Agriculture, Ecosystems and Environment 269 (2019) 116–124

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Nitrous oxide emissions from soils under traditional cropland and apple orchard in the semi-arid Loess Plateau of China

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ARTICLE INFO

Keywords:
Nitrous oxide emission
Nitrogen fertilizer
Wheat field
Apple orchard
Loess Plateau

ABSTRACT

The conversions of cropland to forest, or other tree-based systems, are considered to be important processes affecting regional and global greenhouse gas budgets, especially for nitrous oxide (N_2O). From April 2007 to March 2009, in the rain-fed semi-arid climate of the Loess Plateau, China, soil N_2O emissions were measured using static chambers from a winter wheat field and an apple orchard, which had been established in part of the wheat field 23 years earlier.Annual average N_2O emissions from the apple orchard (2.40 kg N_2O $ha^{-1}yr^{-1}$) were 12.15% higher than those in the wheat field (2.14 kg N_2O $ha^{-1}yr^{-1}$). Seasonal rainfall, in combination with higher nitrogen fertilization, had a promoting effect on N_2O emissions in the apple orchard compared with the wheat field. The amounts and patterns of summer rainfall and winter snowfall were the principal controllers of seasonal and annual N_2O fluxes in these rain-fed semi-arid regions, likely through their influence on soil moisture content. Since there may be a moisture threshold associated with summer rainfall and winter snowfall triggering higher N_2O emissions, climatic regimes should be taken into account when assessing the effects of land use on N_2O emissions in the Loess Plateau.

1. Introduction

Nitrous oxide (N_2O) acts as a greenhouse gas and also contributes to stratospheric ozone depletion (Wuebbles, 2009; Butterbach-Bahl et al., 2013). Globally, soil emissions were estimated to be 6.2 Tg N yr^{-1}, accounting for 36.23% of total N_2O emissions (Schlesinger and Bernhardt, 2013). Nitrous oxide is produced by microbial nitrification and denitrification processes in soil, and is strongly affected by soil temperature, soil moisture, soil aeration, precipitation and mineral nitrogen concentration (Dobbie et al., 1999; Dobbie and Smith, 2003; Davidson et al., 2000; Aguilera et al., 2013; Butterbach-Bahl et al., 2013; Cayuela et al., 2017; Sanz-Cobena et al., 2017). Land use is an important human activity that could change soil hydrological, chemical and physical properties, and thus influence microbially mediated processes of nitrification and denitrification (Livesley et al., 2009), Therefore, land use changes are considered to be important processes affecting regional and global budgets of N_2O (Verchot et al., 1999; Merino et al., 2004; Davidson et al., 2007; Veldkamp et al., 2008; Livesley et al., 2009; Peichl et al., 2009; IPCC, 2013). Studies on the effects of land use changes on N_2O emissions are frequently conducted in the humid tropics and subtropics as well as the humid and semi-humid temperate and Mediterranean conditions (Verchot et al., 1999; Merino et al., 2004; Davidson et al., 2007; Veldkamp et al., 2008; Aguilera et al., 2013, 2015; Cayuela et al., 2017; Sanz-Cobena et al., 2017). However, limited attention has been paid to semi-arid and arid regions, which constitute one-third of the global area, and are experiencing extensive land use changes (Mosier et al., 1991, 1997; Corre et al., 1999; Galbally et al., 2010; Álvaro-Fuentes et al., 2017).Semi-arid and arid lands constitute 43.1% of China's land area and are undergoing extensive land use change due to economic development and population growth. However, associated N_2O emissions from these activities are not well quantified (Lu et al., 2006; Cai, 2012). To our knowledge, the effects of land use changes on N_2O emissions in semi-arid or arid regions of China has been limited to a study by Xu et al. (2003) in the

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https://doi.org/10.1016/j.agee.2018.09.028
Received 6 November 2017; Received in revised form 2 September 2018; Accepted 22 September 2018

semi-arid Inner Mongolia steppe region.

