***Chapter Draft**:* Peatlands and Climate Change

Authors: Angela V Gallego-Sala, Robert K Booth, Dan Charman, I. Colin Prentice and Zicheng Yu

1. Introduction:

The fundamental reason for the presence of peatlands is a positive balance between plant production and decomposition. Organic matter accumulates in these systems because prolonged waterlogged conditions result in soil anoxia (i.e., exclusion of oxygen), and under these conditions decomposition rates can be lower than those of primary production. Climate therefore plays an important role in peat accumulation, both directly by affecting productivity and decomposition processes, and indirectly through its effects on hydrology/water balance and vegetation (for a summary, refer to Yu, Beilman & Jones 2009). Climate provides broad-scale constraints or controls on peatland extent, types and vegetation, and ultimately, ecosystem functioning, carbon accumulation, greenhouse gas exchange and all of the other ecosystem services that peatlands provide.

Peatlands can play a vital role in helping society mitigate and adapt to climate change, because of their carbon and water regulating functions (cross ref to other chapters), while at the same time, the climate sensitivity of peatlands makes them potentially vulnerable to future global warming and changes in spatial and temporal patterns of precipitation, especially if they are in a degraded state. Climate change is likely to alter the hydrology and soil temperature of peatlands, with far-reaching consequences for their biodiversity, ecology and biogeochemistry. Their involvement in the global carbon cycle will also be affected, with the possibility of drier conditions allowing peatland erosion and increases in CO_2 emissions that would result in a positive feedback to climate change (Turetsky 2010). This highlights all the more the need for restoration to ensure peatlands are resilient to change so that they continue to deliver ecosystem services for human well-being.

This chapter describes the interactions between climate and peatlands, in three sections. The first section explains how present climate influences peatlands, by documenting how climate limits peatland geographical extent globally, and how bioclimatic envelope models can predict peatland extent. We indicate how each type of peatland is linked to a specific climate range, and introduce the concept of ecosystem function in relation to climate. The second section looks into the past. It describes how peat preserves a record of past climates and environmental conditions that can be deciphered to reveal the history of peatland vegetation, hydrology and carbon accumulation changes in relation to past changes in climate. We highlight lessons that can be learned from the palaeorecord preserved in peat. The final section discusses the potential effects of present and future climate change on peatlands, their extent, carbon accumulation rates, fire frequency, water table and greenhouse gas exchanges. We also consider how increases in sea level and CO_2 concentration, and decreases in the extent of permafrost, are likely to affect peatlands.

Modern climate controls of peatland distribution and type

2.1 Climate and peatland extent: the basis for bioclimatic envelope models

The geographical distribution and extent of peatlands is largely determined by climate, although at local and regional scales, topography is an important factor that controls peatland boundaries through its effects on hydrology and on mesoclimate. Peatland ecosystems exist therefore within well-defined climatic thresholds (Wieder & Vitt 2006; Yu, Beilman & Jones 2009) (Figure 1 and 2). Because peatland extent is dependent on climate, it is possible to describe their distribution using a bioclimatic envelope model. This type of model characterizes the climatic tolerances limits or thresholds of a species or ecosystem in terms of one or more climatic variables, and has successfully been used to map the regional distributions of peatlands in Canada (Gignac, Halsey & Vitt 2000) and Fennoscandia (Parviainen & Luoto 2007). Bioclimatic envelope models can also be used to project potential changes of peatland extent under future climate scenarios (e.g., Sykes, Prentice & Cramer 1996; Berry *et al*. 2002; Tuck *et al*. 2006; Huntley *et al*. 2007).

There are two kinds of bioclimatic envelope models: statistical and process-based. Statistical envelope models correlate the current species spatial distribution with climate variables using various statistical techniques. The second type are process-based envelope models in which limit values are fitted for selected bioclimatic variables, chosen because of their relation to known or hypothesized physiological causes of the distributional limits (Pearson & Dawson 2003). Process-based envelope models are advantageous because of the direct application of the causal variables that control the distributional limits. They are also simple and parsimonious, i.e. they use a small number of parameters, because separate limits can be fitted to each bioclimatic variable. Process-based models have been used to predict the potential distribution of tree species in Europe under scenarios of future climate change (Sykes, Prentice & Cramer 1996).

