Chapter 7

Conclusions

7.1 The initial questions

As discussed in the first chapter, this thesis focuses on northern wetland CH_4 emissions from the past glacial event. These emissions took place under conditions of rapid climate warming comparable with those of today. Just as in the past, even now wetlands play a key role in the global carbon budget because they are a major source of atmospheric CH_4; boreal and arctic wetlands making the greatest impact due to their extent and because they overlie permafrost. Gathering information about the contribution of northern wetlands to past atmospheric composition is thus of critical importance in gaining understanding of the present warming processes and the consequent changes in climate.

The scientific and policymaking communities are concerned about how a temperature rise could affect these environments, in terms of the generation of thaw lakes and the release of carbon so far safely preserved underground, thanks to the presence of permafrost. Nevertheless, the importance of thaw lakes in these regions has been questioned - these lakes might have shifted from sources to sinks during the Holocene [**?**].

The initial questions aimed at finding a plausible explanation for the massive volume of CH_4 recorded in the EPICA ice core data. Such large amounts of gases quickly released into the atmosphere, raise the possibility that more than one single source was involved. The hypotheses were:

1. The "wetland methane hypothesis", which attributes the emissions to northern wetlands;

2. The "tropical wetlands hypothesis", which locates the main source in the southern hemisphere;

3. The "clathrate gun hypothesis", which proposes a release from seafloor methane hydrates or clathrates;

4. The "deglaciation hypothesis", which considers fluxes to have originated from geological sources.

The initial possibilities have been assessed and sorted by their plausibility. Two of the four alternatives were discarded because the size of their effect did not match the data

recorded in the cores of the LGM. Indeed the deglaciation hypothesis, which involves geological sources, is regarded as a minor contribution to the emissions, while the clathrate gun hypothesis is classified as a possible consequence of a heated up world, rather than as the main cause.

Of the two remaining options, northern and tropical wetlands, we focussed on the northern ones. Wetlands are indeed recognized as the main driver, although their effect is given by different rates: the tropical wetlands display the sharpest emissions increase, but the overall output is restricted by their limited extent. Basically, it is a high percentage of increase over a not so high volume of emissions. Conversely, the northern wetlands have the largest area and their mildly increased contribution sums up to a notable amount, given their wide extent and consequent production of fluxes.

Thus, the reason this thesis focuses on the study of northern wetlands is because this ecosystem has the potential to make a major, and disruptive, impact on global climate if global warming were to trigger an exponential spiral of CH_4 emissions. The goal of this study was to broaden the understanding of the ecosystem, by both modelling and analysing data collected in the field.

7.2 Main findings of this thesis

- The originality of this study is the innovative approach of multi-disciplinary sources to improve the understanding of wetlands governing processes and integrate them into a modelling parametrisation.

- The importance of this thesis lays in its contribution of evaluating feedbacks related to methane release from northern wetlands, in regard to present and future climate change. Huge effort has been put into understanding the creation and the evolution of thermokarst lakes in northern tundra.

- The sensitivity test performed with PEATLAND-VU leads to an improved structure and allows us to reassess the role of some of its key parameters. These improvements result in more accurate output.

- Focusing on vegetation cover in the wetland ecosystem allows a better understanding of key components, with particular emphasis on the different effect of the dominant species on the methane fluxes: positive for the Carex spp. and negative for Sphagnum mosses.

- The role of the bacterial communities related to these Sphagnum mosses is highlighted as relevant factor, important enough to be included as a parameter in any model aiming to predict fluxes with sufficient accuracy to match observed field data.

- The thaw lake model is the first two-dimensional model able to successfully reproduce the genesis of thaw lakes and their life cycle in permafrost areas.

- Drainage has a relevant role in limiting thaw lake expansion and its contribution to CH_4 emissions in tundra environments.

- There is a linear relation connecting climate factors to environmental parameters, such as precipitation which controls lake formation and drainage or mean air temperature affecting lakes re-growth and refreezing processes.

- The study on the paleo thaw lake succession is particularly important for two main reasons:

  1. It shows an undisturbed, complete and unique succession of five thaw lakes on top of each other, therefore providing direct information about the full life cycle.

