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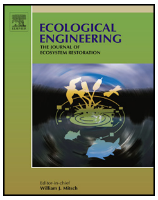

Research Article

The effect of nitrogen deposition rather than warming on carbon flux in alpine meadows depends on precipitation variations

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ABSTRACT

Uncertainties remain regarding the effects of climate warming and increasing nitrogen (N) deposition on greenhouse gas (GHG) flux in alpine grasslands due to a lack of knowledge about how hydrological characteristics control GHG fluxes. Therefore, a simulated warming and N fertilization experiment was conducted in a non-wetland (alpine meadow, AM) and a wetland (alpine swamp meadow, SM). We measured and analysed the key GHG fluxes (ecosystem respiration [Re], CH_4 and N_2O) of each treatment during two contrasting hydrological growing seasons. The results showed that: (i) warming increased the Re in both the AM and SM, warming increased the CH_4 uptake in the AM but had no effect in the SM, and warming increased the N_2O emissions from the AM and resulted in a change of the SM from a N_2O sink into a source; (ii) N fertilization decreased the Re of the AM during the dry growing season and of the SM during the wet growing season, increased the CH_4 uptake of the AM during the dry growing season, and had no effect on the CH_4 and N_2O fluxes of the SM; and (iii) the interaction between warming and N fertilization increased the CH_4 uptake of the AM over the two growing seasons while increasing the CH_4 uptake and N_2O emissions of the SM during the dry growing season. Our results suggest that (i) the GHG flux of wetland ecosystems is more sensitive to precipitation variations than that of non-wetlands and (ii) precipitation controls the carbon (Re and CH_4) flux response to increasing N deposition of these alpine meadows.

1. Introduction

Approximately 40% of the Qinghai-Tibet plateau (QTP) is alpine meadow (Hu et al., 2010). These areas provide important ecosystem services, such as protection of species diversity (Tibetan antelope, Tibetan wild donkey) and tourism (Lu et al., 2017), and they are also fundamental means of production for the survival of local herdsmen. These alpine meadows not only regarded as a very sensitive climate change trigger in the Asian monsoon region, but also have pronounced feedbacks to climate change and human activities (Li et al., 2015). Climate change and anthropogenic activities are the primary driving forces affecting alpine meadows in the QTP (Chen et al., 2014). During the past five decades, the mean annual temperature and precipitation in the QTP have increased by 0.3 °C and 9.1 mm per decade (Piao et al., 2012), respectively. Additionally, anthropogenic activities leading to inorganic nitrogen (N) deposition in the QTP have been increasing since the mid-20th century (Liu et al., 2015a). These climate changes strongly affect the carbon and N dynamics in alpine meadows. For example, the exchange of greenhouse gases (GHG) between the biosphere and atmosphere is a distinct way in which alpine meadows respond to climate change (Chen et al., 2013).

Numerous *in situ* experiments have been performed to investigate the effects of warming and N fertilization on the GHG flux in alpine grasslands. Warming increased ecosystem respiration (Re) (Zhu et al., 2015; Hu et al., 2016) or had no significant effect on the Re (Zhao et al., 2017). N fertilization increased (Peng et al., 2014b; Sun et al., 2013), decreased (Lozanovska et al., 2016; Gao et al., 2014) or had no impact on the Re (Wei et al., 2014; Zhu et al., 2015). These results often depend on variations in soil moisture (Lagomarsino et al., 2016). Increasing the soil temperature and available N will synergistically enhance the activity of microorganisms (Xiong et al., 2016), such as methanotrophs, nitrifiers and denitrifiers. Therefore, warming and N fertilization also have posi-

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tive impacts on the CH_4 uptake and N_2O emissions in non-wetland alpine grasslands (Hu et al., 2010; Liu et al., 2015b). Few studies have been conducted on wetland alpine grasslands, such as alpine swamp meadows. The QTP has approximately 100,000 km^2 of natural wetlands of which more than 50% are alpine swamp meadows (Wei et al., 2015). Thus, uncertainties remain about the effects of climate warming and increasing N deposition on GHG fluxes in alpine grasslands due to a lack of knowledge of how hydrological characteristics control GHG fluxes in both wetlands and non-wetlands. In particular, global warming will make wet/drought events more frequent (Cook et al., 2004; Manabe et al., 2004).

Some researches about GHG flux have been conducted in hydrological contrast years. Bubier et al. (2005) reported that wetlands had a strong CH_4 flux sensitivity to small changes in precipitation because the rainfall controlled the waterlogged condition, which affects air permeability of soils and then affects CH_4 oxidation or other processes. Peng et al. (2014a) also supported that hydrological variations controlled the GHG flux since drought events reduced root biomass by 50.2% thus suppressed soil respiration. Besides, the Re of an alpine meadow (the average soil moisture during the growing season was approximately 15%) was positively correlated with the soil moisture during the dry growing season(the range of soil moisture is from 7.5% to 12.5%) but negatively correlated with soil moisture during the wet growing season(the range of soil moisture is from 11.0% to 22.0%), which indicates that the soil moisture will influence the ecosystem respiration. However, Xia et al. (2009) supported the idea that hydrological variations cannot affect the Re of a temperate steppe (the soil moisture was lower than 10%), because drought would restrain ecosystem C uptake more than C release. These different conclusions are probably still due to the differences in soil moisture among wetlands, non-wetlands and semiarid grasslands. Another reason is that precipitation variations are often accompanied by changes in the air temperature. The long-term observation showed that average air temperature tends to be higher during dry years from 1990 to 2010 (Chen et al., 2014, Fig. 5a). Thus, variations in hydrological conditions will have a complex impact on the GHG flux.

