Reviewer #1:

General comments of the reviewer, author response below

Evaluation of the Interactive effects of plant functional groups and water table on CH4 fluxes in a boreal fen is exciting research and could confirm our understanding of the controls on CH4 fluxes in fen peatlands. Similar assessment studies have been conducted after the study years of 2001-2004. One of strengths of research is that the emissions are partitioned based on vegetation components. This manuscript is concise and written very well with clarity and supports most of the earlier and later similar studies in discussion section. Introduction covers relevant literature and provides clear objectives that are achieved in results and aligned with conclusions. The paper merits publication once improved as per comments.

The study results confirm many reported findings that water table level is the dominant control on CH4 fluxes, with vegetation components affect fluxes only under natural (or higher) water table level conditions. On the other hand, authors conclude that results are relevant for evaluating peatland CH4 flux responses to changing climatic conditions. I believe authors could interpret the study conclusions carefully. To my analysis, these results are relevant for fen peatland (higher water table level) CH4 fluxes only. The results may not be applicable to bog peatland where water table level (in most cases) is deeper than Lakkasuo study fen (natural site) where mean CH4 fluxes decreased to zero (0.03 ± 0.03 CH4 m-2 month-1) after water table drawdown; Therefore authors may project the results relevancy to fen peatlands responding to changing climatic conditions. I notice that authors missed a significant opportunity of developing CH4 emission factor for upscaling emissions for similar fen peatlands. The emission factors could be beneficial in reporting national or IPCC level CH4 emissions. Authors could look at Alm et al. 2007, Couwenberg and Fritz 2012, Levy et al. 2012 (GCB), Wilson et al. 2016, Strack et al. 2017 and few peatland CH4 studies from Western Canada.

Study sites - Was the study site divided into two (wet or natural, and drier or WLD) in 2001 or 2002? It is given how far apart (radially) the two sites were, specifically, how far was the ditch from the wet site? Additionally, being the peatland complex (eccentric), did the authors verified if the two sites were similar in water table level and vegetation composition? These types of field investigations require additional (necessary) work so that the results obtained are solid.

Was the ditch draining to some larger ditch/drain? Authors need to extend and clarify on sites, their chemistry and manipulation

It would be methodologically challenging to create secluded vegetation removal treatments even after using paraffin wax, for example:

• In PS, sedge stubbles/roots could still mediate fluxes

• I believe that removal leaves underground roots/rhizomes, a large amount of substrate, which could result in undesirable data

The authors need to explain how these problems were resolved. Based on earlier findings (for example, Conrad 2009, Hanson et al. 2000), they could support their removal treatments with several justifications – Lignin or associated polysaccharides are not but simpler carbohydrates or photosynthates are the dominant substrates. Clipping or removal disrupts the photosynthates movement to roots, which may not support dominant substrate-dependent CH4 production. The explanations could also help discuss the water level × vegetation component interaction for CH4 fluxes

The underlying mechanisms of CH4 production/release are established; however, authors need to briefly mention in the discussion to help the reader learn or refresh their understanding. The authors need to add some discussion (or sub-heading) on the water table level – vegetation interaction.

We thank the reviewer for the positive overall statement about our manuscript and the comments that helped us to improve our manuscript.

First, we have now specified in the Abstract and Conclusions that our results are applicable for fen peatlands. Second, we have added the suggested CH_4 emission factor calculation, please see L178-179 and L229-230.

The description of the study site and experimental design have now been modified so that all requested information should be more easily found in the text, including pH and more specific information about the water level manipulation (L100-101, L114-120).We would like to thank the reviewer for the interesting insights related to the vegetation manipulation used in this study. We have now added for example a new regression model describing the relationship between sedge leaf area and CH_4 flux (from L195 onwards) as well as extended the description of the methods (from L99 onwards). We would like to keep the original subheading “Water level regulates the role of the vegetation” in the discussion instead of mentioning interaction in the subheading. However, this section has now been extended to include discussion about the new regression model (L364-371).

We agree that after vegetation removal treatments the sedge stubble and roots could still act as conduits for CH_4, and the dead roots and rhizomes could provide substrate for methanogenesis. We have discussed these aspects in Discussion in the section “Delay in the plant removal treatment effect”. Based on the literature, and our own observation of stable fluxes and no more sedge regrowth, it seems that the substrate supply from the decaying roots and rhizomes was exhausted, and the aerenchymatous pathway disappeared, by the 3rd year of the vegetation manipulations. Our quantitative results on the contribution of the vegetation components to the fluxes is based on that year’s (2004) data.

We have also discussed the points mentioned by the reviewer of the tissues of high lignin content being less favoured substrate for methanogenesis and having a positive relationship with methane oxidation rates (L319-322), and that the photosynthates and fresh carbon compounds transported through the roots are the main substrate for methane production (L42-50).

Specific comments, author response indented below each specific comment

Line 13. The hyphen used here is inappropriate and could be replaced with a comma

Replaced as suggested.

Line 14. Which growing seasons?

Specified as suggested (L13).

Line 15. Insert “each of” after “of”

We thank for the comment but think the sentence is more concise without the addition.

I notice the use of super- or sub-scripts is inconsistent. Also, acronyms are not described in their first instances

Super- and sub-scripts as well as acronyms have now been checked throughout the text.

What could be the reasons the shrubs component attenuated the fluxes? References could be used for discussing ideas

We have added discussion on this matter in addition to the existing discussion from L285 onwards.

Line 22. What authors mean high here? Better say natural. Alternately, give how high?

Changed as suggested (L22).

Line 23. Change “in” with “to”

Changed as suggested (L23).

Line 24. Drawdown is a general term when mentioning climate change impacts; could be replaced with “deepening”

We understand the point of the reviewer, but would like to keep the word ‘drawdown’ here as it has been used widely in this context (e.g Strack et al. 2007, Freeman et al. 2012, Kokkonen et al. 2019).

Line 77. How the Lakkasuo peatland complex is an eccentric raised bog – a brief explanation would be helpful for the reader to understand how a nutrient-poor, oligotrophic fen existed within a bog.

We have specified the description on L95 and L100.

Line 81-87. Any visual/coverage estimates (numbers)?

Cover estimates have now been added as suggested (from L 102 onwards).

Line 100. I notice the use of spacing between a digit and a sign (- or +) is not consistent throughout the manuscript

These have now been checked.

Line 102. Additional dot

Corrected

Line 110. Length × Width

Specified as suggested (L139).

Line 124. Water table level

Based on literature this is an issue of personal taste and in here, and in most of the works by our group, we have decided to use term water level. We have now made sure throughout the manuscript that the use of the term is consistent.

Line 129. Any reference for species-specific Gaussian curves?

A reference has been now cited in the sentence (L157).

Line 153-154. I notice authors tested here WL and Veg differences and provide results later in the results section)

Line 238-241. Interesting to note that this study (2001-2004) compares results with earlier as well as later studies

We have tried to include the most relevant references.

Figure 3. Add significance letters

We have now added the letters.

Reviewer #2:

General comments of the reviewer, author response below

This manuscript presents results for methane (CH4) flux from a water table drawdown and vegetation removal study conducted in an oligotrophic fen. All plots were studied for one year prior to any treatments and then the effects of water table lowering and vegetation removal were studied for the following three growing seasons. The authors observed that water table drawdown greatly reduced CH4 flux. In the first two years after treatment, vegetation removal plots often had higher fluxes than intact plots. By year three, plots with removal of dwarf shrubs continued to have higher fluxes than intact plots while plots with removal of shrubs and sedges or shrubs, sedges and Sphagnum had lower fluxes. Differences between vegetation treatments were only significant under wet conditions and not when the water table was lowered.

Overall, this study adds to our understanding of the interactions between water table and the presence of plant functional types on peatland CH4 emissions. However, I do think that the authors could add to the introduction and data analysis to better highlight how this paper moves beyond what we already know based on many of the studies they reference in this manuscript. In particular, I suggest that the authors add specific objectives, and possibly hypotheses, to better highlight the knowledge gap they aim to fill and how their study is unique in doing this. I also suggest that they consider the specific role of sedges more explicitly, potentially with a regression analysis between CH4 flux and sedge LAI, with interaction with water table. Some additional minor suggestions and further details on these revisions are given below.

> We thank the reviewer for the valuable comments that helped us to significantly improve our manuscript. As suggested we objectives and hypothesis on L80 onwards to clarify the aim of our work, and those have now been added. Further, we added the requested regression analysis between CH_4 flux and sedge LAI and the interaction with water table. Please see the extended analysis explained from L195 onwards with results from L276 onwards.

Specific comments, author response indented below each specific comment

Abstract: Just check the superscripts on the CH4 units and correct where necessary

> These have now been checked and corrected where necessary.

Lines 27-28: Wetlands are the largest natural source of CH4, but much of this is from marshes, so I suggest adjusting this sentence. Also Saunois et al. 2016 is probably a better reference here than many that are given. Finally, I believe the correct reference for the first in the list is Mikaloff Fletcher et al. 2004, not Fletcher et al. 2004

> We clarified the sentence and added Saunois et al. 2016 as reference. We also removed some of the references, including Mikaloff Fletcher.

Line 27: Here you use CH4, but later go back to using methane. I suggest you actually define CH4 here (so say methane (CH4)) and then use CH4 throughout the remainder of the manuscript.

> We have now made the suggested changes.

Line 56: But what about trees? There is evidence they vent methane despite being shallow-rooted.

> It is true that trees have been found to transport notable quantities of methane in tropical peatlands, although to our knowledge such studies have not yet been published from boreal peatlands. Our site is an open fen, but it is worth mentioning in the introduction the potential role of trees in transporting methane. We have now modified L59-60.

Line 69: "Fewer the roots" can just be “Fewer roots”

> We have made the suggested change (L76).

Lines 72-74: The introduction ends rather abruptly here and left me fairly unexcited about the study. I suggest that the authors could do a better job of highlighting the specific gap they are addressing here. Maybe also adding specific objectives and hypotheses would also help to transition to the methods here.

We agree with the reviewer and have now added objectives and hypotheses addressing the specific gap.

Line 194: There are two sentence here. Add a period or a connecting word.

We made the suggested modifications.

Lines 199-200: Do you have data to show or a reference to another study to support this statement?

Please see the answer to the next comment.

Lines 199-209: The differences between the years and the link to effects of plant removal and then stabilization seem to be largely conjecture. I agree that this makes sense, but without data to directly support how subsurface inputs were varying, and since weather and WT also varied between the years, I feel that some of the statements in these paragraphs are too definitive. I like how the changing patterns of fluxes are described, but unless there are direct observations to support "stabilization" in 2004, I'd suggest keeping the treatment effects for the discussion.

We have now deleted the first sentence of both of these two paragraphs (L240 and L249) and kept only the information that can be clearly justified by the results of this study. The treatment artefacts and stabilization thereafter have now only been dealt with in the discussion.

Line 229: Did you look at this pattern when the mean at each plot is considered? Since you have taken an average of all the plots for each treatment, this is not too different than looking at differences between plant removal treatments (e.g., Figure 3). Since you have so many replicates for each treatment type, it would be really nice to see how this relationship looks if each plot is a point on the graph in Figure 4. This could also help to illustrate the effect of PSCD being lower than the pattern driven by the other plots, which is currently a tough sell with only 4 points on the line for each water table treatment.

This figure has now been redrawn according to the suggestions.

Lines 238-239: How did sedge cover differences in response to shrub removal affect the CH_4 flux patterns? It would actually be interesting in general to see whether there was a correlation between sedge cover and CH_4 flux when looking across all plots and whether there is an interaction with water table, particularly as this is alluded to in the introduction when reporting results of previous studies. I think this could be a really nice addition to the results and then could support this point made here.

We thank the reviewer for the suggestion and have now conducted the suggested analysis. The methods have been explained from L195 onwards with results from L276 onwards.