  2. It gives insight into paleo-climate systems and their environmental parameters, and how little they have changed over time.

7.3 Current state of modelling northern wetland CH$_4$ fluxes

The present-day climatic warming is expected to be strongest in boreal and arctic areas [250] and the first hypothesis identifies these areas as a major source of CH$_4$. However, recent approaches have challenged some of the previous conclusions about the effectiveness of the impact from northern wetlands [93]. The overall input of CH$_4$ coming from thawed permafrost, warming of inundated areas and their consequent expansion seems to be smaller than expected, when compared to human emissions [93], even if isolated water bodies formed by thermokarst processes are included.

The increase in CH$_4$emission due to wetlands represents a weak climate-warming feedback within this century. Previous studies [8, 73, 277] also imply a small arctic lake/wetland biogeochemical climate-warming feedback. Riley [219] discussed many deficiencies and uncertainties that currently exist in modelling CH$_4$ production and emission. Fundamental processes resulting in small-scale inundation (e.g. thermokarst lake dynamics) have been shown to increase rapidly and may have a large impact on CH$_4$ fluxes [263]. Buffering effects from lake drainage are not explicitly considered, however these effects would further weaken the already small feedback found [18, 277].

7.4 Summary

Wetlands are currently one of the most complex ecosystems on this planet, ruled by processes not yet fully known and constantly shifting to adapt to climate changes. Investigating the behaviour of these systems during the LGM is therefore a very intricate, but indubitably challenging mystery to unravel. To mention, but few of the issues, there is a scarcity of data on the paleogeography of this specific period, knowledge on ice cap extent is lacking, and the size of the Laurentide ice sheet during the MIS3 is unknown.

These were the most stringent reasons to direct the research on the European continent. However, even Europe has a limited amount of sites which have been studied so far. Therefore, several assumptions had to be made about the wetland extent, when it came to select suitable data to be used as input in a wetland model.

Just like solving a puzzle with some missing - or undiscovered - pieces, tackling this thesis required an innovative approach, which involved modelling as well as sourcing new data, in order to obtain an almost complete picture. Modelling entails a number of decisions to be taken, regarding the input data and their use. This is mostly accomplished by the initial decisions all modellers have to make for each project: which parameters

to consider, what are their maximum and minimum values, which factor is better kept constant instead; all inputs have to be "adjusted" until the model represents - in the best possible way - the system to be studied. These fundamental settings do carry with them, however, some degrees of error and uncertainty, which together will limit the reliability of the results. When coupling models, these errors will unfortunately grow bigger. This concept was taken into account during the work presented in three chapters (2, 3 and 4), which accomplished a re-evaluation of the effect of model structure and parameters, leading to a better accuracy in the output values for the first two; followed by a brand new, working thaw lake model for the forth one.

As the work progressed, it seemed logical to aim at deepening the research by providing very much needed insight and data about the wetland systems and their drivers. This was required by several authors in order to reduce the uncertainty linked to the contribution of the wetlands to the global CH_4 budget [178], strictly dependent on an accurate estimation of their area of extent. Chapters 5 and 6 display an array of new data, very much like mirroring pictures of past and present, both of the same ecosystems. Almost as in a children's game, it became possible to recognize similarities and spot their differences. In the first chapter are given general guidelines of this study, completed by a research background and a full overview of the questions addressed, while this last chapter summarises the main findings.

7.4.1 Chapter 2

The contribution of CH_4 emissions from northern wetlands may have crucially influenced climate warming during the last 800,000 years, as well as during the present phase of global warming. Earth system models are widely used to study how feedbacks between climate and atmospheric composition are generated.

The second chapter therefore investigates the sensitivity of a process-based wetland CH_4 flux model, PEATLAND-VU, to its formulation and the values of its parameters in terms of their impact on the model simulations. This model has been used to simulate CH_4 emissions from continental Europe in previous glacial climates and the current climate alike.

This chapter investigates the sensitivity of modelled glacial terrestrial CH_4 fluxes to:

(a) basic tuning parameters of the model,

(b) different approaches to modelling the water table, and

(c) model structure.

