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Multifactor controls on terrestrial N_2O flux over North America from 1979 through 2010

X. F. Xu[1,2], H. Q. Tian[1,2], G. S. Chen[1,2], M. L. Liu[1,2], W. Ren[1,2], C. Q. Lu[1,2], and C. Zhang[1]

[1]Ecosystem Dynamics and Global Ecology (EDGE) Laboratory, School of Forestry and Wildlife Sciences, Auburn University, Auburn, AL, 36849, USA
[2]International Center for Climate and Global Change Research, Auburn University, Auburn, AL, 36849, USA

Correspondence to: H. Q. Tian (tianhan@auburn.edu)

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Abstract. Nitrous oxide (N_2O) is a potent greenhouse gas which also contributes to the depletion of stratospheric ozone (O_3). However, the magnitude and underlying mechanisms for the spatiotemporal variations in the terrestrial sources of N_2O are still far from certain. Using a process-based ecosystem model (DLEM – the Dynamic Land Ecosystem Model) driven by multiple global change factors, including climate variability, nitrogen (N) deposition, rising atmospheric carbon dioxide (CO_2), tropospheric O_3 pollution, N fertilizer application, and land conversion, this study examined the spatial and temporal variations in terrestrial N_2O flux over North America and further attributed these variations to various driving factors. From 1979 to 2010, the North America cumulatively emitted 53.9 ± 0.9 Tg N_2O-N ($1\,\text{Tg} = 10^{12}$ g), of which global change factors contributed 2.4 ± 0.9 Tg N_2O-N, and baseline emission contributed 51.5 ± 0.6 Tg N_2O-N. Climate variability, N deposition, O_3 pollution, N fertilizer application, and land conversion increased N_2O emission while the elevated atmospheric CO_2 posed opposite effect at continental level; the interactive effect among multiple factors enhanced N_2O emission over the past 32 yr. N input, including N fertilizer application in cropland and N deposition, and multi-factor interaction dominated the increases in N_2O emission at continental level. At country level, N fertilizer application and multi-factor interaction made large contribution to N_2O emission increase in the United States of America (USA). The climate variability dominated the increase in N_2O emission from Canada. N inputs and multiple factors interaction made large contribution to the increases in N_2O emission from Mexico. Central and southeastern parts of the North America – including central Canada, central USA, southeastern USA, and all of Mexico – experienced increases in N_2O emission from 1979 to 2010. The fact that climate variability and multi-factor interaction largely controlled the inter-annual variations in terrestrial N_2O emission at both continental and country levels indicate that projected changes in the global climate system may substantially alter the regime of N_2O emission from terrestrial ecosystems during the 21st century. Our study also showed that the interactive effect among global change factors may significantly affect N_2O flux, and more field experiments involving multiple factors are urgently needed.

1 Introduction

Nitrous oxide (N_2O) plays an important role in both contributing to the greenhouse effect (Denman et al., 2007; Rodhe, 1990) and depleting stratospheric ozone (O_3) (Denman et al., 2007; Cicerone, 1987). The atmospheric N_2O concentration has increased from 270 ppb (one part per billion) in 1750 to 319 ppb in 2005 (Forster et al., 2007); terrestrial ecosystems under the impacts of anthropogenic activities have been recognized as one of major sources for this increase (Keller et al., 1986; Bouwman et al., 1993; Del Grosso et al., 2006; Li et al., 1996; Liu, 1996; Repo et al., 2009; Williams et al., 1992; Forster et al., 2007; Denman et al., 2007; Song et al., 2009). Quantifying the magnitude of terrestrial N_2O flux and the underlying mechanisms will be crucial for advancing our understanding on the dynamics of atmospheric N_2O concentration, and further providing helpful information for policy-makers to curb the

continuous increase in atmospheric N_2O concentration (Tian et al., 2010b; Denman et al., 2007).

N_2O flux has been recognized as a result of a suite of microbial processes influenced by a variety of environmental factors (Conrad, 1996; Williams et al., 1992; Pilegaard et al., 2006). Global change will alter these environmental factors and substrates, and further change the N_2O flux (Bouwman et al., 1993; Conrad, 1996; Goldberg and Gebauer, 2009; Kanerva et al., 2007; Kettunen et al., 2005; Williams et al., 1992; Ambus and Robertson, 1999). For example, nitrogen (N) input may stimulate N_2O production by increasing substrate availability (Kettunen et al., 2005; Mcswiney and Robertson, 2005); elevated atmospheric CO_2 may reduce N availability in soil owing to progressive N accumulation in plant biomass (Luo et al., 2004; McGuire et al., 1995), which inhibit the N_2O emission (Phillips et al., 2001); alternatively, elevated atmospheric CO_2 might increase photosynthetic products and stimulate microbial process, and thus increase N_2O emission (Kettunen et al., 2005; Ineson et al., 1998). If these two effects are counterbalanced, it may appear as neutral response of N_2O flux to elevated atmospheric CO_2 (Kanerva et al., 2007; Ambus and Robertson, 1999). Tropospheric O_3 pollution may alter microbial community (Kanerva et al., 2008) and cause an increase or decrease in N_2O emission, depending on time and location (Kanerva et al., 2007). By comparison, the effects of climate variability and land conversion on the N_2O emission are more complicated, largely replying upon the specific site condition (Jiang et al., 2009; Goldberg and Gebauer, 2009; Zhang et al., 2007b).

In the past decades, considerable emphasis has been put on the accurate estimation of terrestrial N_2O flux (Potter et al., 1996; Xu et al., 2008; Liu, 1996; Denman et al., 2007; Matson and Vitousek, 1990; Bouwman et al., 1993). A number of estimates for N_2O flux have been achieved by extrapolating average fluxes from chamber-based measurements to the areal extent of vegetation or soil classes from which the measurements were taken (Keller et al., 1986; Huang et al., 2003; Matson et al., 1989), or by using a simple empirical model (Xu et al., 2008). In these approaches, uncertainties were introduced because the spatial heterogeneity within the classes, as well as the seasonal and inter-annual variabilities in climatic and biotic controls on emission rates, were, at least partially neglected (Potter et al., 1996; Matson et al., 1989). Meanwhile, the empirical methods in estimating regional N_2O flux could not be used to attribute the spatiotemporal variations in terrestrial N_2O flux to environmental drivers. Therefore, a large-scale estimation of terrestrial N_2O flux with consideration of spatial heterogeneity of soil, vegetation, and climate variations that could be used for factorial attribution is highly needed.

The process-based modeling approach is gaining popularity in estimating regional N_2O flux (Del Grosso et al., 2006; Li et al., 2001; Potter et al., 1996). Although process-based models have the potential to explore the relative contributions of each driving force to the spatiotemporal variations in terrestrial N_2O, as they have been used for terrestrial CO_2 flux (McGuire et al., 2001; Tian et al., 2003; Mu et al., 2008) and CH_4 flux (Xu et al., 2010), none of them have been utilized to attribute the spatial and temporal variations in terrestrial N_2O flux to its driving factors.

North America, one of the extensively investigated continents, still lacks accurate estimates due to limitations in methodology and observations (Kort et al., 2008). A number of studies estimated the N_2O emission by solely focusing on one ecosystem type or considering one global change factor (Del Grosso et al., 2006; Xu et al., 2008; Potter et al., 1996). For example, Li et al. (1996) estimated N_2O emission from cropland in the United State of America (USA) by using a process-based model DNDC (DeNitrification DeComposition: Li et al., 1996). Del Grosso et al. (2006) estimated the N_2O flux from cropland in the USA by using the DAYCENT model (Daily Century Model: Del Grosso et al., 2006). One of our previous studies simulated the regional flux of N_2O over North America during 1979–2008 by using a process-based ecosystem model DLEM, driven by multiple global change factors including climate variability, elevated atmospheric CO_2, N deposition, O_3 pollution, N fertilizer application, and land use change (Tian et al., 2010b). In this study, we will extend our previous work and attribute the spatial and temporal variations in terrestrial N_2O flux to various driving factors.

