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Annual N_2O emissions from conventionally grazed typical alpine grass meadows in the eastern Qinghai–Tibetan Plateau

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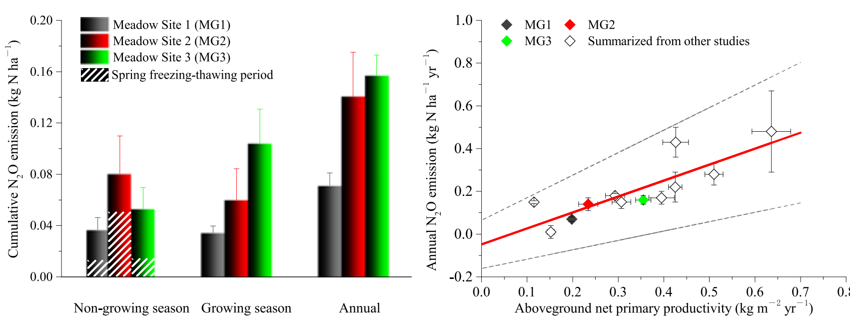
HIGHLIGHTS

- Characteristics of annual N_2O fluxes were clarified across three alpine meadows.
- Air pollutant NO, which is rarely reported in alpine meadows, was observed yearly.
- Up to 50% of annual N_2O emissions were released in the non-growing season.
- A linear dependence of the annual N_2O emissions on the ANPP occurs significantly.

GRAPHICAL ABSTRACT



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ABSTRACT

Annual nitrous oxide (N_2O) emissions from high-altitude alpine meadow grasslands have not been effectively characterized because of the scarcity of whole-year measurements. The authors performed a year-round measurement of N_2O fluxes from three conventionally grazed alpine meadows that represent the typical meadow landscape in the eastern Qinghai–Tibetan Plateau (QTP). The results showed that annual N_2O emissions averaged 0.123 ± 0.053 (2SD, i.e., the double standard deviation indicating the 95% confidence interval) kg N ha^{-1} yr^{-1} across the three meadow sites. N_2O flux pulses during the spring freezing-thawing period (FTP) were observed at only one site, indicating a large spatial variability in association with soil moisture differences. Approximately 34–57% (mean: 46%) of the annual N_2O emissions occurred in the non-growing season, highlighting the substantial importance of accurate flux observations during this period. The simultaneous observations showed conservative, marginal nitric oxide (NO) fluxes of 0.058 ± 0.032 (2SD) kg N ha^{-1} yr^{-1}. The N_2O fluxes across the three field sites correlated negatively with the soil nitrate concentrations during the entire year-round period ($P < 0.05$). Furthermore, a significant joint regulatory effect of topsoil temperature and moisture on the N_2O and NO fluxes was observed during the relatively warm periods. Based on the results of the present and previous studies, a simple extrapolation roughly estimated the annual total N_2O emission from Chinese grasslands to be 73 ± 15 (2SD) Gg N yr^{-1} (1 Gg = 10^9 g). A linear dependence of the annual N_2O fluxes on the aboveground net primary productivity (ANPP) was also found. This result may provide a simple approach for estimating the

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N_2O emission inventories of frigid alpine or temperate grasslands that are ungrazed either in the summer or year round. However, further confirmation of this relationship with a wider ANPP range is still needed in the future studies.

1. Introduction

Nitrous oxide (N_2O) is a potent greenhouse gas and the single largest contributor to global stratospheric ozone depletion (Myhre et al., 2013; Ravishankara et al., 2009). Its atmospheric concentration is still increasing at a rate of approximately 0.3% per year, which is primarily as a consequence of terrestrial ecosystems (IPCC, 2013; Williams et al., 1992). Nitric oxide (NO) is a key precursor of tropospheric ozone, fine aerosol particles involved in haze pollution and a precursor of nitric acid formation in the atmosphere (e.g., Pilegaard, 2013). In fact, the exchanges of N_2O and NO between terrestrial ecosystems and the atmosphere are closely interrelated, as both gases are produced in most cases by the same processes of nitrogen transformation (e.g., Firestone and Davidson, 1989). Therefore, it is necessary to investigate the emissions of both N_2O and NO from terrestrial ecosystems via simultaneous field observations to improve the current understandings of nitrogen biogeochemistry.

