

The dependence of net soil CO₂ emissions on water table depth in boreal peatlands drained for forestry

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SUMMARY

The aim of this study was to build regression models between mean water table depth (WTD, cm) and net soil CO₂ emissions (g m⁻² year⁻¹) using data from boreal peatlands drained for forestry. We found that net soil CO₂ emissions increased linearly with increasing WTD to depths of approximately 60 cm. The regression equations differed between nutrient rich (n = 33) and nutrient poor (n = 39) study sites: net soil CO₂ emissions = -115 + 12 × WTD (nutrient rich); net soil CO₂ emissions = -259 + 6 × WTD (nutrient poor). These regressions can be used to estimate changes in CO₂ emissions associated with changes in forest management practices.

KEY WORDS: carbon dioxide, drainage, forestry, greenhouse gas emission, peat loss

INTRODUCTION

Globally, greenhouse gas emissions from drained peat soils are very large. Leifeld & Menichetti (2018) estimate these emissions at 1.9 Gt of CO₂ equivalents per year. For comparison, Olivier *et al.* (2017) estimate total emissions from land use at 4.1 Gt of CO₂ equivalents per year. Even though emissions from peat soils are likely to be poorly represented in this estimate, it is evident that drained peat soils, covering only 50 million ha (Leifeld & Menichetti 2018), are emissions hotspots. Emissions from peat soils are important, especially in countries with large areas of drained peatlands. In Finland, for example, emissions of 18 Mt of CO₂ equivalents per year are reported for drained peat soils, which amounts to over one third of the emissions from energy production and industry (Statistics Finland 2019).

Peatlands are effective carbon stores due to anoxic soil conditions caused by the water table being close to the soil surface. Drainage of peatlands and lowering of the water table leads to more oxic soil conditions, which in turn stimulate peat decomposition (Silvola *et al.* 1996, Couwenberg *et al.* 2010, Jauhiainen *et al.* 2012). Linear increases in net soil CO₂ emissions (see **METHODS** for a formal definition) with increases in water table depth have been found in temperate (Couwenberg *et al.* 2011, Tiemeyer *et al.* 2016) and subtropical and tropical (Couwenberg *et al.* 2010; Hooijer *et al.* 2010, 2012) drained peatlands. As the reported increase is higher for subtropical and tropical peatlands than for temperate peatlands, and because net soil CO₂ emissions in general vary between land uses and climate zones (Wilson *et al.* 2016), land use and climate zone specific studies are needed.

In this article we present regressions between net soil CO₂ emissions and water table depth for nutrient rich and nutrient poor boreal peatlands drained for forestry. Such regressions have not been previously published, even though available data are plentiful and previous research shows that water table depth is an important factor affecting these emissions (Ojanen *et al.* 2013, 2019; Korhonen *et al.* 2018, Minkkinen *et al.* 2018). The regression models presented here are based on combining all the available published data.

To mitigate climate change, ways to reduce greenhouse gas emissions are needed. One option is to raise water tables in drained peat soils. To understand the effect of raising water table on net soil CO₂ emissions, it is necessary to know how emissions vary with water table depth. Therefore, relationships such as those established here can be useful in targeting management efforts. An additional motivation for our work is that water table depth is much easier to measure than CO₂ emissions. Thus, if a strong relationship can be established between emissions and water table depth, the latter could serve as a proxy for upscaling emissions estimates in, for example, national greenhouse gas inventories.

METHODS

The regressions presented here are based on estimates of annual net soil CO₂ emissions (NE_{CO₂soil}, g m⁻² year⁻¹) at 76 sites drained for forestry. The sites were used for forestry at the time of the measurements and they lie within the south and middle boreal vegetation zones in Finland (Figure 1, Table A1 in the Appendix). At most of the study sites

