5-2015

Coupling Soil Oxygen and Greenhouse Gas Dynamics

Karla M. Jarecke
University of Nebraska-Lincoln, jareckek@gmail.com

Follow this and additional works at: http://digitalcommons.unl.edu/natresdiss

Part of the Terrestrial and Aquatic Ecology Commons

http://digitalcommons.unl.edu/natresdiss/114

This Article is brought to you for free and open access by the Natural Resources, School of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Dissertations & Theses in Natural Resources by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
COUPLING SOIL OXYGEN AND GREENHOUSE GAS DYNAMICS

by

Karla M. Jarecke

A THESIS

Presented to the Faculty of
The Graduate College at the University of Nebraska
In Partial Fulfillment of Requirements
For the Degree of Master of Science

Major: Natural Resource Sciences

Under the Supervision of Professor Amy J. Burgin and Terrence D. Loecke

Lincoln, Nebraska

May, 2015
Dynamic soil hydrology triggers important shifts in soil biogeochemical and physical processes that control greenhouse gas (GHG) emissions. Soil oxygen (O$_2$), a direct control on biogenic GHG production (e.g. nitrous oxide-N$_2$O, 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 correspond to soil GHG concentration and GHG surface flux? Change in subsurface CO$_2$ and N$_2$O concentrations were inversely related to short-term (<48 hrs) change in soil O$_2$ concentration at 10 and 20 cm whereas CH$_4$ concentrations did not change in response to soil O$_2$ dynamics. Although soil O$_2$ dynamics at 10 cm did not correspond with change in surface N$_2$O and CH$_4$ flux, change soil O$_2$ concentration at 10 cm had a significant positive linear relationship with change in surface CO$_2$ flux. Our study suggests that coupling near-continuous soil O$_2$ concentration and soil gas flux under dynamic soil hydrology may lead to greater understanding of climate change feedbacks and serve as a relevant predictive tool for future climate change mitigation.
Acknowledgements

I thank Astrea Taylor, Cain Silvey, Dave Moscicki, Joanna Taylor, Carrie Adkisson, and Monica Christian for their help with field and laboratory analyses. Fondriest Environmental and Stevens Water provided helpful technical support with the sensor network. We also acknowledge Fiver Rivers Metro Parks for allowing us to complete this research on the Great Miami Mitigation Bank. This project was funded by NASA/USDA joint program on Carbon Cycle Science (awards 2011-03007 and 2011-00829).
Table of Contents

Acknowledgements........................................................................................................iii

Introduction......................................................................................................................5

Material and Methods.....................................................................................................7

Results............................................................................................................................12

Discussion.......................................................................................................................15

References.......................................................................................................................20

Table Captions................................................................................................................24

Figure Captions.............................................................................................................24

LIST OF MULTIMEDIA OBJECTS

Table 1............................................................................................................................26

Table 2............................................................................................................................27

Figure 1...........................................................................................................................28

Figure 2...........................................................................................................................29

Figure 3...........................................................................................................................30

Figure 4...........................................................................................................................31

Figure 5...........................................................................................................................32

Figure 6...........................................................................................................................33

Figure 7...........................................................................................................................34
Introduction

Brief periods of disproportionately high rates of soil-atmospheric biogenic GHG (carbon dioxide, CO$_2$, nitrous oxide, N$_2$O and methane, CH$_4$) exchange, known as “hot moments”, contribute significantly to whole-system GHG budgets (Groffman et al. 2009, Vargas et al. 2010). Hot moments in GHG emission are often triggered during transitional periods in soil hydrology (e.g., soil re-wetting and thawing) that induce sudden change in the biological and physical soil environment (Kim et al. 2012, Malodovskaya et al. 2012). Although hot moments may significantly alter estimates of nutrient fluxes (McClain et al. 2003), the biogeochemical and physical mechanisms that drive spatiotemporal variability in GHG emissions from dynamic landscapes are poorly understood (Groffman et al., 2009). Therefore, accurately predicting the occurrence of hot moments and quantifying their magnitude is increasingly important for estimating positive feedbacks to climate change. This will require more precise descriptions of the environmental drivers of CO$_2$, CH$_4$, and N$_2$O production/consumption as well as GHG transport during soil re-wetting and drying (Blagodatsky et al. 2012, Chen et al., Fumoto et al. 2008, Riley et al. 2011).

