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Link to publication in VU Research Portal

Download date: 23. May. 2021

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Uncertainties modelling CH$_4$ emissions from northern wetlands in glacial climates: the role of vegetation

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Abstract

The PEATLAND-VU methane (CH$_4$) model has been used to simulate emissions from
continental Europe under different climatic conditions during the last glacial (LG) and
modern climates. Such emissions are reactive to hydrology and the results presented
by this paper demonstrate high sensitivity to vegetation parameters.

Vegetation influences natural CH$_4$ emissions and thus affects its modelling. In wet-
lands ecosystems various interactions between plants and CH$_4$ do take place and each
type of plant is able to affect fluxes in its own way. However, effects of vegetation factors
are rarely properly assessed in detail for large scale emission models. Consequently,
modelling of CH$_4$ fluxes is currently suffering from lack of information regarding vege-
tation processes and parameter quantification, thus explaining uncertain estimations.

Modelled wetland CH$_4$ emissions during glacial climates are highly uncertain re-
garding the extent and type of vegetation cover. Paleobotanical data indicate that past
(glacial) northern wetland plants associations differed considerably from present moss-
rich tundra vegetations. This study examines the effects of wetland vegetation on CH$_4$
emissions, aiming at more plausible flux estimation as well as identifying the sources
and the processes governing CH$_4$ emissions.

1 Introduction

Vegetation affects CH$_4$ fluxes from wetlands modifying both transfer of labile organic
carbon into anoxic soils and transfer of CH$_4$ from soil to the atmosphere. In large scale
CH$_4$ emission models this is often overlooked and it leads to simplistic descriptions of
the wetland dynamics (Berrittella and Van Huissteden, 2009; Van Huissteden et al.,
2009; Petrescu et al., 2010).

Models commonly include two groups of processes that are strongly related to veg-
etation and wetlands ecosystem. The first group refers to production of labile or-
ganic compounds from gross primary production (GPP), used by methanogens in the

anaerobic soil zone. The second group of processes is related to the transport of CH_4 to the atmosphere via plant stems (Walter, 2000). The latter processes may be influential as shown by spatial heterogeneity in arctic flux measurements (Van Huissteden et al., 2005), but its parameterization is complicated (Verville et al., 1998; Joabsson and Christensen, 2001), as all parameters tend to be difficult to measure and not easily available.

Differences in vegetation effectively influence CH_4 fluxes as proved by King and Reeburgh (2002), who documented the relation between CH_4 and net primary production (NPP) in tundra vegetations. Verville et al. (1998) and Busch and Lösch (1999) have also shown the importance of plant transport through their arenchymous tissues and the differences between vegetation types. During such transport oxidation of CH_4 may also occur; as shown by Raghoebarsingh et al. (2005) symbiosis between *Sphagnum* spp. and methanotrophic bacteria allows these mosses to oxidize CH_4 even when plants are submerged. Considerable spatial variations in fluxes related to vegetations differences have been found in northern wetlands flora (e.g. Turetsky et al., 2002; Wagner et al., 2003; Van Huissteden et al., 2005; Van der Molen et al., 2007). Such a variation has been ascribed to differences in NPP, plant transport and oxidation of CH_4 and can be reproduced by plot-scale models, if the vegetation parameters of the model are correctly specified (Petrescu et al., 2008; Van Huissteden et al., 2009).

For global scale model simulations of CH_4 fluxes the relevance of these vegetation-related processes is difficult to determine, although wetlands generally consist of mosaics of plants which may be constant in wide geographic areas (Charman, 2002). Therefore it could be justified to lump vegetation effects all together. However, a precise characterization of vegetation conditions generally remains out of scope for global scale simulations, even though regional attempts have been already made using remote sensing data (Kutzbach et al., 2004; Goel et al., 2008.)

Several published studies have addressed CH_4 fluxes from wetlands during past glacial climate warming phases to explain the possible origin of elevated CH_4 concentrations in the atmosphere at these times, as seen in the ice core records (Van

Huissteden, 2004; Valdes et al., 2005; Kaplan et al., 2006; Harder et al., 2007). Such warming phases may serve also as indications for the effects of present warming on northern wetlands (Berrittella and Van Huissteden, 2009). However, past climatic conditions complicate the effects of vegetation on CH_4 emissions even more, given that these climatic changes may have induced shifts in vegetation patterns or even complete biomes; therefore vegetation and ecosystems which have no analogue today should be surely included together with paleobotanical data. Global vegetation model simulations involving past climates might indeed be used, although these have yielded results significantly different from paleobotanical data, due to such non-comparable situations (Huntley et al., 2003). For instance, in marine isotope stage (MIS) 3–2 peaty deposits in Europe, *Sphagnum* mosses are practically lacking (Behre, 1989; Ran, 1990; Huntley et al., 2003). In this respect, open wetlands flora during most of the last glacial differed markedly from modern, often *Sphagnum*-rich tundra vegetations. The same holds for last glacial environments in Siberia (e.g. Guthrie, 1990; Walker et al., 2003; Zazula et al., 2003; Zimov, 2005).

During MIS 3 wetlands were largely dominated by *Cyperaceae* spp. (Ran et al., 1990) with the occurrence of other, smaller bryophytes. The cause may have been the ubiquitous presence of soils with generally high pH value caused by frequent cryoturbation processes and erosion/sedimentation of fresh, relatively unweathered sediment (e.g. Ran, 1990) and deposition of generally calcareous loess (Van Huissteden, 1990). However, low atmospheric CO_2 concentrations may have decreased the expansion of *Sphagnum* mosses (Heijmans et al., 2005).

