Soil Biology and Biochemistry 122 (2018) 186–195

Contents lists available at ScienceDirect

Soil Biology and Biochemistry

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

Factors controlling nitrous oxide emissions from managed northern peat soils with low carbon to nitrogen ratio

Maarit Liimatainen[a,*], Carolina Voigt[a], Pertti J. Martikainen[a], Jyrki Hytönen[b], Kristiina Regina[c], Hlynur Óskarsson[d], Marja Maljanen[a]

[a] University of Eastern Finland, Department of Environmental and Biological Sciences, P.O. Box 1627, FI-70211 Kuopio, Finland
[b] Natural Resources Institute Finland (Luke), Natural Resources, Teknologiakatu 7, FI-67100 Kokkola, Finland
[c] Natural Resources Institute Finland (Luke), Bioeconomy and Environment, Tietotie 4, FI-31600 Jokioinen, Finland
[d] Agricultural University of Iceland, Faculty of Agricultural and Environmental Sciences, 311 Hvanneyri, Iceland

ARTICLE INFO

Keywords:
N_2O
Drained peatlands
Land-use
Phosphorus
Copper
C/N ratio

ABSTRACT

Managed northern peatlands are an important source of the strong greenhouse gas nitrous oxide (N_2O). However, N_2O emissions from these managed peatlands display a high spatial variability, and processes governing N_2O production and emissions from these ecosystems are still not well understood. To constrain the factors regulating N_2O emissions from managed northern peat soils, we determined a wide set of soil physical and chemical properties of peatlands with different management histories spread across Finland, Sweden and Iceland. We included eleven peatland sites with available *in situ* N_2O flux data, and complemented our analyses with detailed measurements of soil nitrogen (N) cycling processes such as N_2O production, gross N mineralization and gross nitrification and, in addition, soil microbial biomass. This study included drained peatlands with different land-use types and management intensities, comprising forested, cultivated or only drained peatlands and afforested or abandoned agricultural peatlands. All selected peatland sites displayed a low soil carbon to nitrogen (C/N) ratio of 15–27, traditionally used to predict high N_2O emissions. Despite the narrow C/N range, the N_2O emissions at our sites varied greatly within and between land-use groups, ranging from 0.03 to 2.38 g N m^{-2} y^{-1}. Thus, our findings provide valuable insights into the regulatory factors underlying the variability in N_2O emissions and show that a low C/N ratio in managed peatlands cannot be used to predict high N_2O emissions. Instead, our results demonstrate that higher N_2O emissions are linked to higher peat phosphorus (P) and copper (Cu) content, suggesting that low P and Cu concentrations can limit N_2O production in peat even with sufficient N availability. While known factors such as soil moisture, oxygen content and the degree of peat humification partially explained the variability in N_2O emissions, this study directly links soil P and Cu availability to N_2O production processes. The availability of P and especially Cu seemed to promote nitrification activities, thereby increasing N_2O production. Our study highlights the link between N_2O emissions and soil P and Cu availability and the strong coupling of the soil N and P cycles in peatlands, which is to date severely understudied.

1. Introduction

Nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) are important greenhouse gases. The global warming potential of N_2O is 265 times greater than that of CO_2 and almost ten times greater than that of CH_4 (100-year time horizon; Myhre et al., 2013). With increasing application of nitrogen (N) fertilizers, the tropospheric N_2O concentration is rising (Canfield et al., 2010; Davidson, 2012; Vitousek et al., 1997). While N_2O is stable in the troposphere, in the stratosphere N_2O participates in reactions destroying the ozone layer (Ravishankara et al., 2009). The main natural N_2O sources are terrestrial ecosystems where N_2O is produced by soil microbial processes. From all anthropogenic N_2O sources, including biomass burning and fossil fuels, agriculture is the most important (Fowler et al., 2009). Anthropogenic N_2O emissions contribute with 30–45% to the total N_2O emissions (IPCC, 2013), and over 80% of the anthropogenic emissions are derived from agriculture (Davidson, 2012).