An important, but understudied, driver of soil GHG fluxes is soil O$_2$ availability. Soil O$_2$, by its control on redox potential, is an important control on aerobic and anaerobic biogeochemical processes and subsequent GHG production and consumption (Burgin et al. 2011, Silver et al. 2012). In lieu of rare direct measurements, scientists commonly assume soil O$_2$ availability from soil water content (Heinen et al. 2006). However, measuring soil O$_2$ dynamics may be useful to explore mechanisms of
biogeochemical shifts (Liptzen et al. 2011). The studies that have measured soil O₂, find concentrations to be dynamic on short temporal scales (hours to weeks) under varying hydrological conditions as a result of seasonal water table or precipitation patterns (Burgin and Groffman 2012, Hall et al. 2013, Liptzen et al. 2011, Silver et al. 1999, Teh et al. 2005, Loecke et al. [in review]). In mineral soils, the rate of soil O₂ depletion under saturation depends on temperature (Loecke et al. [in review]), which suggests a strong connection of soil O₂ availability to increased microbial respiration that is commonly observed under increased temperature and labile substrate supply (Fierer and Schimel 2003). Dry soils, in contrast, limit biological activity under low solute diffusion and water stress (Harris 1981), but permit the rapid diffusion of atmospheric O₂ to the soil. Loecke et al. refer to the quick re-supply of atmospheric O₂ to the soil that occurs on an hourly timescale during soil drying as the “big gulp”. Big gulps indicate sudden shifts in soil gas diffusivity that may permit a directionally opposite transport of soil gases to the atmosphere (Loecke et al. [in review]). However, studies that measure soil O₂ concentrations have yet to understand how the timing of soil O₂ fluctuation corresponds to soil-atmospheric GHG fluxes.

Given the important role of soil O₂ availability on biogeochemical processing, our goal is to assess soil O₂ as a biogeochemical driver of GHG production/consumption as well as a physical indicator of soil GHG transport. Short-term soil O₂ fluctuations under varying hydrology may be a useful proxy for understanding the timing of briefly enhanced rates of surface GHG fluxes (hot moments). With the use of high frequency soil O₂ and soil moisture sensors, this study addresses 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$_2$ present in water-filled pore space 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. During soil drainage, we expected the rapid influx of atmospheric O$_2$ (“big gulp”) to co-occur with a decrease in subsurface GHG concentrations and an increase in surface GHG fluxes permitted by rapid soil gas diffusion in air-filled pore space. We discuss how further examination of soil O$_2$ dynamics may improve our ability to model spatiotemporal variability of GHG emissions and understand the importance of hot moments in a changing climate.

Materials and Methods

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. The bank was formed 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 (NRC, 2001). The restoration involved extensive earth moving during 2011 and planting native wetland and upland vegetation during 2012. 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 sites approximately 200 m apart. We chose the location of the sites to represent differences in soil texture across the restored wetland (Figure 1a 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. 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 May 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.

**Sensor and Gas Chamber Installation**

Data loggers at each site (Campbell Scientific CR1000, Nexens 3100-iSIC, and Stevens DOT) recorded hourly soil O$_2$, soil moisture and soil temperature. We sampled GHG subsurface concentrations and GHG surface flux during October 2013 at QD and from June to August 2014 at QD and SD. Each pit consisted of two SO-110 soil O$_2$ (Apogee Instruments, Logan, Utah), two SDI-12 hydra probe (Stevens Water, Portland,
Oregon), and four subsurface gas chambers installed horizontally 15-20 cm from a neighboring sensor at 10 and 20 cm depth (Figure 1b). 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 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 hours for silicone tubing with wall thickness equal to 0.32 cm (DeSutter et al. 2006). Prior to installing soil O$_2$ diffusion heads and subsurface gas chambers, we drilled a hole of slightly smaller diameter into the soil wall with a 1.9 cm auger bit. Above each sampling pit, we placed static surface flux chambers (12.5 cm in length x 25 cm inside diameter) outfitted with a PVC lid with a small sampling port needle vent to permit equilibration of internal and external atmospheric pressure (modified from Robertson et al., 1999). We positioned the center of the permanent collars 30 cm from the pit wall to ensure surface gas fluxes were collected directly above subsurface sensors and gas chambers. Surface gas chamber collars were inserted 3-5 cm into the soil. We saw no visible evidence of cracking at the soil surface and allowed chambers to settle two weeks prior to sampling.

