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The effects of *Eriophorum vaginatum* on N_2O fluxes at a restored, extracted peatland

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ABSTRACT

Restoration of extracted horticultural peatlands commonly includes distribution of vegetation and propagules from nearby undisturbed sites over the recently-exposed surface. The resulting growth includes both mosses and vascular plants, which are important contributors to returning a peatland to a net carbon-storing ecosystem. Nitrous oxide (N_2O) flux has not been widely investigated in these restored ecosystems. We compared the N_2O flux from plots containing a vascular plant, *Eriophorum vaginatum,* to plots lacking vascular plant cover at a recently restored peatland. We hypothesized that *E. vaginatum* would result in decreased N_2O emissions compared to areas with only moss or bare peat due to rapid plant uptake of peat nitrogen. After an early-summer pulse of emitted N_2O, study plots containing *E. vaginatum* transitioned to net consumers of N_2O while bare plots remained sources as the summer progressed. Furthermore, *E. vaginatum* growing in the wettest parts of the study site also had significantly more extractable nitrogen in pore water collected from 75 cm below the surface, beyond the depth of most roots. We suggest the priming effect driven by the roots of this vascular plant, combined with high water levels, frees some nitrogen from previously-inaccessible recalcitrant organic matter that then is taken up by plant roots and/or soil microorganisms, preventing its release as N_2O. Vascular plants may play important roles in both greenhouse gas processes and in the nutrient cycles of restored peatlands and these complex processes need further investigation to guide effective restoration efforts that aim to return these disturbed ecosystems to net greenhouse gas sinks.

1. Introduction

Commercial extraction of horticultural peat removes the living plants, the highly porous surface peat and some of the deeper, more decomposed peat layers, while compressing and drying the remaining material (Graf et al., 2012). Ecological restoration is an effort to return some or all of the functions of a degraded ecosystem to either an original, pre-disturbance state or to a state resembling that of a reference ecosystem. Restoration of extracted peatlands aims to recover a range of ecological functions, including hydrological conditions, plant diversity, and greenhouse gas exchange (Andersen et al., 2010a; Andersen et al., 2010b; Lucchese et al., 2010; Poulin et al., 2013; Price and Whitehead, 2001). Immediately prior to restoration, the recently-exposed surface of an extracted peatland is composed of relatively well-decomposed peat formed during earlier stages of peatland development that may have physical and chemical properties unlike those present prior to disturbance (Graf et al., 2008; Taylor and Price, 2015; Wind-Mulder et al., 1996; Wind-Mulder and Vitt, 2000). Restoration includes raising water tables by filling drainage ditches and spreading living material over the surface gathered at nearby undisturbed areas (González and Rochefort, 2014; Graf et al., 2012; Rochefort et al., 2003).

Prior to disturbance, bogs and some fens in Canada are dominated by bryophytes, particularly of the genus *Sphagnum*, with vascular plants such as the graminoids *Carex* spp., *Eriophorum* spp., and Ericaceous shrubs as well as trees such as *Picea mariana* and *Larix laricina* also present. Vascular plants such as *E. vaginatum* may spontaneously colonize post-extraction peatlands or establish during early stages of the restoration process (Graf et al., 2012; Graf et al., 2008; Mahmood and Strack, 2011) and can extend roots to the mineral soil underlying the peat, often 1 m or more (Adamson, 1918; Wein, 1973) to access water and nutrients that may be unavailable in the near-surface peat accessible to non-vascular bryophytes.

Roots change conditions for below-ground microorganisms by supplying more labile carbon through root exudates and the decomposition of dead root cells, and by providing routes for

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increased movement of oxygen, water, and dissolved materials (Bhullar et al., 2013; Crow and Wieder, 2005; Hardie et al., 2009; Tuittila et al., 2000). As roots grow deeper into the peat, the Priming Effect (Basiliko et al., 2012; Kuzyakov et al., 2000) increases microbial decomposition of relatively recalcitrant highly decomposed peat and leads to release of materials formerly bound to or included in peat such as nutrients (Dijkstra et al., 2013), including nitrogen (Kuzyakov and Xu, 2013).

Plants may affect soil GHG production, consumption, and movement through a range of mechanisms. Plant roots contribute directly to soil respiration and indirectly through microbial decomposition of root exudates and dead roots and root cells (Kuzyakov and Blagodatskaya, 2015). Peatland plants compete with each other (Kool and Heijmans, 2009) and with soil microorganisms for nutrients including nitrogen in mineral and organic forms (Chapin et al., 1993; Jonasson et al., 1999; Kuzyakov and Xu, 2013) and these interactions can lead to lowered emissions of N_2O (He et al., 2016). Emissions of N_2O and other gases may be increased where plants create a route between water-saturated below-ground areas and the atmosphere, especially through the aerenchymatous tissues of some graminoids (Chen et al., 2011; Jørgensen et al., 2012). Oxygen supplied to roots may link N_2O emissions to diurnal cycles (Jørgensen et al., 2012; Sheppard and Lloyd, 2002; Stewart et al., 2012).