Therefore, we conducted a simulated warming and N fertilization experiment in a non-wetland (alpine meadow, AM) and a wetland (alpine swamp meadow, SM) in the hinterlands of the QTP. We measured and analysed the key GHG fluxes (ecosystem respiration [Re], CH_4 and N_2O) of each treatment during two contrasting hydrological growing seasons in 2014 (wet with total precipitation at 37.2% above the long-term mean) and 2015 (dry with total precipitation at 16.2% below the long-term mean)to investigate the impacts of hydrological variations on GHG flux responses to warming and N fertilization. Previous studies reported that simulated warming decreased surface soil moisture in the AM by 2% (Chen et al., 2017b) while increased in the SM by 7.0% (Chen et al., 2017a). Therefore, drought events will probably magnify and reduce the effects of warming on surface soil moisture in the AM and SM, respectively. Our hypotheses are: (i) GHGs fluxes of alpine meadows response to warming will be affected by drought events; (ii) GHGs fluxes of the AM response to drought events will be different from the SM. We intend to use this study to enhance our understanding of how hydrological conditions control the responses of GHG flux in alpine meadows to future warming and higher N deposition.

2. Materials and methods

2.1. Study site

The experiment was conducted in the Fenghuo Mountains region in the hinterlands of the Qinghai-Tibetan Plateau, China. The mean annual temperature is −5.2 °C, the relative humidity is 57% and the mean annual precipitation is 310.7 mm, 80% of which falls during the growing season (from May to September) (Wang et al., 2008). The average air temperatures were 2.79 and 3.17 °C, and the rainfall levels were 292.3 and 245.9 mm for the 2014 (total 426.3 mm) and 2015 (total 267.4 mm) growing seasons, respectively (Chen et al., 2017). The annual precipitation in 2014 was higher (37.2%) than the long-term mean annual precipitation, but it was lower (16.2%) than the long-term mean in 2015. The air pressure was approximately 570 h Pa. The area has a continental alpine cold and dry climate, and the freezing period lasts from September to April of the next year. The study site is underlain by permafrost with an active layer of 0.8–1.5 m. The alpine meadow ecosystem consists primarily of cold meso-perennial herbs that grow under conditions in which a moderate amount of water is available. This ecosystem's primary vegetation consists of *Kobresia pygmaea* (C. B. Clarke), *Kobresia humilis* (C. A. Meyer ex Trautvetter) Sergievskaja, *Kobresia capillifolia* (Decaisne) (C. B. Clarke), *Kobresia myosuroides* (Villars) Foiri, *Kobresia graminifolia* (C. B. Clarke), *Carex atrofusca* Schkuhr subsp. (minor (Boott) T. Koyama), and *Carex scabriostris* (Kukenthal). Alpine swamp meadows are populated by hardy perennial hygrophilous or hygro-mesophilic herbs under waterlogged or moist soil conditions, which primarily occur in patches or strips in the mountains, wide valley terraces and rounded hills, and they represent a small portion of the study region. These areas are dominated by *Kobresia tibetica* Maximowicz, *Stipa aliena* Keng and *Festuca* spp (Li et al., 2011). The vegetation and soil characteristics are shown in Table 1.

2.2. Experimental design

This experiment was conducted using a comparative trial design in the AM (34°43′43.9″N, 92°53′45.3″E, 4754 m a.s.l.) and the SM (34°43′43.9″N, 92°53′34.1″E, 4763 m a.s.l.) (Fig. 1), both of which have vegetation coverage of above 70%. During the warming experiment, we followed the methods of the International Tundra Experiment and used open-top chambers (OTCs) as passive warming devices to generate an artificially warmed environment (Marion et al., 1997; Yang et al., 2011). In June of 2012, we installed twelve OTCs in the AM and the SM, and this experiment is still running. Twelve unwarmed plots (1.5 m × 1.5 m, 2.25 m^2) were established in the vicinity of each OTC in both the AM and the SM. The distance between the OTCs and adjacent unwarmed plots was between 3 m and 6m, and the distance between the replicate blocks ranged from approximately 6–8 m. During the N fertilization experiment, NH_4NO_3 ($4\,g\,N\,m^{-2}\,a^{-1}$) was sprayed onto the N fertilization plots in the AM and the SM in May from 2012 to 2015, with non-N fertilization plots receiving the same amount of water (approximately 0.5 mm). Thus, we set up the following four treatments: a control (C), N fertilization (N), warming (W), warming and N fertilization (WN). Six replicates from each treatment were randomly distributed throughout six warmed plots and likewise in the adjacent unwarmed plots in both the AM and SM (for 24 plots in total). All the treatments were applied for two years (2012–2013) before the start of this experiment. All the plots are enclosed by livestock enclosures to avoid grazing disturbances of the GHG flux.

2.3. GHG measurement

Three replicates from each treatment were randomly selected for GHG flux measurements. The greenhouse gas (GHG) fluxes (Re, CH_4, and N_2O) were measured using the static chamber technique (Werner et al., 2006). The chamber cover (30 × 30 × 30 cm, for the convenience of handling the OTCs; we ultimately reduced the bottom area of the chamber) were manually mounted onto the base collars for GHG flux measurements and removed after the mea-