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Increased N_2O emissions during soil drying after waterlogging and spring thaw in a record wet year

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ABSTRACT

Global climate change is expected to increase the frequency and intensity of extreme precipitation events, which can dramatically alter soil nitrous oxide (N_2O) emissions. However, our ability to predict this effect is limited due to the lack of studies under real-world conditions. We conducted a field experiment in a maize-cultivated black soil in northeast China with six treatments: control without nitrogen (N) application (CK) and N-fertilized treatments with the ratio of urea N to manure N at 100:0 (NPK), 75:25 (OM1), 50:50 (OM2), 25:75 (OM3) and 0:100 (OM4). The experimental year was the wettest on record with an extreme rainfall event of 178 mm occurring in summer 2013. Annual N_2O emissions from CK and NPK were increased by 168% and 171%, respectively, relative to normal wet years. Extreme rainfall saturated soils, resulted in low N_2O fluxes (<20 μg N m^{-2} h^{-1}) lasting for 25 d. However, N_2O flux peaked (169–264 μg N m^{-2} h^{-1}) in all treatments as the soil dried. Total N_2O emissions were 0.43–0.74 kg N ha^{-1} over the drying period, accounting for 47.5–51.2% of the annual budget. High N_2O fluxes occurred when the ratio of soil nitrate (NO_3^-) to dissolved organic carbon was 0.07–0.10 mg N mg^{-1} C, NO_3^- concentration was >3 mg N kg^{-1} and water-filled pore space was 67–76%. Distinctly higher N_2O fluxes were also identified during the spring thaw period, accumulating to 20.1–49.4% of the non-growing season emissions. Emissions upon thawing were likely related to denitrification induced by high moisture conditions as a result of lag effect of the extreme rainfall. Annual N_2O emissions progressively reduced as the ratio of urea N:manure N shifted towards manure, which was also the case during soil drying after waterlogging. Total N_2O emissions were reduced by 25.6% for OM4 than NPK. Overall, our results suggest that soil N_2O emissions were increased in the record wet year but a shift from urea towards manure with more N applied as starter N can minimize the N_2O losses.

1. Introduction

A warmer atmosphere that results from anthropogenic greenhouse gas emissions will increase the frequency and magnitude of extreme intense precipitation (Min et al., 2011; IPCC, 2014). The occurrence of extreme precipitation in the Northern Hemisphere was shown to intensify based on long-term observation and model predictions (Fischer et al., 2013; Cohen et al., 2014). Soil hydrological cycles will change with intensified precipitation regimes, with an increasing risk of waterlogging and flooding (Knapp et al., 2008). It can be expected that altered soil moisture dynamics will have significant consequences for the nitrous oxide (N_2O) production and emissions (Castellano et al., 2010). However, it is a big challenge to address this issue, because climate extremes are rare, variable, and hard to predict (Knapp et al., 2008; Frank et al., 2015).

Nitrous oxide is a potent greenhouse gas and contributes to stratospheric ozone depletion (IPCC, 2014). In soils, N_2O is principally produced via microbial transformations such as nitrification and denitrification, and strongly regulated by soil temperature, water, nitrogen (N) and carbon (C) (Butterbach-Bahl et al., 2013). In microbial denitrification, nitrate (NO_3^-) is gradually converted to nitrite (NO_2^-), nitric oxide (NO), N_2O and dinitrogen (N_2), catalyzed

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by NO_3^- reductase (*narG* or *napA*), NO_2^- reductase (*nirK* and *nirS*), NO reductase (*norB*) and N_2O reductase (*nosZ*), respectively (Canfield et al., 2010). Generally, increased soil N_2O fluxes are found after rainfall as a result of facilitated denitrification by higher moisture content (Barton et al., 2008). However, excessive moisture condition, usually at >60–70% water-filled pore space (WFPS), may suppress N_2O emissions due to a shift toward complete denitrification, i.e., N_2O reduction to N_2 (Davidson et al., 2000). It has been suggested that *nosZ* is most sensitive to oxygen (O_2) among the denitrification enzymes (Richardson et al., 2009), and a lower ratio of $N_2O/(N_2O + N_2)$ has been observed under higher moisture and lower O_2 conditions (Ciarlo et al., 2007; Morley and Baggs, 2010). Moreover, in O_2 limited environments, nitrification can be inhibited, resulting in decreased NO_3^- availabilities (Batson et al., 2015; Tete et al., 2015). Less NO_3^- loading usually generates a lower ratio of $N_2O/(N_2O + N_2)$ because denitrifiers prefer to transfer electrons to NO_3^- rather than N_2O (Miller et al., 2008; Mitchell et al., 2013). Accordingly, it is very likely that soil waterlogging in extreme wet season might reduce soil N_2O emissions, as supported by McNicol and Silver (2014) who reported that N_2O emissions were very minor from flooded peatland. However, in fertilized cropland, soil NO_3^- concentrations are generally higher and thus can promote flooding-induced N_2O emissions (Hansen et al., 2014). In addition, it has been found that during soil drainage after flooding, soil NO_3^- concentration and thus N_2O emissions could be increased (Harrison-Kirk et al., 2015). On the other hand, simultaneously improving the labile C supply as soil becomes oxic may lead to more N_2 production than N_2O (Iqbal et al., 2015). Therefore, a complex regulation of extreme wet events on soil N_2O production exists, as a consequence of the altered dynamics of soil moisture, N and C. To date, the effect of extreme precipitation events on agricultural soil N_2O emissions is poorly studied (Hansen et al., 2014), and *in situ* research is lacking. Thus, there is an urgent need to provide empirical evidence to improve our understanding and model predictions of soil N_2O emissions in response to extreme precipitation events.