Lines 268-284: Do you have any information from other studies at this study site to support this section. Even data on root distribution of the different species would help add confidence to this discussion.

We added here (L344-345) two references to root biomass studies at the same peatland complex than in this study and a nearby bog (Mäkiranta et al. 2018 and Korrensalo et al. 2018).

Figure 2: I understand that the scale on the axes are kept the same on the top and bottom row of plots so that they can be easily compared, but since the effect of water table drawdown on CH4 flux is already clearly shown in Figure 1 and the goal of this figure is to highlight vegetation effects, I suggest altering the scale on the bottom row so that variation between vegetation treatments can be seen. Since the fluxes are quite low post-water table drawdown, nothing can really be seen in this figure the way it is currently drawn. I would just point out the difference in axes in the caption and possibly even direct the reader back to Figure 1 for a clear comparison of control vs. water table drawdown fluxes.

The figure has now been redrawn according to the suggestion.

Reference: Saunois M. et al. 2016. The global methane budget 2000 - 2012. Earth System Science Data, 8, 697-751.

Interacting effects of vegetation components and water ~~table~~ level on methane dynamics in a boreal fen

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Abstract. Vegetation and hydrology are important controlling factors in peatland methane dynamics. This study aimed at investigating the role of vegetation components, ~~–~~ sedges, dwarf-shrubs, and *Sphagnum* mosses, ~~–~~ in methane fluxes of a boreal fen under natural and experimental water level drawdown conditions. We measured the fluxes during ~~four~~ growing seasons 2001-2004 using static chamber technique in a field experiment where the role of the ecosystem components was assessed via plant removal treatments. The first year was a calibration year after which the water level drawdown and vegetation removal treatments were applied. Under natural water level conditions, plant-mediated fluxes comprised 68-78% of the mean growing season flux (1.73~~95~~ ± 0.17~~21~~ g CH_4 m^{-2} $month^{-1}$ from June to September), of which *Sphagnum* mosses and sedges accounted for 1/4 and 3/4, respectively. The presence of dwarf shrubs, on the other hand, had a slightly attenuating effect on the fluxes. In water level drawdown conditions, the mean flux was close to zero (0.03 ± 0.03 g CH_4 m^{-2} $month^{-1}$) and the presence / absence of the plant groups had a negligible effect. In conclusion, water level acted as a switch; only in ~~high~~ natural water level conditions vegetation regulated the net fluxes. The results are relevant for assessing the response of fen peatland fluxes ~~in~~ to changing climatic conditions, as water level drawdown and the consequent vegetation succession are the major projected impacts of climate change on northern peatlands.

Keywords: climate change, dwarf shrubs, methane, peatland, sedges, *Sphagnum*

1. Introduction

Approximately one-third of all terrestrial carbon is stored in boreal and subarctic peatlands (e.g. Yu, 2012)~~.~~ that ~~While~~ generally act~~ing~~ as CO_2 sinks in current climatic conditions. However, pristine wetlands, including peatlands, marshes and floodplains, are also the largest natural source of methane (CH_4) into the atmosphere ~~-~~ (Ciais et al., 2014; Kirschke et al., 2013; Saunois et al., 2016)~~(Bridgham et al., 2013; Ciais et al., 2014; Fletcher et al., 2004; Kirschke et al., 2013; Saunois et al., 2016)~~. The carbon sink function of peatlands is mostly due to the slow decomposition rate resulting

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from waterlogged, anaerobic conditions sustained by a high water~~ table~~ level, which simultaneously favour ~~methane~~ CH_4 production. ~~Methane~~ CH_4 is the end product of anaerobic decomposition by strictly anaerobic methanogenic archaea. It is released from the peat into the atmosphere via diffusion through the peat column, ebullition or plant-mediated transport (Lai, 2009). A considerable part, from 20 to up to 90% (Le Mer and Roger, 2001; Pearce and Clymo, 2001; Whalen, 2005) of the ~~methane~~ CH_4 diffusing through the upper, aerobic part of the peat layer is oxidized to CO_2 by methanotrophic bacteria (MOB) before reaching atmosphere.

Vegetation is a major factor controlling peatland ~~methane~~CH_4 fluxes (Koelbener et al., 2010; Ström et al., 2005, 2012). Fresh root litter and exudates are important substrates for the methanogenic microbes, and a significant proportion of the ~~methane~~CH_4 is formed from this easily available organic matter instead of from old, recalcitrant peat (Koelbener et al., 2010; Ström et al., 2012). Therefore, ~~methane~~CH_4 fluxes have a strong, positive correlation with the CO_2 uptake (Bellisario et al., 1999; Christensen et al., 2000; Rinne et al., 2018), since higher primary productivity leads to a higher input of substrate. Of the vegetation components, deep-rooting aerenchymatous species such as sedges (Cyperaceae) and aerenchymatous herbs are especially important (Leppälä et al., 2011; Ward et al., 2013). In sedge-dominated wetlands, most of the ~~methane~~CH_4 is released through vascular plants (Kelker and Chanton, 1997; Ding et al., 2004; Ström et al., 2005), thus bypassing the aerobic peat layer where ~~methane~~CH_4 oxidation takes place. On the other hand, oxygen transport through the aerenchyma to the rhizosphere may inhibit ~~methane~~CH_4 production (Whalen and Reeburgh, 2000; Fritz et al., 2011) and stimulate ~~methane~~CH_4 oxidation (King, 1994; Popp et al., 2000). The net effect of the presence of aerenchymatous species on ~~methane~~CH_4 fluxes is positive in most cases (Bellisario et al., 1999; Greenup et al., 2000; Rinnan et al., 2003; Couwenberg and Fritz, 2012; Ward et al., 2013), although opposite results have also been reported (Roura-Carol and Freeman, 1999; Strack et al., 2006). Although the influence of the non-aerenchymatous species on the fluxes has been studied relatively little, Gray et al. (2013) showed that plant functional groups based on more complex traits than those related to aerenchyma were good proxies of CH_4 flux. ~~Dwarf~~ In open boreal peatlands, the most abundant non-aerenchymatous vascular plant functional group is dwarf shrubs, that are generally shallow rooted (Korrensalo et al., 2018a) and have a negligible ~~methane~~CH_4 transport capacity (Shannon et al., 1996; Garnet et al., 2005) compared to deep-rooting aerenchymatous species. In plant removal experiments, the presence of shrubs has been shown to decrease CH_4 fluxes (Ward et al., 2013; Robroek et al., 2015). Recently, trees have been shown to transport significant amounts of CH_4 from soil in certain ecosystems, but so far not in forested boreal peatlands (Covey and Megonigal, 2019). *Sphagnum* mosses, in turn, have an impact on CH_4 oxidation as they host partly endophytic methanotrophs in the water-filled, hyaline cells of their leaves and stem (Raghoebarsing et al., 2005; Larmola et al., 2010; Putkinen et al., 2012).

Water level regulates the volume ratio of the aerobic and anaerobic peat and, consequently, the extent of the ~~methane~~CH_4 production and oxidation zones. Therefore, a positive correlation between the water level and ~~methane~~CH_4 fluxes has been reported in numerous studies (Moore and Roulet, 1993; Laine et al., 2007a; Pearson et al., 2015; Turetsky et al., 2014; Chimner et al., 2017). However, the relationship between the water level and ~~methane~~CH_4 fluxes is complex due to the vegetation – water level interaction. Because the plant communities in the wettest habitats are often associated with the sparsest vascular plant cover and lowest productivity (Waddington and Roulet, 2000; Laine et al., 2007b; Riutta et al., 2007b), less substrate for methaneCH_4 production is available in those communities. In the dry end of the water level gradient, fewer the roots reach the anaerobic layer of the peat (Waddington et al., 1996; Kutzbach et al., 2004). Hence, methaneCH_4 fluxes may also show a unimodal relationship to water level (Strack et al., 2004; Brown et al., 2014) or no relationship at all (Rask et al., 2002; Korrensalo et al., 2018b).

In this study, we aim to disentangle the intertwined relationships among water level, vegetation and fen CH_4 fluxes. We test the role assumed for different plant functional groups based on earlier literature and quantify how these roles are modulated by changing water level. Our objective is to quantify the contribution of the different components of the fen plant community, namely sedges, dwarf shrubs, *Sphagnum* mosses, and the underlying peat, to the CH_4 fluxes -inunder wet and dry conditions. , namely sedges, dwarf shrubs, *Sphagnum* mosses, and the underlying peat, to the methaneCH_4 fluxes in wet and dry conditions. To achieve this, weWe applied removal treatments of plant functional groups both under natural and experimentally lowered water level in a factorial study design. of plant removal and water level drawdown treatments.We hypothesized that aerenchymatous plant species enhance CH_4 fluxes and that this effect would be less pronounced under lowered water level as smaller proportion of the roots would extend to the anaerobic peat layer. Further, we hypothesized *Sphagnum* mosses and dwarf shrubs to reduce CH_4 fluxes.

2. Materials and methods

2.1. Study site

The study was carried out at Lakkasuo peatland complex, an eccentric raised bog with minerotrophic laggs situated on the southern boreal vegetation zone (Ahti et al., 1968) in Southern Finland (61°47' N; 24°18' E). Annual precipitation in the region totals 710 mm, of which about a third falls as snow. The average temperatures for January and July are --8.9 and 15.3 °C, respectively (Juupajoki-Hyytiälä weather station, Drebs et al. 2002).

The study site was situated on a nutrient-poor, oligotrophic, treeless fen part of the peatland complex. Surface topography in the site is uniform, mostly lawn. The pH of the surface peat at the site was 4.9 (Juottonen et al., 2005). Sedges dominate the fField layer is dominated by sedges and dwarf shrubs. The where the most abundant sedge species is *Carex lasiocarpa* Ehrh. (% cover in 2001 3.4 ± 3.9, mean ± standard deviation of 40 inventory plots), other typical sedges are *Eriophorum vaginatum* L. (0.9 ± 1.8) and *Trichophorum cespitosum* (L.) Hartm. (0.5 ± 2.4). In addition to sedges, dwarf shrubs comprise a considerable proportion of the field layer. The most abundant shrubs areis the deciduous *Betula nana* L. (4.0 ± 4.2) and other typical shrubs are ericaceous *Andromeda polifolia* L. (6.6 ± 5.7) and *Vaccinium oxycoccos* L. (4.9 ± 4.2). Note that due to the erect growth form of sedges, their % cover is lower than that of shrubs, although their leaf area is higher; see Table 1 and Fig. 2. The moss layer forms a continuous carpet dominated by *Sphagnum papillosum* Lindb. (40.1 ± 31.3) and the species of *S. recurvum* complex~~,~~ (*S. fallax* (Klinggr.) Klinggr.,~~ and~~ *S. flexuosum* Dozy & Molk and *S. angustifolium* (C.E.O.Jensen ex Russow) C.E.O.Jensen) (together 32.7 ± 24.0). The vegetation inventory and variation conducted at the site is described in detail in Kokkonen et al., (2019).

2.2. Experimental design

The study was carried out during four growing seasons from 2001 to 2004. The first season of the study, 2001, served as a calibration year without the WLD treatment, which was implemented in April 2002. The study site was divided into two subsites approximately 20 m apart, namely the wet and the drier water level drawdown (WLD) subsite, by surrounding the WLD subsite with a shallow ditch that lowered the water level by an average 17 ± 1.6 cm (22 ± 3.0 cm in 2002, 12 ± 3.4 cm in 2003 and 16 ± 1.9 cm in 2004). The shallow ditch was located approximately 10 m from the wet subsite and drained to a larger, old ditch. ~~The first season of the study, 2001, served as a calibration year without the WLD treatment, which was implemented in April 2002.~~

We studied the contribution of the ecosystem components to the net CH_4 fluxes in wet and dry conditions by means of plant removal treatments. In the site, we established permanent sample plots of 56 cm × 56 cm consisting of:

- peat, *Sphagnum* mosses, sedges and dwarf shrubs (PSCD, intact vegetation, n = 8 in the wet subsite and n = 8 in WLD subsite)
- peat, *Sphagnum* mosses and sedges (PSC, dwarf shrubs removed, n = 5 + 4)
- peat and *Sphagnum* mosses (PS, sedges and shrubs removed, n = 3 + 3)
- peat (P, all vegetation removed, n = 4 + 4).