The quality of organic matter in the substrate influences microbial metabolism and can act as a major limitation factor in their growth rates (Wagner et al., 2005). Thus, vegetation characteristics affecting the transfer of photosynthesis products to labile organic carbon in the soil may also have a large effect on CH_4 fluxes (King and Reeburgh, 2002), e.g. root exudation and distribution, proportion root/shoots.

We suggest that large differences in vegetation between modern and past northern lowlands may have greatly influenced past northern wetland fluxes and this article

explores the effect of vegetation parameters on a large scale model of CH_4 fluxes. Our modelling experiments on past glacial climates are fully described in Berrittella and van Huissteden (2009), where PEATLAND-VU model output was validated with present-day fluxes from natural wetlands by using the modern climate control experiment of the paleoclimate simulations to drive the CH_4 emission model. The values obtained are annual emissions from the European region displayed in Fig. 1 above and below, respectively for modern and MIS 3 (Stage 3 warm interstadial of LG) climate.

2 The Peatland-VU model and experimental setup

PEATLAND-VU model is a process-based model of CO_2 and CH_4 emissions from peat soils under various climate scenarios. It consists of four sub-models: a soil physics sub-model to calculate temperature (including soil freezing) and water saturation of the soil layers, a CO_2 sub-model, a CH_4 sub-model and an organic production sub-model (Van Huissteden et al., 2006). It contains several vegetation parameters that influence CH_4 fluxes, such as maximum net primary production rate, a factor for all CH_4 that is oxidized during plant transport, shoot and root productions, the fraction of NPP transferred into root exudates (the main substrate for methanogens), and a specific factor quantifying oxidation and speed of plant transport rate (Van Huissteden et al., 2006; Walter, 2000). Several of such parameters are poorly quantified yet strongly determine model results (Van Huissteden et al., 2009). In particular the oxidation factor and plant transport rates are difficult to measure under field conditions and are poorly understood. These parameters are displayed in the following table.

This study focus is on CH_4 fluxes from European wetlands during LG and on the sensitivity of vegetation parameters of the model, such as the oxidation of CH_4 during transport and the input from the roots. Climate data are taken from the Stage 3 climate model runs, which also drive a simple water table model derived from Cao et al. (1996). Stage 3 climate data (average monthly soil surface temperature, snow cover, etc.) and modelled water table are then used as input for PEATLAND-VU.

These climate experiments attempt to simulate the LG interstadial, together with a modern climate control experiment, at a high spatial resolution over Europe. PEATLAND-VU relates to the climate model by output of monthly averaged near surface air temperature, precipitation and evaporation. The PEATLAND-VU output is integrated over a topography-derived wetland map which includes the areas exposed at the lower sea level stands of the LG. These areas have less topographical variation than the present-day land areas; therefore we show the results separately for present-day land and exposed seafloor. For a full description of the model input see Berrittella and Van Huissteden (2009).

3 Effects of plants on fluxes

There are three main pathways -for the CH_4 trapped in soil- to escape to the atmosphere, as described by Chanton (2005);

1. Molecular diffusion, which is dependent on soil characteristics, such as porosity and permeability of the soil;

2. ebullition, effective when a given threshold concentration is reached in water saturated soil, so that gases can coalesce into bubbles and rise to the soil surface;

3. plant transport, providing a fast shortcut to bypass methanotrophic bacteria in oxygenated topsoil, as soon as CH_4 reaches their roots in the most superficial ground layer.

Couwenberg (2009) ranks the importance of each pathway in percentage terms, allocating 2% of the total fluxes to molecular diffusion, while ebullition is held responsible for 48% and plants accounting for the remaining 50%.

As the vegetation density increases, so does the proportion of the flux released to the atmosphere through plants; conversely the value for ebullition related emission decreases (Bazhin, 2003). Otherwise ebullition can be very efficient (Lai, 2009), due to

the low solubility of CH_4 in water and the rapid transfer of bubbles (Boone, 2000) and can be enhanced by a decrease in pressure, either atmospheric (Tokida et al., 2007), or hydrostatic (Strack et al., 2005).

When considering vegetation characteristics, with respect to CH_4 emissions, only limited data are available, although their importance is openly recognized (Hutchin et al., 1996). The widely understood concept of plant functional type appears however to be missing some fundamental aspects and lacks functionalities of the carbon cycle.

To find a more efficient way to group wetland plants, we define a new vegetation classification, aimed at grouping plants according to their CH_4 transport and oxidation capacity. We have therefore translated the plant functional type definition into a simpler ranking, driven by oxidation rate and physical characteristics as emerging aspects and thus better suited to model CH_4 emissions.

For a better classification we define the following three factors which should be taken into account when looking into vegetation and its effects on CH_4 fluxes:

i. The oxidized amount of CH_4; this amount is not necessarily proportional to the length of the stem and is only partly dependent on the time this gas actually spends moving through the plant itself. A major role is played instead by the metabolism of the plant and whether or not there is a bacterial community able to decompose CH_4.

ii. The transport rate; For most vascular wetland plants, aerenchymous tissue in roots and stems allows passive or active transport of gases from the atmosphere to the root system, to exchange reduced soil gases for oxygen (Verville et al., 1998; Joabsson and Christensen, 2001; Oquist et al., 2002). Methanotrophs occupy oxic zones at the root-soil interface (Van der Nat and Middleburg, 1998; Hornibrook, 2009) where oxygen is supplied by plant transport.