*Soil Analyses and Gas sampling*

In June 2014 we collected three replicated 30 cm soil cores at QD and SD one meter from the surface flux chamber where soils were undisturbed during sensor installation. We cut cores in 2 sections: 0-10 cm and 10-20 cm. We assessed each section
for soil physical properties including bulk density, percent sand, percent silt, percent clay, total carbon, total nitrogen, and substrate-induced respiration (West, 1986). The two sites are significantly different ($\alpha = 0.05$) in bulk density, texture characteristics, substrate induced respiration (SIR), and total nitrogen, but do not differ in total carbon (Table 1). Average SIR at 0-10 cm was 5 times greater at SD compared to QD soil at 0-10 cm; average SIR at SD near-surface soil (0-10 cm) was also five times greater than deeper soil (10-20 cm) whereas SIR did not differ between depths at QD (Table 1).

In total, we sampled subsurface soil gas and surface gas flux 20 times at QD during October 2013, 54 times at QD from June to August 2014, and 56 times at SD from June to August 2014. We collected subsurface and surface gas samples 1-2 times prior to precipitation and twice daily immediately following precipitation until soil $O_2$ returned to stable, near-atmospheric concentration at all locations. In August 2014, we used supplemental irrigation to mimic rainfall by pumping water from an artesian well approximately 400 meters to an elevated, rotating sprinkler that distributed water equally at each pit.

Subsurface gas samples were collected into a 6 mL Exetainer (Labco, Exeter UK) vial previously flushed with $N_2$ and consisted of 3 mL of chamber soil gas after flushing 1.5 mL from the lead tubing. Immediately following subsurface soil gas collection, we collected gas samples (10 mL) from soil surface chamber headspace with a stopcock and syringe at 0, 15, 30, and 45 minute time points and transferred into a 6 mL Exetainer vial with atmospheric background. All gas samples were immediately shipped to the University of Nebraska-Lincoln and analyzed on an Agilent gas chromatograph (GC)
using flame ionized detector (FID) for CH$_4$, electron capture detector (ECD) for N$_2$O, and external CO$_2$ analyzer (LICOR 820). For QA/QC, we analyzed one check sample of known CO$_2$, N$_2$O, and CH$_4$ concentration for every twenty field samples; if the coefficient of variation for checks was less than 3% we accepted GC results that fell within the detection limits of our standard curve.

Data Analysis: Characterizing Soil O$_2$ and Saturation Events

Rapid increases in soil O$_2$ or big gulps were characterized by positive change in sequential measurements of soil O$_2$ concentration that exceeds 1.2%. This change in soil O$_2$ concentration also occurred twice within 5 hours to ignore fluctuations in soil O$_2$ concentration due to diurnal change and sporadic noise in soil O$_2$ measurements. We quantified the local minimum and maximum soil O$_2$ concentration within 20 hours before and after the big gulp to understand the magnitude of soil O$_2$ loss. To understand how saturation duration influenced soil O$_2$ loss, we quantified soil saturation using local threshold values for soil moisture (cm$^3$ cm$^{-3}$). We defined local saturation thresholds by subtracting 0.04 from the 99th percentile of measured soil moisture to remove measurement noise. The start of the saturation event occurred when soil moisture measured above the threshold 4 times in 2 hours; the end of the saturation event occurred when soil moisture measured below the saturation threshold 4 times in 2 hours. These criteria ignored short-term (< 2 hours) increases in soil moisture that did not induce change in soil O$_2$ concentration. We used the time at the start and end of the saturation event to calculate the total time soil remained saturated (saturation duration) at each
location. We analyzed the response of soil O₂ loss to saturation duration at QD and SD 10 and 20 cm using linear regression models (α < 0.05).

We collected GHG samples during saturation and within 24 hours of the big gulp at QD 10 cm (n=16), QD 20 cm (n=8), SD 10 cm (n=13), and SD 20 cm (n=10). We determined the percent of these events in which CO₂, N₂O, and CH₄ concentrations at 10 and 20 cm decreased following the big gulp by subtracting the maximum concentration during saturation (start of saturation to big gulp) from the maximum concentration within 24 hours following the big gulp. We repeated this analysis for CO₂, N₂O, and CH₄ surface fluxes to determine the percent of events in which surface flux increased following the big gulp.

