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Tree stand volume as a scalar for methane fluxes in forestry-drained peatlands in Finland

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Forestry drainage is a method used extensively to grow timber in peat soils in Finland. Following drainage, the developing tree stand influences methane (CH_4) emissions by altering plant and microbial communities through water-level drawdown, competition for nutrients and shading. Therefore there should be a close correlation between tree stand volume and CH_4 fluxes in drained peatlands. We used previously published material along with data collected in this research programme to assess the potential of tree stand volume as a tool for estimating CH_4 fluxes for drained peatland forests, and to quantify this relationship under conditions prevailing in Finland. There was a clear negative exponential relationship between tree stand volumes and CH_4 emissions. Sites with small stand volume emitted CH_4 after drainage (up to 4 g CH_4 m^{-2} a^{-1}), while larger stands consumed it (up to 1 g CH_4 m^{-2} a^{-1}); the turning point from source to sink was about 140 m^3 ha^{-1}. Similar relationships were also found for undrained mires, although not as clearly as for the drained sites. Since drained peatland forests in Finland are generally rather young in drainage age and small in stand volumes, they are still estimated to emit CH_4 to the atmosphere, although the rate has substantially decreased after drainage.

Introduction

Forestry drainage is a method used extensively to grow timber in peat soils in Finland. Over 5.4 million ha of peatland were drained for forestry purposes during the 20th century, and 4.9 million ha of the present forest land area is currently classified as drained peatland (Finnish Forest Research Institute 2004).

Following drainage and consequent growth of the tree stand, a secondary succession occurs in the ground vegetation (Laine and Vanha-Majamaa 1992, Laine *et al*. 1995), during which the species composition and biomass relations between different vegetation layers change (Laiho *et al*. 2003). The dominance of shrubs and forest mosses increase while that of sedges and Sphagna decrease.

The developing tree stand decreases the light availability for the ground vegetation and keeps the water-table level down through increased transpiration and decreased throughfall. This also affects the biological processes in the peat soil, e.g. the microbial community structures associated with production (Galand *et al*. 2005) and oxidation (Jaatinen *et al*. 2005) of methane (CH_4)

change, and consequently the emissions of CH_4 decrease (Glenn *et al.* 1993, Roulet *et al.* 1993, Martikainen *et al.* 1995, Roulet and Moore 1995, Minkkinen *et al.* 1997, Nykänen *et al.* 1998).

Mire vegetation suffers from dry conditions, and deep-rooted vascular sedge species important as CH_4 conduits (e.g., Joabsson *et al.* 1999) are among the first to disappear (Laine *et al.* 1995). The longer the post-drainage period and the higher the nutrient level in the soil, the larger the tree stand volume (e.g., Keltikangas *et al.* 1986) and the smaller the amount of remaining deep-rooted sedges (Laine *et al.* 1995).

The developing tree stand affects the processes behind the CH_4 emissions by altering the conditions for plant and microbial communities through water-level drawdown, competition for nutrients and shading. Thus, a close correlation may be expected between tree stand and CH_4 fluxes in drained peatlands.

The impact of forestry drainage on CH_4 emissions has been studied mainly in Fennoscandian countries (Nykänen *et al.* 1998, Alm *et al.* 1999, von Arnold *et al.* 2005a, 2005b) and Canada (Roulet *et al.* 1993, Roulet and Moore 1995, Schiller and Hastie 1996) where such silvicultural treatments have been implemented. The decrease in emissions has been explained by water-level drawdown and vegetation change. Such variables are, however, not routinely measured/available in national forest inventories, and are thus not applicable for upscaling purposes. In contrast, tree stand volume along with site type are generally available for upscaling to the national level in Finland. The aim of the present study was (1) to assess the potential of tree stand volume (along with site type) as a tool for estimating CH_4 fluxes for drained peatland forests, and (2) to quantify this relationship under the conditions prevailing in Finland.

Material and methods

Previously published and unpublished data col-

Table 1. A general description of the material used in the study. Negative CH_4 flux values indicate CH_4 consumption.

