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Divergent responses of nitrous oxide, methane and carbon dioxide exchange to pulses of nitrogen addition in a desert in Central Asia

Xiaobing Zhou[a], Xiangfang Lv[b], Ye Tao[a,c], Lin Wu[d], Caroline A. Havrilla[e], Yuanming Zhang[a,*]

[a] Xinjiang Institute of Ecology and Geography, Key Laboratory of Biogeography and Bioresource in Arid Land, Chinese Academy of Sciences, Urumqi 830011, China
[b] Urumqi Environmental Monitoring Center, Urumqi 830000, Xinjiang, China
[c] Anqing Normal University, Anqing 246000, Anhui, China
[d] Hubei University for Nationalities, Enshi 445000, Hubei, China
[e] University of Colorado Boulder, Boulder, CO 80309-0334, USA

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ABSTRACT

Desert ecosystems are nitrogen-limited, and highly responsive to even small inputs of nitrogen. Recently, desert ecosystems have been affected by increasing levels of nitrogen deposition, which may lead to changes in greenhouse gas efflux. However, the effects of nitrogen deposition on these gases in the desert ecosystems remain poorly understood. To study the dynamics in greenhouse gases under increasing nitrogen, six rates of simulated nitrogen deposition, including 0(N0), 0.5(N0.5), 1.0(N1), 3.0(N3), 6.0(N6), 24.0 (N24) g nitrogen m^{-2} a^{-1}, were applied in soils of the Gurbantunggut Desert in Central Asia. Efflux of nitrous oxide (N_2O), methane (CH_4), ecosystem respiration and net carbon ecosystem exchange were measured across two growing seasons for two years. The efflux of the four gases changed greatly in different seasons, which can explain more variation than nitrogen treatments except for N_2O. Nitrogen input stimulated N_2O emission, especially in the high nitrogen treatments, with N_2O emission 1.6 (N6) and 2.6 (N24) times greater than control (N0). However, N_2O exchange also depended on the seasons, while only minor changes were found in some seasons (late spring 2010 and late summer 2011). Overall, CH_4 uptake (average 31.4 $\mu g\, m^{-2} h^{-1}$) was not significantly affected by the nitrogen addition. At the high nitrogen treatment levels, ecosystem respiration decreased in the late spring and summer of the second year, with similar responses to nitrogen addition in mid-autumn between two years. Net ecosystem carbon exchange also showed gradual responses to nitrogen addition overall, but did not differ significantly across seasons and treatments. Overall, structural equation models showed that the dynamics in N_2O were mostly attributed to variations in nitrogen addition, CH_4 to soil moisture (or temperature), ecosystem respiration to plant species richness (or density) and net ecosystem carbon exchange to soil moisture (or temperature). Our study indicates that the changes in greenhouse gas emissions caused by nitrogen deposition in short time scale were small in these desert soils.

1. Introduction

Nitrogen deposition is a key driver of global change (Lamarque et al., 2005). In recent years, the rates of deposited nitrogen have increased, causing substantial changes in community structure and the function of many terrestrial ecosystems, including forest, grassland and desert ecosystems (Baez et al., 2007; Hyvonen et al., 2007; Phoenix et al., 2006; Stevens et al., 2004). In dryland ecosystems, which cover over a third of the world's terrestrial area (Maestre et al., 2012), increased nitrogen deposition is increasingly observed, and dry deposition is a major part of total nitrogen deposition in these areas, such as central Asia (Li et al., 2013). High dry deposition can form pulse effect on the dryland ecosystems following rainfall (James and Richards, 2006).

Dryland ecosystems are nitrogen-limited and highly responsive to even small inputs of nitrogen (Clark and Tilman, 2008; Vourlitis et al., 2007). Therefore, small increases in nitrogen deposition are expected to be more impactful in drylands than in some other types of ecosystems (Adams, 2003). Previous studies have documented that nitrogen addition in drylands can cause changes in plant growth, diversity and productivity (Baez et al., 2007; Bai et al., 2010; Zhou et al., 2018). Additionally, in drylands, soil biogeochemical processes, such as soil nutrient transformation, microbial activity and gas exchange, are sensitive to increased nitrogen (Schaeffer and Evans, 2005; Zhang et al.,

* Corresponding author at: Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Beijing South Road, Urumqi 830011, China.
E-mail addresses: zhouxb@ms.xjb.ac.cn (X. Zhou), zhangym@ms.xjb.ac.cn (Y. Zhang).