The plant removal treatment plots (PSC, PS and P) were established April 2002~~,~~. In the plant removal treatment plots vascular plants were cut with scissors to the level of the moss (PS plots) or peat (P plots) surface and their above-ground litter was removed. In the ~~bare peat~~P plots the top 1.5 cm of the *Sphagnum* moss carpet was cut off with scissors. All emerging regrowth was clipped off once a week as necessary. Over the course of the study, progressively less clipping was needed, hardly any in 2004. Prior to ~~methane~~CH_4 flux measurements, sedge stubble in P and PS plots was treated with paraffin wax to seal the aerenchymatous pathway of ~~methane~~CH_4.

2.3. Measurements

CH_4 fluxes were measured using the closed chamber method. A stainless steel collar (56 × 56 × 30 cm, length x width x height) was permanently inserted into each sample plot prior to the start of the study. The collars had a water groove to allow chamber placement and air-tight sealing during the measurement. For the flux measurements, an aluminium chamber of 60 × 60 × 30 cm was placed on the water groove of the collar. After the chamber placement, a vent on the chamber roof that ensured pressure equilibration was sealed with a septum plug. A battery-operated fan circulated the air inside the chamber. A 40-ml air sample was drawn into a polypropylene syringe at 5, 15, 25 and 35 minutes after closure. The samples were stored at + 4°C before analysis, which was carried out within 36 hours. Samples were analyzed with a HP-5710A gas chromatograph (GC) from 2001 to 2003 and with a HP-5890A GC in 2004. Both GCs were equipped with a 1-ml loop, 6×1/8" packed column (Hayesep Q in HP-5710A; Poropak Q in HP-5890A) and flame ionization detector. The carrier gas was helium with a flow rate of 30 mL min^{-1}. Column and detector temperatures were 40°C and 300°C, respectively. The precision of the analysis was ±0.16%, determined as the coefficient of variation of the replicate samples.

To relate the fluxes to prevailing environmental conditions, peat temperatures at 5, 10, 20 and 30 cm below the moss surface and water level in a perforated tube adjacent to each plot were measured during the flux measurements. Air and peat temperatures and precipitation were also continuously recorded in the weather station at the site. Green leaf area index (LAI) of each vascular plant species in each plot was determined with the method of Wilson et al. (2007) from April until November, as a product of the total number of leaves (counted monthly) and the average leaf size of marked individuals (measured every two weeks). Species-specific Gaussian curves (Wilson et al. 2007) were fitted to the observations to describe the continuous development of LAI throughout the season. LAI of different species were summed up to sedge, dwarf-shrub and total LAI (LAI_C, LAI_D and LAI_T, respectively). Moss cover at each plot was visually estimated annually.

In addition to CH_4 exchange, CO_2 exchange was measured in the study site. The methods and results are reported elsewhere (Riutta et al., 2007a) in more detail, but some CO_2 exchange estimates are used here to study the relationship between the CO_2 and CH_4 fluxes. In summary, net ecosystem CO_2 exchange (NEE) was measured weekly / biweekly by employing the closed chamber technique in the same plots and during the same period as the CH_4 fluxes. Measurements were carried out in both light and dark, which enabled the partitioning of the fluxes into gross photosynthesis and ecosystem respiration. We constructed nonlinear regression models for photosynthesis and respiration, with water level, temperature and LAI as explanatory factors, separately for each vegetation treatment, to reconstruct the fluxes for the whole growing season.

2.4. Data analyses

CH_4 flux was calculated as the linear change in CH_4 concentration as a function of time by fitting a least-squares regression line. Of the 1300 measurements, <0.5% were rejected due to clear errors, such as leakage or problems in the GC analysis, and 2% were classified as episodic fluxes.

To reconstruct seasonal (June-September) estimates for each sample plot, the biweekly measured fluxes were linearly interpolated between measurement days and the obtained daily values were integrated. In the interpolation, rejected values and episodic fluxes were replaced with the median flux of the corresponding vegetation and water level treatment on the same measurement day. The impact of the episodic fluxes on the seasonal flux was taken into account by using the episodic values as the CH_4 flux estimates of the day they were measured. The reconstructed seasonal fluxes at the wet and WLD subsites were converted to CO_2 equivalent according to Myhre et al., (2013).

We used linear mixed effect models to test the impact of the plant removal treatments and the WLD treatment on WL, LAI and daily measured CH_4 flux. First, we tested the differences in WL, LAI_C, LAI_D, LAI_T and CH_4 flux between the wet and WLD subsites before the WLD treatment was applied (year 2001) and over the years after the WLD treatment (2002-2004), with WLD treatment, year and their interaction as potential fixed predictors. This model included only the plots with intact vegetation (PSCD). The wet subsite in 2001 was the constant against which WLD and other years were compared. Therefore, the difference between the wet and WLD treatment in the model describes the pre-treatment difference among the two subsites in calibration year 2001, and the interaction between WLD treatment and years 2002-2004 describe the impact of WLD after the treatment. Plot and date were included as crossed random effects.

Second, we tested the impact of plant removal on CH_4 flux over the years and the interaction of the plant removal treatments with the WLD treatment with data from years 2002-2004 (no plant removal treatments in 2001). For each year separately, we fitted a model with plant removal treatments, WLD treatment and the interaction between them as potential fixed predictors.

Third, we tested the response of CH_4 flux to leaf area and environmental variables by extending the model fitted to the data of year 2004, that had the maximum amount of time for stabilization after the treatments. In addition to plant removal and WLD treatments, potential fixed predictors were LAI_C, LAI_D, cover of *Sphagnum* mosses, measured WL, temperature in the chamber and peat temperature at the depths of 5, 10 20 and 30 cm (T5, T10, T20 and T30) as well as the potential interactions among these parameters. Potential new predictors were sequentially added and after each addition the significance of all predictors were tested. We reported separately both models for year 2004; one including plant removal and WLD treatments as fixed predictors for CH_4 flux and another including the response of CH_4 flux to leaf area/cover of plant groups and environmental variables.

In each case, aA conditional F-test was used to test in each case if the full model with all fixed predictors and their interactions was significantly better ($p<0.05$) than a simpler model. Plot and date were included as crossed random effects. Resulting models are reported in Table 2. The models were fitted using the function lmer of package lme4 (Bates et al., 2015) of RStudio version 1.1.383.

3. Results

3.1. Impact of the water level drawdown

The pre-treatment water level did not differ between the wet and WLD subsites (p=0.174, comparison between wet and WLD treatment during the calibration year 2001) (Fig. 1a, Table 1). Following the drainage in April 2002, the water level was significantly lower in the WLD subsite ($p < 0.001$, interaction between WLD and year 2002). The WLD treatment lowered the water level by approximately 17 cm, except in July and August 2003 when a severe drought lowered the water level below the ditch, resulting in similar water levels in wet and WLD subsites. In the wet subsite, the water level during the years 2001 and 2004 was similar to the long-term average of the site (Laine 2004), approximately 5 to 10 cm below the moss surface (Table 1) (Laine et al. 2004). During July and August 2002 and 2003, however, the water level was lower than the long-term average. More information on the weather conditions during the study is given in Riutta et al. (2007b).

Prior to the drainage, vegetation composition in the plots with intact vegetation (PSCD) was similar in both subsites (Table 1, Fig. 1b). In the mixed effects model, LAI_C, LAI_D and LAI_T did not differ between wet and WLD subsites in year 2001 (p-values 0.996, 0.656 and 0.878, respectively). In 2001 the peak season average LAI_T was approximately 1.0 m^2 m^{-2}, of which sedges composed 70%. The mean *Sphagnum* cover was 80%. By the third year since WLD 2004 LAI_C had decreased ($p<0.001$) and LAI_D increased ($p<0.001$) in the WLD subsite, resulting in an overall decrease in LAI_T ($p=0.007$) (Table 1, Fig. 1b).

In the PSCD plots, the pre-treatment ~~methane~~CH_4 fluxes did not differ between the wet and WLD subsite ($p=0.654$) (Fig. 1c). After the treatment, in 2002-2004, fluxes were significantly lower in the WLD than in the wet subsite ($p<0.001$ for all years). During the three-year WLD treatment, the mean flux was approximately 51 and 7.0 mg CH_4 m^{-2} d^{-1} in the wet and WLD subsites, respectively. Converted to CO_2 equivalents, the seasonal reconstructed fluxes in the wet and WLD subsites in 2002-2004 were 236 and 32 g CO_2-eq m^{-2} growing season^{-1}, respectively.

3.2. Impact of the plant removal treatments

Plant removal treatments did not lead to major changes in vegetation composition beyond the clipped target groups.~~:~~ ~~the removal of the vascular~~ Vascular plant removal did not affect the *Sphagnum* moss cover, and the removal of ~~the~~ dwarf shrubs did not change the LAI of sedges. LAI_C was similar~~-~~ in PSC and PSCD plots (data for 2004 shown in Table 1) during all years in the wet subsite and during 2003 and 2004 in the WLD subsite (all p-values >0.05). LAI_C was higher in the PSC plots than in the PSCD plots in the WLD subsite in 2002 ($p=0.016$).

~~The first two years of the plant removal treatments were characterised by treatment artefacts caused by the initial disturbance of the clipping and the creation of unnatural amount of new root necromass.~~ During the first season of the removal treatments (2002)~~I~~ in the wet subsite, CH_4 fluxes were higher in the plant removal plots (P, PS and PSC) than in the intact plots (PSCD) ~~during the first season of the removal treatments (2002)~~, in some cases almost triple ($p<0.05$ for all treatments, Fig. 2, upper panels). The fluxes in the plant removal treatment plots also showed a stronger seasonal pattern and larger spatial variation. After the first year of removal treatments the fluxes of the P, PS and PSC plots decreased, and in 2003 P plots had a similar CH_4 flux than the intact plots ($p=0.908$), while PS and PSC plots still had a higher flux than PSCD plots ($p=0.033$ and $p=0.005$, respectively).

~~By the third year of the plant removal treatments (2004), the treatments had stabilised, and the contribution of the vegetation components to the fluxes could be quantified.~~ By the third year of the plant removal treatments (2004), t~~T~~he fluxes in all treatments showed a seasonal pattern similar to that of the intact plots. Bare peat plots had lower fluxes than the intact PSCD plots ($p<0.001$). Fluxes of the PSC plots (shrubs removed) were marginally significantly higher ($p=0.060$) than those of the PSCD plots (shrubs present). In WLD conditions, the fluxes in the plant removal plots (P, PS and PSC) were mostly lower than the fluxes in the intact PSCD plots during all three vegetation treatment years (Fig. 2, lower panel), but the differences were not significant (Table 2b). WLD and plant removal treatments had a significant interaction: in 2004 WLD lowered the fluxes more in ~~PSC and~~ PSCD plots than in the P plots and more in PSC plots than in the P and PS plots ($p<0.05$ for the interaction terms). Seasonal fluxes visualize the patterns tested with the nonlinear mixed effect models: in the WLD subsite fluxes were lower than in the wet subsite in all plant removal treatments (Fig. 3b). In wet conditions, the seasonal flux of the P and PS plots was lower than that of the PSCD and PSC plots in which vascular plants were present (Fig. 3a). Taking the fluxes from bare peat plots as a baseline, the presence of vegetation enhanced the fluxes. Compared with the situation of sedges and *Sphagna* present (PSC), the presence of shrubs (PSCD) seemed to slightly attenuate the fluxes (Fig. 3b, c). In WLD conditions, the differences between plant removal treatments were negligible. The differences between the plant removal treatments can be used as an estimate of the contribution of each plant group to the total flux, although due to the propagation of the errors, uncertainty in these estimates is large. In normal hydrological conditions, plant-mediated flux accounted for 68% ± 23% (comparison of P and PSCD plots) or 78% ± 17% (comparison of P and PSC plots) of the total growing season flux, of which *Sphagnum* mosses and sedges accounted for approximately ¼ and ¾, respectively (Fig. 3c).