Finally, to understand the effect of dynamic soil O₂ on measured GHG concentrations and surface fluxes, we estimated: 1) Change in subsequent GHG concentration and surface GHG flux for samples collected within 48 hours and 2) Simultaneous change in soil O₂ concentration. We analyzed the linear and quadratic response of change in subsurface GHG concentration (10 and 20 cm) and surface GHG flux to simultaneous change in soil O₂ concentration when change in soil O₂ was greater than 3%; 3% represents more than two times the average diurnal change in soil O₂ concentration. All data analysis was performed in R© (R Core Team, 2014).

**Results**

During June-August 2014, soil moisture ranged from 0.1 to 0.6 cm⁻³ cm⁻³; soil O₂ concentration ranged from 1.3 to 21% among QD and SD sampling locations. Following precipitation events in October 2013 and June-August 2014, we observed two repeated
patterns in soil O\textsubscript{2} dynamics: 1) Soil O\textsubscript{2} declined as a lagged response to soil moisture increase (Figure 2b solid arrow) and 2) Soil O\textsubscript{2} increased rapidly (defined as “the big gulp” in Loecke et al. [in review]) during soil drainage (Figure 2b dashed arrow). Soil O\textsubscript{2} loss was spatially variable across 10 and 20 cm sampling locations following June-August 2014 precipitation (Figure 3a-d). On average, SD (slow draining) had greater loss in soil O\textsubscript{2} concentration (%) and longer periods of saturation compared to QD (quick draining) at both 10 and 20 cm (Table 1). At least two occasions of soil O\textsubscript{2} loss greater than 1.2% occurred across sampling locations with the exception of QD “r5” at 20 cm depth (Figure 3). Overall, soil O\textsubscript{2} depletion followed by the big gulp occurred more frequently at 10 cm than 20 cm (Table 1). Soil O\textsubscript{2} loss across all site and depth combinations was a positive linear function of saturation duration (p<0.001; R\textsuperscript{2}=0.30). Soil O\textsubscript{2} loss increased significantly with duration saturated at QD 10 cm (p=0.01; R\textsuperscript{2}=0.25; Figure 4a), SD 10 cm (p=0.01; R\textsuperscript{2}=0.34; Figure 4a), and SD 20 cm (p<0.001; R\textsuperscript{2}=0.75; Figure 4b). Soil O\textsubscript{2} loss at QD 20 cm had the strongest positive relationship with saturation duration (R\textsuperscript{2}=0.75), whereas, the linear response of soil O\textsubscript{2} loss to saturation duration at QD 20 cm was not significant (Figure 4b).

Figure 5 contrasts the response of soil moisture and soil O\textsubscript{2} following June precipitation at QD and SD. At QD soil O\textsubscript{2} remained relatively stable at 10 and 20 cm during soil saturation following quick drainage, as indicated by decreased soil moisture. Simultaneously, CO\textsubscript{2} concentration increases, but N\textsubscript{2}O and CH\textsubscript{4} concentration remain relatively unchanged (Figure 5a,c). In contrast, soil O\textsubscript{2} loss was greater at SD under sustained saturation and increases in soil CO\textsubscript{2}, N\textsubscript{2}O, and CH\textsubscript{4} concentrations were also
greater (Figure 5b,d). Surface CO$_2$ flux was dynamic at both QD (Figure 6a) and SD (Figure 6b) for sampling locations represented in Figure 5. Although CO$_2$ surface flux was dynamic at both sites, N$_2$O surface flux increased more at SD compared to QD whereas CH$_4$ decreased slightly from pre-saturation conditions at both sites (Figure 6a,b).

We predicted that GHG concentration would decrease following big gulps due to the increased diffusion of soil gases under soil drainage. Overall, we observed this pattern most often with N$_2$O. Decreased N$_2$O concentration following the big gulp occurred more often at SD (100% decreasing events at 10 cm and 85% decreasing events at 20 cm) compared to QD. CO$_2$ concentration also decreased more often at SD compared to QD with the greatest number of decreasing events (90%) occurring at SD 20 cm (Table 2); CH$_4$ concentration decreased less frequently overall with the greater number of decreasing events (69%) at SD 10 cm (Table 2). We predicted that increased soil gas diffusion during soil drainage and subsequent big gulps would also result in increased surface GHG fluxes. Surface CO$_2$ flux increased most often following big gulps at 10 cm (63% at QD and 85% at SD) whereas surface N$_2$O flux increased for only 13% of big gulp events at QD and 54% at SD; CH$_4$ flux increased for approximately one-third of big gulp events (31% at QD and 38% at SD) (Table 2).