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2014; Zhou et al., 2012).

Nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) are the three most important greenhouse gases for the evaluation of the global nitrogen and carbon budgets. A significant fraction of the global soil-atmosphere exchange of greenhouse gases occur in drylands (Schoenbach et al., 2012; Zaady et al., 2013). In dryland, precipitation intensity and soil moisture are often the most important contributors to changes in greenhouse gas effluxes. Increases in soil moisture can trigger nitric oxide emission (Hartley and Schlesinger, 2000), alter soil CH_4 consumption (Zhao et al., 2017; Zhuang et al., 2013), stimulate the carbon release (Jia et al., 2014; Liu et al., 2017), switch the net ecosystem carbon exchange between positive and negative (Huxman et al., 2004; Wohlfahrt et al., 2008). In some drylands, experimental warming or nitrogen fertilizer cannot significantly affect the fluxes of CO_2, CH_4 and N_2O, meaning small feedback of greenhouse gases to climate warming might occur in the future (Wang et al., 2011; Xu et al., 2014). However, CH_4 uptake in warmer, drier ecosystems is also reported to respond more strongly to warming, exhibiting less CH_4 uptake with increasing temperature, compared to other ecosystems (Blankinship et al., 2010). Generally, around 5% to 40% of the global soil-atmosphere gas (CH_4, CO, N_2O, and NO_x) exchange occurs in drylands, while for each of these gases there are fewer than a dozen studies to support individual estimates (Galbally et al., 2008). Thus, additional work is needed to estimate the dynamics and responses of these three gases to environmental conditions, and particularly nitrogen addition, in drylands.

Ecosystem soil-atmosphere greenhouse gases exchanges are usually affected by increased nitrogen (Chen et al., 2013; Lu and Tian, 2013), yet assessments of greenhouse gases in response to nitrogen deposition in drylands are lacking (Chen et al., 2013). Nitrogen deposition has been shown to increase soil N_2O emission in most ecosystems (Jassal et al., 2011; Li et al., 2012; Liu and Greaver, 2009). The emission of soil N_2O can alleviate the increased soil nitrogen from deposition and therefore partially balance the total nitrogen in the soil (Jiang et al., 2010). In addition to nitrogen deposition, the N_2O flux is directly and indirectly influenced by soil physicochemical conditions and biotic resources. For example, precipitation events, soil moisture, soil temperature, and pH are correlated with the N_2O flux (Roobroeck et al., 2010; Wang et al., 2005; Xu et al., 2014). In addition, the diffusion of soil, dissolution of N_2O in soil water, or plant absorption and evaporation can affect N_2O flux (Gallo et al., 2014; Stewart et al., 2012).

Most terrestrial ecosystems can take up CH_4, and their net CH_4 flux is negative (Blankinship et al., 2010; Chen et al., 2015; Wang et al., 2005). Among ecosystem types, drylands are one of the largest sinks for CH_4 (Striegl et al., 1992). Soil moisture plays a crucial role in the production and consumption of CH_4 (X. Li et al., 2015a). In addition, the NH_4^+ concentration might be related to the CH_4 flux (Y. Li et al., 2015b). Higher plant diversity may generally enhance CO_2 and N_2O emissions while inhibiting CH_4 uptake because of the relatively higher litter diversity and appropriate chemical traits (Chen et al., 2015). The effects of nitrogen addition on CH_4 emission might be divergent because of the different responses of CH_4-regulated soil processes to increases in nitrogen (Lu and Tian, 2013).