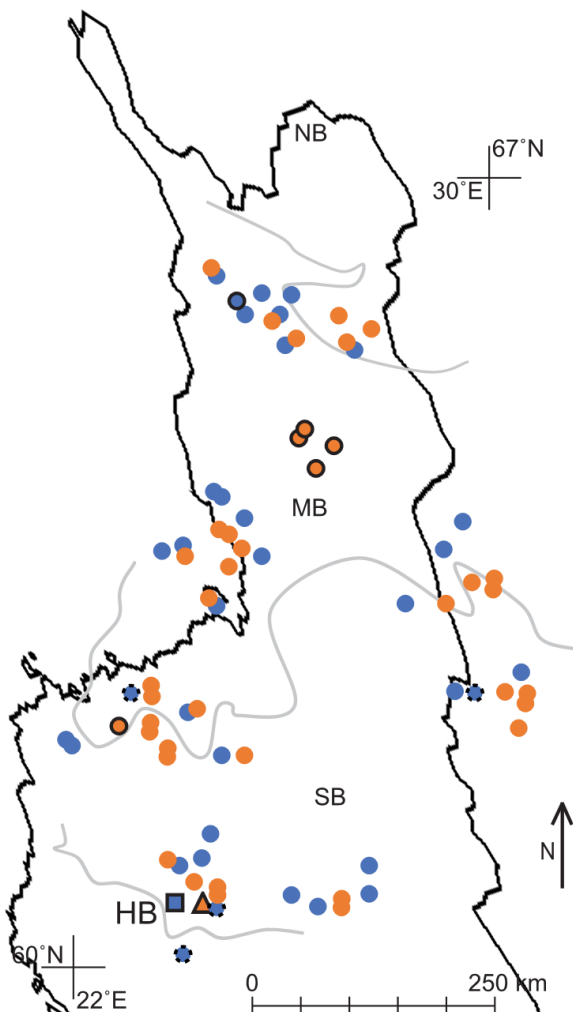


Figure 1. Study sites divided into nutrient rich (blue) and nutrient poor (orange) categories: Ojanen *et al.* (2013) (no border; those excluded from regression with dotted black border), Ojanen *et al.* 2019 (black border), Minkkinen *et al.* (2018) (triangle with black border), Korhonen *et al.* (2018) (square with black border). Grey lines denote the boundaries of vegetation zones (Ahti *et al.* 1968): HB, hemiboreal; SB, south boreal; MB, middle boreal; NB, north boreal.

(Ojanen *et al.* 2013, $n = 68$; and control plots of a fertilisation study by Ojanen *et al.* 2019, $n = 6$), NE_{CO_2soil} is estimated from heterotrophic soil respiration (R_{het}) and total litter production (L):

$$NE_{CO_2soil} = R_{het} - L. \quad [1]$$

R_{het} was measured by infrared gas analyser (EGM-4, PP-Systems, USA) with an opaque closed chamber (modified SRC-1, diameter 31.5 cm, effective height 14.9 cm, PP-systems, USA) biweekly to monthly over two consecutive snow and frost free seasons. R_{het} was annualised by applying nonlinear regressions between R_{het} and soil temperature at 5 cm depth, which was logged year-around (iButton DS1921G, Maxim Integrated, USA). A galvanised steel cylinder was inserted into the soil before the measurements started, to sever tree roots and to prevent their regrowth at the measurement points. In addition, living parts of the ground vegetation were removed in order to include only heterotrophic respiration (Ojanen *et al.* 2013, 2019).

L included aboveground (litter traps over two years) and belowground (biomass from belowground biomass samples \times turnover rate) litter production from trees and aboveground (biomass from aboveground biomass samples \times turnover rate) and belowground (biomass from belowground biomass samples \times turnover rate) litter production from ground vegetation (Ojanen *et al.* 2013, 2019).

In addition, two sites with eddy covariance and tree stand measurements (Korhonen *et al.* 2018, Minkkinen *et al.* 2018) were included. At those sites, soil NE_{CO_2soil} is estimated on the basis of net ecosystem exchange (NEE) and tree stand biomass increment per unit area and per unit time ($\Delta\text{biom}_{trees}$):

$$NE_{CO_2soil} = NEE + \Delta\text{biom}_{trees}. \quad [2]$$

NEE was measured by eddy covariance from a mast above the tree canopy over four to six consecutive years. $\Delta\text{biom}_{trees}$ was calculated as the difference of two consecutive tree stand biomass estimates derived by applying tree stand measurements and biomass models (Korhonen *et al.* 2018, Minkkinen *et al.* 2018).