Change in CO$_2$ surface flux had a positive linear relationship with change in soil O$_2$ concentration at 10 cm (Figure 7a). We observed increased surface CO$_2$ flux during increased soil O$_2$ concentration at 10 cm and decreased surface CO$_2$ flux during decreased soil O$_2$ concentration. Change in N$_2$O and CH$_4$ surface fluxes were not significantly related to change in soil O$_2$ concentration at 10 cm (Figure 7b,c). The
change in CO₂ and subsurface concentration at 10 and 20 cm was inversely related to the change in soil O₂ concentration (Figure 7d p<0.001; R²=0.58 at 10 cm and p<0.001, R²=0.35 at 20 cm). Change in N₂O concentration was also inversely related to change in soil O₂ at 20 cm (Figure 7e p=0.003; R²=0.24). However, N₂O concentration at 10 cm was a quadratic function of soil O₂ change (Figure 7e p=0.03; R²=0.14) with exponential increase in N₂O concentration occurring during soil O₂ decrease. CH₄ concentration did not significantly respond to soil O₂ dynamics at 10 cm or 20 cm (Figure 7f).

Discussion

Our challenge was to understand if soil O₂ availability corresponds to shifts in subsurface GHG concentrations and surface GHG fluxes. We found that the magnitude of soil O₂ loss following short-term (hours to days) saturation varies horizontally and with soil depth (10 and 20 cm) and is predicted by duration of soil saturation. We detected significant increase in subsurface CO₂ and N₂O concentration in response to slow soil gas diffusion and soil O₂ depletion. We also determined that rapid soil O₂ increase corresponds with a decrease in subsurface CO₂ and N₂O concentration and an increase in surface CO₂ flux. We will examine the effect of soil O₂ dynamics on biogenic GHG in greater detail below and explore the implications of soil O₂ dynamics for understanding biogeochemical hot spots and hot moments.

Soil O₂ effects on biogenic greenhouse gases

Subsurface CO₂ concentration dynamics are inversely related to soil O₂ dynamics following soil wetting and drying (Figure 7d,e). CO₂ concentration dynamics had the strongest relationship with soil O₂ dynamics, which suggests that soil O₂ availability
under short-term soil saturation creates conditions for carbon mineralization under increase labile substrate. Several studies report enhanced CO₂ flux during soil re-wetting (Harris 1981, Fierer & Schimel 2002, Ryals & Silver 2013), but the subsequent decrease in soil CO₂ concentration that we observed co-occurs with big gulps (Figure 7d) initiated by soil drainage. In addition, big gulps correspond to increase CO₂ surface flux and soil O₂ loss corresponds with decreased CO₂ surface flux. This link between short-term, dynamic soil O₂ and CO₂ concentrations as well as near-surface soil O₂ concentration and CO₂ surface flux has not been reported by other studies. Furthermore, the greatest change in CO₂ concentrations and CO₂ surface flux occurred at SD where magnitude of soil O₂ loss and subsequent big gulps were greater (Figure 7a,d). Thus, we conclude that greater magnitude of soil O₂ loss triggers greater shifts in short-term (< 48 hrs) CO₂ concentration and surface CO₂ flux.

Unlike CO₂, a terminal product of heterotrophic oxidation of organic matter, N₂O is readily produced and consumed in soil (N₂O reduction to N₂). N₂O is generally controlled by dynamic production and consumption processes—nitrification and denitrification (Burgin et al. 2010). Although production of N₂O often exceed consumption rates, N₂O can be further reduced to N₂ (via denitrification) under diffusional constraints in the soil profile by infiltrating water (Clough et al. 2005) . Similar to CO₂ concentration, change in soil N₂O concentration had an inverse linear relationship with simultaneous change in soil O₂ at 20 cm; at 10 cm, change in soil N₂O concentration had a negative quadratic relationship with change in soil O₂. Greater soil O₂ loss resulted in greater increase in N₂O concentration at SD compared to QD (Figure
Furthermore, the greatest increases in N$_2$O concentration occurred when soil O$_2$ loss exceeded 5%. Liptzen et al. also measure high N$_2$O concentrations at near-atmospheric soil O$_2$ concentration in tropical soils. Thus, the increase N$_2$O concentration that occurred in a relatively oxic soil profile may be a result of nitrification or denitrification in anoxic microsites.