The seasonal ~~methane~~CH_4 fluxes displayed a clear positive, exponential relationship with the seasonal net CO_2 flux (Fig. 4). The relationship was similar among the plant removal treatments in wet and dry conditions. However, the plots with intact vegetation (PSCD) were an exception; they had lower CH_4 fluxes than could have been expected based on their net CO_2 flux, pointing towards the potential suppressing effect of shrubs on CH_4 emissions.

3.3. Response of CH_4 flux to environmental variables and interaction with leaf area

The best predictors of the CH_4 flux in the extended model for the year 2004 were the categorical WLD treatment (which was a better predictor than the measured WL), T20 (best out of the measured temperatures), and LAI_C (which was a better predictor than the categorical vegetation removal treatment). The abundance of the other plant functional groups, LAI_D, or *Sphagnum* cover did not have a significant effect on the fluxes. CH_4 flux was increased by LAI_C and T20 in wet conditions (Table 2c). In the WLD conditions, however, neither LAI_C nor T20 had any impact on the fluxes (coefficient estimates for LAI_C*WLD1 and T20*WLD1 cancel out the coefficient estimates for LAI_C and T20 in wet conditions; Table 2c). The positive coefficient of the WLD treatment seemingly indicated a larger flux at the WLD treatment site compared with the wet site, when LAI_C and T20 both equal zero; however, the measured minimum T20 during the growing season 2004 was 6.1°C, and the model was not intended for any extrapolation. The predicted CH_4 flux in the WLD treatment was similar to or lower than the flux in the wet treatment in the observed T20 and LAI_C range.

4. Discussion

4.1. The effect of the plant types and substrate on the ~~methane~~CH_4 fluxes in natural water level conditions

In line with the previous studies, the plant removal treatments of this study indicated that sedges were the most important plant group in regulating CH_4 fluxes. In other sedge-dominated sites, plant-mediated flux has accounted for 75 to 97% of the total flux (Schimel, 1995; Kelker and Chanton, 1997; Ström et al., 2005; Sun et al., 2012; Noyce et al., 2014) and plant removal experiments have shown that of different plant functional types, removal of graminoids cause the largest decrease on ~~methane~~CH_4 production and flux (Ward et al., 2013; Robroek et al., 2015). Compared ~~to~~ with the bare peat surfaces, the presence of *Sphagnum* mosses seemed to have a slight, although not statistically significant, enhancing effect on the ~~methane~~CH_4 fluxes, similarly to the results of Roura-Carol and Freeman (1999). King et al. (1998) found the presence of mosses to have a slightly attenuating effect on the fluxes, while Greenup and others (2000) did not find significant differences in fluxes after *Sphagnum* removal. Based on this, the CH_4 oxidation by the loosely symbiotic methanotrophs within *Sphagnum* mosses (Raghoebarsing et al., 2005; Larmola et al., 2010; Putkinen et al., 2012) seems to play a minor role in CH_4 dynamics in our site.

Similarly to Ward et al. (2013), we found that the presence of shrubs seemed to have a slightly attenuating effect on the fluxes under natural water level conditions. Robroek et al. (2015) made a similar finding with potential ~~methane~~CH_4 production. In contrast, an aerenchymatous shrub, *Myrica gale*, supported similar potential ~~methane~~CH_4 production than a sedge, *Carex aquatilis*, and did not suppress ~~methane~~CH_4 flux (Strack et al., 2017). Furthermore, in line with the attenuating effect of shrubs, the ~~methane~~CH_4 flux: NEE ratio was lower in the plots with intact vegetation (PSCD, shrubs present) than in the other vegetation treatments. Mechanisms behind that might relate to impact of shrubs on soil chemistry, microbial community or the biomass allocation of sedges ~~or on soil chemistry~~. Shrub litter has higher lignin and leaf dry matter content than sedges, which both are related to lower methanogenesis (Yavitt et al., 2019). Shrub removal has been observed to result in higher dissolved organic C and N and lower C:N ratio (Ward et al. 2013) as well as higher fungal biomass (Robroek et al. 2015). A study on the competitive ability and biomass allocation of a wetland grass, *Molinia caerulea*, revealed that *M. caerulea* allocated more biomass to the roots when it did not face competition by shrubs (Aerts et al., 1991). Similarly, in our study, sedges in the plots where shrubs were removed may have allocated more biomass to the roots than the sedges growing in the sedge and shrub mixture. As a result, methanogenic microbes may have benefited from the higher substrate availability in the shrub removal plots (PSC). CH_4 production has a negative relationship and CH_4 oxidation has a positive relationship with the concentration of certain woody lignin compounds in peat pore water (Yavitt, 2000). In our study, this may be the reason behind the lower fluxes in the presence of the arboreals. The results concerning the attenuating effect of shrubs on methaneCH4 fluxes are, however, only indicative and further, process orientated research is needed.

4.2. Delay in the plant removal treatment effect

We observed a considerable disturbance in the fluxes following the plant removal treatments. In other clipping studies in which the shoots were cut above the water level clipping either increased the CH_4 flux during the first growing season after clipping (Schimel, 1995), had no effect (Kelker and Chanton, 1997; Greenup et al., 2000) or decreased the flux (Waddington et al., 1996; Rinnan et al., 2003). Thus, we assumed that the higher fluxes at the clipped plots during the first two years after the vegetation removal treatments were mainly caused by treatment artefacts. The removal of the above-ground parts of vascular plants led to the gradual death of the below-ground parts, creation of unnatural amount of new root necromass and, thereby, a peak in the amount of available substrate. Methanogenesis in the study site may have been substrate limited (Bergman et al., 1998; Rinne et al., 2007), which could explain the initially high fluxes in the plant removal plots. The mass loss of *Carex* roots and rhizomes is only 10 to 45% during the first 12 months of decomposition, although the litter quality deteriorates (Scheffer and Aerts, 2000). However, after two years the mass loss can be as much as 75% of the original mass (Thormann et al., 2001), which gives more confidence in the results of the third year of the plant removal treatments. Thus, we used the third year of the plant removal treatments to quantify the contribution of the vegetation components to the fluxes and the response of fluxes to environmental conditions. King and others (1998) likewise reported the effects of the plant removal two years after the treatment began. Shrub litter, especially below-ground litter, decomposes slower than sedge litter (Moore et al., 2007), due to the high lignin content (Yavitt et al., 2019). . On the other hand, the shallow majority of dwarf shrub roots grow in the uppermost 20 cm peat layer, while sedge roots extend deeper (Korrensalo et al., 2018a; Mäkiranta et al. 2018), causing a larger proportion of dwarf shrub roots to of shrubs decompose in oxic conditions while at least the deepest sedge roots decompose in anoxic conditions, thus counteracting the differences in litter quality. Even two years after the start of the vegetation removal treatments, some shrub roots still probably remained. However, they were mostly located above the methaneCH_4 production zone.

4.3. Water level regulates the role of the vegetation

Experimental water level drawdown has been used to mimic climate change impact on northern peatland methaneCH_4 fluxes in mesocosm (Freeman et al., 1992; Blodau et al., 2004; Dinsmore et al., 2009) and in the field studies ranging from bogs to rich fens (Laine et al., 2007a; Strack and Waddington, 2007; Turetsky et al., 2008; Ballantyne et al., 2014; Munir and Strack, 2014; Pearson et al., 2015; Peltoniemi et al., 2016; Chimner et al., 2017; Olefeldt et al., 2017). In line with our results, all these studies report some level of decrease in CH_4 flux due to WLD ranging from 3 to ~20cm. Together with temperature and vegetation, water table level is a major regulator of CH_4 flux (Lai, 2009; Turetsky et al., 2014). However, the mechanistic understanding of this process is still limited. While Strack et al. (2004) found only small differences in the methaneCH_4 production and consumption potentials between control and

WLD sites, and thus attributed the the decrease in fluxes mainly to the change in the volume ratio of the anaerobic and aerobic zones, Yrjälä et al. (2011) and Peltoniemi et al. (2016) found that WLD had a stronger impact on emissions through decreasing CH_4 production, than through increasing oxidation,

In this study, the presence or absence of the plant types or LAI_C had no effect on the CH_4 flux in the WLD conditions. This supports the findings by Waddington et al. (1996) as well as Strack et al. (2006) that the impact of the vegetation on the fluxes is strongly dependent on the water level conditions. CH4 flux also responded to peat temperature only in wet conditions. A similar result with water level and temperature response has been previously reported by Moosavi et al., (1996). Our results showed that water level acts as a switch; it turns CH_4 flux on and off, after which temperature and vegetation regulate the flux magnitude. This result is further emphasized by the response model, where WLD treatment including change in the ecosystem following new WT regime rather than seasonally varying WL was a better predictor for CH_4 fluxes. vegetation In conclusion, vegetation is a major controlling factor of the peatland methaneCH_4 dynamics, but only in wet conditions.

5. Conclusions

Vegetation, sedges in particular, regulates the level of peatland fen methaneCH_4 fluxes in normal hydrological conditions, but this vegetation control is strongly dependent on the water level regime. In water level drawdown conditions methaneCH_4 fluxes are significantly lowered, practically to zero, and vegetation composition has no influence on the fluxes. The results are relevant for assessing the response of fen peatlands to changing climatic conditions, as water level drawdown and the consequent vegetation changes are the major projected impacts of climate change on northern peatlands.

Competing interests

The authors declare that they have no conflict of interest.

Data availability

The data associated with the manuscript will be published in PANGAEA repository upon publication. On request, the data can also be obtained from the corresponding author.

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References

Aerts, R., Boot, R. G. A. and van der Aart, P. J. M.: The relation between above- and belowground biomass allocation patterns and competitive ability, Oecologia, 87(4), 551–559, doi:10.1007/BF00320419, 1991.

Ahti, T., Hämet-Ahti, L. and Jalas, J.: Vegetation zones and their sections in northwestern Europe, Ann. Bot. Fenn., 5(3), 169–211, 1968.

Ballantyne, D. M., Hribljan, J. A., Pypker, T. G. and Chimner, R. A.: Long-term water table manipulations alter peatland gaseous carbon fluxes in Northern Michigan, Wetl. Ecol. Manag., 22(1), 35–47, doi:10.1007/s11273-013-9320-8, 2014.

Bates, D., Mächler, M., Bolker, B. and Walker, S.: Fitting Linear Mixed-Effects Models Using lme4, J. Stat. Softw., 67(1), 1–48, doi:10.18637/jss.v067.i01, 2015.

Bellisario, L. M., Bubier, J. L., Moore, T. R. and Chanton, J. P.: Controls on CH_4 emissions from a northern peatland, Glob. Biogeochem. Cycles, 13(1), 81–91, doi:10.1029/1998GB900021, 1999.

Bergman, I., Svensson, B. H. and Nilsson, M.: Regulation of methane production in a Swedish acid mire by pH, temperature and substrate, Soil Biol. Biochem., 30(6), 729–741, doi:10.1016/S0038-0717(97)00181-8, 1998.

Blodau, C., Basiliko, N. and Moore, T. R.: Carbon turnover in peatland mesocosms exposed to different water table levels, Biogeochemistry, 67(3), 331–351, doi:10.1023/B:BIOG.0000015788.30164.e2, 2004.