The model structure was compared to a simpler modelling approach based on wetland primary production estimated from a vegetation model (BIOME 3.5), by tuning CH_4 production rate from labile organic carbon and its temperature sensitivity. As result, the modelled fluxes unexpectedly proved to be relatively insensitive to hydrology, but rather sensitive to microbial parameters and model structure. Glacial climate emissions are also highly sensitive to the extent of ice cover and exposed seafloor. It was also assumed that wetland expansion over low relief exposed seafloor areas did compensate for a decrease of wetland area due to continental ice cover. However, the differences influence modelling of fluxes for different climates in unequal ways, making this task even more challenging.

Using a simple NPP-based approach causes smaller changes between glacial climates and a stronger contrast between glacial interstadial climates and the modern warm climate. The hydrological part of the model chain has a smaller effect. Modelling of water

table position and wetland extent should be as realistic as possible, given the availability of topographic and soil data, and should provide the right timing of the minimum, maximum and average of the water table depth, but smaller temporal differences apparently do not have a conspicuous effect.

Another important conclusion from this study is that paleogeography seems to have a considerable influence on modelled emissions, as the model shows that the contribution of exposed seafloor wetlands may be large. This may be for two different reasons:

1- wetland area is decreased by ice cap extension in glacial climates;

2- wetland area is expanded by wetlands on the exposed seafloor.

This valuable result holds particularly for glacial climates older than the LGM. For the LGM, the extent of ice caps, glacial lakes and shorelines is relatively well known, but for older stadials and interstadials this paleogeography is less precisely defined. For the sake of thoroughness, basic parameters relating microbial CH_4 production and oxidation to climate have been considered as well, but the effect of methanogenesis Q_{10} is relatively small. The final results converge in a range of values that suggest that order-of-magnitude approaches through modelling of CH_4 fluxes under different climate conditions are possible, regardless the uncertainties of large scale CH_4 flux modelling. This study focuses on Europe because it serves as a sensitivity test. A full comparison of modelled values should include glacial wetlands over the Asian continent and North America. This, however, would increase the challenge of the task by reinforcing the paleogeographic biases, in particular concerning the ice sheet extent, adding further to the uncertainty already accounted in this work.

7.4.2 Chapter 3

The next question, tackled in the third chapter, was how sharply vegetation modulates the CH_4 emissions; the answer was found amongst mosses and their symbiotic bacteria. The results include a European database of pristine wetland ecosystems, which was effectively used to validate the model results against present emissions. The focus was on the Marine Isotope Stage 3 (MIS 3) interstadials, which are marked by a sharp increase in the atmospheric (CH_4) concentration, as recorded in ice cores. As mentioned before, wetlands are assumed to be the major source of these CH_4 emissions.

Vegetation effects are usually generalized in modelling CH_4 fluxes, however plants do impact the soil-atmosphere exchange of CH_4 and the production of organic matter as substrate for methanogens. For modelling past CH_4 fluxes from northern wetlands, assumptions on vegetation are highly relevant since paleobotanical data indicate large differences in Last Glacial (LG) wetland vegetation composition as compared to modern wetland vegetation. Beside more cold-adapted vegetation, an interesting conclusion is that *Sphagnum* mosses appear to be much less dominant during large parts of the LG than at present, which particularly affects CH_4 oxidation and transport.

To evaluate the effect of vegetation parameters, PEATLAND-VU was used to simulate emissions from wetlands in continental Europe during LG and modern climates. The effects of parameters influencing oxidation during plant transport (f_{ox}), vegetation net primary production (NPP, parameter symbol P_{max}), plant transport rate (V_{transp}), maximum rooting depth (Z_{root}) and root exudation rate (f_{ex}) were thoroughly tested. The results show that CH_4 fluxes are sensitive to f_{ox} and Z_{root} in particular. The effects of P_{max}, V_{transp} and f_{ex} are of lesser relevance, while interactions with water table mod-

elling are significant for V_{transp}.

