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Nitrous oxide uptake in rewetted wetlands with contrasting soil organic carbon contents

Rongzhong Ye*, William R. Horwath

Department of Land, Air, and Water Resources, University of California, Davis, CA 95616, USA

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Rewetting drained peatlands creates favorable reduced conditions for denitrification, but, the potential of restored peatlands to act as N_2O sink is poorly characterized. We monitored N_2O emissions in rewetted peatlands converted to rice paddies with a range of soil organic carbon (SOC) (6%, 11%, and 23%) during the growing season. Negative N_2O emissions were repeatedly observed in all sites, which were not affected by nitrogen fertilization at 80 kg N ha^{-1}. The highest consumption rates amounted to 8.2 tones CO_2 eq ha^{-1} yr^{-1}, 32% of the average CO_2 emissions from drained peat soils. Porewater N_2O concentrations were frequently less than the calculated *in situ* N_2O equilibrium concentrations, suggesting diffusional constraints on atmospheric N_2O into pore water. Redox potentials were correlated to N_2O emission rates ($r^2 = 0.40$, $p < 0.01$). However, relatively higher frequencies and magnitudes of negative N_2O emissions were mostly observed during the period of water draw down for rice harvest activities, especially in the field with the highest SOC. It is likely that reducing water depth by drainage reduced the diffusional barrier for atmospheric N_2O into the soil. In all, the capacity of rewetted peatlands to act as atmospheric N_2O sinks can be significant and seemingly can be managed through manipulating water depths.

1. Introduction

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) and also plays a significant role in the destruction of stratospheric ozone, making it one of the most reactive forms of nitrogen (N) pollution (Ravishankara et al., 2009; Stocker et al., 2013). Soils are the largest contributors to atmospheric N_2O, accounting for approximately 65% of the total annual emissions with 4.1 Tg N_2O–N yr^{-1} from agricultural and 6.6 Tg N_2O–N yr^{-1} from natural sources (Davidson and Kanter, 2014). Less understood, however, is the role of soils as a N_2O sink.

The main sink for N_2O in soils is its enzymatic reduction to dinitrogen gas (N_2) by N_2O reductase (Richardson et al., 2009). However, unlike the other two major GHGs, CO_2 and methane (CH_4), the underlying controls over N_2O consumption and the capacity of soils to act as sinks have received less attention. High soil moisture, low mineral N, and high soil C have been shown to favor N_2O consumption (Majumdar, 2013). Other factors affecting N_2O consumption include soil pH (Čuhel et al., 2010; Stevens et al., 1998), redox potential (Włodarczyk et al., 2005; Yu and Patrick, 2003), and the ease of diffusion of N_2O within the soil profile (Chapuis-Lardy et al., 2007; Ryden, 1981). However, there are no clear lines of evidence for any factor or combination of factors that can reduce the uncertainty in predicting *in situ* N_2O consumption (Chapuis-Lardy et al., 2007).

Nitrous oxide consumption has been observed under various soil conditions (Audet et al., 2014; Chapuis-Lardy et al., 2007; Warneke et al., 2015). In a recent survey of various natural ecosystems, Schlesinger (2013) concluded that global sinks for N_2O in soils is less than 2% of the current estimated sources of N_2O and is likely not important, largely due to the fact that most observations and measurements of net N_2O uptake were sporadic with a frequency of <10% of the measurements or the measurements were at the detection limits of analysis. However, in a review of soil N_2O uptake, Chapuis-Lardy et al. (2007) suggested that N_2O consumption might be important and should be taken into account, which is also supported by others believing that N_2O consumption can have a larger than realized role in regulating atmospheric N_2O (Jones

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* Corresponding author.
E-mail addresses: rzye@ucdavis.edu (R. Ye), wrhorwath@ucdavis.edu (W.R. Horwath).

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et al., 2014; Richardson et al., 2009; Ryden, 1981). Despite this disagreement, studies have shown large variations in the rates of negative N_2O emission, but the highest negative values were mostly observed in wetlands and peatlands, suggesting N_2O uptake and consumption is more efficient under reduced conditions (Chapuis-Lardy et al., 2007; Schlesinger, 2013).

Peatlands cover only 3% of the world's surface, but contain 30% of soil C stocks (Parish, 2008). The formation and maintenance of peatlands requires a water table close to the surface (Belyea and Baird, 2006), and thus a substantial portion of the soil profile normally undergoes anaerobic conditions. Naturally, water saturated conditions and high soil organic C (SOC) content create favorable environments for denitrification and N_2O reduction (Reddy and DeLaune, 2004), which may at least partially explain why highest negative N_2O emissions were frequently observed in these systems (Schlesinger, 2013). However, drainage and cultivation of these organic soils has modified the oxidation-reduction status, resulting in extensive degradation and GHG emissions, primarily as carbon dioxide (CO_2) and N_2O (IPCC, 2014). Restoring drained peatlands is considered a climate mitigation action in the United Nations Framework Convention on Climate change (UNFCCC) and Inter-Governmental Panel for Climate Change (IPCC) (IPCC, 2014). Rewetting allows for the re-establishments of reduced soil conditions, which is expected to retard SOC decomposition and CO_2 emissions (IPCC, 2014; Joosten et al., 2012). A less considered outcome, however, is the potential of these organic soils to act as a N_2O sink.

