$ (effect size = -0.059) and the other directly over $SWC_{NGS}+SIC_{NGS}$ (effect size = -0.029). It indicates that the freezing effect, i.e. lower air temperature and consequently lower soil temperature during the freezing period, is the most critical reason that leads to high NGS N_2O emissions. With relatively slighter freezing intensity compared to the northwest region, SWC and SIC both influence soil O_2 condition and then N_2O production in this region.

3.4. Mitigation strategies and potentials

N-Fertilizer timing (spring or fall application) and use of NI showed significant influences on N_2O emissions from *ecosys* simulations (Fig. 5). Under the historical climate, the fall application scenario (Fall) resulted

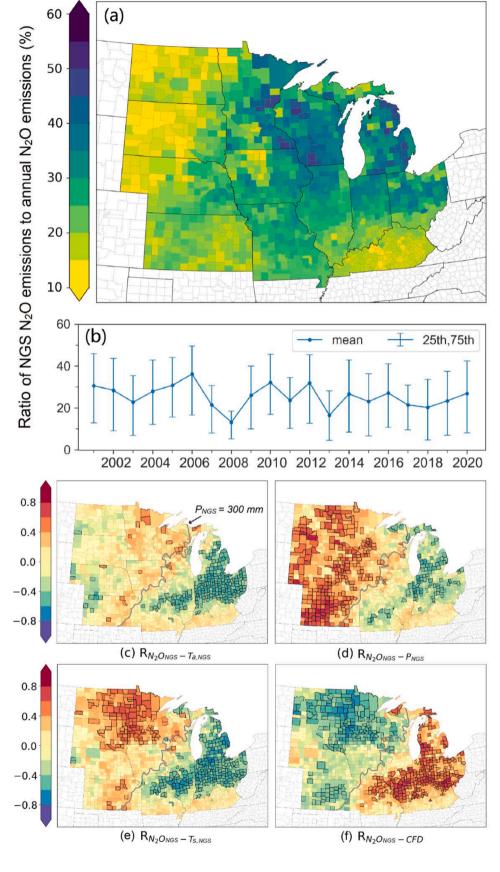


Fig. 2. Spatio-temporal variations of the nongrowing season (NGS) N₂O emissions and their correlations with key environmental variables under continuous corn systems in the US Midwest as simulated by ecosys. (a) Mean NGS/ annual N2O ratio of each county over 2001-2020. (b) Mean, 25th percentile, and 75th percentile of NGS/annual N₂O ratio in each year over all counties. Interannual correlations of NGS N2O emissions with (c) mean NGS air temperature ($T_{a,NGS}$), (d) cumulative NGS precipitation (PNGS), (e) mean NGS soil temperature ($T_{s,NGS}$), and (f) cumulative freezing-degree days (CFD). The thick gray line in (c-f) indicates the contour of $P_{NGS} = 300$ mm, which divides the region into the northwest and the southeast. Linear correlation was detected for each county using 20 years (2001-2020) of data, in which Ta,NGS and PNGS are inputs of the model ecosys and N₂O emissions, and T_s and CFD are outputs from model simulations.

