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Characteristics of N_2O production and transport within soil profiles subjected to different nitrogen application rates in China

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HIGHLIGHTS

- High amount of nitrogen increased the potential risk of N_2O emissions.
- Higher N_2O flux rate coincided with relatively high production rates.
- Much soil effluxes and production of N_2O occurred in the 0 ~ 15 cm soil layer.
- More N fertilizer was applied, greater production occurred in the topsoil.

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ABSTRACT

To better understand the effect of N fertilizer on the responses of subsoil N_2O to N_2O emissions in a high-yield plot, we investigated the subsurface N_2O concentrations at seven mineral soil depths and analyzed the subsoil N_2O fluxes between soil horizons. This study was conducted from 2012 to 2013 in farmland located in the semi-humid area of the Changwu station, Shaanxi, and the results showed that the application of N fertilizer triggered the highest amount of N_2O production and effluxes in the various soil layers. With an increase of N fertilizer, N_2O effluxes and production significantly increased; the mean variation of 380 kg N ha^{-1} treatment was much greater than that of 250 kg N ha^{-1} treatment, particularly after fertilization during the maize growing season (MS). N_2O concentrations increased within 30 cm and maintained low and stable values. However, N_2O fluxes and production decreased with depth (below 30 cm) and then remained low (approximately zero or even negative) at depths of 30–90 cm. The cumulative N_2O fluxes in the 0–15 cm soil layer accounted for 99.0% of the total amount in the soil profile, and high fluxes coincided with periods of relatively high production rates. The cumulative production of N_2O also remained in step with the cumulative fluxes. In addition, more N fertilizer was applied, greater production occurred in the topsoil. A significantly positive relationship was found between N_2O fluxes and mineral N, and a negative relationship was found between the fluxes and the water-filled pore space (WFPS) in the shallow soil. N_2O effluxes increased with increasing amounts of N fertilizer, which was primarily due to nitrification on the Loess Plateau.

1. Introduction

Agricultural soils are responsible for 10–12% of anthropogenic greenhouse gas emissions (Crowley, 2000; IPCC, 2007) and contribute substantially to the “greenhouse” effect (Smith et al., 2003; Tett et al., 1999). These soils are believed to be the predominant source or sink of nitrogen because they contribute approximately 70% of the total N_2O emitted from the biosphere into the atmosphere (Flückiger et al., 1999). Soil is a complex medium that varies temporally and spatially as well as horizontally and vertically, and the coexistence of aerobic and anaerobic zones allows for the production of N_2O, its consumption and its upward, downward and horizontal movement (Liu et al., 2007). The temporal and spatial dynamics of N_2O result in very different patterns of N_2O concentrations in soil profiles (Kellman and Kavanaugh, 2008; Koehler et al., 2012; Hosen et al., 2000; Pei et al., 2004; van Groenigen et al., 2005). Nitrous oxide is derived from the transformation of N by the microbial processes of nitrification and denitrification (Goldberg et al., 2010; Pörtl et al., 2007), and high levels of soil N impel the microbial production of significant amounts of N_2O and NO

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(Mosier et al., 1991, 1996; Akiyama et al., 2000, 2010; Bouwman et al., 2002; Wuebbles, 2009). In addition, temperature and moisture influence N_2O emissions; drastic variability in N_2O production and emission has been observed during investigations of mineralization under different soil temperature and moisture regimes (Fang et al., 2009; Bergstermann et al., 2011; Lan et al., 2013; Liu et al., 2014b, 2012; Braun et al., 2013).

Net soil surface fluxes of gases result from their production, consumption and transport through the underlying soil, and similar N_2O profiles, which are characterized by subsoil production and upward diffusion together with stepwise consumption, have previously been observed in different soils (Kusa et al., 2010; Nishimura et al., 2012; Lessard et al., 1996). A better understanding of the pathways influencing NO_2 flux rates at a given time or place could greatly advance the development of more targeted mitigation strategies and narrow the uncertainty around the prediction of N_2O emissions (Yoh et al., 1997; Snyder et al., 2009; Sanz-Cobena et al., 2014). It is therefore necessary to not only determine soil surface N_2O emissions but also subsoil N_2O effluences.

The Loess Plateau covers an area of 623,800 km^2 in northwest China and has special soil properties, serious soil erosion and low productivity (Li and Ling, 1992), so it is important to increase the yields of cereal grains through fertilizer use and reduce the substantial environmental impacts of intensive agriculture (Chen et al., 2011). We constructed a high-yield and high-efficiency production system, i.e., the Hybrid-Maize model, in which we (Liu et al., 2013) obtained the maximum yield (13.9 Mg ha^{-1}) with 279 kg N ha^{-1}. We further found that the N_2O emissions from the production system increased with an increased N application rate, but the grain yield peaked with 250 kg N ha^{-1}, in which the N being input was nearly equivalent to the N uptake by maize, which resulted in lower emissions (Liu et al., 2014a). Thus, we want to know the effluence of subsoil N_2O to measure and mitigate greenhouse gas emissions. Due to the spatial heterogeneity of soil, we chose a 1-m depth profile for the investigation of soil N_2O responses to N_2O emissions. Through an experiment in the high-yield plot using plastic film mulching, we calculated N_2O fluxes in the soil profile from changes in concentrations with depth and time by Fick's first law to answer the following: (1) do increases in N application increase both subsoil N_2O fluxes and N_2O concentrations; (2) where and how much N_2O is produced in the soil profile; (3) what are the responses of major environmental factors and N_2O effluences to different temperatures and levels of water and N addition. Our results will extract information about soil N_2O profiles and provide an in-depth look into a semi-humid, agro-ecosystem soil.