The water table depths (WTD, cm below soil surface) in the data are arithmetic means for the snow and frost free season (May–October). They were measured manually, in dipwells constructed from perforated plastic tubes, each time R_{het} was measured.

The sites (Figure 1) were divided into two groups: “nutrient rich” ($n = 37$), consisting of meso- and eutrophic sites (herb-rich and *Vaccinium myrtillus* L. site types in the Finnish classification, Laine *et al.* 2012), and “nutrient poor” ($n = 39$), consisting of oligo- and ombrotrophic sites (*Vaccinium vitis-idaea* L., dwarf-shrub and *Cladina* site types). This division corresponds to that of the IPCC Wetlands Supplement (Hiraishi *et al.* 2014) and divides the sites into high- and low-emission categories.

The models were fitted using the lm function of the R programming language (RDocumentation 2019). The 95 % confidence bands for the regression lines shown in Figure 2 were calculated on the basis of parameter variances and their covariance (available in Table 1).

RESULTS

Mean NE_{CO₂soil} (±standard error) was +240±70 g m⁻² year⁻¹ for the nutrient rich sites and -70±30 g m⁻² year⁻¹ for the nutrient poor sites. Statistically significant linear regressions were fitted for both nutrient rich and nutrient poor sites, between WTD (cm) and NE_{CO₂soil} (g m⁻² year⁻¹ of CO₂) (Table 1, Figure 2):

nutrient rich: $NE_{CO_2soil} = -115 + 12 \times WTD$ [3]

nutrient poor: $NE_{CO_2soil} = -259 + 6 \times WTD$ [4]

The data were quite evenly distributed within the WTD range of 0–60 cm, and the regressions could be reliably estimated for that range (Figure 2). Among the nutrient rich sites, there were also four scattered

Table 1. Parameters (intercept, slope), their variances (var), significances (p) and covariance (cov) and water table depth range (WTD), residual variance, coefficient of determination (r²) and number of observations (n) for the linear regressions between mean May–October water table depth (cm from soil surface) and soil CO₂ net emission (g m⁻² year⁻¹) at nutrient rich and nutrient poor forestry-drained boreal peatlands (Equations 1 and 2).

model	nutrient rich	nutrient poor
intercept	-115	-259
var(intercept)	19280	5856
p(intercept)	0.4	0.002
slope	12	6
var(slope)	18	6
p(slope)	0.008	0.01
cov(slope, intercept)	-532	-166
WTD	1–55	7–58
residual var	122376	36487
r ²	0.21	0.16
n	33	39