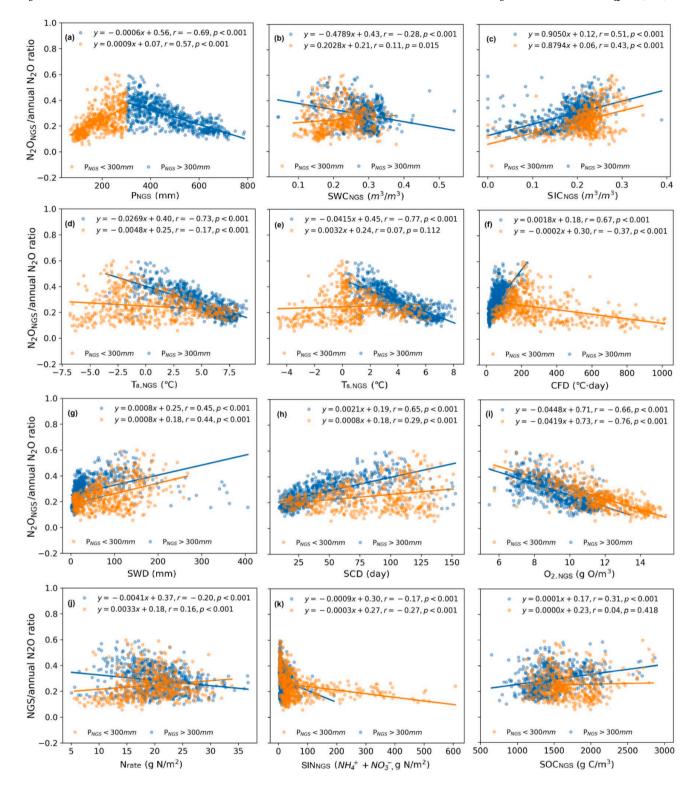


Fig. 3. Spatial correlations between the ratio of the non-growing season (NGS) N_2O emissions to annual N_2O emissions and environmental variables including (a) NGS cumulative precipitation (P_{NGS} , mm), (b) NGS mean soil water content at 5 cm depth (SWC_{NGS} , m³/m³), (c) NGS mean soil ice content at 5 cm depth (SIC_{NGS} , m³/m³), (d) NGS mean air temperature ($T_{a,NGS}$, °C), (e) NGS mean soil temperature at 5 cm depth ($T_{s,NGS}$, °C), (f) cumulative freezing-degree day at 5 cm depth ($T_{s,NGS}$, °C-day), (g) mean snow depth ($T_{s,NGS}$, °C), (f) cumulative freezing-degree day at 5 cm depth ($T_{s,NGS}$, °C-day), (g) mean snow depth ($T_{s,NGS}$, °C), (f) cumulative freezing-degree day at 5 cm depth ($T_{s,NGS}$, °C-day), (g) mean snow depth ($T_{s,NGS}$, °C), (f) cumulative freezing-degree day at 5 cm depth ($T_{s,NGS}$, °C), (f) cumulative freezing-degree day at 5 cm depth ($T_{s,NGS}$, °C), (f) cumulative freezing-degree day at 5 cm depth ($T_{s,NGS}$, °C), (f) cumulative freezing-degree day at 5 cm depth ($T_{s,NGS}$, °C), (g) mean snow depth ($T_{s,NGS}$, °C), (g) mean snow depth ($T_{s,NGS}$, °C), (f) cumulative freezing-degree day at 5 cm depth ($T_{s,NGS}$, °C), (g) mean snow depth ($T_{s,NGS}$, °C), (g) mean sn

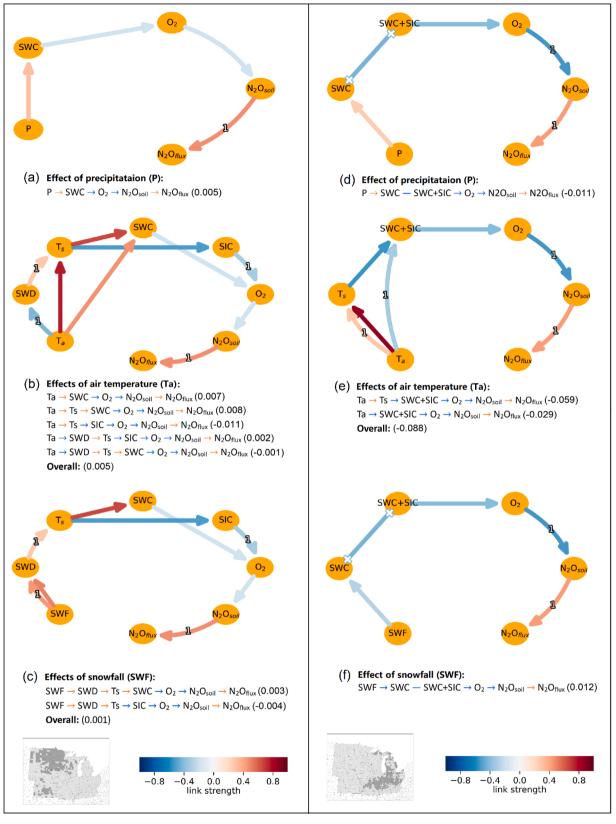


Fig. 4. Casual relationships detected in non-growing seasons (Nov. - Apr.) among N_2O flux (N_2O_{flux}), climatic drivers (precipitation (P), air temperature (T_a), and snowfall (SWF)), and other environmental variables (snow depth (SWD), soil temperature (T_a), soil water content (SWC), soil ice content (SIC), Soil O_2 concentration (O_2), soil O_2 0 concentration (O_2 0, soil O_2 0, soil O_2 0 concentration (O_2 0, soil O_2 0, soil O_2 0 concentration (O_2 0, soil O_2 0, soil O_2 0 concentration (O_2 0, soil O_2 0, soil O_2 0 concentration (O_2 0, soil O_2 0, soil