The Loess Plateau, which has an area of 4.30×10^5 km^2, is located in northwestern China. This area is characterized by a semi-arid and arid climate and high levels of soil erosion. Since the 1970s, in order to control soil erosion and increase the income of local farmers, apple orchards were expanded to a large areas of land (34°–37 °N) previously used mainly as farmland or woodland (Wu et al., 2008). Following the establishment of orchard, changes in soil hydrological, chemical and physical properties may occur due to the development of root and soil organic layer and the alternation of agricultural management (Livesley et al., 2009; Peichl et al., 2009). These changes may alter soil organic carbon contents and N_2O emissions. Although the effects of orchard development on soil carbon have been investigated (Chen et al., 2007), the effects on N_2O emissions are limited to only a one-year study (Pang et al., 2009).Compared to the traditional cropland, there was different seasonal pattern of N_2O emission from the orchard owing to different field management, especially the amounts and times of nitrogen fertilizer applied (Garland et al., 2011, 2014; Schellenberg et al., 2012). At the regional scale, orchard soil was also seen as important N_2O source (Pang et al., 2009; Cheng et al., 2017). In addition, in semi-arid regions, soil N_2O emissions were strongly regulated by soil water content (Corre et al., 1995; Galbally et al., 2010) and the soil water content was mainly affected by precipitation on a seasonal and inter-annual scale. To our knowledge, the effects of inter-annual variation of rainfall on soil N_2O emissions under different land uses are less investigated. In arid and semi-arid regions, where there is a large variability in yearly rainfall, the inter-annual soil N_2O emissions may vary widely and respond differently to land use change. A characteristic of trace gas exchange in semi-arid and arid zones is the rapid and intense production of N_2O following moistening of soil through rainfall or irrigation in a hot dry climate (Barton et al., 2007; Galbally et al., 2008, 2010). Galbally et al. (2010)reported about a 10-fold increase in the N_2O emission rate after watering and suggested that water was the main factor limiting N_2O production in hot and dry climates. Under field conditions in semi-arid Australian agricultural soil, Barton et al. (2007) reported a rapid increase in N_2O emissions following summer rainfall, with over half (55%) of the annual N_2O emissions occurring during summer. Barton et al. (2007) noted, however, that the study was based upon a single year of data, where summer rainfall was two times higher than the annual average, limiting the capacity to identify the principal controllers of annual N_2O fluxes. These studies suggest that changes in the amount and pattern of summer rainfall are key drivers influencing soil N_2O emissions at local scales within semi-arid and arid zones, although the response may vary with land use.

Under climate change conditions in temperate regions of the Northern Hemisphere, altered snowfall patterns, including the duration and magnitude of snowfall cover, may occur (Laternser and Schneebeli, 2003; IPCC, 2007; Liu et al., 2012; Schindlbacher et al., 2014). These changes could impact soil nitrogen mineralization, soil moisture, the frequency of freeze – thaw cycles, and subsequent N_2O emissions (Schimel et al., 2004; Henry, 2007; Wolf et al., 2010; Wu et al., 2014). For example, Schimel et al. (2004)found that deeper snowfall conditions, associated with warmer winter soil temperatures, could dramatically increaseover-winter nitrogen mineralization. Wu et al. (2014) reported higher soil N_2O emissions with increased freeze-thaw cycles under snowfall cover. Furthermore, they suggested that a threshold value of soil moisture might exist, triggering peaks of N_2O emissions during thawing. However, these studies occurred under laboratory conditions, which may present some weaknesses (Henry, 2007) and so are viewed with some caution.