For the sake of completeness, different wetland vegetation types for Marine Isotope Stage 3 (MIS 3) stadial and interstadial climates and the present-day climate were coupled to high resolution climate model simulations for Europe. Experiments assuming dominance of one vegetation type (*Sphagnum* vs. *Carex* vs. Shrubs) show that *Carex*-dominated vegetation can increase CH_4 emissions by 50% to 78% over *Sphagnum*-dominated vegetation depending on the modelled climate, while for shrubs this increase ranges from 42% to 72%. Such experiments did successfully show that in Pleistocene climates CH_4 fluxes were sensitive to wetland vegetation characteristics: oxidation during soil-vegetation-atmosphere exchange, NPP, rooting depth and plant-mediated transport rate. Oxidation proved to be a major parameter which effectively modifies fluxes.

Flux differences between *Carex*-dominated and *Sphagnum*-dominated wetlands may be large, 50% to 78% relative to Sphagnum. The results did show that changes in wetland vegetation may alter CH_4 fluxes drastically. Consequently, during the LG northern wetlands may have had CH_4 emissions similar to their present-day counterparts, despite a colder climate. This opens room to speculation that these mosses could be an environmental tool to counterbalance the ongoing global warming. Shifts in dominant wetland vegetation, therefore, may have driven changes in wetland CH_4 fluxes, in the past as well as in the future.

7.4.3   Chapter 4

In the fourth chapter, all background studies about wetland ecosystems and their embedded processes were combined in order to create the lake model. All basic parameters that can affect the formation and the time span of a lake were successfully assembled in a model that simulates new thaw lakes formation, while taking into account drainage and other major disturbances / wind/ microrelief. Thaw lakes in permafrost areas are sources of CH_4 [207, 196, 1, 305, 257, 163], as they develop mostly in sedimentary lowlands with permafrost and a high excess ground ice volume, resulting in large areas covered with lakes, and drained thaw lake basins (DTLB's)[119, 50]. Their expansion is enhanced by climate warming, and gives increased methane emissions, adding a positive feedback on future climate change [1, 305, 163]. This is the first 2-dimensional landscape scale model that includes the entire life cycle of thaw lakes: lake initiation, expansion, drainage, and eventually repeated lake formation. Application of this model to past and future lake expansion in a continuous permafrost area in northern Siberia shows, that lake drainage strongly limits lake expansion, also when continuous permafrost remains present. This restricts CH_4 emissions from thaw lakes and lowers estimates of future fluxes originating from thaw lake expansion. These simulations are restricted to continuous permafrost, where rapid lake formation is likely [248] and which contains the largest area of ice-rich permafrost. Lake drainage proves to be a critical process. The structure of this model only considers lake drainage combined with lake expansion on the drainage system. Active effects of drainage by channel erosion is not included, nor is underground drainage of lakes through taliks (unfrozen parts in the permafrost). Future warming will result in conversion of continuous permafrost areas to discontinuous and permafrost-free areas, where drainage by groundwater flow is likely to become more important [305]. Despite the deliberate omission of process details, the model allows us to estimate future arctic CH_4 fluxes from lake expansion and shows as well that better quantitative data on ground

ice distribution, thaw lake initiation and expansion is crucial to quantify future arctic lake expansion. Moreover, it is shown that even stabilization of anthropogenic greenhouse gas emissions cannot mitigate the transformation of arctic permafrost landscapes, once permafrost destabilisation is started. Although the CH_4 emissions appear less alarming than suggested by previous estimates, lake expansion on the scale predicted by these findings will profoundly affect permafrost ecosystems, in particular wildlife habitats. Even though this model was criticized for being too simplistic in its approach, it was a valid step towards a better understanding of such a complex matter.

