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Interactive impacts of nitrogen input and water amendment on growing season fluxes of CO_2, CH_4, and N_2O in a semiarid grassland, Northern China

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HIGHLIGHTS

- Nitrogen input stimulated CO_2 uptake and N_2O emission, while inhibited CH_4 uptake in a semiarid grassland.
- Water amendment stimulated CO_2 uptake and N_2O emission, while inhibited CH_4 uptake in a semiarid grassland.
- Background precipitation condition affects the interaction between nitrogen and water on GHG fluxes.

GRAPHICAL ABSTRACT

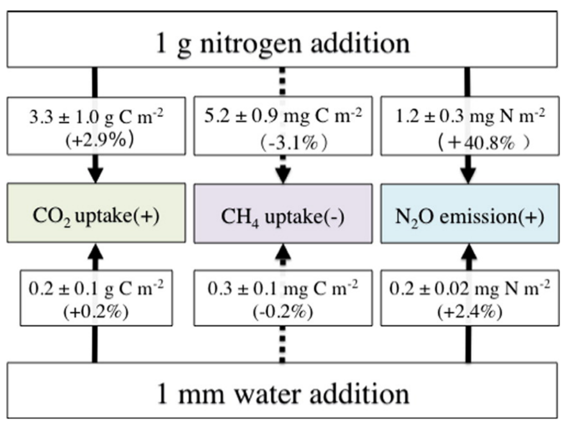

Fig. 5 Summarized impacts of N addition and water amendment on CO_2 flux, CH_4, and N_2O fluxes over the study period (solid lines indicate significance at $P < 0.05$ level, dash lines indicate insignificance at $P < 0.05$ level).

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ABSTRACT

Nitrogen and water are two important factors influencing GHG (primarily CO_2 - carbon dioxide; CH_4 – methane, and N_2O – nitrous oxide) fluxes in semiarid grasslands. However, the interactive effects of nitrogen and water on GHG fluxes remain elusive. A 3-year (2010 − 2012) manipulative experiment was conducted to investigate the individual and interactive effects of nitrogen and water additions on GHG fluxes during growing seasons (May to September) in a semiarid grassland in Northern China. Accumulated throughout growing seasons, nitrogen input stimulated CO_2 uptake by 3.3 ± 1.0 g C m^{-2} (g N)$^{-1}$, enhanced N_2O emission by 1.2 ± 0.3 mg N m^{-2} (g N)$^{-1}$, and decreased CH_4 uptake by 5.2 ± 0.9 mg N m^{-2} (g N)$^{-1}$; water amendment stimulated CO_2 uptake by 0.2 ± 0.1 g C m^{-2} (mm H_2O)$^{-1}$ and N_2O emission by 0.2 ± 0.02 mg N m^{-2} (mm H_2O)$^{-1}$, decreased CH_4 uptake by 0.3 ± 0.1 mg C m^{-2} (mm H_2O)$^{-1}$. A synergistic effect between nitrogen and water was found on N_2O flux in normal year while the additive effects of nitrogen and water additions were found on CH_4 and CO_2 uptakes during all experiment years, and on N_2O emission in dry years. The nitrogen addition had stronger impacts than water amendment on stimulating CH_4 uptake in the normal year, while water was the dominant factor

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affecting CH_4 uptake in dry years. For N_2O emission, the N-stimulating impact was stronger in un-watered than in watered plots, and the water-stimulating impact was stronger in non-fertilized than in fertilized treatments in dry years. The interactive impacts of nitrogen and water additions on GHG fluxes advance our understanding of GHG fluxes in responses to multiple environmental factors. This data source could be valuable for validating ecosystem models in simulating GHG fluxes in a multiple factors environment.

1. Introduction

The semiarid grasslands play an important role in regulating the climate system through the land-atmosphere exchanges of greenhouse gases (GHGs), primarily carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Frey et al., 2013; Friedlingstein et al., 2014; Ringeval et al., 2011; Field et al., 2014). The GHG fluxes are controlled by many environmental factors including soil temperature, soil moisture, vegetation, management practices, etc. (Liu et al., 2014; Merbold et al., 2014; Tian et al., 2012). Over the past century, changes in climate system and human activities (e.g. changes in temperature, precipitation, and nitrogen inputs) have dramatically altered these environmental factors and thus the GHG fluxes in semiarid grasslands (Dermody, 2006; Norby and Luo, 2004; Tian et al., 2015; Xu et al., 2010, 2012). Therefore, quantifying the GHG fluxes and their responses to environmental changes is critically important for projecting the feedback of semiarid grasslands to the climate system (Dermody, 2006; Norby and Luo, 2004; Poulter et al., 2014).