Consistently inundated soils that limit O$_2$ availability can increase CH$_4$ production from methanotrophic bacteria and favor CH$_4$ transport via plants or ebullition (Whalen 2005). The short-term saturation events that occurred in this study can stimulate both CH$_4$ production and oxidation and lead to lower CH$_4$ surface flux in dynamic systems (Altor & Mitsch 2008, van Bodegom et al. 2000). Soil CH$_4$ concentration can have a strong negative non-linear relationship with soil O$_2$ concentration when soil O$_2$ concentration is extremely low (<1%) for extended periods (months) in wet tropical soils (Liptzin et al. 2011). In our study, average soil O$_2$ loss following precipitation ranged from 4.3 to 6.6% (Table 1) and we find change in CH$_4$ concentration in the bulk soil was unaffected by short-term soil O$_2$ dynamics (Figure 7f). The CH$_4$ produced in anoxic microsites in saturated soil was likely quickly oxidized before reaching the soil surface. If QD and SD receive more frequent or longer periods of precipitation, extended water infiltration or water table rise may lead to prolonged periods of low soil O$_2$ and greater soil CH$_4$ concentrations under restricted diffusion.

Using soil O$_2$ to understand biogeochemical hot spots and hot moments

Spatial and temporal variation in near-surface soil O$_2$ dynamics may be useful for understanding the presence (hot spots) and timing (hot moments) of disproportionately
high GHG surface fluxes. The spatial heterogeneity in soil O\textsubscript{2} loss that we observed between and within SD and QD may be strongly linked to soil drainage patterns influenced by site-specific soil physical properties (i.e., soil texture) and topography. In addition to soil hydrologic properties, the spatial differences in soil O\textsubscript{2} loss may reflect heterogeneity in microbial O\textsubscript{2} demand (Rubol et al. 2013). An increase in microbial O\textsubscript{2} demand under prolonged soil saturation would support our observations of greater increases in CO\textsubscript{2} and N\textsubscript{2}O concentrations at SD during greater soil O\textsubscript{2} losses.

Furthermore, SD soil had significantly higher substrate induced respiration rates at 0-10 cm compared to QD (Table 1). Our results support that both hydrologic properties and microbial O\textsubscript{2} demand are important drivers of subsurface GHG concentrations (i.e., CO\textsubscript{2} and N\textsubscript{2}O) during dynamic soil O\textsubscript{2}.

While the spatial heterogeneity in soil O\textsubscript{2} loss may provide new understanding of hot spots, temporal heterogeneity in soil O\textsubscript{2} dynamics may be more important for determining hot moments. Short-term soil O\textsubscript{2} fluctuation was clearly linked to subsurface CO\textsubscript{2} and N\textsubscript{2}O concentration dynamics. The simultaneous decrease in CO\textsubscript{2} and N\textsubscript{2}O that we observed with big gulps (Figure 7d,e) suggests that soil gases are diffusion limited during saturation and soil drainage lifts this limitation. When diffusion constraints were removed, we also observed an increase in surface CO\textsubscript{2} flux that co-occurs with big gulps (Figure 7a). This result supports that the timing of big gulps may play an important role in increased soil-atmospheric gas exchange (hot moments). Change in surface N\textsubscript{2}O and CH\textsubscript{4} fluxes were not significantly related to short-term soil O\textsubscript{2} dynamics perhaps due to the weaker subsurface response of N\textsubscript{2}O concentration and no response of CH\textsubscript{4}.
concentration during dynamic soil O\textsubscript{2} (Figure 7e,f). Since soils were never completely anaerobic in our study, the availability of O\textsubscript{2} may have limited the production of N\textsubscript{2}O and CH\textsubscript{4} under short-term saturation.