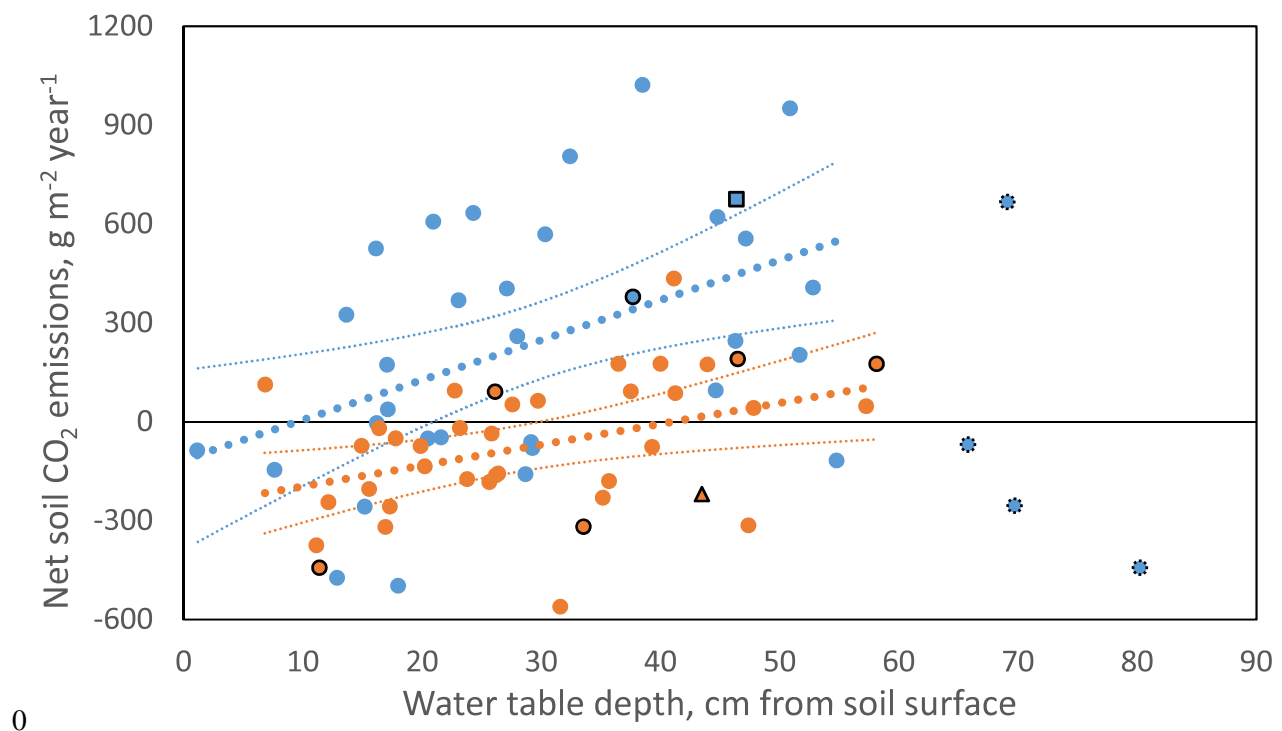


Figure 2. Linear regression, with 95 % confidence band, between mean May–October water table depth and annual soil net CO₂ emissions at nutrient rich (blue) and nutrient poor (orange) forestry-drained boreal peatlands. Data: Ojanen *et al.* (2013) (no border; those excluded from regression with dotted black border), Ojanen *et al.* (2019) (black border), Minkkinen *et al.* (2018) (triangle with black border), Korkiakoski *et al.* (2018) (square with black border). Positive values indicate emissions and negative values indicate removals.

data points at WTD greater than 60 cm. These were excluded from the regression, as they were too few to predict any reliable regression for that range. Random error for NE_{CO₂soil} of a single study site is high (Ojanen *et al.* 2012), meaning that fitting a regression on just a handful of sites is not justified. Also, it seems that emissions did not increase by the same slope beyond WTD = 60 cm.

DISCUSSION

Our findings are in line with those from temperate peatlands drained for agriculture (Couwenberg *et al.* 2011, Tiemeyer *et al.* 2016): net soil CO₂ emissions increase linearly with WTD until it reaches values of 50–60 cm, beyond which the increase seems to cease. Somewhat similarly, Mäkiranta *et al.* (2009) found that heterotrophic soil respiration at a boreal forestry-drained peatland decreased when WTD reached and exceeded 70 cm; i.e., the direction of the relationship changed. Possible explanations for this phenomenon are that drying of the peat surface might suppress decomposition in cases of very deep drainage, or that oxygen is depleted from the soil pore space before it can reach the deepest layers. On the other hand, increases in net soil CO₂ emissions for WTD of at least 100 cm have been found in tropical and subtropical drained peatlands (Hooijer *et al.* 2012).

The slope of the WTD regression for boreal forestry-drained peatlands fitted in this study is twice as high for nutrient rich sites as for nutrient poor sites. These slopes are also an order of magnitude lower than that for temperate peatlands drained for agriculture (~80 g m⁻² year⁻¹ increase in CO₂ emission per 1 cm increase in WTD; Couwenberg *et al.* 2011, Tiemeyer *et al.* 2016). Similarly, Wilson *et al.* (2016) found that net soil CO₂ emissions at undrained and rewetted peatlands were twice as sensitive to increases in WTD in temperate than in boreal climates.