Brown, M. G., Humphreys, E. R., Moore, T. R., Roulet, N. T. and Lafleur, P. M.: Evidence for a nonmonotonic relationship between ecosystem-scale peatland methane emissions and water table depth, J. Geophys. Res. Biogeosciences, 119(5), 826–835, doi:10.1002/2013JG002576, 2014.

Chimner, R. A., Pypker, T. G., Hribljan, J. A., Moore, P. A. and Waddington, J. M.: Multi-decadal Changes in Water Table Levels Alter Peatland Carbon Cycling, Ecosystems, 20(5), 1042–1057, doi:10.1007/s10021-016-0092-x, 2017.

Christensen, T. R., Friborg, T., Sommerkorn, M., Kaplan, J., Illeris, L., Soegaard, H., Nordstroem, C. and Jonasson, S.: Trace gas exchange in a high-Arctic valley: 1. Variationsin CO_2 and CH_4 Flux between tundra vegetation types, Glob. Biogeochem. Cycles, 14(3), 701–713, doi:10.1029/1999GB001134, 2000.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M. and others: Carbon and other biogeochemical cycles, in Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, pp. 465–570, Cambridge University Press, 2014.

Couwenberg, J. and Fritz, C.: Towards developing IPCC methane 'emission factors' for peatlands (organic soils), Mires and Peat, 10, 1-17, 2012.

Covey, K. R. and Megonigal, J. P.: Methane production and emissions in trees and forests, New Phytol., 222(1), 35–51, doi:10.1111/nph.15624, 2019.

Ding, W., Cai, Z. and Tsuruta, H.: Diel variation in methane emissions from the stands of Carex lasiocarpa and Deyeuxia angustifolia in a cool temperate freshwater marsh, Atmos. Environ., 38(2), 181–188, doi:10.1016/j.atmosenv.2003.09.066, 2004.

Dinsmore, K. J., Skiba, U. M., Billett, M. F. and Rees, R. M.: Effect of water table on greenhouse gas emissions from peatland mesocosms, Plant Soil, 318(1–2), 229–242, doi:10.1007/s11104-008-9832-9, 2009.

Freeman, C., Lock, M. A. and Reynolds, B.: Fluxes of CO2, CH4 and N2O from a Welsh peatland following simulation of water table draw-down: Potential feedback to climatic change, Biogeochemistry, 19(1), 51–60, doi:10.1007/BF00000574, 1992.

Fritz, C., Pancotto, V. A., Elzenga, J. T. M., Visser, E. J. W., Grootjans, A. P., Pol, A., Iturraspe, R., Roelofs, J. G. M. and Smolders, A. J. P.: Zero methane emission bogs: extreme rhizosphere oxygenation by cushion plants in Patagonia, New Phytol., 190(2), 398–408, doi:10.1111/j.1469-8137.2010.03604.x, 2011.

Garnet, K. N., Megonigal, J. P., Litchfield, C. and Taylor, G. E.: Physiological control of leaf methane emission from wetland plants, Aquat. Bot., 81(2), 141–155, doi:10.1016/j.aquabot.2004.10.003, 2005.

Gray, A., Levy, P. E., Cooper, M. D. A., Jones, T., Gaiawyn, J., Leeson, S. R., Ward, S. E., Dinsmore, K. J., Drewer, J., Sheppard, L. J., Ostle, N. J., Evans, C. D., Burden, A. and Zieliński, P.: Methane indicator values for peatlands: a comparison of species and functional groups, Glob. Change Biol., 19(4), 1141–1150, doi:10.1111/gcb.12120, 2013.

Greenup, A. L., Bradford, M. A., McNamara, N. P., Ineson, P. and Lee, J. A.: The role of Eriophorum vaginatum in CH4 flux from an ombrotrophic peatland, Plant Soil, 227(1–2), 265–272, 2000.

Joseph B. Yavitt, R. K. W., Christopher J. Williams: Controls on Microbial Production of Methane and Carbon Dioxide in Three Sphagnum-Dominated Peatland Ecosystems as Revealed by a Reciprocal Field Peat Transplant Experiment, Geomicrobiol. J., 17(1), 61–88, doi:10.1080/014904500270503, 2000.

Juottonen, H., Galand, P. E., Tuittila, E.-S., Laine, J., Fritze, H. and Yrjälä, K.: Methanogen communities and Bacteria along an ecohydrological gradient in a northern raised bog complex, Environ. Microbiol., 7(10), 1547–1557, doi:10.1111/j.1462-2920.2005.00838.x, 2005.

Kelker, D. and Chanton, J.: The effect of clipping on methane emissions from Carex, Biogeochemistry, 39(1), 37–44, doi:10.1023/A:1005866403120, 1997.

King, G. M.: Associations of methanotrophs with the roots and rhizomes of aquatic vegetation., Appl. Environ. Microbiol., 60(9), 3220–3227, 1994.

King, J. Y., Reeburgh, W. S. and Regli, S. K.: Methane emission and transport by arctic sedges in Alaska: Results of a vegetation removal experiment, J. Geophys. Res. Atmospheres, 103(D22), 29083–29092, doi:10.1029/98JD00052, 1998.

Kirschke, S., Bousquet, P., Ciais, P., Saunois, M., Canadell, J. G., Dlugokencky, E. J., Bergamaschi, P., Bergmann, D., Blake, D. R., Bruhwiler, L., Cameron-Smith, P., Castaldi, S., Chevallier, F., Feng, L., Fraser, A., Heimann, M., Hodson, E. L., Houweling, S., Josse, B., Fraser, P. J., Krummel, P. B., Lamarque, J.-F., Langenfelds, R. L., Le Quéré, C., Naik, V., O'Doherty, S., Palmer, P. I., Pison, I., Plummer, D., Poulter, B., Prinn, R. G., Rigby, M., Ringeval, B., Santini, M., Schmidt, M., Shindell, D. T., Simpson, I. J., Spahni, R., Steele, L. P., Strode, S. A., Sudo, K., Szopa, S., van der Werf, G. R., Voulgarakis, A., van Weele, M., Weiss, R. F., Williams, J. E. and Zeng, G.: Three decades of global methane sources and sinks, Nat. Geosci., 6(10), 813–823, doi:10.1038/ngeo1955, 2013.

Koelbener, A., Ström, L., Edwards, P. J. and Olde Venterink, H.: Plant species from mesotrophic wetlands cause relatively high methane emissions from peat soil, Plant Soil, 326(1–2), 147–158, doi:10.1007/s11104-009-9989-x, 2010.

Kokkonen, N. A. K., Laine, A. M., Laine, J., Vasander, H., Kurki, K., Gong, J. and Tuittila, E.-S.: Responses of peatland vegetation to 15-year water level drawdown as mediated by fertility level, J. Veg. Sci., 30(6), 1206–1216, doi:10.1111/jvs.12794, 2019.

Korrensalo, A., Kettunen, L., Laiho, R., Alekseychik, P., Vesala, T., Mammarella, I. and Tuittila, E.-S.: Boreal bog plant communities along a water table gradient differ in their standing biomass but not their biomass production, J. Veg. Sci., 29(2), 136–146, doi:10.1111/jvs.12602, 2018a.

Korrensalo, A., Männistö, E., Alekseychik, P., Mammarella, I., Rinne, J., Vesala, T. and Tuittila, E.-S.: Small spatial variability in methane emission measured from a wet patterned boreal bog, Biogeosciences, 15(6), 1749–1761, doi:10.5194/bg-15-1749-2018, 2018b.

Kutzbach, L., Wagner, D. and Pfeiffer, E.-M.: Effect of microrelief and vegetation on methane emission from wet polygonal tundra, Lena Delta, Northern Siberia, Biogeochemistry, 69(3), 341–362, doi:10.1023/B:BIOG.0000031053.81520.db, 2004.

Lai, D. Y. F.: Methane Dynamics in Northern Peatlands: A Review, Pedosphere, 19(4), 409–421, doi:10.1016/S1002-0160(09)00003-4, 2009.

Laine, A., Wilson, D., Kiely, G. and Byrne, K. A.: Methane flux dynamics in an Irish lowland blanket bog, Plant Soil, 299(1–2), 181–193, doi:10.1007/s11104-007-9374-6, 2007a.

Laine, A., Byrne, K. A., Kiely, G. and Tuittila, E.-S.: Patterns in Vegetation and CO_2 Dynamics along a Water Level Gradient in a Lowland Blanket Bog, Ecosystems, 10(6), 890–905, doi:10.1007/s10021-007-9067-2, 2007b.

Larmola, T., Tuittila, E.-S., Tiirola, M., Nykänen, H., Martikainen, P. J., Yrjälä, K., Tuomivirta, T. and Fritze, H.: The role of Sphagnum mosses in the methane cycling of a boreal mire, Ecology, 91(8), 2356–2365, doi:10.1890/09-1343.1, 2010.

Le Mer, J. and Roger, P.: Production, oxidation, emission and consumption of methane by soils: A review, Eur. J. Soil Biol., 37(1), 25–50, doi:10.1016/S1164-5563(01)01067-6, 2001.

Leppälä, M., Oksanen, J. and Tuittila, E.-S.: Methane flux dynamics during mire succession, Oecologia, 165(2), 489–499, doi:10.1007/s00442-010-1754-6, 2011.

Moore, T. R. and Roulet, N. T.: Methane flux: Water table relations in northern wetlands, Geophys. Res. Lett., 20(7), 587–590, doi:10.1029/93GL00208, 1993.

Moore, T. R., Bubier, J. L. and Bledzki, L.: Litter Decomposition in Temperate Peatland Ecosystems: The Effect of Substrate and Site, Ecosystems, 10(6), 949–963, doi:10.1007/s10021-007-9064-5, 2007.

Moosavi, S. C., Crill, P. M., Pullman, E. R., Funk, D. W. and Peterson, K. M.: Controls on CH_4 flux from an Alaskan boreal wetland, Glob. Biogeochem. Cycles, 10(2), 287–296, doi:10.1029/96GB00358, 1996.

Munir, T. M. and Strack, M.: Methane Flux Influenced by Experimental Water Table Drawdown and Soil Warming in a Dry Boreal Continental Bog, Ecosystems, 17(7), 1271–1285, doi:10.1007/s10021-014-9795-z, 2014.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Zhang, H., Aamaas, B., Boucher, O., Dalsøren, S. B., Daniel, J. S., Forster, P., Granier, C., Haigh, J., Hodnebrog, Ø., Kaplan, J. O., Marston, G., Nielsen, C. J., O'Neill, B. C., Peters, G. P., Pongratz, J., Ramaswamy, V., Roth, R., Rotstayn, L., Smith, S. J., Stevenson, D., Vernier, J.-P., Wild, O., Young, P., Jacob, D., Ravishankara, A. R. and Shine, K.: 8 Anthropogenic and Natural Radiative Forcing, , 82, n.d.

Mäkiranta, P., Laiho, R., Mehtätalo, L., Straková, P., Sormunen, J., Minkkinen, K., Penttilä, T., Fritze, H. and Tuittila, E.-S.: Responses of phenology and biomass production of boreal fens to climate warming under different water-table level regimes, Global Change Biology, 24(3), 944–956, doi:10.1111/gcb.13934, 2018.

Noyce, G. L., Varner, R. K., Bubier, J. L. and Frolking, S.: Effect of *Carex rostrata* on seasonal and interannual variability in peatland methane emissions: effect of C. rostrata on CH_4 emissions, J. Geophys. Res. Biogeosciences, 119(1), 24–34, doi:10.1002/2013JG002474, 2014.

Olefeldt, D., Euskirchen, E. S., Harden, J., Kane, E., McGuire, A. D., Waldrop, M. P. and Turetsky, M. R.: A decade of boreal rich fen greenhouse gas fluxes in response to natural and experimental water table variability, Glob. Change Biol., 23(6), 2428–2440, doi:10.1111/gcb.13612, 2017.

Pearce, D. M. E. and Clymo, R. S.: Methane oxidation in a peatland core, Glob. Biogeochem. Cycles, 15(3), 709–720, doi:10.1029/2000GB001323, 2001.