Specifically, the objectives of this study are: (1) to examine the factorial contributions to the spatial variation of terrestrial N_2O flux over North America during 1979–2010; (2) to quantify the factorial contributions to the temporal variations in terrestrial N_2O flux over North America during 1979–2010; and (3) to quantify the factorial contributions to the 32-yr cumulative flux of N_2O over North America at both continental and country levels. The global change factors evaluated in this study include climate variability, rising atmospheric CO_2, N deposition, O_3 pollution, changes in land use and land cover type, and N fertilizer application in cropland. The interactive effects among these six factors were calculated as the difference between simulated changes in N_2O flux driven by all factors together and changes in N_2O flux caused by six individual factors (see Experiment design section for the detail information).

2 Materials and methods

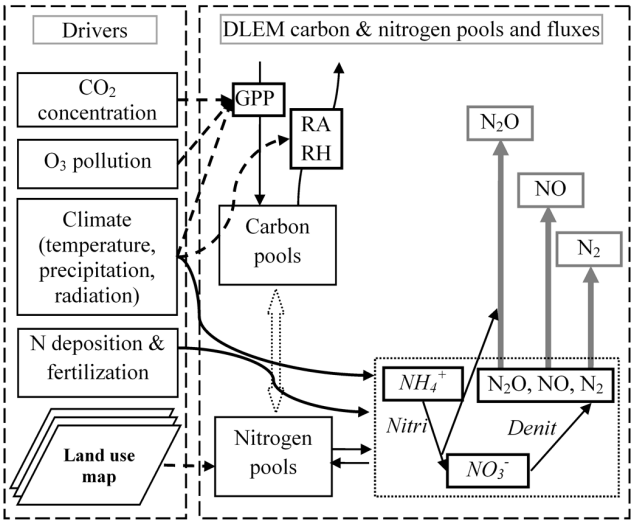
2.1 Brief description of the model used in this study

The model used in this study is a process-oriented ecosystem model DLEM, which couples major biogeochemical cycles, hydrological cycles, and vegetation dynamics to make daily, spatially-explicit estimates of carbon (C), N, and water fluxes and pool sizes in terrestrial ecosystems (Tian et al., 2010b). The DLEM also simulates the managed ecosystems,

including agricultural ecosystems, plantation forests, and pastures. The spatial data set of land management practices, such as irrigation, fertilization, rotation, and harvest, can be used as input information for simulating influences of land management on the structure and functioning of ecosystems. This model has been calibrated against various field data from the Chinese Ecological Research Network (CERN), US Long-Term Ecological Research (LTER) network, and AmeriFlux network, which cover various ecosystems, including forest, grassland, shrubland, tundra, desert, natural wetlands, and cropland. The simulated results have been compared with independent field data and satellite products. The DLEM operates at a daily time step and at varied spatial resolutions, from meters to kilometers, from regional to global. The detailed information for DLEM has been described in our previous publications (Liu et al., 2008; Ren et al., 2007, 2011a, b; Zhang et al., 2007a; Tian et al., 2010a, b, 2011a, b; Xu et al., 2010; Lu et al., 2012), and the N_2O module has been described in detail in Tian et al. (2010b).

In the DLEM, the N_2O module is incorporated into nitrogen cycling; it simulates the nitrification and denitrification processes. Both denitrification and nitrification processes are simulated as one-step process as we do not consider the mid-products in each process. Nitrification, a process converting ammonium into nitrate, is simulated as a function of soil temperature, moisture, and the NH_4^+ concentration (Lin et al., 2000; Tian et al., 2010b). It should be noted that a small portion of N_2O is from nitrification processes. Denitrification, through which the nitrate is converted into N-containing gases, is simulated in the DLEM as a function of soil temperature, moisture, and the NO_3^- concentration (Lin et al., 2000). The empirical equation reported by Davidson et al. (2000) is used to separate N_2O from other gases (mainly NO and N_2).

In summary, multiple global change factors directly and/or indirectly affect N_2O processes in the DLEM (Fig. 1). The elevated atmospheric CO_2 and O_3 pollution yield indirect impacts on N_2O fluxes through their effects on carbon processes and carbon-nitrogen interaction; the climate variability yield direct and/or indirect impacts on N_2O flux; N deposition and N fertilizer application directly affect N_2O flux since they will change available N in soil for N_2O production, and indirectly impact carbon process and C-N interaction; the effect of land conversion is complicated since it might change all the ecosystem properties and hence N_2O flux. It should be noted that there are other environmental factors, for example, soil pH, and soil porosity, etc., that might influence N_2O flux.



Major processes: *Ntri*: Nitrification; *Denit*: Denitrification; GPP is the gross primary productivity; RA is the autotrophic respiration from plant, and RH is the heterotrophic respiration; Drivers are the multiple global change factors which yield controls on or feedback to ecosystem processes in the DLEM framework. The effects from drivers were expressed as the line starting from drivers to ecosystem processes or pools. Solid lines represent direct, while dash lines represent indirect impacts on N_2O processes.

Fig. 1. Conceptual diagram showing major processes for N_2O flux in response to multiple global change factors in the DLEM model (Only nitrification and denitrifiction processes are shown in the figure; other nitrogen processes including nitrogen fixation, mineralization, immobilization etc. are not shown in this figure since they are not the focus of this study; see Tian et al. (2010b) for detailed information).

2.2 Study area and input data

This study mainly focused on North America, which includes the USA, Canada, and Mexico, covering a total area of approximately 24.71 million km^2, approximately 4.8 % of the planet's surface or 16.5 % of its land area. Excluding water bodies, North America consists of 21 237 grids at a spatial resolution of 32 km by 32 km, which is consistent with the North American Regional Reanalysis (NARR) dataset.

We developed gridded (32×32 km), geo-referenced, time-series data sets of climate (including daily average, maximum, and minimum temperatures, precipitation, humidity, and solar radiation), annual N deposition rate, annual land-cover change and land management practices (including fertilization, irrigation) for the entire North America. The data development has been described in detail in a previous publication (Xu et al., 2010). The same dataset was extended to cover the time period of 1900–2010 and used in this study. The climate data was extended to 2010 by processing the NARR dataset (Mesinger et al., 2006).The land use and land cover change data, N fertilizer data, O_3 pollution data, and N deposition were assumed unchanged after 2005; the N fertilizer data and N deposition were assumed unchanged after 2008. The annual atmospheric concentration of CO_2 was updated based on the dataset from National Oceanic and Atmospheric Administration (NOAA) (www.esrl.noaa.gov).

Historical data from 1901 to 2010 are used to drive the transient model simulations in this study. The transient input

Table 1. Experimental design for this study.

Simulation	Climate	Nitrogen deposition	CO_2	O_3	Nitrogen fertilizer	Land conversion
1	1900–2010	1900–2010	1900–2010	1900–2010	1900–2010	1900–2010
2	1900–1979	1900–1979	1900–1979	1900–1979	1900–1979	1900–1979
3	1900–2010	1900	1900	1900	1900	1900
4	1900–1979	1900	1900	1900	1900	1900
5	1900	1900–2010	1900	1900	1900	1900
6	1900	1900–1979	1900	1900	1900	1900
7	1900	1900	1900–2010	1900	1900	1900
8	1900	1900	1900–1979	1900	1900	1900
9	1900	1900	1900	1900–2010	1900	1900
10	1900	1900	1900	1900–1979	1900	1900
11	1900	1900	1900	1900	1900–2010	1900
12	1900	1900	1900	1900	1900–1979	1900
13	1900	1900	1900	1900	1900	1900–2010
14	1900	1900	1900	1900	1900	1900–1979

Note: 1900–2010 indicates that the data for the time period of 1900–2010 was used in the simulation; while 1900–1979 indicates that the data for the time period of 1900–1979 was used in the simulations and the simulations after 1979 was fed by the data of 1979.

data include: (1) daily climate data from 1901 to 2010, including maximum, minimum and average temperatures, relative humidity, solar radiation, and precipitation; the data from 1901 to 1978 were randomly assigned as one year during 1979–2010; (2) annual N deposition from 1901 to 2010; (3) annual O_3 pollution data from 1901 to 2010; (4) atmospheric CO_2 concentration from 1901 to 2010; (5) cropland and urban distribution from 1901 to 2005 – the land use since 2005 was assumed unchanged due to shortage of data; and (6) N fertilizer application data for cropland over the time period of 1901–2010.

