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Coupled soil oxygen and greenhouse gas dynamics under variable hydrology

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A B S T R A C T

Hot spots and hot moments of greenhouse gas (GHG) fluxes can contribute significantly to overall GHG budgets. Hot spots and hot moments occur when dynamic soil hydrology triggers important shifts in soil biogeochemical and physical processes that control GHG emissions. Soil oxygen (O_2), a direct control on biogenic GHG production (i.e., nitrous oxide-N_2O, carbon dioxide-CO_2 and methane-CH_4), may serve as both an important proxy for determining sudden shifts in subsurface biogenic GHG production, as well as the physical transport of soil GHG to the atmosphere. Recent technological advancements offer opportunities to link *in-situ*, near-continuous measurements of soil O_2 concentration to soil biogeochemical processes and soil gas transport. Using high frequency data, this study asked: Do soil O_2 dynamics following short-term (<8 days) soil saturation correspond to changes in soil GHG concentrations and GHG surface fluxes? We addressed this question in a restored riparian wetland in Ohio, USA. Changes in subsurface (10 and 20 cm) CO_2 and N_2O concentrations were inversely related to short-term (<48 h) changes in soil O_2 concentrations. Subsurface CH_4 concentrations, however, did not change in response to soil O_2 dynamics. Changing subsurface GHG concentrations did not necessarily translate into altered surface (soil to atmosphere) GHG fluxes; soil O_2 dynamics at 10 cm did not correspond with changes in surface N_2O and CH_4 fluxes. However, changes in soil O_2 concentration at 10 cm had a significant positive linear relationship with change in surface CO_2 flux. Our study suggests that monitoring near-continuous soil O_2 concentration under dynamic soil hydrology may lead to greater understanding of hot spots and hot moments of GHG emissions. This understanding is increasingly important for estimating the contribution of soil processes to atmospheric GHG concentrations.

1. Introduction

Brief periods of disproportionately high rates of soil-atmospheric biogenic greenhouse gas exchange (GHGs; carbon dioxide, CO_2, nitrous oxide, N_2O and methane, CH_4), known as “hot moments”, contribute significantly to whole-system GHG budgets (McClain et al., 2003; Groffman et al., 2009; Kuzyakov and Blagodatskaya, 2015). GHG hot moments are often triggered during transitional periods in soil hydrology (e.g., soil re-wetting and thawing) that induce sudden changes in the biological and physical soil environment (Smith et al., 2003; Kim et al., 2012; Molodovskaya et al., 2012). Although hot moments may significantly alter estimates of nutrient fluxes, the biogeochemical and physical mechanisms that drive GHG spatiotemporal variability are poorly understood (Groffman et al., 2009; Vargas et al., 2011). Advancing our mechanistic understanding of soil GHG fluxes requires more accurate understanding of the biological drivers of CO_2, CH_4, and N_2O production/consumption as well as physical GHG transport during soil re-wetting and drying (Chen et al., 2008; Riley et al., 2011; Blagodatsky and Smith, 2012).

An important but understudied biological driver of soil GHG fluxes is soil O_2 availability. Soil O_2 controls redox potential and is the master variable determining aerobic and anaerobic biogeochemical processes, including GHG production and consumption (Burgin et al., 2011; Liptzin et al., 2011; McNicol and Silver, 2014). In lieu of rare direct measurements of soil O_2, scientists commonly extrapolate soil O_2 concentration from the more easily measured soil water content (Heinen, 2006; Davidson et al., 2012). Soil moisture predicts soil O_2 concentration under stable conditions, but fails to describe the sudden increase in soil O_2 concentration at

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thresholds in volumetric soil moisture content (Liptzin et al., 2011; Burgin and Groffman, 2012). Studies that measured soil O_2 as an average concentration in the bulk soil (0–21%) find concentrations to be dynamic on short temporal scales (hours to weeks) under varying hydrology as a result of seasonal water table or precipitation patterns (Silver et al., 1999; Teh et al., 2005; Liptzin et al., 2011; Burgin and Groffman, 2012; Silver et al., 2012; Hall et al., 2013). In saturated mineral soils, physical resupply of atmospheric O_2 to the soil is limited and the rate of soil O_2 depletion depends on soil temperature (Papendick and Runkles, 1965), suggesting a strong relationship between the rate of soil O_2 depletion and microbial respiration. Dry soils, in contrast, limit biological activity under low solute diffusion and water stress (Harris, 1981), but permit the rapid diffusion of atmospheric O_2 to the soil. When water-filled soil pores begin to drain after prolonged saturation, a sudden shift in the controls on soil gas diffusion (from diffusion through water to air-filled pore spaces) allows the quick re-supply of atmospheric O_2 to the soil. Herein, for simplicity we refer to the quick re-supply of atmospheric O_2 during soil drainage as the “big gulp”. While we are beginning to understand the controls on soil O_2 dynamics, including big gulps, we do not yet understand how the timing of soil O_2 fluctuations correspond to soil-atmospheric GHG fluxes. This shift in diffusivity also applies to gases at higher concentration in the soil than in the atmosphere, e.g., N_2O. For example, rapid influx of atmospheric O_2 to the soil may co-occur with an efflux of soil gases to the atmosphere.