Species displaying any combination of low oxidation and fast transport will give CH_4 fluxes higher than those species with high oxidation and low transport

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(see Fig. 2). Transport rate itself cannot be sufficient to define the effectiveness of a plant relative to CH_4 emissions.

iii. The spatial distribution of plants; how species are spread over the wetlands and whether or not they have specific environmental requirements such as appropriate pH in the soil or the ability to survive flooding. Their distribution will clearly effect the contribution to the fluxes of a given area, the emissions being proportional to the abundance of species with certain transport and oxidation characteristics.

Classification of vegetation classes and species

The plants representing each CH_4 Oxidation Class (OC) are typical wetland species. While a single plant is named to be a class, the aim is that it should stand for several plants with the same functional type and comparable rates of produced CH_4 due to physical/physiologic similarities and common characteristics.

We examine two different types of species, *Carex* spp. and *Sphagnum* spp., both know for their extreme diversity of behavior. *Carex* spp. are characterized by high adaptation to anoxic and extremely wet soil conditions, with hollow roots and stems providing high gas transport and low oxidation rate (see Fig. 2). This results in high CH_4 emission rates consistently registered in wetlands where the vegetation is *Carex*-dominated (Van Huissteden et al., 2005, 2009). *Sphagnum* mosses, non vascular plants, display a minimal root system, adaptability to either wet or dry conditions and a well documented symbiosis with methanotrophic bacteria (Raghoebarsingh et al., 2005). Therefore, CH_4 emissions from areas dominated by these mosses are usually less conspicuous than others, as *Sphagnum* ssp. are able to decrease CH_4 fluxes from the soil from 40% to 90% of what would otherwise been emitted into the atmosphere (Raghoebarsingh et al., 2005) and improve the net sink capacity of the area where these mosses are dominant (Glenn et al., 2006).

Shrubs, such as *Betula nana* and *Salix* ssp., have been also taken into account by comparison and they appear to display intermediate behavior, showing neither rapid

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rates of transport nor high oxidation potential. Generally these plants occupy drier sites in northern wetlands and are only adapted to occasional flooding. These are widespread species and ubiquitous in present-day northern wetlands.

Other species groups from drier habitats have not been included here as they cannot affect CH_4 emissions (Holzapfel-Pschorn et al., 1986; Laanbroek, 2009).

Other vegetation characteristics, for instance a fundamental factor such as the leaf area index – LAI, so important in CO_2 exchange quantifications, have no direct effect on CH_4 fluxes.

Although it is difficult to define where production and oxidation of CH_4 actually take place, several studies have attempted it. According to an experiment of Berestovskaya et al. (2005), CH_4 oxidation was found to occur in bog water, in green parts of peat moss and in all the soil horizons investigated, while its production was recorded in peat horizons, in clay with plant roots and in peaty moss areas. The CH_4 oxidation rate exceeded the rate of its production in all the horizons of mossy–lichen tundra and of tussock tundra; methanogenesis instead, prevailed only in sedge–peat moss bogs. Gas consumption by methane-oxidizing bacteria in the vegetation is also supported by data from incubation of marsh plants (*Pontederia cordata* and *Sparganium eurycarpum*). Such species displayed 88% and 63% respectively of CH_4 depletion in oxic root medium, and up to 68% under suboxic conditions (Calhoun and King, 1997).

4   Model runs

The runs performed to compare the emissions of single OC were made using parameter values as reported in Table 3.

These factors are based on the morphology of the plants, reproducing their characteristics for root length, shoot production and physiology related values. Other parameters have been derived from literature or have resulted from model optimization (Van Huissteden et al., 2009).

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In the introduction we mentioned how Stage 3 wetlands vegetation differed considerably from actual northern wetlands (see maps in Fig. 1 for wetland distribution). In order to test the effects of observed differences between MIS3 wetland and present-day moss-rich tundra vegetation we undertook experiments with three dominant covers: *Sphagnum* spp.; *Cyperaceae* spp., and Shrubs.

These values assume 100% cover of each selected OC, but a total value can be calculated according to the real distribution of plants and it results in the order of 4.0–4.2 Gtons. Such number approaches the estimation given by Velichko for the same climate, where annual emissions are quantified at 3.8 Gtons for tundra and forest-tundra areas (Velichko et al., 1998).

We test also other vegetation parameters such as maximum NPP (amount which is transferred to labile soil carbon/root exudates as substrate for methanogenic bacteria) and maximum rooting depth. All these parameters potentially affect CH_4 emissions through their control on substrate availability and on plant transport rate.

5   Results

5.1   Sensitivity of vegetation

All fluxes displayed in the diagrams of this section are calculated in Giga Tons of production per year for the area shown in Fig. 1, under a forcing of factor $Q_{10} = 3$. Climate parameters are always set for MIS (Stage 3 Warm of LG), when not otherwise specified. Other factors are referred to as listed in the previous Tables 1 and 3.

In order to highlight the role of different OC, runs have been performed assuming that each of these plants groups is the only one present, so results show what their final CH_4 flux would be (Fig. 2) for the given climate dataset.

Amounts of CH_4 oxidation take place inside the plants and their rate may affect significantly the emissions of a region dominated by certain species. Figure 3 helps quantifying the impact of this process.

