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Soil fluxes of methane, nitrous oxide, and nitric oxide from aggrading forests in coastal Oregon

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ABSTRACT

Soil exchanges of greenhouse and other gases are poorly known for Pacific Northwest forests where gradients in nutrient availability and soil moisture may contribute to large variations in fluxes. Here we report fluxes of methane (CH_4), nitrous oxide (N_2O), and nitric oxide (NO) over multiple seasons from three naturally N-rich, aggrading forests of coastal Oregon, USA. Mean methane uptake rates (3.2 mg CH_4 m^{-2} d^{-1}) were high compared with forests globally, negatively related to water-filled pore space (WFPS), but unrelated to N availability or temperature. Emissions of NO (6.0 μg NO–N m^{-2} h^{-1}) exceeded N_2O (1.4 μg N_2O–N m^{-2} h^{-1}), except when WFPS surpassed 55%. Spatial variation in NO fluxes correlated positively with soil nitrate concentrations (which generally exceeded ammonium concentrations, indicating the overall high N status for the sites) and negatively with soil pH, and at one site increased with basal area of N_2-fixing red alder. Combined NO and N_2O emissions were greatest from the site with highest annual net N mineralization and lowest needle litterfall C/N. Our findings of high CH_4 uptake and NO/N_2O ratios generally >1 most likely reflect the high porosity of the andic soils underlying the widespread regenerating forests in this seasonally wet region.

1. Introduction

Forest soils are widely known as important sources of carbon dioxide (CO_2) (e.g., Raich et al., 2002), yet are crucial in regulating the fluxes of additional gases involved in climate forcing including methane (CH_4) and nitrous oxide (N_2O). Forest soils also regulate fluxes of nitric oxide (NO); which although not a greenhouse gas is important for the formation of tropospheric ozone, which is a greenhouse gas (IPCC, 2007).

Despite a relatively solid understanding of the climate forcing of these gases, the strengths and trends of various ecosystem sources and sinks are still poorly known (IPCC, 2007). In a recent global synthesis, estimates of nitrogen oxide (N_2O and NO combined) emissions were not made for temperate coniferous forests because of a bias towards studies in eastern North America and Europe (Stehfest and Bouwman, 2006). Yet temperate coniferous forests cover a large area (approximately 2.4×10^6 km^2, Melillo et al., 1993) and thus need to be characterized more completely. Smith et al. (2000) point out the paucity of CH_4 flux data, specifically name the Pacific Northwest as an understudied region, and call for studies including those that are relatively short-term.

Soil N availability is a key regulator of N oxide fluxes from soil. N oxide emissions from temperate forest soils have been positively related to litter or soil nitrate concentrations (Stark et al., 2002; Kitzler et al., 2006), net (Stark et al., 2002; Hart, 2006) and gross rates of nitrification (Ambus et al., 2006; Rosenkranz et al., 2006), and N deposition (Butterbach-Bahl et al., 2002) and negatively related to litter or soil C/N ratios (Klemedtsson et al., 2005; Ambus et al., 2006). Soil moisture also regulates N oxide fluxes from soil (Firestone and Davidson, 1989; Davidson et al., 2000) as has been shown in tropical (Erickson et al., 2002; Hall and Asner, 2007) and temperate (Stark et al., 2002; Venterea et al., 2003) forests. Barring N limitation, NO emissions will peak at soil moisture contents below 60% water-filled pore space (WFPS) while N_2O emissions peak at greater moisture contents (Davidson et al., 2000).

Well-aerated temperate forest soils are typically sources of NO, and some of the highest emissions of NO globally are from conifer forest soils (Yan et al., 2005; Pilegaard et al., 2006). Temperate coniferous forest soils are also sources of N_2O, though fluxes are often low (Hart, 2006; Fest et al., 2009; Livesley et al., 2009), below

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detection (Stark et al., 2002), or even negative, indicating a N_2O sink under N limited conditions (Rosenkranz et al., 2006; Chapuis-Lardy et al., 2007; Jassal et al., 2008; Goldberg and Gebauer, 2009).

Forest soils typically consume CH_4 (e.g., Keller et al., 1983; Steudler et al., 1989; Castro et al., 1995; Price et al., 2004), which is an important service globally as soils are the only known biological sink for CH_4. Globally, temperate forest soils have some of the highest CH_4 uptake rates (Smith et al., 2000; Dutaur and Verchot, 2007; Dalal and Allen, 2008) though variability is high and not well understood. CH_4 entering soil is oxidized by methanotrophic bacteria, a process largely driven by gas diffusivity and temperature (Borken et al., 2000; Smith et al., 2000); the former is often inversely related to soil water content. Soil N availability may limit CH_4 consumption due to an inhibitory effect of NH_4^+ on CH_4 oxidation (Castro et al., 1995; Roslev et al., 1997).

Coniferous forests in the Pacific Northwest exhibit a wide range of N availability (Prescott et al., 2000; Perakis et al., 2006), suggesting soil N oxide and CH_4 fluxes may also be spatially variable. The current or historical presence of N_2-fixing red alder (*Alnus rubra* Bong.) (Scott et al., 2008), which often increases soil N status and cycling (Binkley et al., 1992; Rothe et al., 2002), is largely responsible for the wide range of N availability observed in conifer stands of this region (Perakis et al., 2011).