7.4.4 Chapter 5

The fifth chapter explores how the current ecosystem functions at present, by adopting an innovative method based on a multidisciplinary approach. The aim is to change the perspective from which wetlands are seen, to find new insight about the processes ruling them, as well as providing new data to the scientific community. One of the major issues in this field is that most models have a one-dimensional structure, treating wetlands as a single vegetation/soil/micro-relief unit, although clearly the processes they attempt to describe are three-dimensional. Such models may therefore miss the dynamic responses to warming conditions [221], responses such as localized changes in soil moisture, vegetation shifts, water interactions with surface landscape [228]. In spite of several calls to cover these gaps in the peatland dynamics [315, 228], it is difficult to find studies attempting to offer a broader overview of how all parameters interact in this type of ecosystem, to indicate spatial variability in CH_4 emissions to vegetation and micro-relief. This is exactly the direction this study follows, using a particular site: Kytalyk, a natural reserve located in Siberia, in an ancient drained thaw lake basin. The focus area is well studied, covered by eddy covariance data confirming the particularly high level of CH_4 emissions, which stands out even compared to the rest of the region.

The spatial variability of the plant species has an effective impact on CH_4 emissions, because the vegetation cover relates to ground ice and surface runoff patterns, affecting the CH_4 production. Soil and vegetation characteristics are identified as the main driver for most of the spatial variation and its characteristics can be used to predict which CH_4 flux processes are likely to develop in a given wetlands ecosystem.

All signs point to a vegetation cover that may strongly interfere with the CH_4 fluxes, by drastically reducing them (as in the case of Sphagnum mosses) or letting them escape without oxidation (as for sedges). This agrees with the results of the third chapter of this thesis: model runs had more accurate values, compared to selected validation sites, whenever the experiment was set with initial parameters that accounted for the differences in the vegetation cover. In wet areas, the presence of Sphagnum mosses modulates the CH_4 fluxes due to the large consumption rates of methanotrophic bacteria. These communities of Archaea play an important role that seems unaffected by geographical location.

Permafrost wetland ecosystems differ in some fundamental aspects from other wetlands, by showing a distinct microrelief as a result of close interaction between vegetation, ground ice, active layer thickness, soil hydrology and nutrients on a small scale. This site presents some deviations in comparison with the typical polygonal tundra, ubiquitous in high northern wetlands within the continuous permafrost zone. Next to low and high centred polygons, an alternation of low palsas and shallow vegetated drainage channels appears to dominate the surface pattern. Moreover, the typical low centred polygon re-

lief commonly seen over wide areas in arctic wetlands, may degrade into other types of wetland surface, such as the palsa/vegetated channel micro-relief found at the site studied here. Therefore, based on these observations, this study hypothesized these differences may be a more mature stage of polygon development, resulting from a further maturity stage of the drainage system interfering with the polygons.

7.4.5   Chapter 6

The sixth chapter presents a study of a succession of lake deposits dating from the Middle Wicheselian and it combines exposure data and drilled cores. One of the cores is outstanding because it contains five different cycles of thaw lakes, providing an unprecedented overview of their evolution over time. Thaw lakes develop in sedimentary lowlands as ice-rich permafrost thaws. Their formation can be initiated by any process interfering with the soil heat balance, and release large amounts of CH_4, resulting from the decomposition of organic matter from melting permafrost. A similar expansion of thaw lakes may have contributed to sharp rises of atmospheric CH_4 during climate warming phases at the end of the Last Glacial, as recorded in ice cores. Paleo-thaw lakes dating from the Last Glacial (Oxygen Isotope Stage 3) have been found in western and eastern Europe, while in the south of the Netherlands older deposits (ages up to 400 ka) with similar facies are likely to share the same origin. Like arctic present-day thaw lakes, these paleo-thaw lakes may have been important sources of CH_4.

Thaw lake formation may have occurred throughout the periglacial zone in the Middle Weichselian, triggered by climate oscillations at that time; however, hard evidence is lacking because of the fragmentary nature of the associated paleoclimatic records. Cyclic behaviour of the thaw lake system itself cannot be excluded, but is less likely, because the permafrost may have been relatively thin and could have been penetrated by lake talik formation. In contrast to the Middle Weichselian, permafrost degradation at the termination of the LG occurred under drier conditions in Europe.