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The diagram in Fig. 4 displays values of Maximum Primary Productivity for vegetation, showing a linear trend of CH_4 emissions with increasing value of this factor.

5.2 Interactions with water table

The water table (WT) strongly influences the CH_4 emissions, which are usually decreasing as water level lowers (Moore et al., 1989, 1993; Roulet et al., 1992). The WT is expected to interact with the representation of vegetation in the model following two different cases: a simple, fixed WT (Van Huissteden, 2004) or a simulated WT based on climate model output (Berrittella and Van Huissteden, 2009), c.f. Cao et al. (1996).

In order to highlight the effects due to the vegetation and those inferred by changes in water levels, the model ran with both fixed and simulated WT values. Figure 5 displays CH_4 transport performed by different type of plants. Such transport shows a slow decrease in flux values for the modelled WT.

In the following diagram, Fig. 6, is examined the effect of root exudation as mass fraction of below-ground CH_4 production. The fluxes increase slightly with higher value of the factor from the land, while the difference is hardly noticeable in fluxes from the seafloor parts.

Illustrated in Fig. 7 a comparison of WT effects and values for the $R0$ factor, which indicates the CH_4 production rate factor for fresh organic C, expressed in µM/h.

The following Fig. 8 shows how root depth influences emissions for two different climates datasets. The land flux for Modern climates also represents the final flux, given the default zero value imposed to the seafloor flux.

Flux rates may vary thus according to the emitting plant. In Fig. 9 below the output of our model runs, with the settings reported in Table 3.

In the final experiment we verified how the temperature may affect the representative plants and therefore their emissions. Results are shown in following Fig. 10.

6 Discussion

Model reconstructions are fundamental tools providing data and assessing parameters whenever proxies are missing, but they are based on assumptions derived from background knowledge and therefore cannot be expected to offer strict accuracy. The delimitations of ice cover extent or ice-free areas, i.e. as close as they might be to recovered data, are subject to huge uncertainties. PEATLAND also uses the outputs from the STAGE 3 Project and BIOME 3.5 as inputs for climate and vegetation respectively, while the area of exposed seafloor is based on other models (such as those from Van Andel et al., 2002; Arnold et al., 2002), so some error propagation has to be accounted for it as well.

Nonetheless, our values are still consistent with those published by Van Huissteden (2004) and in line with earlier estimates by Brook et al. (2000) based on inverse modelling.

Errors may also be attributed to the huge climate variability during the past glacial cycle. According to Helmes et al. (2007), northern Finland was ice-free and permafrost was absent in central Europe at high altitude, while temperatures were present-day like during Isotope Stage 3 warm phases, allowing widespread thaw lake formation. Such eventuality could be explained considering periods with different (warmer) climates in limited areas of central Europe, so to account for higher temperatures than in north-western Europe. Another reason could be that the geographical location itself was already too southern to allow those conditions necessary for permafrost to take consistently place.

With regard to vegetation, the higher uncertainty derives from unknown characteristics which our model reveals to be very important. In the case of paleo-wetland fluxes, vegetation parameters need to agree with paleobotanical reconstructions. The *Sphagnum* mosses are proven to be important in the actual CH_4 cycle, but their contribution cannot be applied to paleo-climates given the lack of support to this hypothesis from the vegetation fossil records, showing no trace of such a plant during interstadials (hence

the exclusion from Fig. 2, stage 3 warm climate). Conversely, *Carex* spp. and sedges in general are proven to be the most effective pathways to transport CH_4 from soil into the atmosphere (Hornibrook et al., 2009). Low transport, high oxidation vegetation (*Sphagnum*-type) produces much lower fluxes than high transport rate, low oxidation vegetation (*Carex*-type), with Shrubs intermediate as summarized in Fig. 9. Furthermore the plant transport rate clearly interacts with the water table input of the model, as shown in Sect. 5.2.

The fluxes increase slightly also with higher root exudation factor, as seen in Fig. 6. For the land fluxes the modelled water table causes fluxes 20% higher than with the fixed value. This difference is entirely due to the effect of applying a different water table model, as discussed by Berrittella and Van Huissteden (2009). An interaction with the water table input and the seafloor fluxes is not observable, given the similar trend even when factor increases. Most likely this is caused by a relatively small topographical variation of the exposed seafloor areas, resulting in less variation of precipitation and evaporation calculated by the climate model. The production of labile organic matter in the root zone had only a minor effect, thus negligible.

Another striking result is a difference in trend. In Fig. 7, a change in the production rates of the land flux is displayed: faster for lower values and slower when the optimal value (0.8) is exceeded. Although sea floor emissions amount to about 1 GTon, the shape of the line is entirely due to the land production.

Figure 5 shows CH_4 transport performed by different type of plants. When fixed water level values are imposed, the fluxes detectably change in both magnitude (that decreases) and trend (which increases). This consideration holds for both land and seafloor fluxes, although the latter involves less conspicuous quantities

Such results agree with the findings of our previous paper (Berrittella and Van Huissteden, 2009) where similar trends were entirely due to water table levels and vegetation cover did not play any role. This interesting interaction with the hydrology settings likely derives from the different values of root depth for each OC.