The likely explanation for variation of the slope between climate zones and land uses is that, in addition to its sensitivity to (i) oxygen availability controlled by WTD, aerobic decomposition is sensitive to (ii) temperature (e.g. Lloyd & Taylor 1994) and (iii) the decomposability of organic matter (e.g. Tuomi *et al.* 2009). The rate of decomposition is determined as an interaction of these three factors. The temperature sensitivity leads to higher emissions in warmer climate zones. The decomposability differentiates site types and land-uses from each other. It is higher at nutrient rich than at nutrient poor forestry-drained peatlands due to higher nutrient availability and pH and higher share of easily

decomposable herbaceous plant litter in organic matter at the nutrient rich peatlands (Laiho 2006; Straková *et al.* 2010, 2011). In agriculture, repeated liming and fertilisation raise the decomposability of peat compared to forestry.

The regressions fitted in this study could be used to estimate the potential benefits of avoided net soil CO₂ emissions from improved forestry practices. For example, ditch cleaning, and the consequent CO₂ emissions, could often be avoided if practising continuous cover forestry instead of clear-cut based management (Nieminen *et al.* 2018). Typically, ditch cleaning increases WTD by ~5 cm (Ahti & Päivänen 1997, Sarkkola *et al.* 2010), and this effect lasts for about 20 years. Assuming an initial increase in WTD of 5 cm and a linear decrease to 0 cm in 20 years gives total net soil CO₂ emissions of 6.3 t ha⁻¹ at nutrient rich sites and 3.2 t ha⁻¹ at nutrient poor sites during the 20 years following ditch cleaning.

If the ditches in the 1.8 million ha of nutrient rich and 2.5 million ha of nutrient poor peatland forests in Finland (Korhonen *et al.* 2017) were not cleaned (instead of cleaning every 30 years), the avoided emission would be 0.64 Mt CO₂ per year. This is 24 % of the net soil CO₂ emissions, assuming the mean emissions for nutrient rich and nutrient poor sites of this study.

There are basically two alternatives for reducing greenhouse gas emissions from drained peat soils. Either management practices should be improved to keep the water table as high as possible, or the soils should be rewetted to reinstate the greenhouse gas dynamics of undrained peatlands (Wilson *et al.* 2016). Our results provide a basis for evaluating what CO₂ emission reductions can be achieved through improved management practices at boreal peatlands drained for forestry.

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Appendix

Table A1. Study sites, their coordinates (ETRS89/WGS84), site types (Laine *et al.* 2012), trophic levels, mean May–October water table depth in cm (WT), soil CO₂ net emissions (g m⁻² year⁻¹) (CO₂) and data sources. Key to site types: Rhtkg = Herb-rich type, Mtkg = *Vaccinium myrtillus* type, Ptkg = *Vaccinium vitis-idaea* type, Vatkg = Dwarf shrub type, Jätkg = *Cladina* type. These data are also provided in Excel format, as supplementary material.