The work done analysing these sections from Hengelo demonstrates that during the Middle Weichselian thaw lakes developed in ice-rich permafrost, similar to present-day permafrost areas. In at least one case, unequivocal evidence of a thaw lake origin of lacustrine sediments is found, in the shape of ice wedge pseudomorphs, located directly below the lake sediments. Further information comes from sedimentary structures of the lake infilling, indicating the presence of actively eroding banks, thus providing sediment to shelf-like benches along the lake shore. The lake may have been at least 2.5 m deep. These lake deposits near Hengelo may have resulted from repeated new formation of lakes, but more likely were part of a larger lake system, frequently shifting shape by expanding and contracting over time. Indications of interference with the fluvial system have been found, common also in present-day thaw lake systems. Lake infillings range from largely clastic (silts) with a few percent of organic matter to organic (gyttja), or silts with interbedded (benthic) mosses. The isotopic signature indicates mostly organic matter that has not been strongly decomposed, supporting the important role of these lakes in the CH_4 global budget.

Processes of formation and rapid expansion of thaw lakes are generally linked to sharp rises of atmospheric CH_4; this study successfully contributes an array of new data in agreement with such a statement. Significant clues, to help understanding the processes governing CH_4 emissions, can be given by each of these data: the isotopic values found in

the samples, together with their OM content; the drier climate of the Middle Weichselian; the rapidly changing environment of the investigated area. All of them are valuable inputs for future modelling experiments, in order to reconstruct climate and environment of Middle Weichselian. The evidence of paleo-thaw lake successions of the Last Glacial in Europe, their sedimentary facies and their possible modern analogues are a valid indication to evaluate the potential contribution from older thaw lakes to atmospheric CH_4 fluxes from northern wetlands.

7.5 A critical look

Uncertainty in answering the research question arises from several sources: the simulated grid fractional saturation in models that have water-saturated soil, that is of first-order importance to CH_4 emission estimates; spatially heterogeneous field-based CH_4 emission flux; parameters associated with the temperature dependence of CH_4 production. A possible increase of geological emissions from shallow subsoil CH_4 or hydrate reservoirs by permafrost warming on land or sub-sea permafrost is not considered. Although the satellite reconstruction provides a good estimate of global inundation, it is inadequate in characterizing small, isolated water bodies, including some of those formed by the thermokarst process. Other factors that could be important but not explicitly considered include: the insulating peat [160] and fire disturbance for permafrost thaw as well as soil moisture and vegetation dynamics, and methane oxidation removal processes ongoing in soils, sediments and water. According to the modelling outputs for present-day climate change, the additional warming would be no greater than $0.1°C$ by 2100. Furthermore, for this temperature feedback to be doubled (to approximately $0.2°C$) by 2100, at least a 25-fold increase in the CH_4 emission that results from the estimated permafrost degradation would be required [93]. Major uncertainties in comparing past and present northern wetlands are summarized in the following Table 7.1 on page 126.

Table 7.1: Differences between past and present wetlands.

PAST	PRESENT	APPROACH
Wetland distribution is uncertain due to missing paleogeography data (ice cover, exposed seafloor)	Wetlands distribution is uncertain, particularly in regards of open water distribution	Used data on paleogeography whenever available, assuming that flat relief produces wetlands
Vegetation may have been different in the past (e.g. presence/absence of species like Sphagnum)	Vegetation composition is known, but not used in detail in models	Tested model with effects of various vegetation sets, comparing actual and paleobotanical data
Detailed climate data: temperature, precipitation, snow cover	Station and reanalysis data available	Used paleoclimate model results (only available over Europe)
Extent of permafrost not exactly known	Extent of permafrost better defined	Model computes soil temperature and active layer
Water bodies / thermo-karst presence poorly known; only very local observations	Present extent better defined, but data on rates of lake changes and their life cycle is very limited	Model with basic approach, inventorization of paleo-thermokarst lake data
Methane producing and oxidating bacterial population unknown	More data available on production rates and temperature sensitivity	Used present-day data in modelling, data collection, sensitivity experiments
Soil hydrology uncertainties	Strong relation between soil hydrology, microrelief, vegetation and excess ice content in the soil	Study in present-day arctic environment on soil ice/ vegetation/relief/hydrology relations, sensitivity experiments with model
Hydrates and deep permafrost methane	Minor emissions today	Not modelled, conditions do not apply