The diagram of Fig. 8 illustrates how roots influence the emissions from vegetation. A decreasing trend is clearly displayed – even in case of different climate – when the plant roots reach a greater depth, as the below-water table root distribution determines allocation of labile OM and soil-atmosphere transport of CH_4. Such a decrease hints at a lower flux being emitted as consequence of reduced production of CH_4 in the deeper layers of ground, possibly because of less available OM or scarcely present bacterial communities. Interesting to point out is that the total flux of the warm interstadial is less than the one from the modern climate, regardless the fact that contribution from seafloor is zero.

One more experiment (results in Fig. 10) was carried out within this current study on the interaction of vegetation with Q_{10} factor (temperature effect on methanogenic metabolic rate) with progressively increasing values. The change can be seen more clearly when looking at the single oxidation class, thus it is visible how the flux shifts from the average 5% higher for *Sphagnum* mosses to an average of 8% higher for sedges. It is therefore possible to suggest that temperature affects oxidation classes resulting in increased rates of emissions, even when the climatic conditions are staying the same.

In present-day northern wetland environments, a permafrost thaw or an active layer thickness increase are often accompanied by change from *Sphagnum* spp. dominated areas towards a vegetation cover with predominant *Carex* spp. and *Eriophorum* spp., leading to higher CH_4 emissions (Christensen et al., 2004; Van Huissteden et al., 2005). Our results show that such an increase in *Carex* dominated wetland ecosystems may result in a considerable rise of CH_4 fluxes, although this may also be compensated by a larger rate of CO_2 uptake (Turetsky et al., 2007).

7 Conclusions

The overall flux of CH_4 from wetland soils to the atmosphere is not only a matter of hydrology and wetlands area, but also depends on a more complicated balance between all the sources consuming and producing methane within the soil-(vegetation)-atmosphere interface, including all methanotrophic and methanogenic bacteria involved in such reactions. Indeed transport to the atmosphere is both a physical (diffusion and ebullition) and biological process (plant transport) (Lai, 2009). All these processes create a CH_4 reservoir that does not necessarily escape from the soil where it is trapped; much depends on the effectiveness of the pathways described in Sect. 3 of this paper.

Our model experiments show wetland vegetation during the LG to be sensitive to rapid increases of fluxes by changing water table levels and NPP values. For the early Holocene, the decreasing trend of CH_4 (EPICA members, 2004; Ruddiman, 2007) may also be caused by the gradual expansion of *Sphagnum*-dominated wetlands at the expense of other wetland types.

The PEATLAND model indicates that CH_4 emissions of both LG and present climate wetlands are sensitive to assumptions about the vegetation type and all variables related to:

a. soil-atmosphere CH_4 transport

b. within-plant oxidation of CH_4

c. water table levels

Our results show vegetation characteristics cannot be neglected when paleo-wetland fluxes are modelled, due to the close interaction, and therefore paleobotanical information needs to be taken into account to estimate past CH_4 fluxes.

We have also shown that vegetation characteristics may have enhanced the sensitivity of glacial wetland CH_4 emissions to climate change by the predominance of

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strongly emitting vegetation types. Possibly the expansion of *Sphagnum*-rich wetlands contributed to the decrease of the atmospheric CH_4 concentration during the early Holocene.

Assuming the vegetation is steadily interacting with the hydrology allows to explain differences in fluxes which only appear not to be consistent with the given climate conditions of LG. Furthermore, to consider how processes take place in present-day vegetation cover may offer a valid interpretation of fluxes behaviour during interstadials.

Our findings also suggest that the biosphere should be given a primary role in a new generation models of wetland CH_4 emissions and vegetation be considered a main driver in the studied systems. Small scale processes are indeed responsible for large scale effects; therefore detailed knowledge of vegetation can lead to a more realistic and effective representation in models.

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Table 1. Standard parameters used in PEATLAND-VU.

Parameter	Description	Units/Range	References
Plant type	Vegetation type factor for gas transport by plants	Range: 0–15	Walter and Heimann (2000)
Oxidation rate	Fraction of methane that is oxidized during transport in plants	Fraction of 1	Walter and Heimann (2000)
Max primary productivity	taking into account a growing season of 4 months for non-manured Grasslands on peat, the primary may be reduced to approximately 60%	$kgC/m^2/day$	Shaver et al. (1996), Arctic and Alpine Research, 28:363-379
$R0$	Methane production rate factor for fresh organic C	Micro M/h, values: 0.3 to 0.6 at high latitude sites and 2.8 at tropical sites	Walther and Heimann (2000)
Q_{10}	Value for temperature correction methane production	Range 1.7–16	Walther and Heimann (2000)
Shoots factor	Mass fraction of primary production that consists of shoots, the remainder is root growth	Fraction of 1	Shaver et al. (1996), Arctic and Alpine Research, 28:363-379

Table 2. Oxidation classes and their main characteristics.

Plant oxidation class	Description	Transport	Oxidation	Spatial distribution
Carex	Long hollow stem plants, sedges or typha spp.	Rapid and effective	Minimal oxidation	River banks, coastal areas, wetlands
Sphagnum	Bryophyte, mosses	Minimal to no transport	Very high oxidation rates inside plant	Wetlands, in hummocks and pools
Shrubs	Betula nana, willow, vaccinum	Slow transport	Low oxidation	Widely present in moist to dry areas, cannot tolerate anaerobic condition too long
Grass	Vascular plants, *Eriophorum*	Intermediate transport	Minimal to no oxidation	Overall, species resistant to wet conditions

Table 3. Standard and class adapted values for vegetation parameters.

