Science of the Total Environment 647 (2019) 169–181

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Impacts of drainage, restoration and warming on boreal wetland greenhouse gas fluxes

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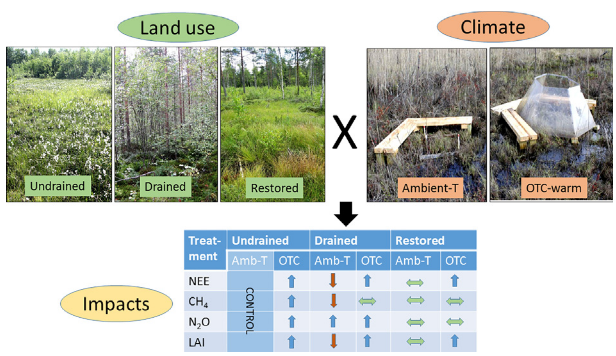
HIGHLIGHTS

- Land use had a clear impact of on CO_2 exchange.
- Forestry drainage increased respiration, decreased CO_2 uptake and leaf area.
- No differences in leaf area or any gas flux components between restored and undrained sites
- Warming increased leaf area and CO_2 uptake across all land use types.
- Gas fluxes were primarily controlled by water table, leaf area and temperature.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 May 2018
Received in revised form 25 July 2018
Accepted 27 July 2018
Available online 31 July 2018

Editor: Elena PAOLETTI

Keywords:
Forestry drainage
Greenhouse gas
Land use
Peatland
Restoration
Open top chamber

ABSTRACT

Northern wetlands with organic soil i.e., mires are significant carbon storages. This key ecosystem service may be threatened by anthropogenic activities and climate change, yet we still lack a consensus on how these major changes affects their carbon sink capacities. We studied how forestry drainage and restoration combined with experimental warming, impacts greenhouse gas fluxes of wetlands with peat. We measured CO_2 and CH_4 during two and N_2O fluxes during one growing season using the chamber method.

Gas fluxes were primarily controlled by water table, leaf area and temperature. Land use had a clear impact of on CO_2 exchange. Forestry drainage increased respiration rates and decreased field layer net ecosystem CO_2 uptake (NEE) and leaf area index (LAI), while at restoration sites the flux rates and LAI had recovered to the level of undrained sites. CH_4 emissions were exceptionally low at all sites during our study years due to natural drought, but still somewhat lower at drained compared to undrained sites. Moderate warming triggered an increase in LAI across all land use types. This was accompanied by an increase in cumulative seasonal NEE. Restoration appeared to be an effective tool to return the ecosystem functions of these wetlands as we found no differences in LAI or any gas flux components (PMAX, Reco, NEE, CH_4 or N_2O) between restored and undrained sites. We did not find any signs that moderate warming would compromise the return of the ecosystem functions related to C sequestration.

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https://doi.org/10.1016/j.scitotenv.2018.07.390

1. Introduction

Northern wetlands with organic soil i.e., mires have accumulated a large quantity of peat, accounting for some 30% of global soil carbon (e.g. Yu, 2012). In general, mires have had a small net cooling effect on climate over the Holocene (Frolking and Roulet, 2007). Although most undisturbed mires currently act as CO_2 sinks (e.g. Lund et al., 2010) and CH_4 sources (e.g. Lai, 2009) to the atmosphere, it is highly uncertain whether mires have a positive or negative feedback in response to global change (Meng et al., 2016). Moreover, this ecosystem function (i.e., carbon sequestration) that mires provide is sensitive to climate variability (Turetsky et al., 2008) and land use change (Ojanen et al., 2013; Renou-Wilson et al., 2014). Utilization of mires for food or timber production usually requires drainage, as the shallow aerobic surface layer of undrained mires is inadequate to support profitable timber or crop growth (Paavilainen and Päivänen, 1995). Altogether 30 Mha of non-tropical and 20 Mha of tropical mires have been disturbed by human activities (Joosten, 2010), and of this, approximately half has been drained for forestry (Paavilainen and Päivänen, 1995; Miettinen et al., 2016). Forestry drainage causes a regime shift from open mires towards forests as it alters the hydrology, increases the aeration of peat and redirects the vegetation succession towards forest species (Laine et al., 1995; Vompersky and Sirin, 1997; Mälson et al., 2008). Drainage increases decomposition and therefore CO_2 efflux, while CH_4 emissions usually decrease. In most cases, the increased respiration rates are not exceeded by increased productivity and therefore drained mires functions as C sources and have a climate warming impact (Maljanen et al., 2010; Ojanen et al., 2013; Renou-Wilson et al., 2014; Jauhiainen et al., 2016). There are indicators that some nutrient poor forestry drained mires may continue to act as carbon sinks, however (e.g. Lohila et al., 2011; Ojanen et al., 2013; Hommeltenberg et al., 2014; Ojanen et al., unpublished data). In addition to CO_2 and CH_4, nitrous oxide is a strong potent GHG. Generally, N_2O emissions from pristine mires are low and insignificant, but may increase significantly after drainage, especially with more nutrient rich conditions (Regina et al., 1996; Ojanen et al., 2010; Pearson et al., 2015).