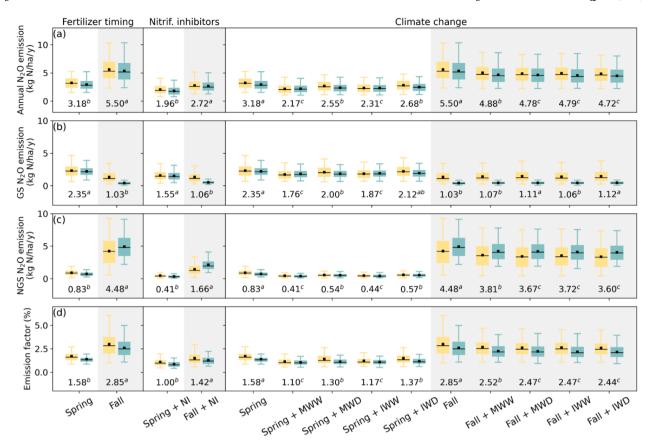


Fig. 5. Estimated N_2O emissions under different fertilizer management and climate scenarios. County-level model simulations of N_2O emissions under continuous corn systems during 2001–2020 were used. (a) Annual N_2O emissions, (b) growing season (GS) N_2O emissions, and (c) non-growing season (NGS) N_2O emissions. (d) The emission factor (annual N_2O emission / N-fertilizer rate) under different fertilizer timing, use of nitrification inhibitors, and climate change. Spring or Fall means the N_2O emissions under scenarios of different fertilization timings (spring and fall applications); NI means the scenarios with nitrification inhibitors; MWW means the scenarios with moderate warming and dryer climate change; IWW means the scenarios with intense warming and dryer climate change; IWW means the scenarios with intense warming and dryer climate change. The black line and square denote median and mean, respectively. The northwestern Midwest and the southeastern Midwest are divided by the $P_{NGS} = 300$ mm line under historical climate as shown in Fig. 2c. Numbers indicate the mean of each scenario, and different superscript letters indicate significant differences (P < 0.05) among scenarios in the groups of fertilizer timing (Spring and Fall), the use of nitrification inhibitors (Spring+NI and Fall+NI), climate change under spring application (Spring, Spring + MWW, Spring + MWD, Spring + IWW, and Spring + IWD), and climate change under fall application (Fall, Fall + MWW, Fall + MWD, Fall + IWW, and Fall + IWD).

in significantly higher annual and NGS N_2O emissions but lower GS N_2O emissions than the spring application scenario (Spring) at the regional scale. The mean annual N_2O emissions (5.50 kg N/ha/y) under Fall scenario were 73% higher than that (3.18 kg N/ha/y) under Spring scenario (Fig. 5a). This difference was largely attributed to greater NGS N_2O emissions with fall applications, which on average contributed 81% to annual emissions over all counties (Fig. 5c). Compared to baseline spring application, spring application with NI (Spring + NI) reduced GS and NGS N_2O emissions by 34% and 51%, respectively, resulting in a 38% reduction in annual N_2O emissions. Fall application with NI (Fall + NI) significantly reduced annual N_2O emissions by 51% compared to that without NI, with NGS N_2O emissions reduced by 63% and GS N_2O emissions increased by 3%. Introducing NI to fertilizer application greatly reduced the N_2O emission difference from 2.3 to 0.8 kg N/ha/y when switching from spring applications to fall applications (Fig. 5).