7.6 Going forward

This study improves the knowledge of permafrost processes in Earth system modelling and contributes to a better understanding of the role of arctic land surfaces in the climate system. Future modelling work would benefit from the inclusion of more detailed wetlands processes linked to permafrost [220] and for this purpose specific small-scale data are required. The work done in order to validate the thaw lake model provided insightful understanding about the evolution of thaw-lake life span and the surrounding environment. However, it also highlights that there is hardly any evidence on present-day lake change rates in permafrost regions. What if it were possible to correlate the evolution of these lakes to climate changes? What if the major parameters - the main drivers in the model - could be used as pointers, measuring tools or even as a proxy for global warming? Particular attention should be paid to furthering the understanding of key parameters like Q_{10} and vegetation cover (or plant functional types), as well as the bacterial activity related to methanogenesis processes. Comparing the LGM/MIS3 to the present situation, it is possible to spot one main difference in the vegetation. Sphagnum mosses were almost absent during the last glaciation. It is known by few examples of peat remnants in glacial successions that these mosses were still abundant in the Early Weichselian [27]. But there is very little fossil data for sphagnum peat after that period, their absence being explained as affected by low CO_2 atmospheric concentrations rather than shifted temperature. Indeed the relation of these mosses with CO_2 is not well known, as high levels of the gas could be detrimental for them [104], as well as trigger their growth [184]. Nowadays however, these mosses are spread worldwide. Why? Were they triggered by the global warming, as a natural response to the increasing temperature? A question worth answering with further research.

To exploit to the fullest the benefits of this approach, it should be deployed on a larger area. Starting point would be a site with an available database of CH_4 emission or a monitoring device such as any meteorological tower, able to detect and measure fluxes of CH_4 and CO_2. It would be very interesting to further the multidisciplinary methodology to validate data and fine tune the values for factors and parameters to be used for modelling purposes, so to attain a better accuracy.

Drilling over a grid of a larger extent would demonstrate if lateral changes in the different layers of the ground do have a considerable range, or are instead to be considered just punctual variations. It would also give a detailed mapping of the active layer depth. The extracted cores should be used to obtain soil samples labelled according to how deep they are, i.e., 5 cm intervals, analysed and then used to obtain a 3D map of the area, which would contain all harvested data and would therefore illustrate any gradient in the properties of the soil. This includes ice, water and OM content, changes in the grain size and mineralogical composition, presence of bacterial communities, radio dating and presence of specific cryo-structures. On the surface, a mapping of water bodies and runoff patterns could be studied in relation to the active layer depth in the soil, while their drainage system could give clues about the evolution of the region. Variations and spatial distribution of the vegetation cover could be taken into account for CH_4 emissions, by use of chamber measurements. All this new information would be available for environmental models.

A more ambitious aim could be achieved as well. By performing all these analyses, not only could it be possible to validate the emissions measured by the external tower and to account for environmental corrections, if mismatched; but the area would also have

been fully assessed in terms of Green House Potential. Essentially, we would have calculated the threshold, the maximum potential value of GHG this area contains, considered as carbon reservoir, and could be released into the atmosphere. It could be used to estimate the expected range of emissions, based upon specific environmental parameters, such as precipitation or air temperature. It could be a valuable tool to obtain reliable data, predicting the wetlands emissions under various global warming scenarios.

Scientific network / Affiliations

This project was embedded in the research programmes of the Cluster Earth and Climate of the VU University, Amsterdam. As part of the Department of Hydrogeology and Geoenvironmental Sciences, the project was connected to national and international research programmes on water and the carbon cycle in which the department participates (BSIK MME1 programme, TCOS, CarboEurope, Greencycles, Darwin Research Centre for Biogeology). In some cases there has been close cooperation with PhD students in these programmes. This research was also related to projects on paleoclimate modelling (rapid climate warming in the past) and climatic impact on fluvial systems. The project was part of the research programme of NSG (Netherlands Research School of Sedimentary Geology), research themes 'Lithosphere, Biosphere, Climate and Surface processes' and 'Bio-geochemistry and water' and has been funded by the NWO, grant nr.815.01.007.