Plant Ox Class	$R0$	Oxidation rate	Shoot factor	Roots depth
Standard value	0.4	0.2	0.7	0.3
Shrubs	0.3	0.5	0.3	0.5
Carex	0.5	0.2	0.5	0.4
Sphagnum	0.1	0.9	0.8	0.1
Grass	0.3	0.1	0.5	0.3
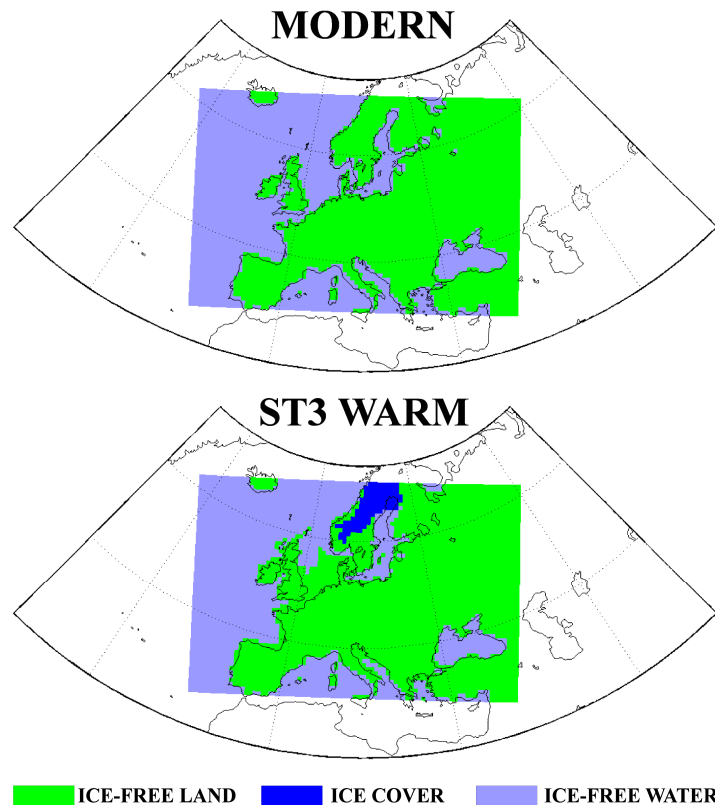
Fig. 1. Topography maps for modern (above) and MIS (ST3 – Stage 3 warm – below) climate model. Emission values are annual and relative to wetland area extent.
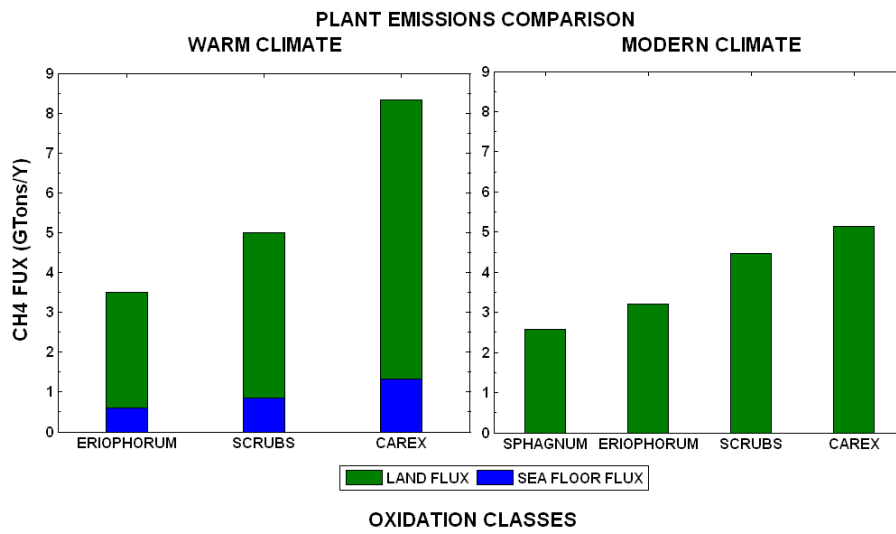
Fig. 2. Fluxes of CH$_4$ deriving from each type of plants, under the conditions of Warm interstadial and Modern climate. Seafloor flux is zero by default for Modern climate.
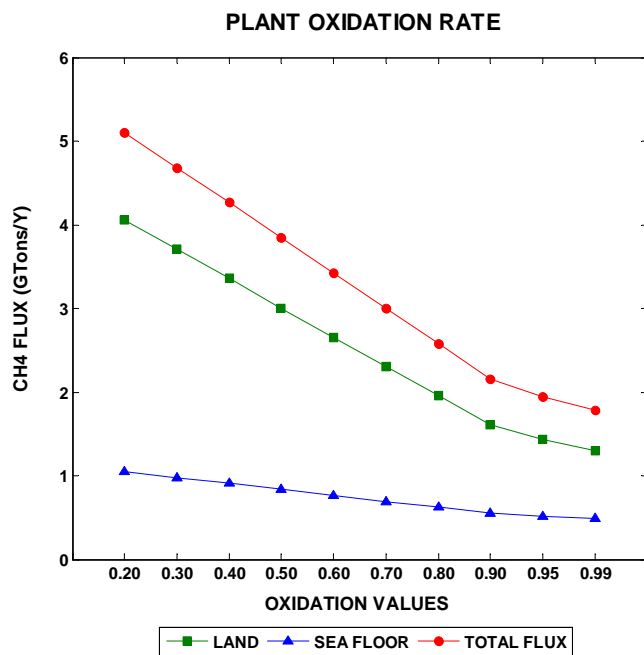
Fig. 3. Rate of emission changes according to varying oxidation rates.
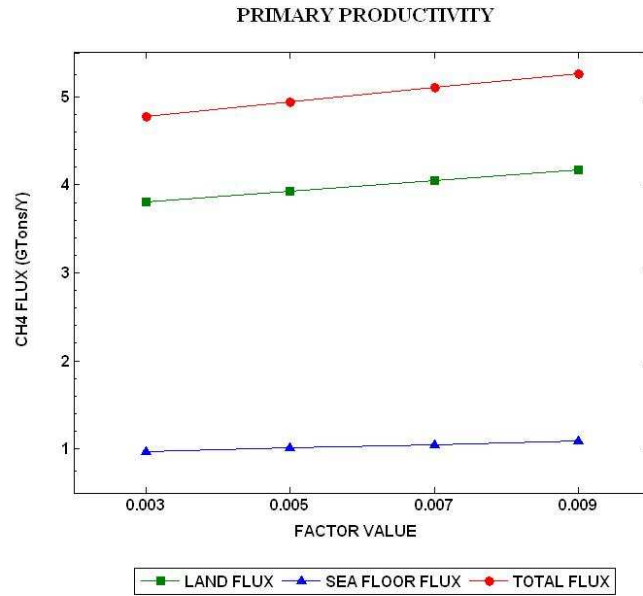
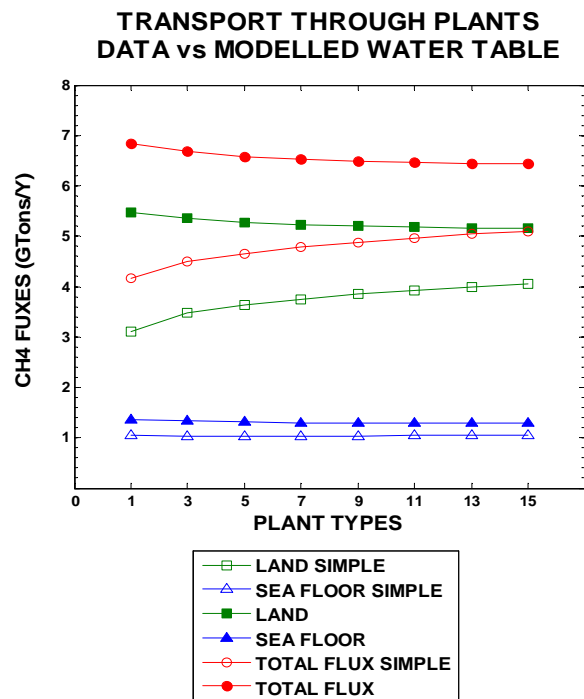**Fig. 4.** Increasing values of maximum primary productivity (kg C/m^2/day). Default value is 0.0057.