According to the scenario simulations, N_2O emissions are likely to be reduced with warming conditions irrespective of increased or decreased precipitation in the study area. Under the four climate change scenarios: moderate warming and wetter (MWW), moderate warming and drier (MWD), intense warming and wetter (IWW) and intense warming and drier (IWD), mean annual N_2O emissions were all reduced compared with those under historical climate scenarios, which can be primarily attributed to reductions in NGS (Fig. 5). Changing historical climate to the four hypothesized conditions with spring application reduced NGS

N₂O emissions up to 32% by the Spring + MWW scenario, and with fall application up to 14% by the Fall + IWD scenario (Fig. 5c). However, those reductions induced by climate change were not as remarkable as those by applying NI with fertilizer. Hypothesized climate scenarios reduced GS and NGS N2O emissions under spring application and NGS N₂O emissions under fall application consistently compared with historical climate scenarios, while they enhanced GS N2O emissions under fall application (Fig. 5b, c). In terms of N2O emission factors (EFs), which is the proportion of nitrogen in N2O emissions to N-fertilizer rate, the mean EFs of Spring scenario (1.58%), Spring + NI scenario (1.00%), and the four spring scenarios under climate change (1.10-1.37%) are comparable to the IPCC Tier 1 disaggregated EF for synthetic fertilizers, 1.6% (1.3–1.9%) (Fig. 5d). The mean EFs of scenarios under fall application ranged from 2.44% (Fall + IWD) to 2.85% (Fall) in addition to the lowest for Fall + NI (1.42%), indicating that Tier 1 estimates may underestimate N2O emissions due to ignoring the higher emissions under fall fertilizer applications.

Despite the lack of validations for N leaching and SOC, we calculated the monetized social benefits as the sum of costs (negative) and benefits (positive) of simulated corn yield, N_2O emissions, N leaching, and ΔSOC to hypothetically assess crop production and the associated environmental impact. We first calculated the baseline scenario of spring application, and then compared it to scenarios of spring application with NI, fall application, and fall application with NI to estimate changes in

social benefits under alternative management strategies (Fig. 6). Results showed that per ha social benefits ranged from -294 \$ to 183 \$ (Fig. 6a), with counties in Ohio, Illinois, and South Dakota having the highest per ha social benefits, and counties in Missouri, Kansas, and Michigan having the lowest values (Table S5). Northern Illinois showed the highest county-level social benefits due to high per ha social benefits and large corn planting area (Fig. 6b). By introducing NI to spring application, per ha social benefits increased in the majority of counties (Fig. 6c) thanks to reductions in $\rm N_2O$ emissions and N leaching according to model simulations (Fig. S8). The use of NI with fall application increased regional overall corn yields but not that with spring application

(Fig. S8d). However, the effects of using NI on corn yield varied across counties. This inconsistency across space was also observed in site-scale observations that the use of NI does not necessarily increase corn yield and the performance varies with different locations and N rates (Burzaco et al., 2013; Sistani et al., 2011; Venterea et al., 2011, R.T. 2016). The greatest increases in social benefits were found in Iowa (271.6 million \$), Minnesota (237.5 million \$), and Illinois (235.7 million \$), accounting for 63% of the total increase (1173.9 million \$) across the 13 states (Table S5). Switching spring application to fall application reduced per ha social benefits in most counties except that some counties in the area connecting Iowa, Minnesota, Nebraska, and South Dakota

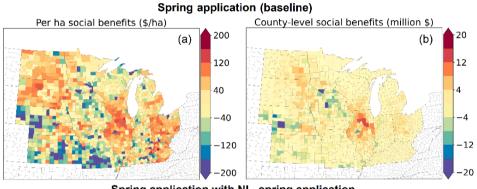
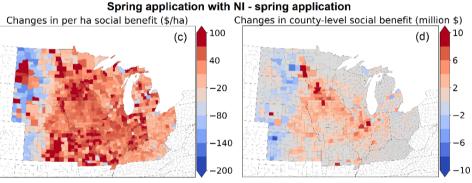


Fig. 6. Estimates of annual social benefits for corn cropping at the county level in the US Midwest. (a) Marginal social benefits (US dollars per hectare) and (b) county-level social benefits under the baseline scenario, spring fertilizer application. Changes in per ha social benefit of (c) spring fertilizer application with nitrification inhibitors (NI), (e) fall fertilizer application, and (g) fall fertilizer application with NI compared with the baseline scenario. Changes in county-level social benefit of (d) spring fertilizer application with NI, (f) fall fertilizer application, and (h) fall fertilizer application with NI compared with the baseline scenario.