Water plays a major role in peatland function and in structuring patterns of net GHG emissions, principally through the formation of restricted-oxygen zones in water-saturated soil (Groffman et al., 1998; Groffman and Tiedje, 1991; Haapalehto et al., 2014; Strack and Waddington, 2007). N_2O emissions from pristine peatlands have not been widely studied, but existing estimates suggest extremely low emissions, sometimes not distinguishable from zero, though disturbances such as drainage and conversion to forestry or crop production can lead to increased N_2O emissions (Beyer and Höper, 2015; Frolking et al., 2011; Mustamo et al., 2016). During restoration of disturbed peatlands, water levels may fluctuate more than is typical in undisturbed peatlands (Holden et al., 2011; Price, 1997; Taylor and Price, 2015), potentially increasing N_2O emissions by generating conditions suitable for the production of N_2O by ammonia-oxidizing and denitrifying organisms (Andersen et al., 2013; Firestone et al., 1980; Richardson et al., 2009). However, to our knowledge, N_2O emissions from restored peatlands in Canada have yet to be quantified.

N_2O is a potent greenhouse gas, with a CO_2-equivalence of 298 over a 100-year time horizon (IPCC, 2007) and accounts for a large fraction of the total GHG exchange of some ecosystems (Tian et al., 2012). In terrestrial ecosystems, N_2O is produced through ammonia oxidation, also known as nitrification, and through denitrification, which is also the only biological sink for N_2O, as the final step is the reduction of N_2O to N_2 (Firestone and Davidson, 1989). Most ammonia oxidizing bacteria are active only under aerobic conditions, while denitrification occurs under anaerobic conditions; complete denitrification including the final reduction of N_2O to N_2 typically occurs only under conditions in which most other electron acceptors including O_2, Fe^{3+}, and $SO_4{}^{2-}$ are depleted or absent (Achtnich et al., 1995; Firestone and Davidson, 1989; Firestone et al., 1980; Gutknecht et al., 2006). As a result, reducing conditions generated by water-saturated soils often result in N_2O production that shifts to consumption only after redox conditions within the soil are further reduced by either biological activity such as respiration or abiotic processes that remove or block the entry of O_2 and other materials (Schipper et al., 1993); net production of N_2O may be maximized at intermediate or fluctuating water levels (Jungkunst et al., 2008). Ammonia oxidation is inhibited by low pH, thus most N_2O production in acidic bogs is likely to be from denitrification (Allison and Prosser, 1993; Maljanen et al., 2003).

In addition, in restored peatlands, increased microbial activity driven by the growth and presence of the roots of vascular plants leads to increased rates of peat mineralization and greater availability of nitrogen (Kuzyakov and Xu, 2013) in forms microorganisms may convert to N_2O through either ammonia oxidation or denitrification (Conrad, 1996; Gutknecht et al., 2006). However, the role of vascular plants in N_2O emissions from restored peatlands has not been broadly investigated outside of Europe (Maljanen et al., 2012; Nykänen et al., 1995; Vanselow-Algan et al., 2015), and has not been previously measured in Canada. The primary objective of this study was to examine the effect of vascular plant colonization on net N_2O emissions of a restored, cutover peatland where the long-term goal of the restoration is a *Sphagnum*-dominated bog. We hypothesized that areas on a recently-restored peatland containing vascular plants would release lower amounts of N_2O to the atmosphere than comparable plots containing moss or bare peat without vascular plants, due to the ability of peatland vascular plants such as *E. vaginatum* to efficiently uptake mineral and organic N in soil (Gebauer et al., 1995; Silvan et al., 2005; Silvan et al., 2004). Furthermore, we hypothesized that high water levels in the wet part of the study site would decrease N_2O emissions by restricting oxygen-dependent ammonia-oxidation, the major source of N_2O in other wetlands with low nitrate available for denitrification (Bayley et al., 2005; Verhoeven et al., 1990).

2. Methods

2.1. Experimental site

Plots were established in two areas at a peat bog/fen complex near Seba Beach, Alberta, Canada (53° 27′ 17" N, 114° 52′ 50" W) where horticultural peat had been extracted, with restoration efforts commencing in late 2012. The site covers approximately 50 ha across a gradient of peat depth and a bog/fen transition. From 1995–2010 the mean annual temperature was 3.5 °C, with an average temperature of −11.3 °C in January to 16.5 °C in July, and an annual total precipitation average of 550 mm, of which approximately 125 mm falls as snow (Environment Canada, 2016); the nearest reporting station is at Entwistle, Alberta, approximately 18 km northwest of the site. Extraction and restoration activities levelled the surface and peat depth now ranges from approximately 100–350 cm across the study area. Restoration activity in winter and spring 2013 included blocking and completely refilling ditches, leading to higher water levels to support the growth of transplanted materials collected in a nearby, undisturbed, ombrotrophic, treed bog following the moss layer transfer technique (Graf et al., 2012; Rochefort et al., 2003). After two full growing seasons, this site featured nearly complete vegetation cover in most areas, with a clear water level gradient from a wet area in the centre to drier areas near the margins.

Plots consisting of steel collars 60 × 60 cm and adjacent pore water samplers, water-level wells and associated boardwalk were constructed in May 2015. Water-level wells consisted of a 150 cm long PVC plastic pipe with holes drilled approximately every 2 cm to allow water level in the pipe to equilibrate with soil water level; the outside of each well was covered with nylon mesh and the pipe was inserted into a 1 m deep hole excavated with a hand auger.

Plots were established in pairs with at most 2 m between the members of each pair, with one plot encompassing either one large individual *E. vaginatum* tussock or several smaller tussocks covering more than 50% of the area of the plot, and the other plot containing no vascular plants at the time of establishment; each pair was considered a replicate for statistical analysis. Four pairs of plots were established near the middle of the field, in an area with some standing water and saturated surface peat we desig-