In most studies, measurements of N_2O emissions are limited to the growing season (Lampe et al., 2006; Yang et al., 2015). However, recent work has revealed that emissions during the non-growing season, especially the spring thaw period, can be a large contributor to the annual N_2O budget. For example, 72% of the annual N_2O emission in an ungrazed steppe was derived from the spring thaw pulses (Wolf et al., 2010). Likewise, Yanai et al. (2011) reported that the winter-to-spring N_2O fluxes contributed 58–85% of the annual amount in a Japanese agricultural field. However, many studies have not found significant N_2O fluxes from the soil freeze-thaw cycle (e.g. Li et al., 2012; Burchill et al., 2014). These inconsistent results could be attributed to differences in winter temperature, frost severity, snow cover and fertilizer regimes (Yanai et al., 2011; Kariyapperuma et al., 2012; Risk et al., 2013). Currently, the mechanisms responsible for high N_2O fluxes following soil thaw remain debatable. Bremner et al. (1980) first suggested that thaw emissions were due to the release of N_2O previously produced and accumulated in frozen soil, which was verified by later studies (Teepe et al., 2001; Singurindy et al., 2009). However, mounting evidence indicates that most of the N_2O losses after thawing are produced *de novo* through microbial processes, i.e., nitrification and particularly denitrification (Müller et al., 2002; Wagner-Riddle et al., 2008; Risk et al., 2013). Wu et al. (2014) found a positive effect of watering before soil freezing on N_2O fluxes after thawing in a laboratory experiment. Frank et al. (2015) pointed out that apart from the concurrent impacts of climate extremes on ecological processes, lag effects should also be responsible. Accordingly, we hypothesize that extreme rainfall occurring during the growing season might also result in increased soil moisture content and thus N_2O emissions during the non-growing season, particularly the spring thaw period.

As a common regional practice, combined application of inorganic fertilizer and manure is used to increase soil organic carbon (SOC) and ensure nutrient supply for crop growth in northeast China (Fan et al., 2012). However, high N_2O emissions can be induced by simultaneous addition of C and N (Gentile et al., 2008). In a previous study, we found that a combined application of manure and inorganic fertilizer increased N_2O emission by 8.1–91.9% compared with inorganic fertilizer alone. However, N_2O emission declined with increasing manure application rate from 25% to 50% of total applied N (Chen et al., 2014). Aguilera et al. (2013) pointed out that the effect of manure on N_2O emissions was highly dependent on its application rates and types, and the prevailing climatic conditions. There is an urgent need to make clear the effects of different fertilizer regimes on soil N_2O emissions under extreme events to develop effective mitigation strategies under future climate change. However, at present, no study has addressed this issue in detail. The objectives of this study were (1) to investigate soil N_2O emissions during the growing and non-growing seasons in response to the extreme wet conditions and (2) to explore the regulation of different fertilizer regimes on N_2O emissions in a record wet season.

2. Material and methods

2.1. Study site

The study site is a rainfed cropland located in the Hailun National Agro-ecological Experimental Station, Heilongjiang Province, China (47°26′N, 126°38′E). The region has a temperate continental monsoon climate. The long-term (1953–2013) mean annual air temperature is 1.9 °C, with the lowest monthly temperature (−21.8 °C) in January and the highest (21.7 °C) in July (sourced from the National Meteorological Information Center, http://cdc.nmic.cn/home.do). Mean annual precipitation is 560 mm, of which 370 mm is received during summer. Before the experiment, the field had been cultivated under a maize-soybean rotation with a N-fertilizer application rate of about 200 kg ha^{-1} for maize and 120 kg ha^{-1} for soybean. The soil is derived from loamy loess and classified as black soil or Typic Hapludoll based on genetic classification and the USDA soil taxonomy, respectively. The surface soil (0–20 cm) has a clay loam texture with 8% sand, 72% silt and 20% clay. Additional physicochemical properties are given in Table 1. Soil pH was analyzed in a 1:2.5 soil:water ratio and the bulk density was measured using the intact core method. Particle size was determined on a laser particle size analyzer (LS13320, Beckman Coulter, Brea, USA). The SOC and total N content were determined using the wet-oxidation redox method and the Kjeldahl procedure, respectively.

2.2. Field experiment

A randomized complete block experiment with four replicates of six treatments was established in 2013–2014. Replicate plots were 4.2 m wide × 4 m long. The six treatments were a control without N fertilizer (CK), and five N-fertilized treatments with different ratios of urea N to pelleted chicken manure N: 100:0 (NPK), 75:25 (OM1), 50:50 (OM2), 25:75 (OM3) and 0:100 (OM4) (Table 2). In all N-fertilized treatments, the total N (urea + manure) application rate was 150 kg N ha^{-1}. Manure was commercially available and its main properties are listed in Table 1. All manure was applied before maize planting. However, urea application was split between starter fertilizer and side-dressing (Table 2). The field was split into ridges and furrows at a distance of 70 cm by rotary