Changes in per ha social benefit (\$/ha)

(e)

100

40

-20

-80

-140

Changes in county-level social benefit (million \$)

6

2

-6

-200

Fall application - spring application

Fall application with NI - spring application

Changes in per ha social benefit (\$/ha)

(g)

100

(h)

10

6

2

-20

-80

-140

-200

-140

(Fig. 6e). Hotspots of reduced county-level social benefits were concentrated in Illinois, Indiana, Iowa, and Wisconsin (Fig. 6f), with a total of 2703.3 million \$ loss compared with the baseline (Table S5). Compared with fall application, adding NI greatly reduced the negative impact on social benefits to 777.4 million \$ (Table S5) and brought a positive impact to more counties (Fig. 6g and h), mainly due to decreased N₂O emissions and N leaching (Fig. S8). Compared with the baseline, fall fertilizer application with NI reduced state-level social benefits majorly in Illinois (-329.3 million \$) and Indiana (-282.4 million \$), but brought extra benefits to Nebraska (174.8 million \$), Minnesota (59.8 million \$), South Dakota (54.3 million \$), and Kansas (45.8 million \$) (Table S5). However, those estimates are only based on model simulations as stated above. Further validations on those unvalidated components would bring more certainty to the social benefit evaluation.

4. Discussion

In this study, we validated a process-based model and then applied it to simulate county-level N2O emissions during 2001-2020 in the US Midwest. Two seasonal components, GS N2O emissions and NGS N2O emissions were evaluated separately to identify their key drivers and specific driving processes. While reducing N inputs is probably the most direct measure to mitigate GS N2O emissions, the effectiveness may be limited in NGS (Mosier et al., 2006). Our study identified interannual and spatial climatic differences as key factors that explain the spatio-temporal variations of NGS N2O emissions, bringing regional understanding with explicit causal interdependencies to previous evidence (Shang et al., 2020; Wang et al., 2019). Our results suggest that T_a NGS and PNGS dominantly drive the magnitude and variation of unignorable NGS N₂O emissions. More importantly, the driving effects spatially differed in the southeast and northwest of the Midwest, which may also be anticipated in other primary crop production regions. Thus, mitigation efforts towards N2O emissions need to be seasonal- and spatial-specific. Although we validated the model at multiple sites and under various management situations to represent one of the most comprehensive N2O studies for the Midwest, there are uncertainties in our regional estimates of N2O emissions that come with model limitations, estimation of observations, and lack of validations on NGS N2O emissions in the northwest counties, N leaching, and SOC. It was shown that improvements of a specific PBM may not bring extra simulation accuracy globally for N2O emissions because performances of different models vary greatly with climate and soil conditions (Zhang and Yu, 2021). Thus, adding ecosys in an PBM ensemble that incorporates advantages of different models can be a good way to improve global simulation accuracy for N2O emissions in the future. Here we focus on the interpretations of the spatial and temporal patterns and differences manifested by the model simulations where we assume that the uncertainties arising from inputs and the model are at the same level over space and time in the study area.

In the relatively warm and humid region of the study area i.e. the southeastern Midwest, soil temperature has the dominant power in influencing NGS N2O emissions among climatic factors. In this region, the negative interdependencies of NGS N2O emissions with Ta,NGS and soil temperature and the positive correlation of NGS N2O emissions with CFD indicate that the freezing effect is the decisive factor that influences soil N₂O production (Fig. 4b). It is in line with field or lab observations that higher NGS N₂O releases are associated with increasing freezing intensity, shown as larger CFD (Koponen and Martikainen, 2004; Wagner-Riddle et al., 2007), longer freezing duration (Singurindy et al., 2009) and higher freeze-thaw frequency (Gao et al., 2018). Besides soil O2 consumption by microbes and gas transfer blocked by soil freezing, it is possible that there is soil O2 removal in the process of soil water-ice phase transition, i.e. soil ${\rm O}_2$ is degassed by ice expansion. This type of O2 depletion was stated in previous studies but has not been well evidenced (Gao et al., 2018; Grant et al., 2020a). The causal analysis indicates that PNGS and SWF show more power on N2O emissions via

influencing soil moisture over soil temperature as the overall insulation of snowpack is limited in this region (Fig. 4d and f). However, the insulation effect seems to be greater in counties with thick snowpacks (SWD > 200 mm) and long snow cover duration (SCD > 125 days), which leads to lower N₂O emissions (Fig. 3g and h).