2.3 Experimental design

In this study, we performed fourteen simulation experiments to determine the relative effects of N deposition, O_3 pollution, climate variability, elevated atmospheric CO_2, land-use change, and N fertilizer application on terrestrial N_2O flux over North America. One overall simulation was set up to simulate the terrestrial N_2O flux over North America by considering the temporal and spatial dynamics of all six global change factors. Six additional simulations were set up to simulate the effects of each individual factor on N_2O flux. For example, to determine the effects of climate variability alone, we ran DLEM using the gridded historical daily data for air temperature, including maximum, minimum, and average air temperatures, relative humidity, solar radiation, and precipitation; but kept all other five global change factors at the levels of 1900: the atmospheric CO_2 concentration, N deposition, O_3 pollution, N fertilizer application for cropland, and the land cover type (potential vegetation map with cropland and urban land in 1900). To determine the effects of CO_2 fertilization alone, we ran DLEM using the historical atmospheric CO_2 concentrations, but kept all other five global change factors constant: a 30-yr averaged daily climate data was used to represent the mean climate condition, the potential vegetation map with crop and urban land in 1900 was used to represent the constant land cover type, and the N deposition, O_3 pollution, and N fertilizer application data were kept constant in the year of 1900. For each of the above seven simulations, we set up one corresponding simulation except the input data in 1979 was used to drive the post-1979 simulations. This simulation design was used to capture the internal dynamics of the system, which served as baseline; the difference between each pair of simulation is defined as the factor-induced N_2O flux. For example, the time-series difference between simulation #1 and simulation #2 for 1979–2010 is caused by all global change factors and their interaction because the internal system dynamic defined as results from simulation #2 was excluded (Table 1).

The implementation of DLEM simulation included the following steps: (1) equilibrium run, (2) spinning-up run, and (3) transient run. In this study, we used potential vegetation, long-term mean climate during 1979–2010, the levels of N deposition, O_3, and atmospheric CO_2 concentration in the year 1900 to drive the model simulations to an equilibrium state (i.e. the inter-annual variations are $<0.1\,g\,C\,m^{-2}$ for carbon storage, $<0.1\,g\,N\,m^{-2}$ for N storage). After the system reached an equilibrium state, the model was run with an addition of cropland and urban areas for another 3000 yr for spinning-up purposes. Finally, the model was run in transient mode with daily climate data, annual CO_2 concentration, and N deposition inputs from 1901 to 2010 to simulate the terrestrial N_2O flux. The outputs between 1979 and 2010 were analyzed to show the spatial and temporal patterns of terrestrial N_2O flux in North America's terrestrial ecosystems. Urban was treated as grassland, which is the same strategy used in other terrestrial biosphere models. Baseline flux was defined as the terrestrial N_2O flux during 1979–2010

Table 2. Changing rates of driving factors from 1979 to 2010 for DLEM simulations.

Variables		Changing rates (Mean ± SD)
Climate	Maximum temperature ($°C\,a^{-1}$)	0.04 ± 0.01*
	Minimum temperature ($°C\,a^{-1}$)	0.03 ± 0.01*
	Average temperature ($°C\,a^{-1}$)	0.03 ± 0.01*
	Precipitation ($mm\,a^{-1}$)	0.09 ± 0.62
	Relative humidity ($\%\,a^{-1}$)	-0.01 ± 0.01
	Solar radiation ($W\,m^{-2}\,a^{-1}$)	0.19 ± 0.03*
Others	Tropospheric O_3 pollution ($ppm\text{-}h\,a^{-1}$)	0.96 ± 0.08*
	N deposition ($mg\,m^{-2}\,a^{-1}$)	1.96 ± 0.05*
	N fertilizer application ($mg\,m^{-2}\,a^{-1}$)	0.02 ± 0.01*
	Atmospheric CO_2 concentration ($ppm\,a^{-1}$)	1.68 ± 0.02*

* indicates the changing rate is significantly different from zero; positive values represent increase through the study period, and negative values represent decrease through the study period.

Table 3. Land area of the major biomes in North America.

Plant functional type	Tundra	Forest	Shrub	Grassland	Wetland	Desert and others	Cropland
Area (million km^2)	4.05	$6.93 \sim 6.99$	$3.57 \sim 3.59$	$2.61 \sim 2.64$	$2.06 \sim 2.07$	$0.53 \sim 0.60$	$2.51 \sim 2.59$
Percentage	18.09	31.10	15.98	11.72	9.23	2.49	11.39

Biome-level areas may not sum to totals because of the effects of rounding in reporting those values.

simulated by the DLEM driven by the input data of 1979. The changes thereafter compared to baseline flux were assumed solely caused by global change factors, individually or in combination.

2.4 Model parameterization

The model parameterization and validation at both site and regional levels were documented in our previous publication (Tian et al., 2010b). We will not describe them in detail in this paper.

2.5 Statistic method

The regression analysis was used in this study to quantify the long-term changing trend of input data and terrestrial N_2O fluxes estimated by various simulations. All the statistical analyses were conducted using the R program 12.0 for Windows XP.

3 Results

3.1 Environmental changes over North America during 1979–2010

For the climate variables, maximum, minimum, and average temperatures, and solar radiation showed significantly increasing trends at the rates of 0.04 ± 0.01 $°C\,a^{-1}$, $0.03 \pm 0.01\,°C\,a^{-1}$, $0.03 \pm 0.01\,°C\,a^{-1}$, and $0.19 \pm 0.03\,W\,m^{-2}\,a^{-1}$, respectively; yet precipitation and relative humidity did not show any significantly changing trends over the study period. All the other driving factors significantly increased since 1979; the long-term increasing rates were $0.96 \pm 0.08\,ppm\text{-}h\,a^{-1}$ for tropospheric O_3 pollution, $1.96 \pm 0.05\,mg\,m^{-2}\,a^{-1}$ for N deposition, $0.02 \pm 0.01\,g\,m^{-2}\,a^{-1}$ for N fertilizer application, and $1.68 \pm 0.02\,ppm\,a^{-1}$ for atmospheric CO_2 concentration, respectively (Table 2). The areas of different land cover types changed slightly throughout the study period; the cropland area increased from 2.51 million km^2 to 2.59 million km^2; the area of forest, shrubland, grassland and wetland changed in a very small magnitude (Table 3).

Spatial variations of input data were shown in a previous paper (Xu et al., 2010). Normally, the severely O_3-polluted area over North America locates in western part of North America such as the northwestern USA which could be as high as more than $5000\,ppb\,h^{-1}$ (monthly cumulated hourly O_3 dose over a threshold of 40 ppb in ppb-h), while the other areas, especially northern end of continental North America, were featured by low tropospheric O_3 pollution. The regions with high N fertilizer application (larger than $10\,g\,N\,m^{-2}\,a^{-1}$) concentrate in USA, including western, central, and eastern coastal areas of USA. The Canada and Mexico had a small amount of cropland and received lower application rate of N fertilizer. The high N deposition primarily occurred in eastern part of the continental North America, including southeastern Canada, eastern USA and portions of Mexico (larger than $1\,g\,N\,m^{-2}\,a^{-1}$), while the northern

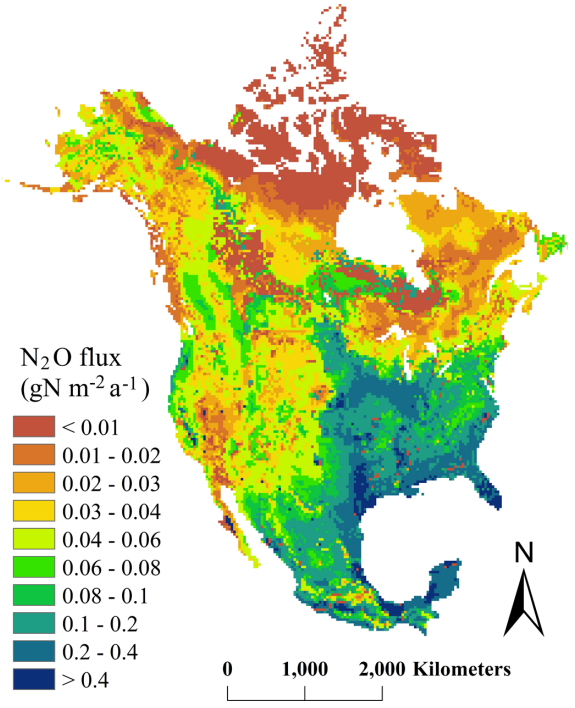


Fig. 2. Spatial variations of terrestrial N_2O fluxes caused by global change factors over North America from 1979 to 2010.