The timing and magnitude of big gulps are associated with soil drainage patterns (e.g., QD vs. SD saturation duration) driven by differences in soil properties such as soil texture and bulk density (Table 1). Furthermore, big gulps occur at a relatively consistent value of soil moisture near field capacity when soils begin to drain (Loecke et al. [in review]). This suggests that hot moments may depend on site-specific soil moisture patterns that correlate to big gulps. Others predict peak N\textsubscript{2}O fluxes when soils are near field capacity due to the abundance of anaerobic microsites and increased diffusivity in the bulk soil (Davidson et al. 2000). In addition, field capacity at which max N\textsubscript{2}O flux occurs depends on differences in soil properties that influence soil drainage patterns (i.e., total porosity and bulk density) (Castellano et al. 2010). Therefore, determining the soil physical properties that influence the magnitude and timing of big gulps may also reveal the abiotic factors that control the magnitude and timing of hot moments.

Surface GHG flux is a balance between the biogeochemical production/consumption of GHG and the transport of soil gases (Blagodatsky & Smith, 2012). Many studies describe increased soil gas flux rates due to soil re-wetting when low GHG surface flux from dry soils preceded rewetting events (Kim et al. 2012). Previous studies, however, lack mechanistic understanding of the environmental drivers of the microbial-mediated process rates, position of reactions sites, and physical transport of gases in the soil profile. With technical advancement and increased wide-spread use of
soil sensor networks, soil O\(_2\) dynamics show greater potential for gleaning new information on coupled biogeochemical and soil physical processes under varying soil hydrology.

Soil O\(_2\) dynamics are reported across multiple ecosystem (Burgin and Groffman 2012, Liptzen et al. 2010, Silver et al. 2012); yet, drivers of soil O\(_2\) fluctuation are not well-represented in current ecosystem models that simulate soil O\(_2\) directly from soil moisture (Loecke et al. [in review]). According to our study, soil O\(_2\) dynamics can improve our mechanistic understanding of biogeochemical and physical shifts in the soil environment that influence hot spots and hot moments in GHG emission. The tight link between subsurface soil O\(_2\) and CO\(_2\) concentrations suggest that accurately modeling soil O\(_2\) dynamics may further our capacity to predict rates of biogeochemical processes such as organic matter decomposition (Davidson et al. 2012). Additionally, near-continuous measurement of surface GHG fluxes may discern the time lag between subsurface GHG accumulation under soil O\(_2\) depletion and short-term, enhanced rates of surface GHG fluxes under rapid soil gas transport. We recommend future efforts to collect soil GHG flux at higher temporal resolution following prolonged saturation (> 1 week) in order to highlight the influence of soil O\(_2\) dynamics on biogeochemical hot moments.

References


Table Captions

**Table 1.** Average ± standard error for soil physical properties and substrate induced respiration at QD (n = 30) and SD (n = 18); *p<0.01 for QD and SD t test at 0-10 cm; **p<0.01 for QD and SD t test at 0-10 cm and 10-20 cm. Average ± standard error for soil O₂ loss and saturation duration at QD 10 cm (n = 9 in 2013 and n = 24 in 2014), QD 20 cm (n = 7 in 2013 and n = 18 in 2014), SD 10 cm (n = 20 in 2014), and SD 20 cm (n = 15 in 2014).

**Table 2.** Percent of events in which CO₂, N₂O, and CH₄ concentration decreased following the big gulp and percent of events in which CO₂, N₂O, and CH₄ surface flux increased following the big gulp; n = total number of big gulp events with GHG collected during saturation and within 24 hours following the big gulp.

Figure Captions

**Figure 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 at the wetland (a); the design of subsurface gas sampling chambers, soil sensors, and surface flux chamber for each soil pit at QD and SD (b).

**Figure 2.** Soil O₂ and soil moisture from June through August 2014 at SD “r1” 10 cm (a) and 20 cm (b).

**Figure 3.** Soil O₂ loss following June-August 2014 precipitation events at QD 10 cm (a), SD 10 cm (b), QD 20 cm (c), and SD 20 cm (d).
**Figure 4.** The relationship between saturation duration and the soil $O_2$ loss for QD and SD 10 cm (a) and 20 cm (b) following precipitation events in October 2013 and June-August 2014.

**Figure 5.** Subsurface $CO_2$, $N_2O$, and $CH_4$, and $O_2$ concentration at QD “r1” 10 cm (a), SD “r1” 10 cm (b), QD “r1” 20 cm (c), and SD “r1” 20 cm (d).