Ecological restoration aims to assist the recovery of an ecosystem that has been degraded, damaged, or destroyed (Hobbs and Cramer, 2008) and recent global and national policies (EU Biodiversity Strategy to 2020; Aichi Biodiversity Targets, 2011) regard restoration as a crucial means to safeguard biodiversity. Mire restoration has also been promoted as a key climate mitigation tool (e.g. Bonn et al., 2014), and as a means to decrease a country's greenhouse gas (GHG) emissions (IPCC, 2013). At the same time, carbon markets have been identified as possible funding sources for mire restoration schemes (Bonn et al., 2014). However, data on GHG fluxes from restored mires, especially from those restored after drainage for forestry, are very limited.

The principal restoration methods for forestry drained boreal mires are the blocking of ditches to re-create the high water table level, and the removal of excess trees to reduce the transpiration rate and reinstate the landscape typical of natural mires (e.g., Tarvainen et al., 2013). Most research on mire restoration has concentrated on the restoration of peat harvesting areas, which presents quite a different starting point for restoration compared to forestry drainage (Chimner et al., 2017). The few existing studies on C gas fluxes or carbon accumulation rates on restored peat harvesting areas (e.g. Tuittila et al., 1999; Waddington et al., 2010; Strack and Zuback, 2013; Wilson et al., 2016) and forestry drained mires (Komulainen et al., 1998, 1999; Urbanová et al., 2012; Kareksela et al., 2015; Koskinen et al., 2016) indicate that the rising water table increases the rate of field layer photosynthesis, decreases CO_2 efflux and increases CH_4 emissions, thereby partially or fully restoring natural mire functions.

Projected global warming in northern latitudes (IPCC, 2013) is going to have its own impact on mire GHG exchange. Experimental warming studies on mires have been carried out with increasing frequency since 2000 (e.g. Wiedermann et al., 2007; Turetsky et al., 2008; Dorrepaal et al., 2009; Chivers et al., 2009; Johnson et al., 2013; Ward et al., 2013; Munir and Strack, 2014; Pearson et al., 2015; Peltoniemi et al., 2016; Voigt et al., 2017; Gill et al., 2017; Mäkiranta et al., 2018). These studies, which mostly use open top chambers (OTC's), have shown varied responses of vegetation, microbial communities and gas fluxes to warming within a few years' study periods. In most cases warming has increased respiration, but the impact on photosynthesis and methane emissions has been context dependent and strongly influenced by species composition and water table level: under wet conditions these fluxes may increase, while, under dry conditions and lower water table, in most cases, photosynthesis and methane emissions either decrease or remain unchanged (Turetsky et al., 2008; Dorrepaal et al., 2009; Ward et al., 2013; Munir and Strack, 2014; Pearson et al., 2015; Peltoniemi et al., 2016; Gill et al., 2017; Voigt et al., 2017). Denitrification and consequently N_2O fluxes have high temperature sensitivity (Butterbach-Bahl et al., 2013) due to which warming should increase N_2O emissions. This far there have been only a few studies including warming impacts on N_2O emission, and in these, either no changes (Ward et al., 2013; Pearson et al., 2015) or increased emissions (Voigt et al., 2017) have been observed. Further, how warming impacts GHG exchange under different land uses (drainage/restoration) has not been documented in mires thus far.

Our aim is to quantify how forestry drainage and restoration impact GHG dynamics and whether the effects of moderate warming differ between the land uses. To tease out the direct impact of warming we measured CO_2, CH_4 and N_2O fluxes, and leaf area development at six wetlands with peat or primary mires (sensu Joosten et al., 2017) over two growing seasons. Primary mires are successionally young wetlands that, under suitable climatic conditions, will develop into deep peat mires (Tuittila et al., 2013; Joosten et al., 2017) and they are known to rapidly respond to climatic variation (Laitinen et al., 2008; Leppälä et al., 2011a). Four of the sites have experienced long-term water table drawdown due to ditching for forestry in the 1970s, while restoration of two of these sites in 2008 raised water table levels back to the same level as in the two undrained (control) sites (see Laine et al., 2016). Open top chambers (OTC) were used to warm the plots.

We hypothesized that 1) drainage increases CO_2 and N_2O release and decreases CH_4 emissions in comparison to undrained sites. 2) Restoration returns ecosystem functions back to the level of undrained sites rapidly (<5 years); this means that the restored sites are CO_2 sinks, CH_4 emitters and have very low N_2O emissions. 3) Warming promotes ecosystem respiration but the response of photosynthesis and methane emissions depends on the prevailing hydrology; under undrained and restored conditions warming increases photosynthesis and methane emissions, but under drained conditions these functions remain unchanged. 4) Warming promotes N_2O emissions.

2. Material and methods

2.1. Study area

The study was carried out on the Finnish coast of the Gulf of Bothnia in Siikajoki (drained and restored sites: ~64°48′93 N, 24°37′39E; undrained sites: 64°46′91 N, 24°38′65E). We selected six primary mires belonging to three land use categories: two undrained (UD1, UD2), two forestry drained in 1970's (D1, D2), and two drained (1970's) sites restored in 2008 (R1, R2). The drainage of site D2 had not resulted in effective regime shift towards forested ecosystem, and the water table was clearly higher than at D1 (see Laine et al., 2016). Restoration was carried out by felling most trees so that ~0–5 trees were left per 100 m^2, and blocking ditches with soil excavated near the ditches. The sites have been formed in the coast following post-glacial land uplift approximately 100–200 years ago (Ekman, 1996). They are located