The Sacramento-San Joaquin Delta (hereafter the Delta) was once a 1400 km^2 tidal marsh influenced by runoff from the Sierra Nevada Mountains, but drained for agriculture in the mid-1800s, resulting in extensive soil C loss and subsidence and large continuous CO_2 and N_2O emissions (Deverel and Leighton, 2010; Drexler et al., 2009). Restoration of these degraded agriculture systems by rewetting has been increasingly recognized as a regional solution to reduce or reverse soil subsidence and mitigate GHGs emissions (Knox et al., 2015). We have recently observed significant net N_2O uptakes in a rewetted drained peatland (containing 15% SOC) during a water draw-down period before rice harvest (Morris et al., in preparation). The negative emission rates ranged from -17 to -102 with a median of -38 $\mu g\ m^{-2}\ h^{-1}$ and the frequency of negative emissions observed was 30% of the measurements. The median and frequency are 9.5 and 3 times of those reported by Schlesinger (2013) in a survey of various natural ecosystems, demonstrating the potential of rewetted peatlands to serve as N_2O sinks. We therefore explored this potential with three more rewetted degraded peatland sites containing contrasting SOC contents (6%, 11%, and 23%). It is expected that similar frequencies and magnitudes of net N_2O uptake would be observed in these rewetted peatlands, where soils are highly organic, while porewater inorganic N were minimal (Kirk et al., 2015), both of which are seemingly favorable for denitrification and N_2O reduction (Chapuis-Lardy et al., 2007).

2. Materials and methods

2.1. Site description

Field studies were conducted on Twitchell Island (38.1053 N, 121.6542 W) in the Sacramento-San Joaquin Delta in 2013. Mean annual precipitation for this region is 380 mm and over 80% occurs from November to March. Yearly average high and low temperature is 22 °C and 9 °C. The areas were once expansive wetlands, but drained and converted to agricultural production in late 1800's, which resulted in severe soil oxidation and subsidence (Deverel and Leighton, 2010). The soils are Rindge silt loams classified as Eutric Rheic Sapric Histosol (Hyperorganic) (FAO WRB) or euic, thermic Typic Haplosaprists (USDA) with organic C contents ranging from less than 5 to greater than 25% in concentration depending on the degree of soil oxidation. Rice (*Oryza sativa* L.) has been grown on the site since 2009 to test its potential as a regional solution to reduce soil subsidence, mitigate GHG emissions, and improve Delta water quality.

2.2. Experimental design and field setup

The experiment was embedded in an N rate trial across a gradient of SOC (Espe et al., 2015). Three sites with contrasting SOC (6, 11, and 23%) were selected for this study with the distance between each site less than 1.25 km. The SOC gradients cover most of the SOC ranges across the Delta (Deverel and Leighton, 2010). A total of five N rates (0, 40, 80, 120, 160 kg N ha^{-1}) were conducted as a randomized complete block design with four replicates in each site. Only two rates (0 and 80 kg N ha^{-1}) were chosen for this study. The 80 kg N ha^{-1} was chosen as it was the highest recommended N rate for rice production in this range of SOC contents (Espe et al., 2015). All sites were managed the same throughout the entire season. Each experimental plot was 4 × 5 m^2. Rice variety 'M-206' was planted on mid-April in 2013 in all fields, except for the 23% C field, where 'M104' was planted by accident. Both varieties are medium grain having similar yield potential (data available online at http://www.carrb.com/Variety/M-206.htm) and N requirements (Mutters et al., 2013). In statewide yield tests, 'M-206' flowered three days later than 'M104', had improved lodging resistance, and improved resistance for blanking caused by temperatures. Following N fertilization as urea and recommended amounts of phosphorus and potassium, fields were flooded on May 15 for plant growth and drained on August 10 for harvest in 2013.

2.3. N_2O emissions

N_2O fluxes were monitored weekly during the growing season and every other day following paddy drainage prior to harvest. Emissions were measured with close vented chambers from 10:00 a.m. to 3:00 p.m. (Parkin et al., 2003). The chambers have an inner diameter of 25 cm and a height of 9, 69, and 99 cm, depending on the height of the rice plants. A PVC ring (25 cm in diameter and 15 cm in depth) was driven into soils one week prior to seasonal measurements and protruded 2–3 cm above the soil surface. The rings were removed at harvest then reinstalled. Before measurements, chambers were placed on rings and sealed with a wide rubber strip made from a cross cut section of a tire inner tube that overlapped the chamber and ring by 5 cm. A fan was used to mix the chamber headspace for 10 or 60 s (depending on chamber height) to avoid gas gradients (Parkin et al., 2003), followed by extracting 20 mL of air from the chamber every 10 min during a 30 min period for a total of 4 samples including time 0. Air samples were transferred completely to 12 mL pre-vacuumed vial and subsequently analyzed for N_2O on a GC-2014 gas chromatograph (Shimadzu, Columbia, Maryland). N_2O emission rates were calculated with a linear regression model of their concentrations against time and expressed as $\mu g\ m^{-2}\ hr^{-1}$ after adjusting for soil temperature and chamber volumes (Pittelkow et al., 2013). If the determinant coefficient (R^2) for N_2O was <0.9, emissions were set to zero, which were mostly observed when NH_4^+ concentration was less than 0.5 mg L^{-1} and no NO_3^- was detected (<0.01 mg L^{-1}). We assumed that N_2O emission was minimal when these substrates for nitrification and denitrification were both limited (Baggs, 2011; Reddy and DeLaune, 2004).