Pearson, M., Penttilä, T., Harjunpää, L., Laiho, R., Laine, J., Sarjala, T., Silvan, K., Silvan, N. and others: Effects of temperature rise and water-table-level drawdown on greenhouse gas fluxes of boreal sedge fens, Boreal Environment Research 20, 489-505, 2015.

Peltoniemi, K., Laiho, R., Juottonen, H., Bodrossy, L., Kell, D. K., Minkkinen, K., Mäkiranta, P., Mehtätalo, L., Penttilä, T., Siljanen, H. M. P., Tuittila, E.-S., Tuomivirta, T. and Fritze, H.: Responses of methanogenic and methanotrophic communities to warming in varying moisture regimes of two boreal fens, Soil Biol. Biochem., 97(Supplement C), 144–156, doi:10.1016/j.soilbio.2016.03.007, 2016.

Popp, T. J., Chanton, J. P., Whiting, G. J. and Grant, N.: Evaluation of methane oxidation in therhizosphere of a Carex dominated fen in northcentral Alberta, Canada, Biogeochemistry, 51(3), 259–281, doi:10.1023/A:1006452609284, 2000.

Putkinen, A., Larmola, T., Tuomivirta, T., Siljanen, H. M. P., Bodrossy, L., Tuittila, E.-S. and Fritze, H.: Water Dispersal of Methanotrophic Bacteria Maintains Functional Methane Oxidation in Sphagnum Mosses, Front. Microbiol., 3, doi:10.3389/fmicb.2012.00015, 2012.

Raghoebarsing, A. A., Smolders, A. J. P., Schmid, M. C., Rijpstra, W. I. C., Wolters-Arts, M., Derksen, J., Jetten, M. S. M., Schouten, S., Damsté, J. S. S., Lamers, L. P. M., Roelofs, J. G. M., Camp, H. J. M. O. den and Strous, M.: Methanotrophic symbionts provide carbon for photosynthesis in peat bogs, Nature, 436(7054), 1153–1156, doi:10.1038/nature03802, 2005.

Rask, H., Schoenau, J. and Anderson, D.: Factors influencing methane flux from a boreal forest wetland in Saskatchewan, Canada, Soil Biol. Biochem., 34(4), 435–443, doi:10.1016/S0038-0717(01)00197-3, 2002.

Rinnan, R., Impiö, M., Silvola, J., Holopainen, T. and Martikainen, P. J.: Carbon dioxide and methane fluxes in boreal peatland microcosms with different vegetation cover?effects of ozone or ultraviolet-B exposure, Oecologia, 137(3), 475–483, doi:10.1007/s00442-003-1366-5, 2003.

Rinne, J., Riutta, T., Pihlatie, M., Aurela, M., Haapanala, S., Tuovinen, J.-P., Tuittila, E.-S. and Vesala, T.: Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique, Tellus B Chem. Phys. Meteorol., 59(3), 449–457, doi:10.1111/j.1600-0889.2007.00261.x, 2007.

Rinne, J., Tuittila, E.-S., Peltola, O., Li, X., Raivonen, M., Alekseychik, P., Haapanala, S., Pihlatie, M., Aurela, M., Mammarella, I. and Vesala, T.: Temporal Variation of Ecosystem Scale Methane Emission From a Boreal Fen in Relation to Temperature, Water Table Position, and Carbon Dioxide Fluxes, Glob. Biogeochem. Cycles, 32(7), 1087–1106, doi:10.1029/2017GB005747, 2018.

Riutta, T., Laine, J. and Tuittila, E.-S.: Sensitivity of CO2 Exchange of Fen Ecosystem Components to Water Level Variation, Ecosystems, 10(5), 718–733, doi:10.1007/s10021-007-9046-7, 2007a.

Riutta, T., Laine, J., Aurela, M., Rinne, J., Vesala, T., Laurila, T., Haapanala, S., Pihlatie, M. and Tuittila, E.-S.: Spatial variation in plant community functions regulates carbon gas dynamics in a boreal fen ecosystem, Tellus B Chem. Phys. Meteorol., 59(5), 838–852, doi:10.1111/j.1600-0889.2007.00302.x, 2007b.

Robroek, B. J. M., Jassey, V. E. J., Kox, M. A. R., Berendsen, R. L., Mills, R. T. E., Cécillon, L., Puissant, J., Meima-Franke, M., Bakker, P. A. H. M. and Bodelier, P. L. E.: Peatland vascular plant functional types affect methane dynamics by altering microbial community structure, edited by N. Wurzburger, J. Ecol., 103(4), 925–934, doi:10.1111/1365-2745.12413, 2015.

Roura-Carol, M. and Freeman, C.: Methane release from peat soils: effects of Sphagnum and Juncus, Soil Biol. Biochem., 31(2), 323–325, doi:10.1016/S0038-0717(98)00125-4, 1999.

S. C. Whalen, W. S. Reeburgh: Methane Oxidation, Production, and Emission at Contrasting Sites in a Boreal Bog, Geomicrobiol. J., 17(3), 237–251, doi:10.1080/01490450050121198, 2000.

Saunois, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J. G., Dlugokencky, E. J., Etiope, G., Bastviken, D., Houweling, S., Janssens-Maenhout, G., Tubiello, F. N., Castaldi, S., Jackson, R. B., Alexe, M., Arora, V. K., Beerling, D. J., Bergamaschi, P., Blake, D. R., Brailsford, G., Brovkin, V., Bruhwiler, L., Crevoisier, C., Crill, P., Covey, K., Curry, C., Frankenberg, C., Gedney, N., Höglund-Isaksson, L., Ishizawa, M., Ito, A., Joos, F., Kim, H.-S., Kleinen, T., Krummel, P., Lamarque, J.-F., Langenfelds, R., Locatelli, R., Machida, T., Maksyutov, S., McDonald, K. C., Marshall, J., Melton, J. R., Morino, I., Naik, V., O'Doherty, S., Parmentier, F.-J. W., Patra, P. K., Peng, C., Peng, S., Peters, G. P., Pison, I., Prigent, C., Prinn, R., Ramonet, M., Riley, W. J., Saito, M., Santini, M., Schroeder, R., Simpson, I. J., Spahni, R., Steele, P., Takizawa, A., Thornton, B. F., Tian, H., Tohjima, Y., Viovy, N., Voulgarakis, A., van Weele, M., van der Werf, G. R., Weiss, R., Wiedinmyer, C., Wilton, D. J., Wiltshire, A., Worthy, D., Wunch, D., Xu, X., Yoshida, Y., Zhang, B., Zhang, Z. and Zhu, Q.: The global methane budget 2000–2012, Earth Syst. Sci. Data, 8(2), 697–751, doi:10.5194/essd-8-697-2016, 2016.

Scheffer, R. A. and Aerts, R.: Root decomposition and soil nutrient and carbon cycling in two temperate fen ecosystems, Oikos, 91(3), 541–549, doi:10.1034/j.1600-0706.2000.910316.x, 2000.

Schimel, J. P.: Plant transport and methane production as controls on methane flux from arctic wet meadow tundra, Biogeochemistry, 28(3), 183–200, doi:10.1007/BF02186458, 1995.

Shannon, R. D., White, J. R., Lawson, J. E. and Gilmour, B. S.: Methane Efflux from Emergent Vegetation in Peatlands, J. Ecol., 84(2), 239–246, doi:10.2307/2261359, 1996.

Strack, M. and Waddington, J. M.: Response of peatland carbon dioxide and methane fluxes to a water table drawdown experiment, Glob. Biogeochem. Cycles, 21(1), doi:10.1029/2006GB002715, 2007.

Strack, M., Waddington, J. M. and Tuittila, E.-S.: Effect of water table drawdown on northern peatland methane dynamics: Implications for climate change: northern peatland CH_4 dynamics and climate change, Glob. Biogeochem. Cycles, 18(4), doi:10.1029/2003GB002209, 2004.

Strack, M., Waller, M. F. and Waddington, J. M.: Sedge Succession and Peatland Methane Dynamics: A Potential Feedback to Climate Change, Ecosystems, 9(2), 278–287, doi:10.1007/s10021-005-0070-1, 2006.

Strack, M., Mwakanyamale, K., Hassanpour Fard, G., Bird, M., Bérubé, V. and Rochefort, L.: Effect of plant functional type on methane dynamics in a restored minerotrophic peatland, Plant Soil, 410(1–2), 231–246, doi:10.1007/s11104-016-2999-6, 2017.

Ström, L., Mastepanov, M. and Christensen, T. R.: Species-specific Effects of Vascular Plants on Carbon Turnover and Methane Emissions from Wetlands, Biogeochemistry, 75(1), 65–82, doi:10.1007/s10533-004-6124-1, 2005.

Ström, L., Tagesson, T., Mastepanov, M. and Christensen, T. R.: Presence of Eriophorum scheuchzeri enhances substrate availability and methane emission in an Arctic wetland, Soil Biol. Biochem., 45, 61–70, doi:10.1016/j.soilbio.2011.09.005, 2012.

Sun, X., Song, C., Guo, Y., Wang, X., Yang, G., Li, Y., Mao, R. and Lu, Y.: Effect of plants on methane emissions from a temperate marsh in different seasons, Atmos. Environ., 60, 277–282, doi:10.1016/j.atmosenv.2012.06.051, 2012.

Thormann, M. N., Bayley, S. E. and Currah, R. S.: Comparison of decomposition of belowground and aboveground plant litters in peatlands of boreal Alberta, Canada, Can. J. Bot., 79(1), 9–22, doi:10.1139/cjb-79-1-9, 2001.

Turetsky, M. R., Treat, C. C., Waldrop, M. P., Waddington, J. M., Harden, J. W. and McGuire, A. D.: Short-term response of methane fluxes and methanogen activity to water table and soil warming manipulations in an Alaskan peatland, J. Geophys. Res., 113, G00A10, doi:10.1029/2007JG000496, 2008.

Turetsky, M. R., Kotowska, A., Bubier, J., Dise, N. B., Crill, P., Hornibrook, E. R. C., Minkkinen, K., Moore, T. R., Myers-Smith, I. H., Nykänen, H., Olefeldt, D., Rinne, J., Saarnio, S., Shurpali, N., Tuittila, E.-S., Waddington, J. M., White, J. R., Wickland, K. P. and Wilmking, M.: A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands, Glob. Change Biol., 20(7), 2183–2197, doi:10.1111/gcb.12580, 2014.

Waddington, J. M. and Roulet, N. T.: Carbon balance of a boreal patterned peatland, Glob. Change Biol., 6(1), 87–97, doi:10.1046/j.1365-2486.2000.00283.x, 2000.

Waddington, J. M., Roulet, N. T. and Swanson, R. V.: Water table control of CH4 emission enhancement by vascular plants in boreal peatlands, J. Geophys. Res. Atmospheres, 101(D17), 22775–22785, doi:10.1029/96JD02014, 1996.

Ward, S. E., Ostle, N. J., Oakley, S., Quirk, H., Henrys, P. A. and Bardgett, R. D.: Warming effects on greenhouse gas fluxes in peatlands are modulated by vegetation composition, edited by W. van der Putten, Ecol. Lett., 16(10), 1285–1293, doi:10.1111/ele.12167, 2013.

Whalen, S. C.: Biogeochemistry of Methane Exchange between Natural Wetlands and the Atmosphere, Environ. Eng. Sci., 22(1), 73–94, doi:10.1089/ees.2005.22.73, 2005.

Wilson, D., Alm, J., Riutta, T., Laine, J., Byrne, K. A., Farrell, E. P. and Tuittila, E.-S.: A high resolution green area index for modelling the seasonal dynamics of CO2 exchange in peatland vascular plant communities, Plant Ecol., 190(1), 37–51, doi:10.1007/s11258-006-9189-1, 2007.