In the relatively cold and arid region of the study area, i.e. the northwestern Midwest, NGS N_2O emissions are under the control of the positive impacts of $T_{a,NGS}$ and P_{NGS} , indicating that the thawing effect probably drives the soil N_2O production. Colder weather and deeper snow cover in this region result in a long and stable freezing period (Fig. S9b). $T_{s,NGS}$ will not drop dramatically as $T_{a,NGS}$ does due to snow cover insulation. NGS N_2O emissions increase as P_{NGS} , SWD, and SCD increase, suggesting that N_2O production during freeze-thaw cycles is enhanced by higher P_{NGS} and heavier snowmelt that increase soil moisture (Wagner-Riddle et al., 2007; Risk et al., 2013).

This study clarifies an important knowledge gap that NGS N2O production during a freezing-thawing cycle can either be dominantly driven by the freezing effect or the thawing effect. While many studies have found that intense freezing and snowmelt enhance NGS N2O emissions (Koponen and Martikainen, 2004; Wagner-Riddle et al., 2007; Yanai et al., 2011), there is also evidence that NGS N₂O pulses may not increase with enhanced soil thaw and snowmelt (Libby et al., 2020) and that deeper snow cover has inconsistent effects on NGS N2O fluxes at different sites (Chen et al., 2021; Ruan and Robertson, 2017; Yanai et al., 2011). Our results suggest that the dominant place of the freezing effect in controlling NGS N2O emissions seems to decrease with an increased thawing effect towards a decreasing PNGS and TaNGS gradient. This change in control could be used to explain that deeper snow cover leads to higher NGS N2O emissions due to an enhanced thawing effect in northeast China with a cold climate similar to the northwestern Midwest (Chen et al., 2021), while it also leads to lower NGS N₂O emissions due to reduced freezing effect in relatively warmer places in Michigan (Ruan and Robertson, 2017) and Japan (Yanai et al., 2011). Thus, mitigation strategies in NGS need to be spatially adaptive. Attention can be paid to those field practices that can influence soil moisture and soil temperature in NGS. For example, delaying the harvest of the main crop may reduce soil moisture in a way that does not lead to yield damage (Darby and Lauer, 2002); cover cropping is possibly an ideal practice that reduces soil moisture and increases soil temperature during NGS (Kahimba et al., 2008). With regard to the choice of cover crops in the northwest, broadleaf species that grow fast may be most effective to reduce soil moisture, and less effective to influence T_{s,NGS} as they are mostly frost-sensitive. Winter hardy cover crops, e.g. rye, barley, and clover, have been proved to increase T_{s,NGS} during the freeze-thaw cycles (Kahimba et al., 2008; Yang et al., 2021). However, the real influences of cover cropping and other NGS field management practices on NGS N2O emissions need to be demonstrated. The ability of ecosys to simulate cover cropping systems has been demonstrated in a recent study (Qin et al., 2021). Due to the lack of established model parameters and field observations for some cover crops, and spatial-explicit information on cover cropping systems, we did not conduct cover crop simulations in this study.

We investigated the responses of N_2O emissions to fertilizer timing, the use of NI, and hypothesized climate scenarios. Although our results indicate that annual and NGS N_2O emissions in the Midwest reduce in general by shifting fall fertilizer application to spring fertilizer application and applying fertilizer with NI, the responses vary in different counties. This spatial heterogeneity is supported by existing observational evidence in previous studies. Spring fertilizer application was widely observed to lead to lower GS N_2O emissions than fall application (Akiyama et al., 2010; Ruser and Schulz, 2015; Gilsanz et al., 2016; Gao and Bian 2017; Hao et al., 2001), but not at other sites due to greater emissions in early growing seasons (Tenuta et al., 2016; Thilakarathna et al., 2020). Using NI is an effective way to reduce N_2O emissions regardless of fertilizer timing, but the effectiveness is not shown at some sites in certain years (Chen et al., 2021; Parkin and Hatfield, 2010;

Gurung et al., 2021). Our study suggests that dividing N_2O emissions into seasonal-explicit components, i.e. GS and NGS parts may help better understand the mitigation effects of different fertilizer management practices. For example, applying NI in the fall is likely to only reduce NGS N_2O emissions (Fig. 6). Further, climate mitigation cannot be made on N_2O emissions alone. Using integrative metrics such as the monetized social benefits that reflect agronomic and environmental impacts can provide more direct and attractive practice recommendations to stakeholders.