Canada was featured by quite low N deposition (lower than $0.01\,g\,N\,m^{-2}\,a^{-1}$).

3.2 Spatial distribution of N_2O flux over North America during 1979–2010

The terrestrial N_2O flux over North America showed a significant spatial variation, with a strong source in southeastern continental North America, including southeastern USA and the majority of Mexico, and a weak source in the northern part of North America (Fig. 2). At the country level, central and southeastern USA featured high N_2O emission, up to nearly $1\,g\,N\,m^{-2}\,a^{-1}$, while western USA had relatively low N_2O emission rates. There was a north-to-south increasing gradient of N_2O emission across Canada: the N_2O emission rate was as low as $0.0001\,g\,N\,m^{-2}\,a^{-1}$ in northern Canada, and as high as nearly $0.4\,g\,N\,m^{-2}\,a^{-1}$ in southern Canada; the entire Mexico acted as a strong source for N_2O, with the national N_2O emission being $>0.1\,g\,N\,m^{-2}\,a^{-1}$ over the past 32 yr.

3.3 Factorial contribution to the spatial variations in terrestrial N_2O flux during 1979–2010

Nitrogen release as N_2O is one of major pathways for nitrogen loss from terrestrial ecosystem. Throughout the study period, the cumulative N_2O emission over North America was composed of two components: one is the background emission, defined as the N_2O flux during 1979–2010 simulated by the DLEM driven by the input data of 1979; the other is the flux contributed by changes in various individual and interactive effects of several global change factors. After removing the baseline flux of N_2O, the remaining changes in N_2O fluxes over the study period are resulted from six global change factors and their interaction.

Over the 32-yr study period, climate variability enhanced N_2O emission over the majority of central Canada, while decreased N_2O emissions over portions of western Alaska, majority of the USA, and a portion of Mexico (Fig. 3a). N deposition enhanced N_2O emission over the entire continental North America, with prominent increases over southeastern USA and Mexico (Fig. 3b). The elevated atmospheric CO_2 enhanced N_2O emissions in southeastern USA and a portion of Mexico, while decreased N_2O emissions in western USA, central Canada, and the majority of Mexico (Fig. 3c). The O_3 pollution increased N_2O emissions in portions of southeastern USA, while no significant impacts on N_2O flux were found in other areas (Fig. 3d). The N fertilizer application enhanced N_2O emission in central USA, which is agricultural land (Fig. 3e). Land conversion only affected a small amount of area that experienced land use conversion between natural vegetation and cropland or urban in the past few years (Fig. 3f). The interactive effect among global change factors enhanced N_2O emissions in central USA, while decreased N_2O emissions in southeastern USA and central Canada (Fig. 3h). Combining all the effects from various global change factors, the N_2O emissions were enhanced across central Canada and central USA and portions of Mexico, yet were decreased in western and southeastern USA and eastern Canada (Fig. 3g).

3.4 Temporal patterns of N_2O flux over North America during 1979–2010

The continental-level terrestrial flux of N_2O over North America showed a significant inter-annual fluctuation during 1979–2010 (Fig. 4). The mean annual N_2O flux over North America's terrestrial ecosystems was $1.68 \pm 0.15\,Tg\,N_2O\text{-}N\,a^{-1}$, with an overall increasing rate of $5.47 \pm 2.74\,Gg\,N_2O\text{-}N\,a^{-1}$ ($1\,Gg = 10^9\,g$) over 32 yr ($P = 0.055$). The long-term increasing trend and inter-annual fluctuation in terrestrial N_2O flux resulted from multiple global change factors (Fig. 4). Climate variability exerted a significant inter-annual variation in N_2O flux, with a slightly increasing rate of $2.72 \pm 2.07\,Gg\,N_2O\text{-}N\,a^{-1}$ ($P = 0.199$). N deposition contributed to an increasing rate of $1.67 \pm 0.03\,Gg\,N_2O\text{-}N\,a^{-1}$ ($P < 0.001$), and N fertilizer application contributed to an increasing rate at $2.39 \pm 0.13\,Gg\,N_2O\text{-}N\,a^{-1}$ for continental N_2O emission ($P < 0.001$). O_3 pollution contributed to an increasing rate of $0.54 \pm 0.03\,Gg\ N_2O\text{-}N\,a^{-1}$ ($P < 0.001$). The increased atmospheric CO_2 concentration continuously decreased N_2O emission, which generated a decreasing rate of $1.33 \pm 0.06\,Gg\,N_2O\text{-}N\,a^{-1}$ ($P < 0.001$) over the study

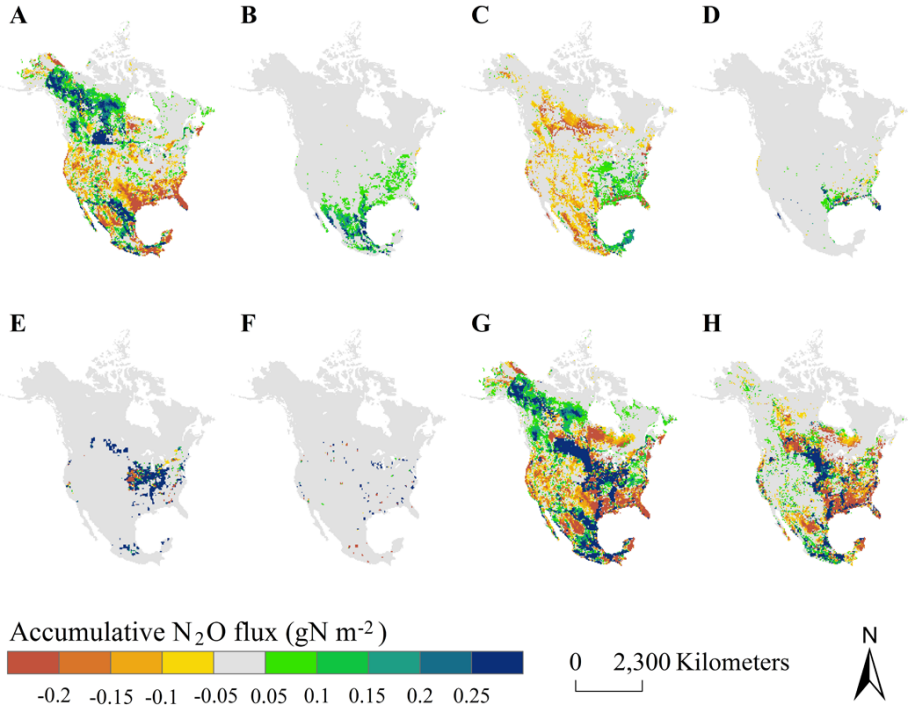


Fig. 3. Factorial contributions to the spatial variations in cumulated N_2O flux over North America from 1979 to 2010 (**A**: climatic variability; **B**: N deposition; **C**: CO_2; **D**: tropospheric O_3 pollution; **E**: N fertilizer application; **F**: land conversion; **G**: all combined; **H**: interaction).

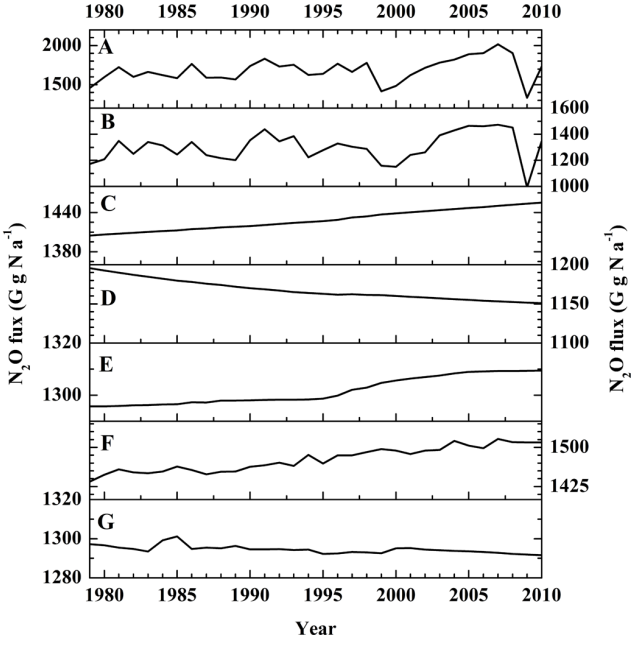


Fig. 4. Temporal variations of terrestrial N_2O flux caused by global change factors over North America from 1979 to 2010 (**A**: all combined simulation; **B**: climate only simulation; **C**: N deposition only simulation; **D**: CO_2 only simulation; **E**: tropospheric O_3 pollution only simulation; **F**: N fertilizer application only simulation; **G**: land conversion only).

period, while land conversion did not yield significant changing trends of N_2O emission over the study period.