Site name (ref.)	Coordinates	Elevation (m .a.s.l)	Site types[3]	Drainage year	Number of plots	Stand volume (m^{-3} ha^{-1})	CH_4 flux (g m^{-2} a^{-1})
Drained sites							
Loppi, Kalevansuo	60°39´N, 24°22´E	123	Vatkg	1971	1	115	–0.3
Vesijako, pine site	61°22´N, 25°07´E	115	Ptkg	1915	3	164–203	–0.82 to –0.56
Vesijako, spruce sites	61°24´N, 25°02´E	115	Mtkg–Rhtkg	1905–1918	5	159–289	–0.73 to –0.15
Lakkasuo[1]	61°48´N, 24°19´E	150	Jätkg–Mtkg	1961	4	20–95	–0.22 to 3.24
Lakkasuo[2]	61°48´N, 24°19´E	150	Jätkg–Mtkg	1961	7	13–108	–0.015 to 3.47
Mekrijärvi[2]	62°46´N, 30°58´E	145	Jätkg–Mtkg	1950	3	5–120	–0.24 to 0.99
Kivalo	66°21´N, 26°37´E	180	Mtkg	1933	1	136	–0.03
Kolpene	66°28´N, 25°51´E	79	Mtkg	1959	2	143–195	0.62 to 0.69
Undrained sites							
Lakkasuo[1]	61°48´N, 24°19´E	150	RaTR–RhRiN	–	3	0–5	2.1 to 6.5
Lakkasuo[2]	61°48´N, 24°19´E	150	LkN–RhRiN	–	7	0–52	1.98 to 31.04
Mekrijärvi[2]	62°46´N, 30°58´E	145	KeR–RhRiN	–	7	0–20	0.64 to 38.48
Kivalo	66°20´N, 26°36´E	177–267	RaR–RhSN	–	6	1–5	1.93 to 24.08
Imari	66°29´N, 25°29´E	104	TSR–KR	–	3	5–60	0.43 to 9.46
Kolpene	66°28´N, 25°51´E	79	VSR–RhK	–	4	5–112	2.23 to 21.51
Vesijako, spruce sites	61°24´N, 25°02´E	115	MK–RhK	–	2	163–228	–0.34 to 0.61

[1] Minkkinen & Laine 2006, [2] Nykänen *et al.* 1998

[3] Drained sites: Rhtkg = herb-rich type; Mtkg = *Vaccinium myrtillus* type; Ptkg = *Vaccinium vitis-idaea* type; Vatkg = dwarf shrub type; Jätkg = *Cladina* type. Undrained sites: RaTR = cottongrass pine bog with *Sphagnum fuscum* hummocs, RhRiN = herb rich flark fen, LkN = Low-sedge bog, KeR = ridge-hollow pine bog, RaR = *Sphagnum fuscum* bog, TSR = cottongrass-sedge pine fen, KR = spruce-pine swamp, VSR = tall-sedge pine fen, RhK = herb-rich hardwood-spruce swamp, MK = *Vaccinium myrtillus* spruce swamp.

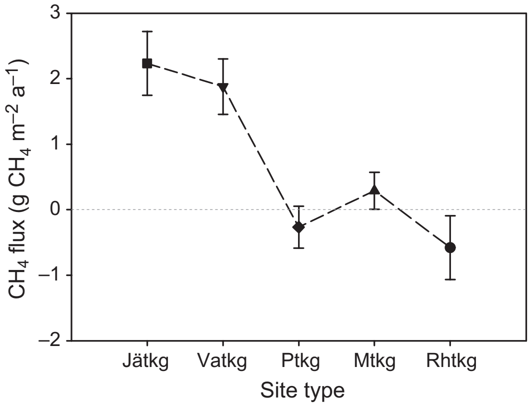

Fig. 1. Average CH_4 fluxes in different site types in forestry drained peatlands. Values are least-square estimates from a linear model; CH_4 flux = constant + site type + *e*. For site-type descriptions *see* Table 1.