In situ studies of soil N_2O emissions during freeze-thaw cycles in semi-arid and arid zones receiving snowfall are limited. In semi-arid Inner Mongolia temperate grasslands, Wolf et al. (2010) found that annual N_2O emissions from ungrazed grasslands more than doubled compared to heavily grazed sites, which they attributed to a higher capture of snowfall and N_2O emissions during the freeze-thaw cycles at the ungrazed sites. Whether this in situ response is observed in other land uses within semi-arid and arid regions is mostly unknown.A similar response would be possible, mediated at local spatial scales by the interaction of different land use and management, including vegetation cover, N fertilizer, irrigation and soil tillage inputs, with short- and long-term climate conditions. Further measurement of in situ soil N_2O conditions under different land uses within semi-arid and arid regions is important for improving our mechanistic understanding of soil N_2O emissions. Emphasis should be put on the differentiation between management effects and climate, especially amounts and pattern of summer rainfall and winter snowfall.

The aim of this study was to assess the intra- and inter-annual variation of soil N_2O emissions and their relationship with climatic factors, such as soil moisture, air and soil temperature, and rainfall under two land use types (wheat field and apple orchard) in the semi-arid Loess Plateau, China. We hypothesized that the magnitude and pattern of summer rainfall and winter snowfall are the main controllers of the seasonal pattern of N_2O emissions and the annual N_2O fluxes in these rain-fed, semi-arid regions.

2. Material and methods

2.1. Study site

The field experiment was carried out at the Changwu State Key Agri-Ecological Station, Loess Plateau (107°41′E, 35°14′N, and 1200 m above sea level) in Changwu County, Shaanxi Province, China (Fig. 1). The site has a typical semi-arid climate, with mean annual rainfall of 565 mm, with nearly half of that amount falling between July and September, according to meteorological monitoring from 1984–2004. The ratio of rainfall to potential evapotranspiration is 0.361, making this region semi-arid, according to the UNDP/UNSO (1997) definition. Based on meteorological monitoring from 1984 to 2004, the annual average temperature was 9.1 °C, and there were 171 annual frost-free days. The soil is classified as coarse-textured dark loessial soil, according to the Chinese classification system.

Two neighboring fields on flat land were selected for N_2O measurement: (i) a winter wheat field and (ii) an apple orchard, which had been converted from a wheat field in 1984. Both the apple orchard and the wheat field were approximately 1 ha in size. The main physical and chemical characteristics of the soil of the wheat field and the apple orchard were, respectively: 0–10 cm soil organic carbon of 5.79 ± 0.10 g kg^{-1} and 6.26 ± 0.28 g kg^{-1}; total nitrogen of 0.95 ± 0.01 g kg^{-1} and 1.03 ± 0.02 g kg^{-1}; pH of 8.35 ± 0.01 and 8.33 ± 0.15; 0–30 cm bulk density of 1.35 ± 0.02 g cm^{-3} and 1.24 ± 0.06 g cm^{-3}; 0–10 cm nitrate of 11.88 ± 3.44 µg g^{-1} and 43.61 ± 8.90 µg g^{-1}; and 0–10 cm ammonium of 2.96 ± 1.18 µg g^{-1}and 48.44 ± 4.01 µg g^{-1}. Rainfall is the only source of water for both fields.

2.2. Field practices

Winter wheat (*Triticum aestivum* L) was sown on the wheat field in late September and harvested in late June of the following year. The wheat cultivar was Winter Wheat Changhan 58. The field was annually mechanically tilled around late July or early August to incorporate residue and weeds into the soil (about 0.49 kg N ha^{-1}). A second tillage was conducted on the same day as sowing in late September. Before sowing, 138 kg N ha^{-1} of urea and 750 kg ha^{-1} of monocalcium phosphate monohydrate was applied at the surface of the soil and then mechanically incorporated into soil at about 20 cm depth, as soon as possible.

The apple orchard was planted with Fuji apple trees (*Malus pumila*Mill). Trees were planted at a density of 5×5 m^2. Trees were pruned annually (April/May) and managed at a crown size of about 3.5 m. The apple orchard was fertilized twice a year, once in late March,