**Figure 6.** Surface $CO_2$, $N_2O$, and $CH_4$ fluxes and $O_2$ concentration at 10 cm at QD “r1” (a) and SD “r1” (b).

**Figure 7.** Change in surface $CO_2$ (a), $N_2O$ (b), and $CH_4$ (c) flux and subsurface $CO_2$ (d), $N_2O$ (e), and $CH_4$ (f) concentration (10 and 20 cm) as a function of change in soil $O_2$ concentration (*p<0.05) during October 2013 and from June-August 2014.
## Tables

<table>
<thead>
<tr>
<th></th>
<th>QD 0-10 cm</th>
<th>QD 10-20 cm</th>
<th>SD 0-10 cm</th>
<th>SD 10-20 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bulk Density</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(g cm⁻³)</td>
<td>1.26 ± 0.05</td>
<td>1.78 ± 0.03</td>
<td>1.40 ± 0.03</td>
<td>1.63 ± 0.02</td>
</tr>
<tr>
<td><strong>% Sand</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>52.76 ± 3.61</td>
<td>45.65 ± 4.83</td>
<td>22.61 ± 0.57</td>
<td>30.72 ± 3.19</td>
</tr>
<tr>
<td><strong>% Silt</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>24.36 ± 3.52</td>
<td>34.00 ± 4.62</td>
<td>52.96 ± 0.56</td>
<td>39.20 ± 3.39</td>
</tr>
<tr>
<td><strong>% Clay</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>% Carbon</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.21 ± 0.12</td>
<td>1.61 ± 0.09</td>
<td>2.18 ± 0.07</td>
<td>1.66 ± 0.02</td>
</tr>
<tr>
<td><strong>% Nitrogen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*</td>
<td>0.13 ± 0.006</td>
<td>0.13 ± 0.003</td>
<td>0.21 ± 0.004</td>
<td>0.17 ± 0.002</td>
</tr>
<tr>
<td><strong>Substrate Induced</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiration *</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(CO₂ mg C g⁻¹ soil hr⁻¹)</td>
<td>0.05 ± 0.01</td>
<td>0.04 ± 0.004</td>
<td>0.25 ± 0.01</td>
<td>0.06 ± 0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>QD 10 cm</th>
<th>QD 20 cm</th>
<th>SD 10 cm</th>
<th>SD 20 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>O₂ loss (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.55 ± 0.46 (2014)</td>
<td>4.36 ± 0.57 (2014)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Saturation duration (days)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.8 ± 0.13 (2014)</td>
<td>0.83 ± 0.17 (2014)</td>
<td>1.04 ± 0.13 (2014)</td>
<td>2.54 ± 0.46 (2014)</td>
</tr>
<tr>
<td></td>
<td>1.77 ± 11.65 (2013)</td>
<td>4.11 ± 1.17 (2013)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.
<table>
<thead>
<tr>
<th>% increasing (mg m(^{-2}) hr(^{-1}) surface flux)</th>
<th>CO(_2)</th>
<th>N(_2)O</th>
<th>CH(_4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=16 (QD); n=13 (SD)</td>
<td>QD=63</td>
<td>QD=13</td>
<td>QD=31</td>
</tr>
<tr>
<td></td>
<td>SD=85</td>
<td>SD=54</td>
<td>SD=38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% decreasing (ppm(_v), at 10 cm)</th>
<th>CO(_2)</th>
<th>N(_2)O</th>
<th>CH(_4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=16 (QD); n=13 (SD)</td>
<td>QD=50</td>
<td>QD=63</td>
<td>QD=44</td>
</tr>
<tr>
<td></td>
<td>SD=62</td>
<td>SD=85</td>
<td>SD=69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% decreasing (ppm(_v), at 20 cm)</th>
<th>CO(_2)</th>
<th>N(_2)O</th>
<th>CH(_4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=8 (QD); n=10 (SD)</td>
<td>QD=38</td>
<td>QD=88</td>
<td>QD=63</td>
</tr>
<tr>
<td></td>
<td>SD=90</td>
<td>SD=100</td>
<td>SD=50</td>
</tr>
</tbody>
</table>

Table 2.
Figures

a.

![Histogram showing frequency of sand percentage](image)

b.

![Diagram of soil sample with labels](image)

= soil gas chamber (CO₂, CH₄, and N₂O)  
= hydra probe (soil moisture)  
= Apogee sensor (soil O₂)

Figure 1.
Figure 2.
Figure 3.
Figure 4.
Figure 5.
Figure 6.
Figure 7.