Peatlands cover only 3% of the Earth's surface, but they store one third of the global organic carbon pool (Köchy et al., 2015; Strack, 2008). Among managed Northern soils, drained peatlands are one of

* Corresponding author.
E-mail address: maarit.liimatainen@uef.fi (M. Liimatainen).

https://doi.org/10.1016/j.soilbio.2018.04.006
Received 27 November 2017; Received in revised form 4 April 2018; Accepted 6 April 2018

Table 1
The study sites and their soil characteristics: degree of peat humification (*H*), C/N ratio, N_2O flux, water table level (WT), field bulk density (BD) and soil phosphorus (P) concentration. L1 refers to the surface layer of 0–10 cm and L2 to the deeper layer of 10–20 cm. The first letter of the site code refers to land-use type: F = forest, C = cultivated, A = afforested field, D = drained but not used for agriculture or forestry, B = abandoned field. The letter in subscript defines the site. The N_2O values are annual averages and in all cases ± denotes standard deviation.

Land-use	Site	Location	Country	Soil sampling	*H**		C/N ratio		N_2O flux	WT	BD	P (mg kg^{-1})	
					L1	L2	L1	L2	(g N m^{-2} y^{-1})	(cm)	0-20 cm	L1	L2
Forests	F_S	63°54′N, 23°56′E	Finland	18/06/2012	7–8	8	23 ± 0.0	22 ± 0.4	1.43 ± 0.59[a]	−41[a]	0.20[a]	943	1260
	F_J	63°52′N, 23°44′E	Finland	18/07/2011	6–7	7–8	19 ± 0.1	18 ± 0.1	0.07 ± 0.03[a]	−36[a]	0.17[a]	861	1340
Cultivated fields	C_S	63°54′N, 23°56′E	Finland	22/09/2011	8–9	8–9	17 ± 0.0	17 ± 0.0	2.38 ± 1.49[b]	−60[b]	0.22[b]	3280	3060
	C_I	64°34′N, 21°46′W	Iceland	12/07/2011	7–8	7–8	15 ± 0.1	16 ± 0.1	0.03[c]		0.23[g]	1660	964
	C_K	60°54′N, 23°31′E	Finland	23/04/2012	9	9	23 ± 0.2	22 ± 0.1	0.73 ± 0.12[d]	−82[d]	0.48[h]	1470	1560
Afforested fields	A_L	64°06′N, 24°21′E	Finland	23/08/2011	7	7–8	17 ± 0.1	18 ± 0.2	2.14 ± 0.60[e]	−52[e]	0.25[e]	2870	1760
	A_R	64°06′N, 24°21′E	Finland	23/08/2011	8–9	8–9	24 ± 0.2	27 ± 0.1	0.07 ± 0.07[e]	−25[e]	0.25[e]	1640	1190
	A_G	58°23′N, 12°09′E	Sweden	09/05/2011	7–8	9–10	25 ± 0.2	27 ± 0.0	0.26 ± 0.08[f]	−80[f]	0.20[i]	1000	862
Drained	D_I	64°34′N, 21°46′W	Iceland	12/07/2011	5–6	6–7	15 ± 0.0	16 ± 0.1	0.04[c]		0.34[g]	956	801
Abandoned fields	B_A	63°54′N, 23°56′E	Finland	25/04/2012	8–9	8–9	20 ± 0.2	23 ± 0.0	0.41 ± 0.17[e]	−35[e]	0.30[e]	1460	1270
	B_B	63°54′N, 23°56′E	Finland	25/04/2012	9–10	9–10	25 ± 0.5	26 ± 1.3	1.42 ± 0.68[e]	−51[e]	0.42[e]	944	1010

* Degree of humification was estimated according to von Post (1922).
[a]Maljanen et al. (2014), [b]Maljanen et al. (2009), [c]Maljanen et al. (2010a,b), [d]Regina et al. (2004), [e]Maljanen et al. (2012), [f]Klemedtsson et al. (2010), [g]Hlynur Óskarsson; personal communication, [h]Lohila et al. (2003), [i]Björk et al. (2010).

the largest emitters of N_2O (Maljanen et al., 2010a) due to their high N stocks and high N mineralization rates, which are the key for the high N_2O production in these soils (Strack, 2008). In the Northern latitudes, most of the peatlands are located in Russia, Canada, USA and the Nordic countries of Europe. Agricultural use, forestry, and peat extraction require drainage of peatlands, but the extent of drainage varies. In most countries agriculture is the main use of peatlands (Strack, 2008). In Finland, however, only 1% of peatlands are currently used for agriculture (Myllys and Sinkkonen, 2004), whereas over half of the peatlands have been drained for forestry (Strack, 2008).