Yavitt, J. B., Kryczka, A. K., Huber, M. E., Pipes, G. T. and Rodriguez, A. M.: Inferring Methane Production by Decomposing Tree, Shrub, and Grass Leaf Litter in Bog and Rich Fen Peatlands, Front. Environ. Sci., 7, doi:10.3389/fenvs.2019.00182, 2019.

Yrjälä, K., Tuomivirta, T., Juottonen, H., Putkinen, A., Lappi, K., Tuittila, E.-S., Penttilä, T., Minkkinen, K., Laine, J., Peltoniemi, K. and Fritze, H.: CH4 production and oxidation processes in a boreal fen ecosystem after long-term water table drawdown: CH4 production and oxidation processes, Glob. Change Biol., 17(3), 1311–1320, doi:10.1111/j.1365-2486.2010.02290.x, 2011.

Yu, Z. C.: Northern peatland carbon stocks and dynamics: a review, Biogeosciences, 9(10), 4071–4085, doi:10.5194/bg-9-4071-2012, 2012.

Table 1. Growing season average (standard deviation) water level (WL) relative to moss surface (unit is cm), negative values indicating water level below the surface, growing season peak LAI of sedges (LAI_C) and dwarf shrubs (LAI_D), and projection cover of *Sphagnum* mosses (Spha) (units are $m^2\ m^{-2}$) in different plant removal treatments in wet and WL drawdown subsites. Year 2001 was a calibration year without the WL drawdown and plant removal treatments, which were implemented in 2002. Vegetation treatments: PSCD - plots with intact vegetation, consisting of peat, *Sphagnum* mosses, sedges and shrubs; PSC - plots consisting of peat, *Sphagnum* mosses and sedges (shrubs removed); PS - plots consisting of peat and *Sphagnum* mosses (shrubs and sedges removed), P- plots consisting of bare peat (all vegetation removed).

		~~Control~~Wet				WL drawdown			
Year	Vegetation	WL	LAI_C	LAI_D	Spha	WL	LAI_C	LAI_D	Spha
2001	PSCD	-7 (4)	0.7 (0.3)	0.2 (0.1)	0.8 (0.2)	-5 (3)	0.7 (0.3)	0.3 (0.2)	0.8 (0.1)
2004	PSCD	-10 (4)	0.6 (0.2)	0.3 (0.1)	0.9 (0.1)	-24 (6)	0.3 (0.1)	0.3 (0.1)	0.6 (0.2)
	PSC	-10 (5)	0.7 (0.5)		0.7 (0.2)	-29 (7)	0.8 (0.3)		0.7 (0.3)
	PS	-11 (3)			0.8 (0.2)	-26 (7)			0.7 (0.2)
	P	-7 (4)				-21 (8)			

Table 2. Parameter estimates of the linear mixed-effects model describing (a) the differences in CH_4 flux, water table level (WLT, cm), and total, sedge and dwarf-shrub leaf area index (LAI_T, LAI_C and LAI_D), and CH_4 flux between control wet (WLD0) and water level drawdown (WLD1) subsites and years before (2001) and after (2002-2004) the WLD treatment in plots without vegetation removal, and (b) the differences in CH_4 flux between the vegetation removal treatments in years 2002-2004 and (c) the response of CH_4 flux in year 2004 to leaf area and environmental variables. Vegetation treatments: PSCD – intact vegetation, PSC - plots consisting of peat, *Sphagnum* mosses and sedges (shrubs removed); PS - plots consisting of peat and *Sphagnum* (sedges and shrubs removed); P - plots consisting of bare peat (all vegetation removed).

(a)	WT			LAI_T			LAI_C			LAI_D			CH_4 flux		
Fixed part	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**
Constant (WLD0, Year 2001)	-6.9	2.8	0.018	0.6	0.1	<0.001	0.5	0.1	<0.001	0.2	0.04	<0.001	3.1	0.5	<0.001
WLD1	1.6	1.1	0.174	0.02	0.1	0.878	0.0006	0.1	0.996	0.02	0.04	0.656	0.2	0.3	0.654
Year 2002	-8.2	3.6	0.030	0.2	0.1	0.118	0.2	0.1	0.031	-0.03	0.03	0.366	-0.3	0.6	0.571
Year 2003	-14.2	3.7	<0.001	-0.02	0.1	0.879	-0.007	0.1	0.952	-0.02	0.03	0.642	-2.0	0.6	0.002
Year 2004	-2.1	3.5	0.550	-0.1	0.1	0.364	-0.1	0.1	0.214	0.01	0.03	0.648	-1.3	0.6	0.034
WLD1*Year 2002	-16.6	0.7	<0.001	-0.06	0.05	0.173	-0.1	0.04	0.029	0.03	0.01	0.006	-2.3	0.3	<0.001
WLD1*Year 2003	-11.3	0.7	<0.001	-0.06	0.05	0.192	-0.1	0.05	0.034	0.04	0.01	0.006	-1.1	0.3	<0.001
WLD1*Year 2004	-16.3	0.7	<0.001	-0.1	0.05	0.007	-0.2	0.05	<0.001	0.05	0.01	<0.001	-2.1	0.3	<0.001
Random part															
SD (Measurement day)	7.5			0.28			0.22			0.06			1.2		
SD (Plot code)	2.0			0.25			0.21			0.09			0.5		
Residual SD	2.9			0.19			0.19			0.05			1.1		

(b)	2002			2003			2004		
Fixed part	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**
Constant (PSCD, WLD0)	3.8	1.1	<0.001	1.4	0.3	<0.001	1.9	0.3	<0.001
P	2.8	1.3	0.040	0.1	0.5	0.908	-1.2	0.3	<0.001
PS	6.0	1.6	0.001	1.3	0.6	0.033	-0.4	0.4	0.373
PSC	7.2	1.5	<0.001	1.5	0.5	0.005	0.7	0.4	0.060
WLD1	-2.2	1.0	0.036	-1.0	0.4	0.022	-1.9	0.3	<0.001
P*WLD1	-4.4	1.8	0.020	-0.4	0.7	0.622	1.2	0.4	0.008
PS*WLD1	-8.2	1.9	<0.001	-1.6	0.8	0.049	0.6	0.5	0.256
PSC*WLD1	-9.0	1.6	<0.001	-1.9	0.7	0.009	-0.5	0.4	0.224
Random part									
SD (Measurement day)	1.6			0.7			0.9		
SD (Plot code)	3.0			0.7			0.4		
Residual SD	3.8			1.3			0.9		

(c)			
Fixed part	**Coeff.**	**SE**	**P-value**
Constant (WLD0)	-1.8	0.4	<0.001
LAI_C	2.5	0.3	<0.001
T20	0.2	0.03	<0.001
WLD1	1.6	0.4	<0.001
LAI_C*WLD1	-2.5	0.5	<0.001
T20*WLD1	-0.2	0.03	<0.001
Random part			
SD (Measurement day)	0.5		
SD (Plot code)	0.4		
Residual SD	0.8		

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(a)	WT			LAI_T			LAI_C			LAI_D			CH_4 flux		
Fixed part	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**
Constant (WLD0, Year 2001)	-6.9	2.8	0.018	0.6	0.1	<0.001	0.5	0.1	<0.001	0.2	0.04	<0.001	3.1	0.5	<0.001
WLD1	1.6	1.1	0.174	0.02	0.1	0.878	0.0006	0.1	0.996	0.02	0.04	0.656	0.2	0.3	0.654
Year 2002	-8.2	3.6	0.030	0.2	0.1	0.118	0.2	0.1	0.031	-0.03	0.03	0.366	-0.3	0.6	0.571
Year 2003	-14.2	3.7	<0.001	-0.02	0.1	0.879	-0.007	0.1	0.952	-0.02	0.03	0.642	-2.0	0.6	0.002
Year 2004	-2.1	3.5	0.550	-0.1	0.1	0.364	-0.1	0.1	0.214	0.01	0.03	0.648	-1.3	0.6	0.034
WLD1*Year 2002	-16.6	0.7	<0.001	-0.06	0.05	0.173	-0.1	0.04	0.029	0.03	0.01	0.006	-2.3	0.3	<0.001
WLD1*Year 2003	-11.3	0.7	<0.001	-0.06	0.05	0.192	-0.1	0.05	0.034	0.04	0.01	0.006	-1.1	0.3	<0.001
WLD1*Year 2004	-16.3	0.7	<0.001	-0.1	0.05	0.007	-0.2	0.05	<0.001	0.05	0.01	<0.001	-2.1	0.3	<0.001
Random part															
SD (Measurement day)	7.5			0.28			0.22			0.06			1.2		
SD (Plot code)	2.0			0.25			0.21			0.09			0.5		
Residual SD	2.9			0.19			0.19			0.05			1.1		

(b)	2002			2003			2004		
Fixed part	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**	**Coeff.**	**SE**	**P-value**
Constant (PSCD, WLD0)	3.8	1.1	<0.001	1.4	0.3	<0.001	1.5	0.4	<0.001
P	2.8	1.3	0.040	0.1	0.5	0.908	-0.8	0.4	0.056
PS	6.0	1.6	0.001	1.3	0.6	0.033	1.1	0.4	0.004
PSC	7.2	1.5	<0.001	1.5	0.5	0.005	0.4	0.4	0.373
WLD1	-2.2	1.0	0.036	-1.0	0.4	0.022	-1.3	0.4	0.002
P*WLD1	-4.4	1.8	0.020	-0.4	0.7	0.622	0.7	0.5	0.212
PS*WLD1	-8.2	1.9	<0.001	-1.6	0.8	0.049	-1.1	0.5	0.050
PSC*WLD1	-9.0	1.6	<0.001	-1.9	0.7	0.009	-0.6	0.5	0.256
Random part									
SD (Measurement day)	1.6			0.7			0.9		
SD (Plot code)	3.0			0.7			0.4		
Residual SD	3.8			1.3			0.9		

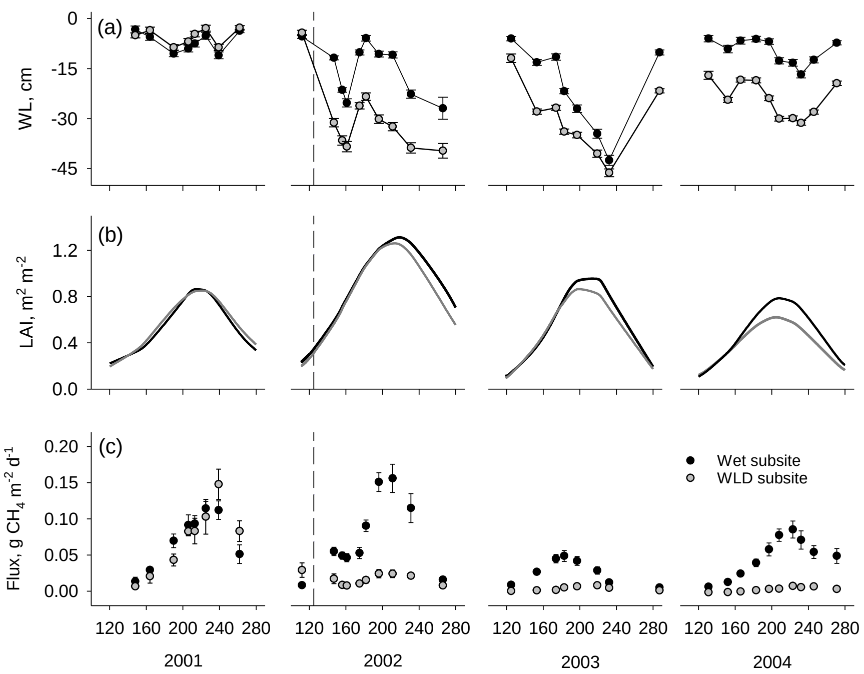

Figure 1. Mean a) water level (WL), b) leaf area index (LAI), and c) CH_4 flux in plots with intact vegetation in wet and water level drawdown (WLD) subsites. Error bars are standard errors of the mean. Units on the x-axis give the day of year. The start of the water level drawdown treatment is indicated with the vertical dashed line in 2002. Water level is negative when it is below the moss surface. Positive CH_4 fluxes indicate emission to the atmosphere.