Site	N	E	Site type	Trophic level	WT	CO ₂	Source
115104	60.5436	26.4321	Rhtkg	meso-eutrophy	38	1022	Ojanen <i>et al.</i> 2013
173504	60.9435	24.0628	Rhtkg	meso-eutrophy	51	951	Ojanen <i>et al.</i> 2013
213703	61.2329	24.3339	Rhtkg	meso-eutrophy	16	526	Ojanen <i>et al.</i> 2013
331901	62.0043	21.5140	Rhtkg	meso-eutrophy	22	-47	Ojanen <i>et al.</i> 2013
397502	62.5128	30.1228	Rhtkg	meso-eutrophy	29	-61	Ojanen <i>et al.</i> 2013
516101	63.4020	27.9771	Rhtkg	meso-eutrophy	21	-50	Ojanen <i>et al.</i> 2013
573304	63.8028	23.4439	Rhtkg	meso-eutrophy	18	-498	Ojanen <i>et al.</i> 2013
653704	64.3908	24.0315	Rhtkg	meso-eutrophy	15	-258	Ojanen <i>et al.</i> 2013
834711	65.7605	25.6870	Rhtkg	meso-eutrophy	14	325	Ojanen <i>et al.</i> 2013
864101	65.9629	24.6206	Rhtkg	meso-eutrophy	29	-80	Ojanen <i>et al.</i> 2013
Könölä	65.9628	24.4933	Rhtkg	meso-eutrophy	38	378	Ojanen <i>et al.</i> 2019
53304	60.0765	23.8527	Mtkg	mesotrophy	69	666	Ojanen <i>et al.</i> 2013
133701	60.6520	24.3821	Mtkg	mesotrophy	70	-254	Ojanen <i>et al.</i> 2013
134704	60.6834	25.8440	Mtkg	mesotrophy	32	805	Ojanen <i>et al.</i> 2013
135704	60.6880	27.3080	Mtkg	mesotrophy	13	-474	Ojanen <i>et al.</i> 2013
173302	60.9296	23.7688	Mtkg	mesotrophy	45	96	Ojanen <i>et al.</i> 2013
175704	60.9752	27.3108	Mtkg	mesotrophy	47	556	Ojanen <i>et al.</i> 2013
313903	61.9557	24.5761	Mtkg	mesotrophy	45	621	Ojanen <i>et al.</i> 2013
331902	62.0079	21.5134	Mtkg	mesotrophy	21	607	Ojanen <i>et al.</i> 2013
373501	62.3663	23.9238	Mtkg	mesotrophy	55	-117	Ojanen <i>et al.</i> 2013
392702	62.4805	22.6702	Mtkg	mesotrophy	80	-443	Ojanen <i>et al.</i> 2013
396902	62.5305	29.1916	Mtkg	mesotrophy	46	246	Ojanen <i>et al.</i> 2013
397103	62.5289	29.5026	Mtkg	mesotrophy	66	-70	Ojanen <i>et al.</i> 2013
417703	62.6524	30.4499	Mtkg	mesotrophy	52	203	Ojanen <i>et al.</i> 2013
513702	63.3802	24.1366	Mtkg	mesotrophy	28	260	Ojanen <i>et al.</i> 2013
573101	63.7838	23.1212	Mtkg	mesotrophy	23	369	Ojanen <i>et al.</i> 2013
574301	63.8231	25.0670	Mtkg	mesotrophy	53	408	Ojanen <i>et al.</i> 2013
576701	63.8226	28.9666	Mtkg	mesotrophy	29	-160	Ojanen <i>et al.</i> 2013
614101	64.1053	24.7192	Mtkg	mesotrophy	24	633	Ojanen <i>et al.</i> 2013
616903	64.1118	29.3155	Mtkg	mesotrophy	17	37	Ojanen <i>et al.</i> 2013
653702	64.3836	24.0325	Mtkg	mesotrophy	17	173	Ojanen <i>et al.</i> 2013
835503	65.7088	27.0180	Mtkg	mesotrophy	8	-145	Ojanen <i>et al.</i> 2013
864501	65.9722	25.3242	Mtkg	mesotrophy	16	-5	Ojanen <i>et al.</i> 2013
894302	66.1885	24.9546	Mtkg	mesotrophy	30	569	Ojanen <i>et al.</i> 2013
894702	66.1962	25.6636	Mtkg	mesotrophy	1	-87	Ojanen <i>et al.</i> 2013