Carbon dioxide is the most contributing greenhouse gas to global warming (IPCC, AR5). Dryland ecosystems have large annual sink for CO_2, playing a larger role in global carbon cycling than previously assumed (Wohlfahrt et al., 2008). Plant photosynthesis can consume CO_2, and sequestrate carbon as plant biomass, balancing a portion of CO_2 emissions in the soil-atmosphere layer (Niu et al., 2010; Wang et al., 2017). Therefore, estimating ecosystem respiration without considering uptake by plants is not adequate to assess net ecosystem carbon exchange. Ecosystem respiration is often measured to indicate the ability to produce CO_2 and be stimulated by nitrogen enrichment (Cleveland and Townsend, 2006; Niu et al., 2009; Yue et al., 2018). Net ecosystem carbon exchange is often measured to indicate the balance between gross ecosystem productivity and ecosystem respiration. Responses of net ecosystem carbon exchange to nitrogen enrichment have been mixed, showing either positive (Niu et al., 2010; Shaver et al., 1998) or no response (Bubier et al., 2007; Harpole et al., 2007).

Overall, the effects of nitrogen deposition on N_2O emissions, and CH_4, and CO_2 exchanges have rarely been estimated in dryland soils. To address this knowledge gap, we conducted a nitrogen addition experiment in the temperate, Gurbantünggüt Desert in Central Asia. Our main objective was to compare the greenhouse gases fluxes among different rates of nitrogen addition treatment and among different growing seasons. Our study is also important to understanding global carbon and nitrogen budgets under experiment change. We hypothesize that high levels of nitrogen addition 1) increases N_2O emissions due to the high rate of nitrification and denitrification following nitrogen addition (Sitaula et al., 2001); 2) decreases the CH_4 uptake because of the high osmotic stress on related microbes after nitrogen application (Bodelier, 2011); and 3) decreases ecosystem respiration because of the reduction in plant species richness and biomass under high nitrogen treatments (Zhou et al., 2018). We also hypothesize that the nitrogen effects would vary throughout the growing season because of season-specific environmental conditions, such as soil moisture, temperature or plant community.

2. Materials and methods

2.1. Study site

The study site is located in the centre of the Gurbantunggut Desert, which is the second largest desert in China. The site is about 120 km in the north of Urumqi, Capital of Xinjiang Province (44.87° N, 87.82°E). The mean annual temperature is 8.3 °C. The annual precipitation is about 129 mm, half of which falls between April and July. The potential annual evaporation exceeds 2000 mm. During winter, approximately 20 cm of deep snow covers the desert surface, which can provide abundant water during the snow –thaw season. Thus, herbaceous plants grow well during the spring, and the cover can reach 40% at some sites. The dominant shrub species in the desert are *Haloxylon ammodendron* and *H. persicum*, which appear mainly in the middle to upper ranges of dunes. The soil characteristics in this area was list in Table 1.

2.2. Experimental treatments

In October 2008, sixty 8 × 8 m plots were established at the study site. The plots were flat, and the vegetation compositions were homogeneous in the field before treatments. Six rates of nitrogen were applied on the plots to simulate gradients of nitrogen deposition, with ten replicates for each treatment. The six rates were 0, 0.5, 1.0, 3.0, 6.0 and 24.0 g nitrogen $m^{-2} a^{-1}$, hereafter donated as N0, N0.5, N1, N3, N6 and N24, respectively. The application rates of N0-N6 were selected according to the nitrogen deposition in a nearby city (Urumqi) of the desert, where total nitrogen deposition can reach 4.6 g nitrogen $m^{-2} a^{-1}$ (Li et al., 2013). N24 were also included to study the effects of high nitrogen on the desert ecosystem and obtain the load levels of nitrogen in the desert ecosystem. Nitrogen applications were conducted in late March after snow thaw and late October before snow fall each year (2008–2014), with the first treatments beginning in October 2008. These times were chosen because agriculture activities such

Table 1
the soil characteristics in the study area (Chen et al., 2007).

Characteristics	Value
Soil type	Sandy
Predominant particle size	0.5–0.25 mm
Ratio of sand-silt-clay	842:141:17
pH	8
Organic carbon	1 g/kg