Grassland ecosystems are one of the most important terrestrial biome types, covering approximately 20% of the global land surface (Adams et al., 1990; Zhang et al., 2010). Global emissions of N_2O from grasslands were estimated at 2.5 Tg N yr^{-1}, accounting for approximately 18% of the global estimate of the total source flux (Lee et al., 1997). Generally, microbial nitrification (as an aerobic process) and denitrification (as an anaerobic process) have been identified as the major pathways for N_2O production in soils (Firestone and Davidson, 1989). A multitude of interacting biotic (e.g., vegetation type, plant-microbe interaction) and abiotic (soil climate, physical and chemical properties) variables, which regulate the biological processes in soils, lead to the very variable and dynamic characteristics of soil N_2O losses (Butterbach-Bahl et al., 2013). For example, Yao et al. (2010a) showed that soil moisture is a primary regulator of spatial variability in N_2O emissions by measuring the N_2O fluxes of soil cores from 30 representative field sites. In another instance, Abalos et al. (2014) carried out a greenhouse mesocosm experiment and found that plant species composition is a key driver of N_2O emissions from grassland ecosystems. Meanwhile, numerous field measurements have shown that the N_2O fluxes from grassland ecosystems are strongly influenced by vegetation species, soil physiochemical parameters, environmental factors and management regimes (e.g., Li et al., 2015; Wolf et al., 2010; Yang et al., 2015). Clearly, although the fluxes of this gas from grasslands have been investigated globally (e.g., Cowan et al., 2015; Mosier et al., 1991, 2002; Turner et al., 2008), the flux estimates are still highly uncertain due to the scarcity of data, and the limited observations do not reliably represent the known variability in soil types, soil properties and environmental conditions (Yao et al., 2010b). Therefore, further knowledge of N_2O fluxes and their driving factors influencing this gas from various grassland types under different climate zones and management patterns is essential to reduce the uncertainties in nitrogen trace gas emission inventories of grassland ecosystems at the regional, national and global scales.

Alpine meadows are the most productive grassland ecosystems in montane regions such as the eastern Qinghai–Tibetan Plateau (QTP). Thus, they serve to sustain the global market of grazing-oriented animal husbandry substantially. Accurate quantification and a thorough understanding of the regulatory factors of N_2O and NO emissions from alpine meadow areas are essential for the development of environmental- and climate-friendly grazing-oriented animal husbandry in montane regions. The QTP, known as "the Third Pole" of the Earth, covers nearly one-quarter of the land area of China (Chen et al., 2013a). It is one of the largest areas of alpine grasslands in the world. Alpine meadow is the dominant vegetation type and covers approximately 35% of the entire QTP land area (Cao et al., 2008). Due to vast expanse of the QTP and its high fragility to environmental disturbances, the alpine meadows in the plateau area are highly sensitive to climate change and human activity and consequently show pronounced feedbacks to both of these influences (Hu et al., 2010; Jiang et al., 2010; Li et al., 2015; Wu et al., 2010b; Zhang et al., 2014; Zheng et al., 2012). These feedbacks to changes in the climate and/or human activity may be shown, to some extent, by variations in N_2O and NO emissions, as the fluxes of these gases from grasslands are mainly regulated by the environmental and management variables mentioned above. In addition to the scarcity of NO observations, previous in situ N_2O measurements in alpine meadows in the QTP either focused on the growing season exclusively (Jiang et al., 2010; Zhang et al., 2014) or were conducted annually with a very coarse temporal (i.e., monthly or seasonally) resolution in the non-growing season (e.g., Li et al., 2015; Pei et al., 2003). The available studies with full-year observations performed in the grassland areas of other temperate regions indicated that emissions occurring during the non-growing season, particularly the spring freezing–thawing period (FTP), significantly contribute to annual N_2O emissions (Wagner-Riddle et al., 2007; Wolf et al., 2010; Yang et al., 2015). Based on the measured fluxes of nitrogen trace gases from seasonally snow-covered soils in a subalpine meadow, Filippa et al. (2009) indicated that microbially mediated emissions of gaseous nitrogen oxides could be a significant part of the nitrogen cycle during the winter. However, reliable full-year observations from high-altitude alpine meadows are scarce due to the harsh conditions for field operations during the cold winter season. This situation seriously hinders our understanding of annual N_2O emissions and our insight into the nitrogen cycle within high-altitude alpine meadows.

In the present study, the authors performed a study based on full-year field measurements of N_2O and NO fluxes from typical high-altitude meadows at three field sites in the eastern QTP. The goals of this study were to (i) characterize the full-year N_2O emissions from typical alpine meadow ecosystems in the eastern QTP; (ii) evaluate the contributions from the non-growing season, particularly the spring FTP, to annual N_2O emissions; and (iii) investigate the key regulatory factors on N_2O and NO fluxes. These investigations were conducted to test the following hypotheses: (i) the non-growing season can contribute substantially to annual emissions of N_2O from high-altitude alpine meadows; (ii) N_2O fluxes are regulated by abiotic factors, such as soil temperature and other physical variables; and (iii) annual N_2O emissions are related to the biotic variable aboveground net primary production.

2. Materials and methods

2.1. Descriptions of the selected field sites

In this study, three adjacent field sites (see the geographic coordinates in Table 1) were selected in the northernmost terrain of Zoige County, Sichuan Province, China. The selected field sites are located in the source region of the Pai–Lung River, which is a subbranch of the upper Yangze River, and they represent typical high-altitude meadows of the eastern QTP. This region is subject to a frigid, humid monsoon climate. According to meteorological records from the Zoige