2. Experiments

2.1. Site description

The Changwu Agro-ecological Station is situated on the Loess Plateau (35.28° N, 107.88° E, approximately 1200 m ABSL), which is a typical, semiarid farming area with an average annual rainfall of 555 mm and annual evaporation of 1565 mm. The yearly average solar radiation varies from 131 to 137 Wm^{-2} with an average annual temperature of 9.2 °C. The frost-free period is 171 days, and the groundwater depth is 50 m to 80 m. Generally, one crop is grown per year in this region (wheat or maize). According to Chinese soil taxonomy, the soils at the study site are Cumuli-Ustic Isohumosols (Gong et al., 2007) and contain 37% clay, 59% silt and 4% sand. Soil samples from the top 20 cm were collected from the experimental field site before planting in 2009 and had the following properties: a pH of 8.4, a bulk density of 1.3 g cm^{-3}, an organic matter content of 16.4 g kg^{-1}, a total N content of 1.05 g kg^{-1}, an Olsen-P content of 20.7 mg kg^{-1}, and an NH_4OAc-extractable K content of 133.1 mg kg^{-1}. This study was conducted in 2012 and 2013, and the annual precipitation was 480.8 mm and 577.3 mm in 2012 and 2013, respectively. During the MS, the precipitation was 363.4 mm in 2012 and 411.5 mm in 2013, which accounted for 75.6% and 71.3% of the yearly totals, respectively. The daily average air temperature varied from approximately −5.0 °C in January to approximately 23 °C in August.

2.2. Experimental design and crop management

The field experiment was situated within 50 m of the experimental site and depended solely on natural rainfall. There were three treatments: no N applied (N0), N fertilizer applied at a rate of 225 kg N ha^{-1} plus manure (cow dung) applied at a rate of 30 t/ha (C/N of 20 and N content of 0.28% seasonally increased by 25 kg N ha^{-1}) (N250), and N fertilizer applied at rate of 380 kg N ha^{-1} (N380). These treatments were maintained throughout the entire year with three replications in 9 plots (with a buffer zone of 1.0 m between the plots) distributed in a completely randomized block design. After ridging the treatment plots, chemical fertilizers were broadcast over the soil at rates of 90 kg N ha^{-1} (in the form of urea, 46% N), 40 kg P_2O_5 ha^{-1} (in the form of calcium super phosphate, 12% P_2O_5), and 80 kg K_2O ha^{-1} (in the form of potassium sulfate, 45% K_2O). The soil was then turned over by plowing to transfer the fertilizer to the subsurface. The N topdressing was applied in the form of urea (46% N) at the jointing (June 21, 2012 and June 30, 2013) and silking stages (July 14, 2012 and July 16, 2013) using a hole-sowing machine in the furrows at a rate of 67.5 kg N ha^{-1}. The maize was sown in April at a depth of 5 cm and a density of 85,000 plants per ha and harvested on September 8, 2012 and September 12, 2013.

2.3. Sample collection and measurements

2.3.1. Subsurface soil gases

Subsurface soil gases were sampled from multiport-wells in situ (see Cates and Keeney, 1987; Wang et al., 2013), and the soil-air samplers were composed of poly-vinyl chloride (PVC) tubes with an inner diameter of 44 mm (for more details, see Nan et al., 2015a). These sampling wells were composed of six gas chambers and were installed at depths of 7, 15, 30, 50, 70 and 90 cm (covering a range of 2.5 cm above and below each depth). Each gas chamber was connected to the soil surface with a glass tubule (inner diameter of 4 mm) with a plastic, three-way stopcock. Gas samples were collected weekly from each gas chamber in the morning between 8:00 and 11:00. Between April 2012 and September 2013, the N_2O concentrations from the ambient gas (0 cm) were concurrently measured above the soil surface and in the soils. Samples of N_2O were measured by injecting 1 ml directly into a gas chromatograph (Agilent 7890A) equipped with an electron capture detector and analyzed at 300 °C. Samples from the same day were always measured within 24 h.

2.3.2. Soil indexes and grain yield

When taking gas samples, the soil temperature was measured at depths of 0, 7, 15, 30, 50, 70 and 90 cm using portable digital thermometers (JM624, Jinming Instrument Ltd., Tianjin, China) to relate the soil gas concentrations to major environmental factors. In the following analysis, we used the sampling day to calculate the mean temperature of each soil horizon for a sampling period.

Soil samples were collected weekly at depths of 7 cm and 15 cm. In addition, soil samples were collected biweekly at depths of 20–40, 40–60, 60–80 and 80–100 cm during the maize growing season (MS) and approximately every 20 or 30 days at various depths during the fallow season (FS). However, no soil samples were collected when the soil was frozen (December to early March of the following year). During sampling, three sub-samples were randomly collected from the areas between the maize rows using a soil auger 4 cm in diameter and were combined to obtain one sample for each plot. Next, the samples were oven-dried at 105 °C to a constant weight to determine soil gravimetric water content, and the soil water-filled pore space (WFPS, %) was subsequently calculated. The soil bulk density was measured using a cutting-ring (to a volume of 100 cm^3). These data were collected monthly from the depths of 0–10 cm and 10–20 cm, and at depth