Forest harvesting over the last century in the Pacific Northwest has left a vast area of young to middle-aged aggrading forests and only 5–10% of original old-growth forest. Despite the sizable area of young forests and the potential for conifer forests to play an important role in regulating soil-gas emissions (as explained above), there are few reports of N oxide gaseous emissions from these forests (Stark et al., 2002; Jassal et al., 2008). None, to our knowledge, provide concurrent measures of CH_4, N_2O, and NO. In particular, we lack information from younger forests in the Oregon Coast Range where accelerated rates of soil N cycling and nitrate leaching from some of these stands (Perakis and Sinkhorn, 2011) suggest the potential for high fluxes of N_2O or NO (c.f. Firestone and Davidson, 1989; Davidson et al., 2000).

We aimed to measure soil fluxes of CH_4, N_2O, and NO and examine possible controls including soil N availability, soil moisture, and temperature in three planted Douglas-fir forests in the Oregon Coast Range. Given the high rainfall in the Coast Range (~2000 mm MAP), we expected that NO/N_2O ratios would be <1 with some seasonal variation. In the summer, when soils are dry and warm, we expected that N oxide fluxes would become dominated by NO and that CH_4 uptake would be relatively high.

2. Materials and methods

2.1. Site descriptions

Soil gas fluxes were measured five times from August 2007 through September 2008, and again in February and April 2011, at three Douglas-fir forests (sites 16, 22, and 58, see Table 1). We acknowledge this represents a limited time sample; our objectives were to establish baseline flux measurements in this understudied and potentially important region and from this to guide future sampling efforts. The stands are located within 65 km of each other, ~20 km from the Pacific Ocean on the west slope of the Oregon Coast Range. Dry summers and wet winters characterize the region; only about 10% of annual precipitation falls from June through September. Precipitation falls mostly as rain, with only occasional snowfall.

The sites were selected from a larger set of stands where soil N cycling and nitrate leaching had been studied previously (Perakis and Sinkhorn, 2011). They were planted with Douglas-fir in the late 1970s – early 1980s after clearcut harvesting and broadcast burning. Prior to harvesting, one stand (16) was dominated by Sitka spruce while the other two (22 and 58) were dominated by Douglas-fir. Earlier (based on 1936 aerial photographs) stand 16 contained second growth conifers, while the other two (22 and 58) were mostly hardwoods, including N_2-fixing red alder (Pers. Com., Alan Kanaskie, Oregon Department of Forestry). Volunteer red alder now comprises 1–8% of total basal area. Light pre-commercial thinning of suppressed stems occurred >15 years prior to this study at sites 22 and 58, but not at 16. Tree canopies at the sites were mostly closed. Cover of the dominant understory plant, western sword fern (*Polystichum munitum* (Kaulf.) C. Presl.), was 13%, 50%, and 6% for sites 16, 22, and 58 respectively; remaining understory cover was sparse (<10%).

Soils at all sites are well-drained Andic Dystrudepts, loamy to silt-loamy in texture (Table 2), and formed from sandstone or siltstone-derived colluvium. Surface soil N concentrations (0–10 cm) ranged from a low of 0.41% (site 58) to a high of 0.60% (site 16) (Table 2). Soils are acidic, with $pH_{(H2O)}$ ranging from 4.7 to 5.5; they rarely freeze in winter.

2.2. Gas sampling

N_2O and CH_4 gas fluxes were measured seven times (August, September, and October 2007, June and September 2008, and February and April 2011), with a single visit per site each time, for a total of 168 individual flux measurements per gas. NO fluxes were measured on the same dates as above except for August 2007, for a total of 144 flux measurements.

At each site, 8 PVC chamber bases (25 cm inside diameter, 18 cm height, with a bevel on the upper outside edge to facilitate top placement) were placed randomly along four parallel 12 m transects located 10 m apart. To avoid potential impacts on fluxes with installation, bases were inserted ~5 cm into mineral soil 30 days prior to the first sampling and left in place for the study. To minimize soil disturbance, understory plants growing within the chambers were removed by hand only if they interfered with flux measurements.

N_2O and CH_4 fluxes were measured using a static, vented closed-chamber technique (Livingston and Hutchinson, 1995). Teflon-lined acrylonitrile butadiene styrene chamber tops were constructed to fit snuggly on top of the chamber bases. Chamber volume averaged 7.6 L, though varied somewhat depending on base insertion depth and top placement. Height from the ground was measured in 4

Table 1
Site characteristics of the 3 Douglas-fir plantations. Numbers in parentheses after site names refer to original plot designations.

Site	Location (Lat, Long)	MAP[a] (mm)	MAT[a] (° C)	Elevation (m)	Distance from coast (km)	Stand age in 2008	Aspect (degrees)	Slope (percent)
Jenck Road (16)	45.171 N, 123.914 W	2100	10.7	120	4.8	28	240	15
Toledo (22)	44.606 N, 123.909 W	1860	10.5	150	8	31	100	25
Sam's Creek (58)	44.722 N, 123.810 W	1920	10.7	50	19	25	75	15

[a] MAP and MAT represent 30 year averages from 1971 to 2000. Data obtained from the PRISM climatic mapping system (http://prism.oregonstate.edu/, accessed April 24, 2009).