3.5 Factorial contributions to the cumulated N_2O flux over North America during 1979–2010 at continental and country levels

To quantify the relative contributions of multiple global change factors to the N_2O flux over North America during 1979–2010, we summed up the individual factor-induced changes in N_2O flux over the 32 yr to analyze the contributions of the six single factors and their interaction. To quantify the uncertainties associated with the cumulated N_2O flux caused by the six individual factors and their interaction, we treated the thirty two annual fluxes as a sample to calculate the average flux and its standard error. Finally, the 32-yr cumulated flux and its standard error over the study period were reported. During the 32-yr study period, the cumulative N_2O flux over North America was 53.89 ± 0.85 Tg N_2O-N, of which 51.48 ± 0.58 Tg N_2O-N was resulted from baseline flux and 2.41 ± 0.99 Tg N_2O-N was caused by global change factors (Fig. 5). Elevated atmospheric CO_2 decreased the N_2O emission by 0.46 ± 0.06 Tg N_2O-N from North America's terrestrial ecosystems, while all the other single factors increased N_2O emission. Climate variability, N deposition, O_3 pollution, N fertilizer application, land conversion, and multi-factor interaction enhanced continental N_2O emission (Table 4).

To examine the factorial contributions to cumulated terrestrial N_2O flux for the three countries, we further partitioned continental level N_2O flux into country-level fluxes (Fig. 6). The 32-yr cumulative N_2O emission was 32.29 ± 0.58 Tg N_2O-N for USA, 9.38 ± 0.22 Tg N_2O-N for Canada, and 12.21 ± 0.37 Tg N_2O-N for Mexico, respectively (Table 4). For the USA, climate variability and elevated atmospheric CO_2 decreased N_2O emission, while N deposition, O_3 pollution, N fertilizer application, land conversion, and multi-factor interaction increased the country-level N_2O emission (Table 4). After removing the baseline emission, the global change factors increased N_2O emission from USA's terrestrial ecosystems from 1979 to 2010. For Canada, climate variability, N deposition, O_3 pollution, N fertilizer application, and land conversion increased N_2O emission during 1979–2010; while elevated atmospheric CO_2 and multi-factor interaction decreased N_2O emission (Table 4). After removing the baseline emission, the global change factors increased N_2O emission from Canada's terrestrial ecosystems over the 32-yr period. For Mexico, climate variability, N deposition, O_3 pollution, N fertilizer application, and multi-factor interaction enhanced N_2O emission during the time period of 1979–2010; while elevated atmospheric CO_2 and land conversion decreased N_2O emission (Table 4). After removing the baseline flux, the global change factors stimulated N_2O emission from Mexico's terrestrial ecosystems from 1979 to 2010.

For the country-level cumulative terrestrial N_2O fluxes, the baseline emission made the biggest contribution: it accounted for 95.54 % of the continental N_2O emission, and 97.18 %, 94.37 %, and 92.09 % of the N_2O flux in the USA, Canada, and Mexico, respectively (Table 4).

3.6 Factorial contributions to the inter-annual variations in N_2O flux over North America during 1979–2010 at continental and country levels

Inter-annual variation is one of major attributes of ecosystem processes; it may be caused by internal mechanisms or external environmental controls. Inter-annual variation in terrestrial N_2O flux was shown over North America from 1979 to 2010 (Fig. 7). To examine the controlling factors for this inter-annual variation, we further attributed the changes in terrestrial N_2O flux for each year to the six global change factors and their interaction (results shown in Fig. 7). Over the entire North America, rising atmospheric CO_2 continuously decreased, while N deposition and N fertilizer application continuously increased terrestrial N_2O emission. O_3 pollution yielded very small positive effects on terrestrial N_2O emission, while land conversion yielded small yet fluctuating effects on terrestrial N_2O emission (Fig. 7). The climate variability primarily dominated the inter-annual fluctuation in terrestrial N_2O flux from 1979 to 2010. Climate variability and multi-factor interaction co-dominated the increases in N_2O emission in three specific time periods: 1979–1987, 1990–1998, and 2001–2008. For the specific years, such as 1988, 1989, and 1999 when the climatic contribution to the N_2O flux was neutral, the interactive effect among multiple factors dominated the changes of terrestrial N_2O flux compared to the baseline flux (Fig. 7).

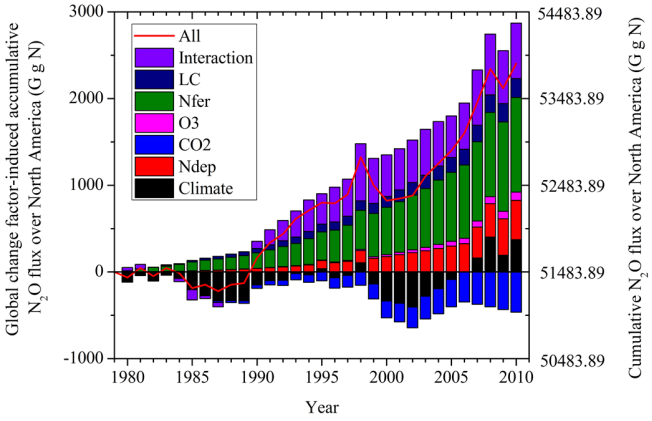


Fig. 5. Factorial contributions to cumulated N_2O flux over North America during 1979–2010 (The right y-axis shows the cumulative N_2O flux with baseline; *All* means N_2O flux derived from all combined simulation; *Interaction* means contribution from multi-factor interaction; *LC* means contribution from land conversion; *Nfer* means contribution from N fertilizer application; O_3 means contribution from tropospheric O_3 pollution; CO_2 means contribution from elevated atmospheric CO_2; *Ndep* means contribution from N deposition; *Climate* means contribution from climate variability).

After partitioning continental flux into country-level fluxes of N_2O, we further analyzed and identified the major factors controlling the inter-annual fluctuation in terrestrial N_2O over each country. It was found that the major factors leading to inter-annual fluctuation in terrestrial N_2O flux varied among countries. Climate variability and multi-factor interaction co-dominated the inter-annual fluctuations in terrestrial N_2O flux over the USA. During the periods of 1979–1986, 1990–1998, and 2009, the climatic effects dominated the terrestrial N_2O emission over the USA. Meanwhile, interactive effects among the factors contributed to the flux of terrestrial N_2O over the entire study period except the years of 2002–2003 (Fig. 8a).

Climate variability outweighed other factors in controlling the increases in terrestrial N_2O emission over Canada during most of the study period (Fig. 8b). For instance, the climate-induced increases in terrestrial N_2O flux were much higher than contributions from other factors during 2003–2010. However, in the years of 1982, 1989, 1992, 1995, 1998, and 2002, the climate-induced increases in terrestrial N_2O were offset by the other factors' effects. Similar to the USA, the rising atmospheric CO_2 continuously decreased N_2O emission. O_3 pollution, N input, and land conversion exerted minor effects on terrestrial N_2O flux. The multi-factor interaction yielded very complex effects: it varied significantly through the study period, positive or negative,

Table 4. Factorial contributions to the cumulated N_2O from 1979 to 2010 (*Climate* represents the impacts of climate variability only; *Ndep* represents the impacts of N deposition; CO_2 represents the impacts of CO_2 variation; O_3 represents the impacts of Tropospheric O_3 pollution; *Nfer* represents the impacts of N fertilizer application; *Land conversion* represents the impacts of land cover change only; *Interaction* represents the interactive effects of the six environmental factors).