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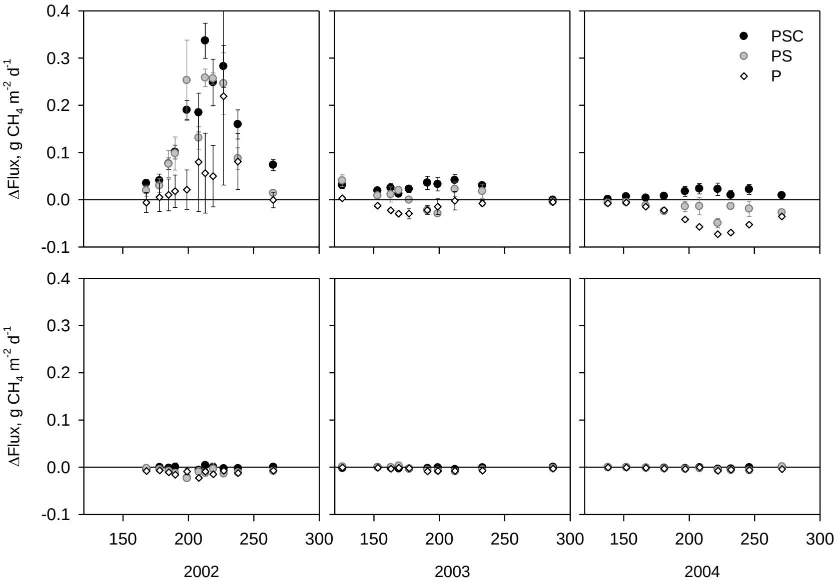


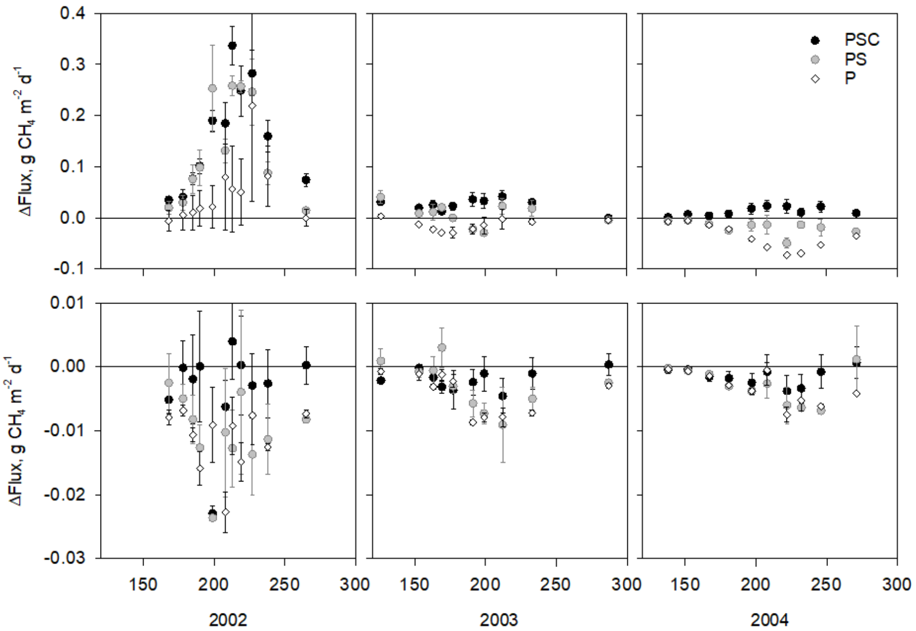
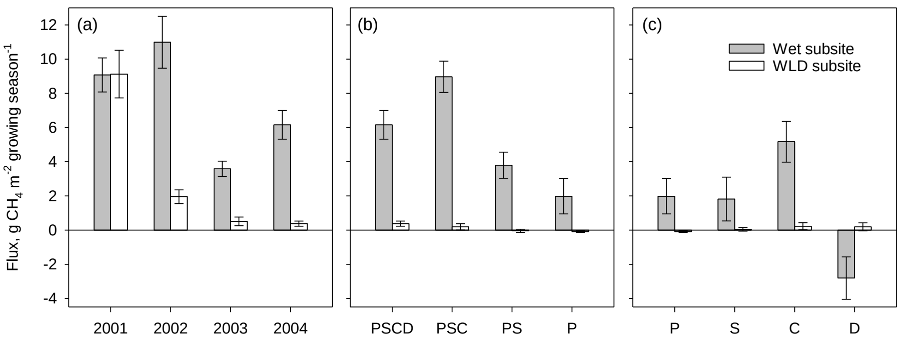


Figure 2. Difference of the measured CH_4 fluxes in plots with plant removal treatments and the mean flux in the plots with intact vegetation on each measurement day in control subsite (upper panels) and water level

drawdown subsite (lower panels). Positive values indicate that fluxes in the plant removal treatment plots are higher than in the intact plots. Units on the x-axis give the day of year. Note the difference scales of the y-axes in the upper and lower panels. Error bars are standard errors of the mean. Vegetation treatments: PSC - plots consisting of peat, *Sphagnum* mosses and sedges (shrubs removed); PS - plots consisting of peat and *Sphagnum* (sedges and shrubs removed); P - plots consisting of bare peat (all vegetation removed). Intact plots consisted of peat, *Sphagnum* mosses, sedges and shrubs. Removal treatments were established in 2002.



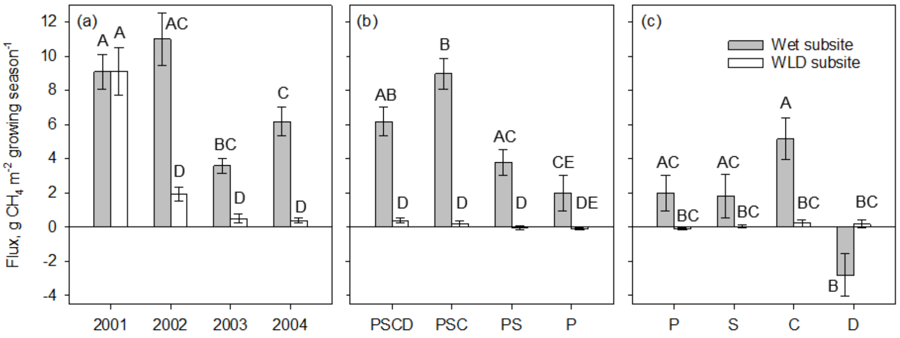


Figure 3. Seasonal (June-September) CH_4 flux (mean ± 1 standard error) in wet and water level (WLD) drawdown subsites a) in plots with intact vegetation (PSCD) during the four study years (2001 was a calibration year before the implementation of the WLD treatment), b) in different plant removal treatments plots in 2004 and c) by each plant group, the contribution of which to the total flux in 2004 was estimated from differences between the different plant removal treatments. Letters above bars denote differences among treatments, where bars with no letter in common are significantly different based on mixed-effects models presented in Table 2 (panels a and b) and based on two-way ANOVA test with Tukey pairwise comparisons (panel c). Plant removal treatments in (b): PSCD - plots with intact vegetation, consisting of peat, *Sphagnum* mosses, sedges and shrubs; PSC - plots consisting of peat, *Sphagnum* mosses and sedges (shrubs removed); PS - plots consisting of peat and *Sphagnum* mosses (shrubs and sedges removed), P - plots consisting of bare peat (all vegetation removed). Plant groups in (c): P – bare peat, S – *Sphagnum* mosses, C – sedges, D – dwarf shrubs.

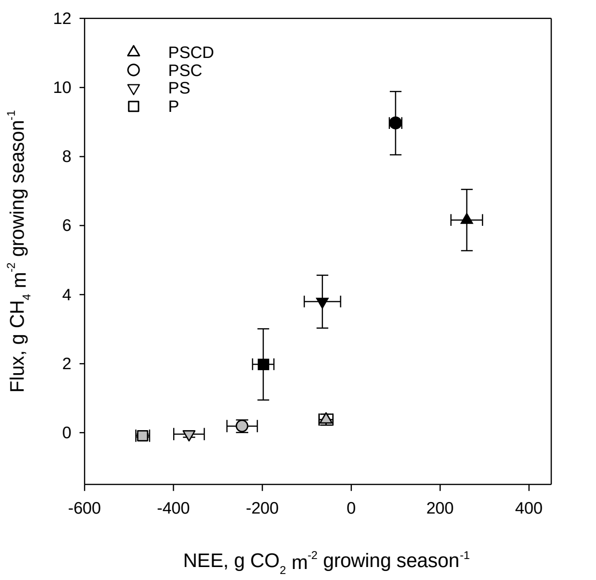


Figure 4. The relationship between the net ecosystem CO_2 uptake (NEE) and methane flux during the growing season 2004 in the different plant removal treatments in wet (black) and water level drawdown (grey) subsites. The values are means ± 1 standard error by each plant removal treatment – water level treatment combination. Vegetation treatments: PSCD - plots with intact vegetation, consisting of peat, *Sphagnum* mosses, sedges and shrubs; PSC – plots consisting of peat, *Sphagnum* mosses and sedges (shrubs removed); PS – plots consisting of peat and *Sphagnum* mosses (shrubs and sedges removed), P -plots consisting of bare peat (all vegetation removed). NEE is positive when the fen is a net sink of atmospheric

CO2. Methane flux is positive when the fen is a source of CH_4 to the atmosphere.

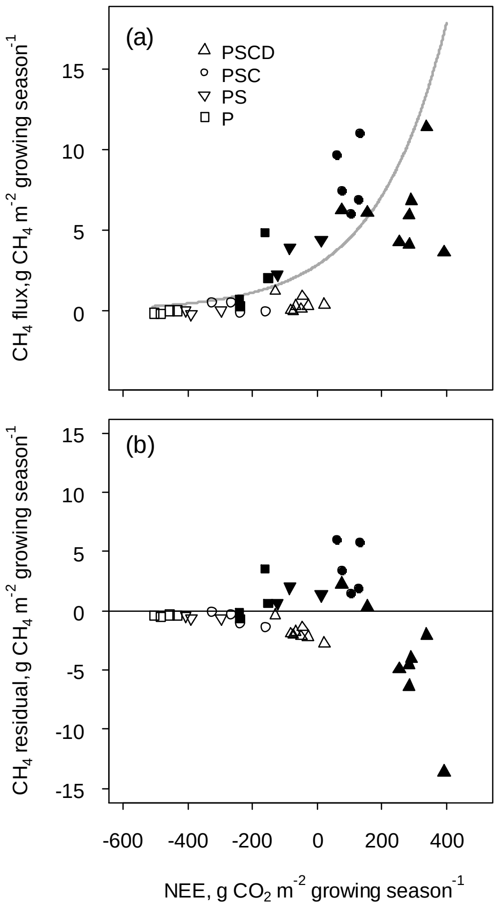


Figure 4. a) The relationship between the net ecosystem CO_2 uptake (NEE) and CH_4 flux during the growing season 2004 described with an exponential model and b) the residuals of the model, in the different plant removal treatments in wet (solid symbols) and water level drawdown (open symbols) subsites-. Vegetation treatments: PSCD - plots with intact vegetation, consisting of peat, *Sphagnum* mosses, sedges and shrubs; -PSC - plots consisting of peat, *Sphagnum* mosses and sedges (shrubs removed); PS - plots consisting of peat and *Sphagnum* mosses (shrubs and sedges removed), P- plots consisting of bare peat (all vegetation removed). NEE is positive when the fen is a net sink of atmospheric CO_2. Methane flux is positive when the fen is a source of CH_4 to the atmosphere.