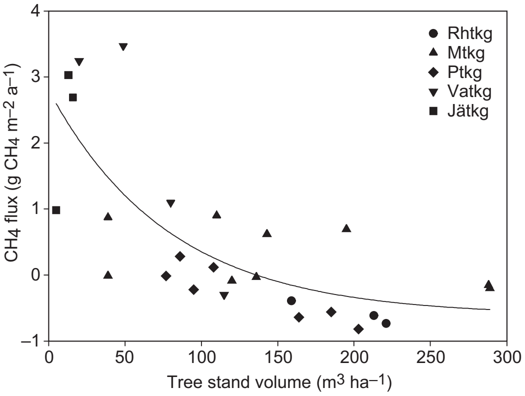

Fig. 2. Regression ($CH_4 = y_0 + ae^{-bV}$) between the tree stand volume (V, m^3 ha^{-1}) and the annual methane emission (g CH_4 m^{-2} a^{-1}) in peatlands drained for forestry. Parameter estimates, mean (± a.s.e): $y_0 = -0.613$ (± 0.551), $a = 3.419$ (± 0.617), $b = 0.0126$ (± 0.0067), $r^2 = 0.58$. For site-type descriptions *see* Table 1.

lected during this research programme (Greenhouse impact of the use of peat and peatlands in Finland) on CH_4 fluxes in forestry-drained peatlands were gathered (Table 1). The variables included were site type, tree stand volume and annual CH_4 emission. The information on tree stand volume was not available in any studies conducted outside Finland and pertains only to Finland. For comparison, data from natural mire sites were also collected if available from the same sources. The material gathered covered the variability in site-type fertility and climatic conditions, from the poorest bogs to the most fertile spruce swamps and from southern Finland to Lapland (Table 1). The drained site types were classified according to Laine (1989).

The CH_4 fluxes were measured using the closed chamber technique (for method descriptions *see* Alm *et al.* (2007)). The independent variable is the annual CH_4 flux between soil and the atmosphere (g CH_4 m^{-2} a^{-1}) and includes varying amounts of spatial and temporal variation averaged to one number. In other words, in all studies this variable is based on several individual measurements in space and time: typically at least three measurement spots over 1–2 years. Depending on the study, the flux estimate is either integrated from measurements or modelled using regression technique (Table 1). Since these flux estimates were regarded as independent observations, ordinary linear and nonlinear regression methods (Systat 10, SPSS Inc., USA) were used to model the effect of tree stand volume and site type on the annual CH_4 flux.

To estimate the CH_4 emissions from the land base of drained peatlands in the whole of Finland, the area of drained peatlands was divided into 12 classes according to stand volume (< 15, 15–45, 45–75, ..., 275–315 and > 315 m^3 ha^{-1}), data for which was obtained from the 9th Finnish National Forest Inventory. The regression model was then run for each class, using the mean stand volume of each class as a driving variable. Finally the class-wise fluxes were weighted by the area and summed up.

Results

The annual CH_4 fluxes in the forestry-drained peatlands were small, varying between –1 and +4 g CH_4 m^{-2} a^{-1}. Notable emissions were found only on the poorest site types (*Cladina* and dwarf shrub types) where the post-drainage tree stand growth had been very weak, or the stands were only recently drained. A linear model with site type as the only explanatory variable explained 62% of the variation in fluxes among the five site types (Fig. 1).

There was a clear negative relationship between tree stand volumes and CH_4 emissions (Fig. 2). The exponential relationship fitted to the data explained 58% of the variation. Peatlands

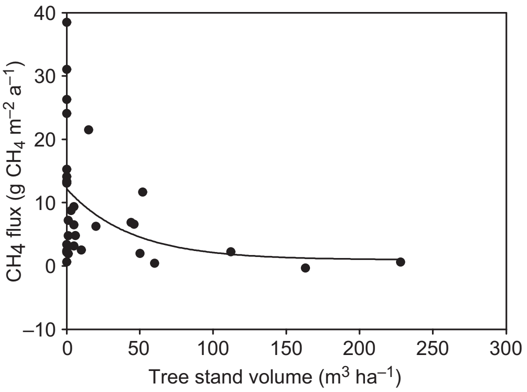

Fig. 3. Regression ($CH_4 = y_0 + ae^{-bV}$) between the tree stand volume (V, m^3 ha^{-1}) and the annual methane emission (g CH_4 m^{-2} a^{-1}) in undrained mires. Notice the 10-fold scale in *y*-axis compared with that in Fig. 2. Parameter estimates, mean (± a.s.e): y_0 = 0.290 (± 9.031), a = 11.7613 (± 9.024), b = 0.0166 (± 0.029), r^2 = 0.12.

with smaller tree stands (young or nutrient-poor drainage areas) emitted CH_4 after drainage, while stands with larger volumes consumed CH_4; according to the model the switch from positive to negative flux is about 140 m^3 ha^{-1}. Similar relationships were also detected within individual site types (Fig. 2). Together these variables (site type and tree stand volume) explained 73% of the variation in ((CH_4 flux + 1)$^{0.5}$-transformed) CH_4 fluxes (Table 2).