	Baseline	Climate	Ndep	CO_2	O_3	Nfer	Land conversion	Interaction	Total flux
					USA				
Cumulative N_2O flux (T g N)	31.38 ± 0.45	-0.42 ± 0.48	0.20 ± 0.02	-0.17 ± 0.03	0.08 ± 0.01	0.84 ± 0.09	0.26 ± 0.02	0.12 ± 0.36	32.29 ± 0.58
Percentage (%)	97.18	−1.41	0.61	−0.53	0.24	2.60	0.82	0.38	100
					Canada				
Cumulative N_2O flux (T g N)	8.85 ± 0.12	0.75 ± 0.33	0.03 ± 0.005	-0.21 ± 0.02	0.004 ± 0.001	0.09 ± 0.01	0.007 ± 0.002	-0.14 ± 0.08	9.38 ± 0.22
Percentage (%)	94.37	7.98	0.34	−2.27	0.04	0.93	0.07	−1.47	100
					Mexico				
Cumulative N_2O flux (T g N)	11.25 ± 0.35	0.05 ± 0.41	0.22 ± 0.04	-0.08 ± 0.01	0.01 ± 0.003	0.16 ± 0.01	-0.05 ± 0.01	0.65 ± 0.13	12.21 ± 0.37
Percentage (%)	92.09	0.38	1.83	−0.67	0.11	1.34	−0.43	5.34	100
					NA				
Cumulative N_2O flux (T g N)	51.48 ± 0.58	0.37 ± 0.67	0.45 ± 0.06	-0.46 ± 0.06	0.10 ± 0.02	1.09 ± 0.11	0.22 ± 0.02	0.64 ± 0.39	53.89 ± 0.85
Percentage (%)	95.54	0.69	0.84	−0.86	0.18	2.02	0.41	1.19	100

Country- or individual factor-based estimates may not sum to totals because of the effects of rounding in reporting those estimates; positive values represent stimulating effects of global change factors on N_2O flux; negative values represent inhibiting effects of global change factors on N_2O flux.

small or large. For Mexico, although climate variability yielded significant effects on inter-annual variations in terrestrial N_2O flux, the contributions from multi-factor interaction were predominated in several time periods. For example, in 2005, the multi-factor interaction outweighed other factors and played an important role in controlling terrestrial N_2O flux; for the time period of 1983–1993, the contributions from multi-factor interaction also prevailed. The contributions from all other factors were in small magnitude (Fig. 8c).

4 Discussion

4.1 Comparisons with other studies

We compared our modeled results against previous studies to evaluate the factorial effects on N_2O flux for major biomes (Table 5). Our estimated continental-scale average response to double CO_2 was −36.33 % for forest ecosystems, which is consistent with Phillips et al.'s report that the N_2O emission will be suppressed by elevated CO_2 (Phillips et al., 2001). DLEM simulated a 17.54 % decrease of N_2O emission from grassland, which is consistent with a previous estimate (Baggs et al., 2003). All field observations reported that the effects of elevated CO_2 on N_2O emission depend on N availability; this could be explained by N limitation theory (Luo et al., 2004). Several studies have concluded that majorities of forest and grassland on the planet are N limited (Aber et al., 1998; Aber and Melillo, 2001; Vitousek and Farrington, 1997; Vitousek et al., 1997), so the elevated CO_2 might suppress N_2O emission from these ecosystems. Our study found that the elevated CO_2 suppressed N_2O emission over North America's forest and grassland. This study also found that N deposition could stimulate N_2O emission in all major biomes, which is consistent with field observations (Liu and Greaver, 2009; Ambus and Robertson, 2006; Kettunen et al., 2005). DLEM simulations indicate that N deposition could stimulate N_2O emission at rates of 28.55 ± 0.24 mg N m^{-2} a^{-1}/(g N m^{-2} a^{-1}) for forest, 49.15 ± 0.19 mg N m^{-2} a^{-1}/(g N m^{-2} a^{-1}) for grassland, 47.77 ± 0.88 mg N m^{-2} a^{-1}/(g N m^{-2} a^{-1}) for wetland, and 13.94 ± 0.10 mg N m^{-2} a^{-1}/(g N m^{-2} a^{-1}) for cropland, respectively. These responses are larger than the summarized values by Liu and Greaver (2009). This might be related to the fact that our simulation study covered more heterogeneous space than Liu and Greaver (2009) did. There is only one reported field study for the effect of O_3 pollution on N_2O emission from grassland (Kanerva et al., 2007). Both DLEM-estimation and field observation showed very small, or nearly neutral effect of O_3 pollution. O_3 has been found to be an inhibitor of plant growth (Ashmore, 2005; Kanerva et al., 2007; Wang et al., 2007); worse plant growth means lower N uptake, which will, in turn, increase N availability in soil and thus stimulate N_2O emission.

A newly developed country-level inventory data of N_2O fluxes was reported by United Nationals Framework Convention on Climate Change (UNFCCC) (http://unfccc.int) in late 2011. A comparison shows that results from UNFCCC

Table 5. Comparison of factorial effects on N_2O fluxes against other studies (positive values mean increase; negative values mean decrease in N_2O emission).

	Biome	Experiment design	This study	Other studies	Literature
Elevated CO_2	Forest	Double CO_2	−36.33 %	Negative, neutral or positive effects, depending on seasons and nitrogen availability	Ambus and Robertson (1999); Phillips et al. (2001)
	Grassland	600 ppm vs. 360 ppm CO_2	−17.54 %	−5.65 % ∼ −26.01 % for low nitrogen input; 1.43 % ∼62.27 % for high nitrogen input	Baggs et al. (2003); Ineson et al. (1998); Kanerva et al. (2007); Ambus and Robertson (2006)
Nitrogen deposition	Forest		28.55 ± 0.24 ($mg\,N\,m^2\,a^{-1}$/ $g\,N\,m^2\,a^{-1}$)	6 ± 1 ($mg\,N\,m^2\,a^{-1}$/ $g\,N\,m^2\,a^{-1}$)	Liu and Greaver (2009)
	Grassland		49.15 ± 0.19 ($mg\,N\,m^2\,a^{-1}$/ $g\,N\,m^2\,a^{-1}$)	6 ± 1 ($mg\,N\,m^2\,a^{-1}$/ $g\,N\,m^2\,a^{-1}$)	Liu and Greaver (2009)
	Wetland		47.77 ± 0.88 ($mg\,N\,m^2\,a^{-1}$/ $g\,N\,m^2\,a^{-1}$)	36 ± 13 ($mg\,N\,m^2\,a^{-1}$/ $g\,N\,m^2\,a^{-1}$)	Liu and Greaver (2009)
	Cropland		13.94 ± 0.10 ($mg\,N\,m^2\,a^{-1}$/ $g\,N\,m^2\,a^{-1}$) for nitrogen deposition; 18.23 ± 0.05 ($mg\,N\,m^2\,a^{-1}$/ $g\,N\,m^2\,a^{-1}$) for nitrogeN fertilizer application	9 ± 1 ($mg\,N\,m^2\,a^{-1}$/ $g\,N\,m^2\,a^{-1}$)	Liu and Greaver (2009)
Tropospheric O_3 pollution	Grassland	40–50 ppb in Open-top chambers	1.5 %	Decrease yet not significantly	Kanerva et al. (2007)

and this study are comparable yet different in magnitude due to different methods or datasets; for example, the UNFCCC estimates that N_2O emission from agricultural soils in US is for $0.79 \sim 0.88\,Tg\,N\,a^{-1}$ from 1990 to 2009, while it is $0.35 \sim 0.44\,Tg\,N\,a^{-1}$ estimated by DLEM; this might be due to the fact that UNFCCC considers all agricultural land while DLEM only considers cropland.

4.2 Factorial controls on N_2O flux at temporal and spatial scales

Spatial variations in terrestrial N_2O flux over North America simulated in this study were consistent with other studies (Xu et al., 2008; Potter et al., 1996). The major source for atmospheric N_2O locates in southeastern continental North America, including the south part of central Canada, southeastern USA, and all of Mexico, which is associated with large cropland distributions and relatively high temperatures (Fig. 3). The weak source in northern Canada is probably due to its low temperature and rainfall, as N_2O emission is significantly controlled by temperature and soil moisture (Chapuis-Lardy et al., 2007; Conrad, 1996; Goldberg and Gebauer, 2009).