In the long run, field practices are also required to be adaptive to the integrated effects of climate change, expansion of global croplands, growth of fertilizer use, and change in nitrogen use efficiency (Kanter et al., 2016; Reay et al., 2012). In this context, modeling studies using integrative process-based models keep playing main roles in evaluating mitigation effectiveness and making future projections. Our results suggest that N2O emissions from corn fields, especially the NGS components, are likely to decrease if the current level of N-fertilizer use is kept, due to decreased soil moisture and reduced freezing intensity in freeze-thaw cycles. Although precipitation is predicted to increase in the Midwest, soil moisture may not increase due to higher evapotranspiration (IPCC6; Forster et al., 2021). Negative effects of elevated T_a on N₂O emissions were found in the majority of field enrichment experiments (Wang et al., 2021). Existing projections of future N₂O emissions in the Midwest using PBM found that agricultural direct N2O emissions are likely to decrease (Kanter et al., 2016) or slightly increase (Griffis et al., 2017). Major uncertainty in those estimates comes from the model configuration of management practices and limited representation in soil inputs. Our simulations assume the scenarios of rainfed, continuous corn systems with no tillage, which may underestimate the regional N2O emissions. Overall, N2O emissions are expected to be higher in irrigated systems than rainfed systems (Mei et al., 2018), be lower in no-till (Decock, 2014; Feng et al., 2018), and be similar in continuous corn systems and corn-soybean rotation systems (Decock, 2014). Although only 3.8% of cornfields are irrigated in the Corn Belt (Perlman et al., 2014), irrigation has significant impacts in relatively arid areas, such as western Nebraska, and may expand as an adaptation to future climate change. We generated soil profiles in croplands using SSURGO dataset but didn't differentiate soils in continuous corn systems from other systems due to the lack of accurate spatial information. Further research specifically on mapping different cropping rotations and their outputs can lend such types of studies more resources and accuracy in the future. Mapping from high-resolution satellite imagery and improved ground-based databases that provide spatially explicit information on management practices (e.g. irrigation, tillage, and crops) can lend strength to advance this study (Peng, 2020; Kim et al., 2021).

5. Conclusions

In this study, we validated the performances of a process-based model, ecosys, on N2O emissions and related energy, water, and carbon variables. Then we applied this model to county-level simulations to investigate the magnitude, spatio-temporal patterns, and drivers of NGS N2O emissions in the US Midwest. Results showed that simulated NGS N2O emissions on average accounted for 26% of the annual fluxes in 2001-2020 under continuous corn systems, ranging from 6 to 60% in different counties. NGS precipitation of 300 mm was found to be a threshold that divides the southeast and the northwest of the Midwest, where precipitation and soil temperature showed differing correlations with NGS N₂O emissions. To help explain the spatial division, we used a data-driven causal inference method, PCMCI, to further understand the complex relationships between N2O emissions and key environmental drivers. It indicates that more intensive freezing caused by lower air temperature is the dominant driver that leads to higher NGS N2O emissions in the southeast, while higher precipitation and higher air temperature cooperatively result in higher soil moisture at soil thaws that enhances NGS N2O production in the northwest. Further, we explored the responses of annual, GS, and NGS N_2O emissions to different fertilizer timing, with or without NI, and climate change. Results suggest that shifting fall application to spring application and applying NI can greatly reduce annual N_2O emissions at the regional scale. Simulations of the four hypothesized climate scenarios suggest that annual N_2O emissions in the study area are likely to reduce under climate change primarily due to the reduction of NGS N_2O emissions. Based on the scenario simulations, we estimated social benefits regarding corn yield, N_2O emissions, N leaching, and $\triangle SOC$. Spring vs. fall application and applying with vs. without NI are more beneficial for most counties. However, the social benefits can be the opposite for some areas, which calls for spatial-specific mitigation practices. This study deepened the knowledge of year-round agricultural N_2O emissions, and provided spatial-explicit effective mitigation directions in a world primary agricultural region.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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