Site	N	E	Site type	Trophic level	WT	CO ₂	Source
923703	66.3911	23.8637	Mtkg	mesotrophy	27	404	Ojanen <i>et al.</i> 2013
Lettosuo	60.6420	23.9593	Mtkg	mesotrophy	46	675	Korkiakoski <i>et al.</i> 2018
115302	60.5373	26.7237	Ptkg	oligotrophy	26	-157	Ojanen <i>et al.</i> 2013
115303	60.5409	26.7236	Ptkg	oligotrophy	11	-375	Ojanen <i>et al.</i> 2013
153504	60.8000	24.0764	Ptkg	oligotrophy	57	47	Ojanen <i>et al.</i> 2013
314103	61.9607	24.8808	Ptkg	oligotrophy	39	-77	Ojanen <i>et al.</i> 2013
352901	62.1998	23.0184	Ptkg	oligotrophy	12	-244	Ojanen <i>et al.</i> 2013
357701	62.2153	30.3998	Ptkg	oligotrophy	36	176	Ojanen <i>et al.</i> 2013
373502	62.3700	23.9241	Ptkg	oligotrophy	32	-561	Ojanen <i>et al.</i> 2013
392903	62.4934	22.9792	Ptkg	oligotrophy	26	-183	Ojanen <i>et al.</i> 2013
392904	62.4969	22.9787	Ptkg	oligotrophy	26	-162	Ojanen <i>et al.</i> 2013
397703	62.5091	30.4333	Ptkg	oligotrophy	48	42	Ojanen <i>et al.</i> 2013
513701	63.3767	24.1370	Ptkg	oligotrophy	17	-319	Ojanen <i>et al.</i> 2013
516704	63.4031	28.9378	Ptkg	oligotrophy	20	-135	Ojanen <i>et al.</i> 2013
537102	63.5291	29.5899	Ptkg	oligotrophy	47	-314	Ojanen <i>et al.</i> 2013
537301	63.5194	29.9106	Ptkg	oligotrophy	35	-230	Ojanen <i>et al.</i> 2013
573301	63.7922	23.4452	Ptkg	oligotrophy	41	434	Ojanen <i>et al.</i> 2013
593904	63.9670	24.4036	Ptkg	oligotrophy	41	87	Ojanen <i>et al.</i> 2013
834712	65.7659	25.6867	Ptkg	oligotrophy	18	-51	Ojanen <i>et al.</i> 2013
835513	65.7769	27.0836	Ptkg	oligotrophy	7	113	Ojanen <i>et al.</i> 2013
855702	65.8483	27.3684	Ptkg	oligotrophy	23	-19	Ojanen <i>et al.</i> 2013
864502	65.9777	25.3237	Ptkg	oligotrophy	17	-258	Ojanen <i>et al.</i> 2013
133702	60.6556	24.3818	Vatkg	ombro-oligotrophy	24	-174	Ojanen <i>et al.</i> 2013
133704	60.6628	24.3812	Vatkg	ombro-oligotrophy	16	-20	Ojanen <i>et al.</i> 2013
173303	60.9331	23.7681	Vatkg	ombro-oligotrophy	40	176	Ojanen <i>et al.</i> 2013
313102	61.9253	23.3592	Vatkg	ombro-oligotrophy	20	-73	Ojanen <i>et al.</i> 2013
313104	61.9325	23.3583	Vatkg	ombro-oligotrophy	23	94	Ojanen <i>et al.</i> 2013
352903	62.2069	23.0174	Vatkg	ombro-oligotrophy	26	-36	Ojanen <i>et al.</i> 2013
397702	62.5056	30.4328	Vatkg	ombro-oligotrophy	36	-180	Ojanen <i>et al.</i> 2013
537304	63.5300	29.9118	Vatkg	ombro-oligotrophy	28	52	Ojanen <i>et al.</i> 2013
553901	63.6695	24.4308	Vatkg	ombro-oligotrophy	37	93	Ojanen <i>et al.</i> 2013
574104	63.8291	24.7415	Vatkg	ombro-oligotrophy	30	63	Ojanen <i>et al.</i> 2013
593901	63.9564	24.4044	Vatkg	ombro-oligotrophy	44	174	Ojanen <i>et al.</i> 2013
865302	65.9866	26.7321	Vatkg	ombro-oligotrophy	16	-204	Ojanen <i>et al.</i> 2013
923702	66.3857	23.8643	Vatkg	ombro-oligotrophy	15	-73	Ojanen <i>et al.</i> 2013
Jylkky	64.8828	26.1011	Vatkg	ombro-oligotrophy	26	90	Ojanen <i>et al.</i> 2019
Kalevansuo	60.6475	24.3578	Vatkg	ombro-oligotrophy	44	-220	Minkkinen <i>et al.</i> 2018
Leppiniemi	64.8483	26.0585	Vatkg	ombro-oligotrophy	47	190	Ojanen <i>et al.</i> 2019
Pelso	64.4929	26.3060	Vatkg	ombro-oligotrophy	58	175	Ojanen <i>et al.</i> 2019
Lylynneva	62.1733	22.8105	Jätkg	ombrotrophy	11	-443	Ojanen <i>et al.</i> 2019
Rantasuo	64.7888	26.4992	Jätkg	ombrotrophy	34	-319	Ojanen <i>et al.</i> 2019