Given the important role of soil O_2 availability on biogeochemical processing, we ask: 1) Does measured soil O_2 correlate to variation in soil GHG concentrations and fluxes? and 2) Can measured soil O_2 act as a physical indicator of soil GHG transport? We predict that short-term soil O_2 fluctuations under varying hydrology may be a useful proxy for understanding the timing of briefly enhanced rates of surface GHG fluxes (hot moments). Using high frequency soil O_2 and soil moisture sensors, we evaluated how soil GHG concentrations and surface GHG fluxes correspond to near-surface (10 and 20 cm depth) soil O_2 dynamics. During sustained soil saturation, we expected the depletion of soil O_2 and restrictive diffusion of soil GHGs to the atmosphere to result in an increase in subsurface GHG concentrations at 10 and 20 cm and a decrease in GHG surface fluxes. Upon drainage, we expected the rapid influx of atmospheric O_2 (“big gulp”) into soil pore space to co-occur with a decrease in subsurface GHG concentrations and an increase in surface GHG fluxes.

2. Materials and methods

2.1. Study site

Our research is conducted at the Great Miami Wetland Mitigation Bank, a 46 ha restored wetland in Trotwood, Montgomery County, Ohio, United States (36°46′51″ N, 84°20′26″ W). Five Rivers Metro Parks, Dayton, OH funded and managed the restoration project, which serves as a wetland mitigation bank to provide compensatory mitigation for impacted waters of the United States, including wetlands and streams, which result from activities authorized under the Clean Water Act (National Research Council, 2001). The restoration involved extensive earth moving during 2011 and planting native wetland and upland vegetation during 2012. Herbaceous plants (a mix of perennial and annual grasses and forbs) dominate the vegetation. The site, previously drained for row crop production for over 100 years, is underlain by poorly drained silty clay loam (Brookston, Fine-loamy, mixed, active, mesic Aeric Endoaqualfs). Average annual regional precipitation is 1005 mm and average annual temperature is 10.8 °C. Average daily temperature during our study was 11.93 °C in October 2013 and 21.37 °C from June–August 2014. The site received a total 147 mm of rain in October 2013 and approximately 178 mm from June to August 2014.

We installed soil sensors and gas sampling chambers at two locations within the larger site, approximately 200 m apart. We chose the location of the sites to represent differences in soil texture across the restored wetland (Fig. 1 and Table 1). Soil texture at 0–10 cm across the restored wetland was estimated from 120 soil cores collected post-construction in November 2011, summarized as a histogram in Fig. 1. The soil at the quick draining (QD) site is sandy clay loam soil at 0–10 and 10–20 cm, which had shorter saturation duration following precipitation events in 2014 compared to the slow draining (SD) site with clay soil (0–10 cm) and clay loam soil (10–20 cm) (Table 1). In September 2013, we installed the QD site with five replicated sampling pits positioned approximately two meters from the nearest neighboring pit. In June 2014, we added the SD site with three replicated sampling pits positioned approximately two meters apart. QD is located in an area where intensive earth moving occurred (2010–2011); SD experienced minimal impact under construction activity.

2.2. Sensor and gas chamber installation

Data loggers at each site (Campbell Scientific CR1000, Nexens 3100-iSIC, and Stevens DOT) recorded soil O_2, soil moisture and soil temperature at 30 min intervals. We sampled GHG subsurface (10 and 20 cm) concentrations and GHG surface (soil to atmosphere) fluxes during October 2013 at QD and from June to August 2014 at QD and SD. Each pit consisted of two SO-110 soil O_2 sensors (Apogee Instruments, Logan, Utah), two SDI-12 hydra probes (Stevens Water, Portland, Oregon), and four subsurface gas sampling chambers installed horizontally 15–20 cm from a neighboring sensor at 10 and 20 cm depth (Fig. 2). The soil O_2 sensor has internal temperature composition circuitry and the data are expressed as relative concentration, i.e., the mixing ratio as a percentage. We used the sensor mV output in open air at 100% humidity to calibrate individual O_2 sensors relative to the atmosphere. Soil O_2 sensors were secured vertically to a 30.5 cm diffusion head made of perforated polyvinyl chloride (PVC) pipe (1.9 cm ID, 2.54 cm OD). Subsurface gas chambers were constructed with 30.5 cm of silicone tubing (1.27 cm ID, 0.32 cm wall thickness) secured in perforated PVC pipe (1.9 cm ID, 2.54 cm OD) and fit to a tygon lead that ran to the surface for sampling with a stopcock and syringe. The average time to 95% equilibration with surrounding CO_2 concentration is 9.1 h for silicone tubing with wall thickness equal to 0.32 cm

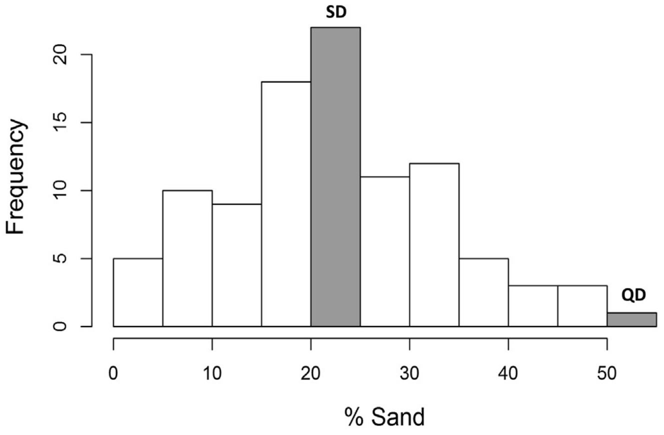

Fig. 1. Distribution of percent sand at 0–10 cm from 120 soil cores collected across the post-construction wetland in 2011; site QD and SD were established in October 2013 and June 2014 and represent differences in soil texture across the wetland.