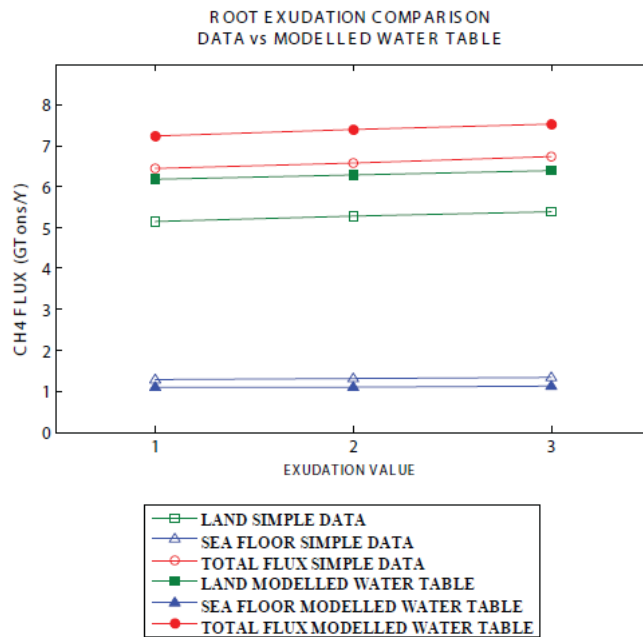**Fig. 5.** The effects of plant transport with fixed (simple) and modelled water table values, showing interaction between plant transport and WT model.

ROOT EXUDATION COMPARISON
DATA vs MODELLED WATER TABLE

Fig. 6. The effects of variation in the root exudates factor as fraction of below-ground production. On the *x* bar, 1 = 0.1, 2 = 0.2 (default value), 3 = 0.3.
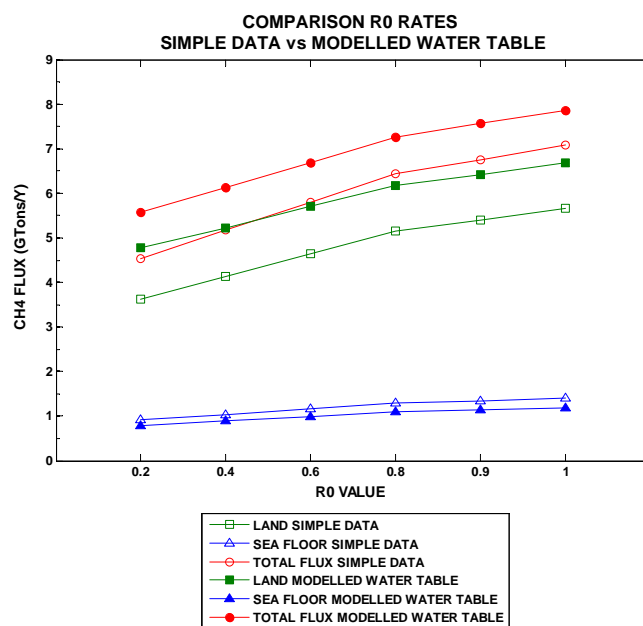
COMPARISON R0 RATES
SIMPLE DATA vs MODELLED WATER TABLE

Fig. 7. Interaction between the water table model and the CH$_4$ production. Default (standard) value is 0.4.