A similar relationship between stand volume and CH_4 flux was also found in the data for undrained mires, although not as clearly as for the drained sites (Fig. 3). The data consisted mainly of sites with very sparse and small tree stands. Among these sites wide variation in nutrient and water levels and vegetation structures is commonly found. It can be noted, however, that even natural mires with the largest tree stands (usually spruce swamps) emitted only small amounts of CH_4 or were even net consumers (Fig. 3).

Table 2. Variance analysis of ((CH_4 flux + 1)$^{0.5}$-transformed) CH_4 emissions. r^2 = 0.73.

Source	SS	df	MS	*F* ratio	*p*
Site type	1.3566	4	0.3391	4.3712	0.0106
Tree stand volume	0.5237	1	0.5327	6.7502	0.0172
Error	1.5517	20	0.0776		

Upscaling of the methane effluxes according to the distribution of drained peatland area by stand volume class resulted in an aggregate estimate of 0.048 Tg CH_4 a^{-1} , i.e. 1.1 Tg CO_2 eq. (using the 100-year CH_4/CO_2 GWP-factor 23) from Finnish drained peatland forests.

Discussion

The CH_4 emissions from drained peatlands are small compared with those from natural mires. Consumption of CH_4 begins after drainage in those sites with higher nutrient levels, whereas poor sites remain small CH_4 sources. This phenomenon is related to two factors: (1) drying of the peat soil, and (2) the succession of vegetation and microbial communities. These factors are connected with tree stand development, including increased tree stand transpiration and interception, and with the increased shading and competition for nutrients by tree stands. Thus, the site nutrient level, which largely determines post-drainage stand growth (Keltikangas *et al.* 1986), is also closely connected with the post-drainage CH_4 fluxes.

The objective of forestry drainage is to produce timber that will be removed in fellings. This reduces evapotranspiration by removing the transpiring tree stand, with a consequent rise in the water-table level (Päivänen 1980, Dubé *et al.* 1995), creating conditions more favourable for CH_4 production. Water level rise is, however, generally so small and brief that no notable changes in CH_4 fluxes after fellings have been detected (Huttunen *et al.* 2003, Minkkinen *et al.* 2004). Thus, if sufficient drainage is retained, during the following tree-stand rotations the sites in active production forestry will most probably continue acting as CH_4 sinks, regardless of the prevailing tree stand volume.

CH_4 flux is the end result of CH_4 production and oxidation in the peat. Many process-based models exist that use the primary (or near-primary) factors in explaining these processes (soil moisture or water level, soil temperature, vegetation composition, plant leaf area) in soil (e.g., Kettunen 2003). These factors are, however, not extensively measured and process-based models are not generally applicable for upscaling to larger areas. In contrast, high-quality information is available on tree stand volumes in various upland and peatland soil site types throughout Finland (Finnish Forest Research Institute 2004). Thus, regression models based on tree stand and/or site type as described here, may be useful tools for upscaling information from individual measurements to the national level. Since the forestry-drained area is large, even small fluxes may have national importance in greenhouse gas inventories.

It has been estimated (Hökkä *et al.* 2002, Minkkinen *et al.* 2002) that 10%–30% of forestry drainage has been undertaken in areas too poor for forest production. Drained forests are also still rather young, since most of them were drained in the late 1960s and 1970s. For these reasons the proportion of low-stocked tree stands in drained peatland forests is still rather high; according to the results from the latest National Forest Inventory (NFI9), the mean stand volume in drained peatland stands in Finland was only 81 m^3 ha^{-1}. The methane efflux estimated for drained peatlands in Finland using the regression model constructed in this study resulted in a somewhat smaller aggregated estimate than earlier estimate (Minkkinen *et al.* 2002) calculated using site-type models and distributions. Although well-growing stands with high volumes mainly act as CH_4 sinks, we conclude that in general, especially when possible emissions from ditches (Minkkinen *et al.* 1997, Minkkinen & Laine 2006) are included, drained peatland forests in Finland still emit CH_4 to the atmosphere.

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