For semiarid grasslands, nitrogen and water are two of the most important limiting factors which individually and interactively affect plant growth and GHG fluxes at the ecosystem scale (Lu et al., 2014; Niu et al., 2009). A number of field experiments have been carried out to investigate the individual impacts of nitrogen and water on GHG fluxes in semiarid grasslands. For example, studies showed that nitrogen deposition stimulated N_2O emission (Liu et al., 2014; Zhang et al., 2014), which partially canceled out the stimulating impact on CO_2 uptake (Niu et al., 2010; Niu et al., 2009; Volk et al., 2011); few other studies found that nitrogen addition stimulated CH_4 flux in semiarid grasslands (Chen et al., 2013; Li et al., 2012; Louro et al., 2013; Šimek et al., 2014; Stiehl-Braun et al., 2011; Zhang et al., 2014); manipulative experiments found that increased precipitation enhanced ecosystem CO_2 uptake through its stimulating effect on gross primary production (Chimner et al., 2010; Nagy et al., 2007; Yan et al., 2011). For CH_4 uptake, the impact of water addition could be inhibition (Blankinship et al., 2010a; Liu and Greaver, 2009), neutral (Liu and Greaver, 2009; Mariko et al., 2007), or stimulating (Blankinship et al., 2010b; Xu et al., 2015); while for N_2O emission, the impact of water addition could be stimulating (Horváth et al., 2010; Zhang and Han, 2008) or neutral (Liu and Greaver, 2009; Unteregelsbacher et al., 2013) in semiarid grasslands.

Although the individual effects of nitrogen input and water amendment on GHG fluxes have been extensively investigated (Chen et al., 2013; Niu et al., 2009; Blankinship et al., 2010a, 2010b), the interactive impacts between nitrogen and water inputs remain elusive (Woodward et al., 2010). The importance of interactive impacts between nitrogen and water has been widely recognized (Norby and Luo, 2004) and modeling approaches have been used to quantify the interaction (Xu et al., 2012). For instance, a number of modeling studies have concluded significant interactions between climate change, nitrogen input and land use change on CH_4 and N_2O fluxes; while the model validation is solely based on single factor field experiment (Xu et al., 2010, 2012; Tian et al., 2011, 2015). Limited field experiments were carried out with two or more manipulated environmental factors (Xia et al., 2009a, 2009b; Zhou et al., 2006). Additive and non-additive (synergistic or antagonistic) effects have been proposed for the impacts of multiple factors (Ball et al., 2008; Blankinship et al., 2010b; Dijkstra et al., 2012). In this aspect, how nitrogen interact with water affecting GHG fluxes is critically important to advance our understanding of ecosystem responses to multiple global change factors. Therefore, investigating the interactive impacts between nitrogen addition and water amendment is essential for predicting grassland responses to multi-factor global change (Ball et al., 2008; Dijkstra et al., 2012; Blankinship et al., 2010a, 2010b).

The grassland in northern China has been proved to be typically representing semiarid grassland (Xia et al., 2009a, 2009b; Niu et al., 2009; Poulter et al., 2014); they play an important role in regulating the climate system. Recent studies have projected increases in nitrogen input and precipitation in northern and central Asia in the 21st century (IPCC, 2013). Therefore, designing a manipulative experiment to investigate the nitrogen and water impacts on GHG fluxes in the semiarid grassland in northern China would be valuable to better understand the semiarid grasslands and their role on the terrestrial ecosystems-climate feedback (Poulter et al., 2014).

Theoretically, nitrogen stimulates CO_2 uptake by enhancing ecosystem productivity, stimulates N_2O emission by enlarging substrate pool, and decreases CH_4 uptake due to competition between NH_4^+ and CH_4 for methanotrophy; meanwhile, water amendment stimulates CO_2 uptake by enhancing ecosystem productivity, stimulates N_2O emission by creating favorable condition for denitrifiers, and decreases CH_4 uptake by enhancing methanogenesis. Considering the complexity of the biological system, we expect an interactive impact between nitrogen and water on GHG fluxes. Thus, this study was designed to test three hypotheses about individual effects and interactive effects of nitrogen and water additions on three GHGs: (i) nitrogen deposition has primarily positive effects on CO_2 sequestration and N_2O emission but negative effects on CH_4 uptake; (ii) water addition has positive effects on CO_2 sequestration and N_2O emission but negative effects on CH_4 uptake; (iii) there are strong interactive impacts between nitrogen addition and water amendment in terms of affecting GHG fluxes in semiarid grasslands.

2. Materials and methods

2.1. Site description and experimental design

The study site is a typical semiarid temperate grassland in northern China, located in Duolun County (42°02′N, 116°17′E), Inner Mongolia. Long-term mean annual temperature is 2.11 °C with monthly mean temperatures ranging from −17.5 °C in January to 18.9 °C in July. Mean annual precipitation is 383 mm year^{-1}, with an obvious seasonality, peak rainfall occurring between May and October. Soil properties and plant species for the study site have been described in our previous publication (Zhang et al., 2014). The soil was composed of approximately 63% sand, 20% silt, and 17% clay at depths of 0–10 cm. The site plants were mainly perennial plants such as *Stypa srylovii*, *Artemisa frigida*, *Potentilla acaulis*, *Cleistogenes squarrosa*, *Allium bidentatum*, and *Agropyron cristatum*.

The annual precipitation was 329 mm in 2010, 232 mm in 2011, and 269 mm in 2012, respectively, varied substantially both intra- and inter-annually (Fig. 1A–C). The long-term mean annual precipitation has been estimated at 383 mm (Yan et al., 2010); the years of 2011 and 2012