ROOTS DEPTH
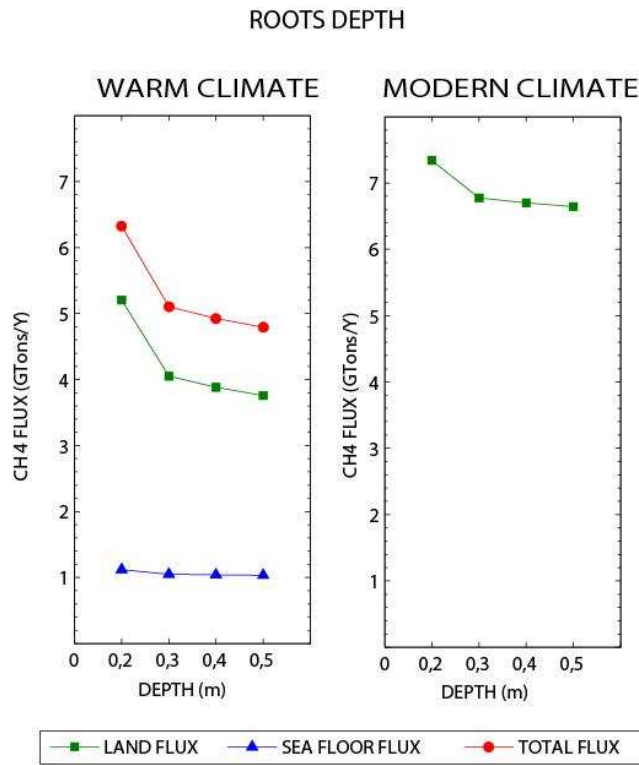
Fig. 8. The depth reached by the roots influences the emissions. Here the comparison between MIS Warm interstadial and Modern climate. Seafloor flux is zero by default for Modern climate.
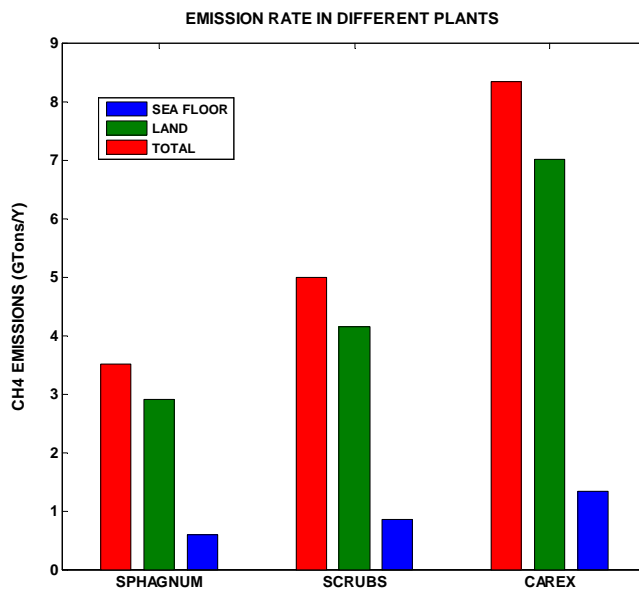
Fig. 9. Emissions from OC plants, displayed by increasing total value, for MIS climate.
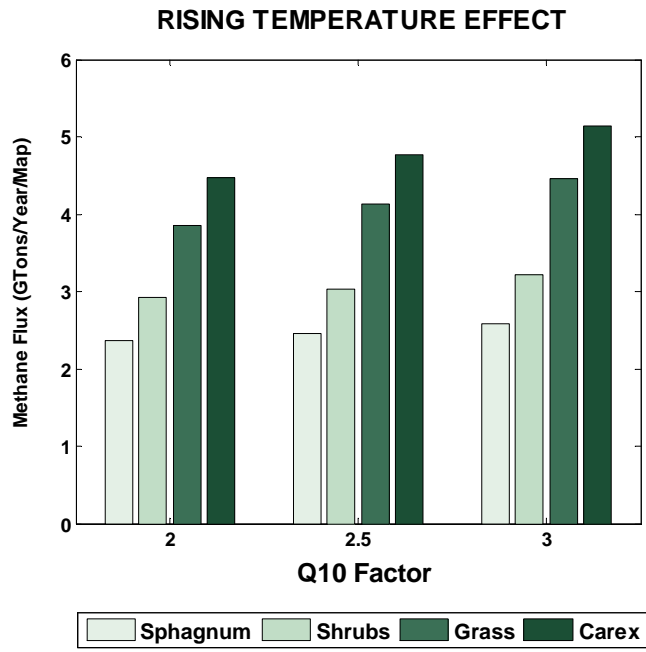
RISING TEMPERATURE EFFECT

Fig. 10. Effects of temperature on OC classes.