N_2O flux was primarily controlled by environmental factors, substrate availability, and energy source (Brumme et al., 1999; Williams et al., 1992; Conrad, 1996). Global change factors alter terrestrial N_2O flux through their effects on these processes (Dong et al., 2003; Kettunen et al., 2005; Mcswiney and Robertson, 2005; Kanerva et al., 2007; Zhang et al., 2007b). As consistent with previous studies (Mosier et al., 1991; Li et al., 1996; Mcswiney and Robertson, 2005; Zhang et al., 2007b), N input, including N deposition and N fertilizer application, enhanced the N_2O emission from terrestrial ecosystems. O_3 has been confirmed to be a pollutant which may decrease productivity (Ashmore, 2005; Wang

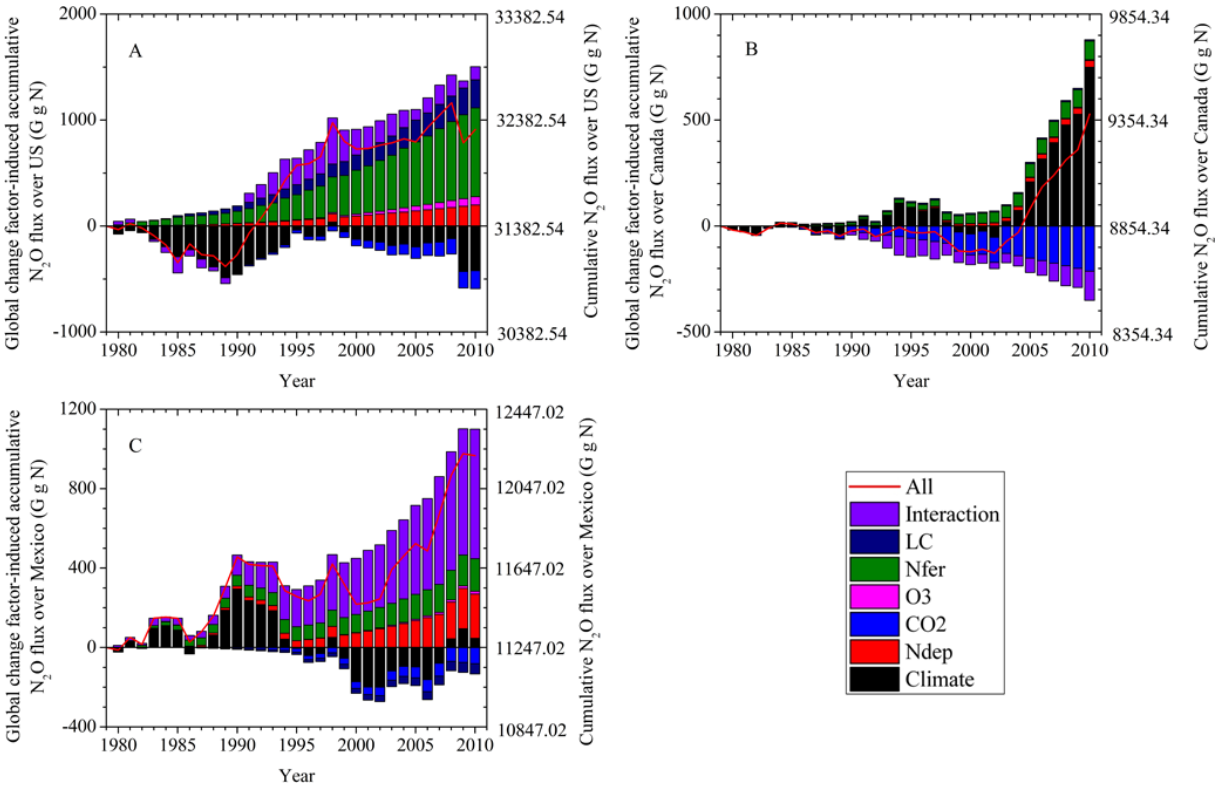


Fig. 6. Factorial contributions to cumulated N_2O flux at country-level during 1979–2010 (**A**: United States of America; **B**: Canada; **C**: Mexico) (The right y-axis shows the cumulative N_2O flux with baseline; *All* means N_2O flux derived from all combined simulation; *Interaction* means contribution from multi-factor interaction; *LC* means contribution from land conversion; *Nfer* means contribution from N fertilizer application; O_3 means contribution from tropospheric O_3 pollution; CO_2 means contribution from elevated atmospheric CO_2; *Ndep* means contribution from N deposition; *Climate* means contribution from climate variability).

et al., 2007), and thus suppress carbon source for microbial processes responsible for N_2O production, and finally cause decreases in N_2O emission. However, it is also reasonable to infer that the O_3 pollution inhibits productivity (Wang et al., 2007); and less N uptake might increase N availability in soil and in turn increase N_2O emission. This study showed that the O_3 pollution enhanced N_2O emission from terrestrial ecosystems in southeastern USA due to slightly higher N availability.

The elevated atmospheric CO_2 decreased N_2O emission at continental scale; while the effects varied across North America. The stimulation effects of elevated atmospheric CO_2 on N_2O emission were also observed over southeastern USA and portions of Mexico (Fig. 3c). In field experiments, both positive and negative effects of elevated atmospheric CO_2 on N_2O emission were observed (Kammann et al., 2008; Phillips et al., 2001). The positive or negative effects might be determined by soil N availability; a field experiment concluded that a small amount of N fertilizer will relieve N limitation under elevated CO_2 concentration (Kettunen et al., 2007). If no progressive N limitation occurs under elevated CO_2, enhanced N_2O emission will be observed. As the theory of progressive N limitation predicts (Luo et al., 2004), rising atmospheric CO_2 could lead to low N availability in soil and thus lead to low N_2O emission (Kettunen et al., 2005; Barnard et al., 2004). In this study, the elevated atmospheric CO_2 substantially decreased the N_2O emission from terrestrial ecosystem over North America, which is due to the N limitation for major biomes throughout the entire North America (Vitousek and Farrington, 1997; Aber and Melillo, 2001).

4.3 Inter-annual variability in N_2O flux

The increasing long-term trend and substantial inter-annual fluctuation in terrestrial N_2O flux over North America during 1979–2010 resulted from complicated impacts from multiple factors (Chapuis-Lardy et al., 2007; Conrad, 1996; Ambus and Robertson, 1999). The highly varied climatic variability dominated the inter-annual flux of N_2O over North America, and solely dominated the N_2O flux over Canada. N deposition, O_3 pollution, and atmospheric CO_2 concentrations increased at relatively stable rates through the studied 32 yr, which resulted in the long-term trend of N_2O flux (Fig. 8).

Using stepwise regression analysis, we found that climate variability was the predominating factor controlling

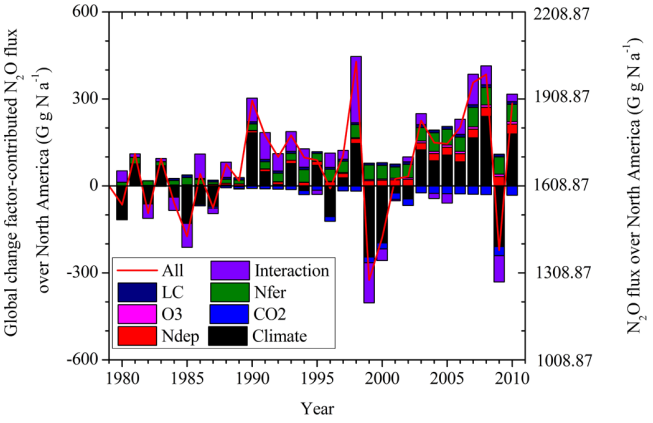


Fig. 7. Factorial contribution to the inter-annual variations in N_2O flux over North America (The right y-axis shows the N_2O flux with baseline; *All* means N_2O flux derived from all combined simulation; *Interaction* means contribution from multi-factor interaction; *LC* means contribution from land conversion; *Nfer* means contribution from N fertilizer application; O_3 means contribution from tropospheric O_3 pollution; CO_2 means contribution from elevated atmospheric CO_2; *Ndep* means contribution from N deposition; *Climate* means contribution from climate variability).

inter-annual variations in terrestrial N_2O flux at both continental and country levels. Following climate variability, multi-factor interaction played an essential role in contributing temporal variations in terrestrial N_2O flux. This is consistent with our previous analysis showing that climate variability, followed by multi-factor interaction, co-dominated inter-annual variations in terrestrial N_2O flux at both continental and country levels (Sect. 3.6). The importance of climate variability in controlling inter-annual N_2O emission indicates the important role of climate variability in controlling variations in atmospheric N_2O concentration (Fluckiger et al., 1999).