Nitrous oxide is produced by soil microbial processes, especially during nitrification and denitrification (Butterbach-Bahl et al., 2013). During ammonium oxidation N_2O can be produced through two pathways, either as a by-product in the first step of nitrification or during nitrifier denitrification (De Boer and Kowalchuk, 2001; Wrage et al., 2001). During denitrification, nitrate (NO_3^-) is reduced to N_2O by facultative anaerobic bacteria, which can be further reduced to N_2, depending on the environmental conditions such as pH (Šimek and Cooper, 2002) and oxygen (O_2) status (Khalil et al., 2004). Although nitrification and denitrification are the main known processes for N_2O production in soils, other less well studied processes can also produce N_2O in soils (Butterbach-Bahl et al., 2013).

Natural peatlands display negligible N_2O emissions and can even act as net sinks for N_2O. After drainage, however, when the peat is exposed to O_2, N_2O emissions can increase strongly (Martikainen et al., 1993; Regina et al., 1996). Exposure to O_2 accelerates organic matter (OM) decomposition and N mineralization, as well as nitrification. After drainage, the increase in N_2O emissions is higher in nutrient rich than in nutrient poor peatlands. Cultivated peat soils, which are generally rich in nutrients due to fertilization, show the highest N_2O emissions among drained peatlands (Kasimir-Klemedtsson et al., 1997; Maljanen et al., 2010a). Although only 10% (250 000 ha) of the total cropland area in Finland is on peat soils, N_2O emissions from cultivated peat soils account for 43% of N_2O emissions from agricultural soils (Statistics Finland, 2017). Nitrous oxide emissions from cultivated peatlands are generally 5–20 times higher than those from peatland forests (Martikainen et al., 1993; Kasimir-Klemedtsson et al., 1997). Yet, while N_2O emissions from peatland forests are often negligible (Ojanen et al., 2010), some peatland forests display N_2O emissions that are nearly as high as those from cultivated peat soils (Maljanen et al., 2010a, 2010b).

Drainage and associated lowering of the water table is a key factor enhancing N_2O emissions from peatlands (Martikainen et al., 1993). Therefore, regulating the water table level in managed peatlands is suggested to be the most efficient way to mitigate N_2O emissions (e.g. Regina et al., 2015). The soil C/N ratio is often used to predict the magnitude of N_2O emissions, which are generally highest in drained peatlands with a low (< 30) C/N ratio (Klemedtsson et al., 2005; Leppelt et al., 2014; Maljanen et al., 2010a). In drained peatland forests N_2O emissions have been shown to decrease straightforwardly with increasing C/N ratio (Klemedtsson et al., 2005). However, over the wide variety of land-use types and management practices in northern peatlands and other organic soils, N_2O emissions display a high spatial and temporal variability (Leppelt et al., 2014; Maljanen et al., 2010a; Tiemeyer et al., 2016): even within the narrow C/N range of 15–30, which is considered the optimum range for high N_2O production and emissions, N_2O fluxes vary greatly.

The aim of this study was to identify factors explaining the high variability in N_2O fluxes from managed northern peatlands within this narrow C/N range, where N_2O production is clearly not limited by N availability. We selected eleven sites with available year-round *in situ* N_2O flux data and a low (< 27) C/N ratio. The selected sites were managed peatlands under different land-use, and were spread across Finland, Sweden and Iceland. We determined a wide set of peat physical-chemical characteristics, including trace elements and macronutrients, for two soil layers, 0–10 and 10–20 cm, of each site. We complemented these soil analyses with a detailed array of process-based measurements related to N-cycling, including N_2O production (both layers), gross N mineralization (10–20 cm) and gross nitrification (10–20 cm), as well as soil microbial biomass C (10–20 cm). The aim of our study was to investigate whether these soil physical, chemical, and biological parameters provide new insights for predicting N_2O emissions from managed peatlands that cannot be fully explained by the C/N ratio.

2. Materials and methods

2.1. Study sites

The site selection was based on the data availability of annual N_2O emissions, including wintertime emissions, since a major part of the