4.4 Interactions among multiple factors

The interaction among global change factors has been long recognized as an important factor (Dermody, 2006). A large amount of field experiments still treat it as negligible, although a few experiments have introduced this in their experiment design (Xia et al., 2009; Reich et al., 2006). Through this study, the multi-factor interaction was recognized playing an important role in contributing to terrestrial N_2O flux (Sect. 3.6). Since the various climate variables are associated in reality, the separation of each climate variable might be biased. Because the field experiments are usually labor intensive, multi-factor experiment might be hard to carry out; the interactive effects among more than three factors are still short of investigation (Heimann and Reichstein, 2008; Norby and Luo, 2004). This study shows that the modeling approach may serve as one complementary tool for field experiments in addressing interactive effect in a multi-factor world (Norby and Luo, 2004).

4.5 Uncertainties and future research needs

Considering the limitations in existing manipulative field experiments on N_2O fluxes, and the complexities in the related nonlinear processes and multiple controlling factors, numerical experiments with models like DLEM that represent the fundamental mechanisms in N and N gas processes and the coupled biogeochemical cycles become an important approach to gain insights into the dynamics of N-containing gas emission in the context of global changes. This is the reason why process-based models are widely used in climate change studies, and why our study places so much emphasis on the relative contribution and interactions of multiple environmental controls. Through this study, rather than try to draw any conclusions on this issue, we hope to provide some insight on the patterns and dynamics of the N gas emission and to raise some questions about the effects of multiple environmental factors on the process.

This study was able to attribute the spatial and temporal variations in N_2O flux over North America's terrestrial ecosystems during 1979–2010, but there are several issues that still need to be improved. First, this study only considered the land conversion between cropland and natural vegetation, and would generate more accurate results if other land use changes such as afforestation were included. Second, the pre-1979 legacy effect may cause some biases in this study, which solely analyzed N_2O flux over the time period of 1979–2010. Third, the soil may act as a sink of atmospheric N_2O (Chapuis-Lardy et al., 2007); however, owing to incomplete understanding of this phenomenon, we did not incorporate this mechanism in this study, so the model may have overestimated the terrestrial N_2O flux at both continental and county levels. More field studies are needed to understand the mechanisms for N_2O sink in soil, which will improve the regional estimation of N_2O flux.

Fourth, although we have compared our estimated factorial impacts on N_2O flux with other studies, the effects of global change factors on N_2O have not been comprehensively calibrated and validated because of the scarcity of field observations on factorial N_2O fluxes (Dermody, 2006). Fifth, the thawing-freezing cycle has long been identified as a major factor on N_2O emission, especially in temperate and boreal regions (de Bruijin et al., 2009; Repo et al., 2009; Christensen and Tiedje, 1990), yet the real mechanisms are still not well investigated (de Bruijin et al., 2009). So this study might have underestimated the N_2O emission due to lack of freezing-thawing effect. Sixth, although the regional data used in this study are fairly updated, improvements of the dataset might provide more accurate estimations. For instance, nitrogen deposition data was interpolated based on three annual maps of spatial distribution of nitrogen deposition (Dentener, 2006); improved atmospheric transport

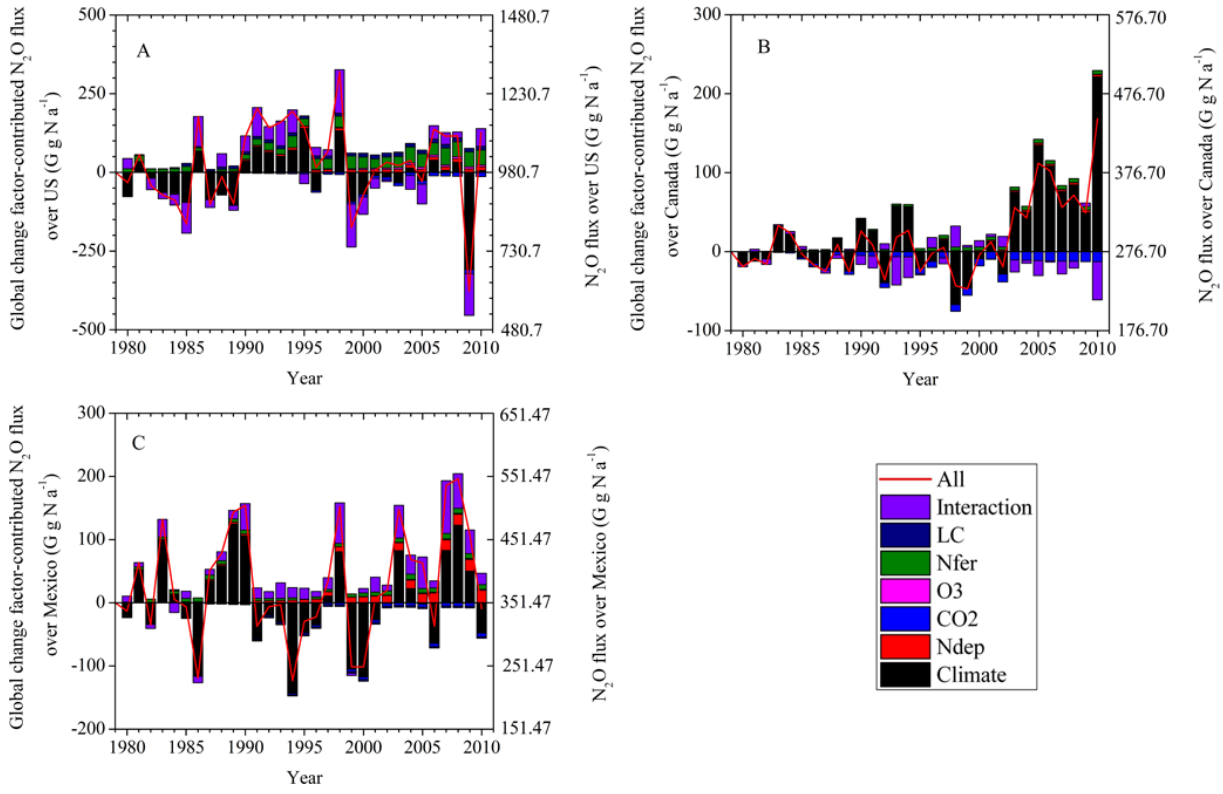


Fig. 8. Factorial contribution to the inter-annual variations in N_2O flux at country level (**A**: United States of America; **B**: Canada; **C**: Mexico) (The right y-axis shows the N_2O flux with baseline; *All* means N_2O flux derived from all combined simulation; *Interaction* means contribution from multi-factor interaction; *LC* means contribution from land conversion; *Nfer* means contribution from N fertilizer application; O_3 means contribution from tropospheric O_3 pollution; CO_2 means contribution from elevated atmospheric CO_2; *Ndep* means contribution from N deposition; *Climate* means contribution from climate variability).

model associated with more field observations might provide more accurate nitrogen deposition data. Seventh, further work on N_2O flux in cropland is needed to reduce the uncertainty because of the dominance of fertilized cropland as N_2O source and the shortage of extensive validation of DLEM-simulated N_2O flux. Last but not least, it will be an improvement when additional environmental factors such as wild and prescribed fires, harvests, insect outbreaks, etc. are considered. Meanwhile, we acknowledged that the precision is different from accuracy; although many simulations were performed and uncertainty analysis was conducted, more efforts are needed to increase the accuracy of estimated N_2O fluxes.

5 Conclusions

This study examined the factorial contributions to the terrestrial N_2O flux over North America at both continental and country levels by using a highly-integrated process-based ecosystem model driven by multiple global change factors, including changing climate, N deposition, rising atmospheric CO_2, O_3 pollution, N fertilizer application, and land conversion. The improvements in input data and model mechanisms are needed for more accurate estimates. Nevertheless, this study is helpful in advancing our understanding of the dynamics of atmospheric N_2O concentration as well as beneficial for the policy-makers to curb the increase in atmospheric N_2O concentration. The complicated effects of multi-factor interaction on N_2O flux suggest that the current field experiments, which usually ignore the interactive effects from multiple factors, may lead to biases in the estimation of N_2O flux. This study also pointed out that the models driven by only a few global change factors may bring bias in estimating N_2O flux.

This study is among the first attempts to attribute the spatiotemporal variations in regional terrestrial N_2O flux to multiple global change factors over a long time period. A collaborative effort between field ecologists and modelers is necessary for further investigation of the underlying mechanisms responsible for spatial and temporal variations in N_2O flux.

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