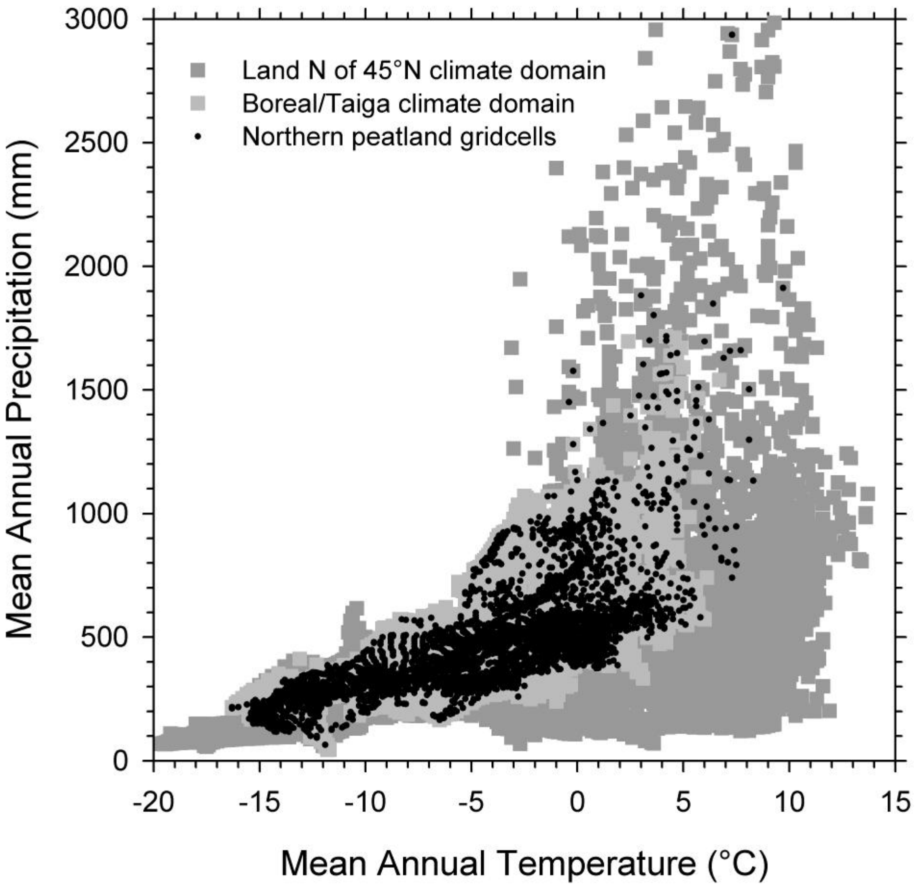

Figure 1. The climate space of mean annual temperature and precipitation (T-P space) of total land area north of 45°N latitude (dark gray), the boreal/taiga biome (light gray), and northern peatland regions based on 0.5° x 0.5°-gridded instrumental climate data for the period 1960–1990. Adapted from Yu, Z.C., D.W. Beilman and M.C. Jones. 2009.

The limitations of bioclimatic envelope models for species distribution have been extensively described and mainly stem from neglected factors such as biotic interactions, evolutionary change or dispersal ability, and it has been suggested that dynamic vegetation models are better equipped to predict changes in species distribution (Woodward & Beerling 1997; Davis *et al*. 1998; Pearson & Dawson 2003). For applications to understanding peatland distribution, bioclimatic envelope models may not be able to capture all peatland types, for example, those peatlands such as percolation mires or valley mires that are strongly dependent on topography. It is also important to highlight that peatlands are resilient and adaptive ecosystems, able to respond to and survive variations in their environment and their exact response to changes in the climate remains ambiguous (Lindsay 2010a). If a bioclimatic model predicts that a peatland falls outside its bioclimatic envelope in the future, it would not imply a sudden and complete loss of the peatland habitat, its carbon storage capabilities or any other ecosystem service it presently provides, because of the resilience of the established peatland system. Although bioclimatic models are unable to make predictions about rate of carbon loss or possible resilience of peatlands to a changing climate, they can help identify which peatlands may be more vulnerable to future climate changes.

2.2 Climate limits and controls of peatland types

Climate influences not just the extent but also the type of peatland that is found in each region, because peatland type is primarily a function of vegetation and water source (Wieder & Vitt 2006). Vegetation affects the amount of photosynthesis, the quality and amount of organic matter produced, as well as the physical properties of the peat. Precipitation is the only source of water in many peatlands (i.e. ombrotrophic peatlands or bogs) (Natural Wetlands Working Group 1988). This means that a combination of high precipitation frequency (high number of wet days) and low evapotranspiration (cool wet climates with low relative humidity) maintain high water tables and anoxia. However, ombrotrophic peatlands can also form in much warmer climates if there is adequate precipitation (e.g. in tropical areas such as Borneo). Other types of peatlands (minerotrophic peatlands or fens) are fed by ground water as well as precipitation, and although these are less reliant on climate, they still only grow in areas with a positive climatic water balance.

If we define a climate space by mean annual precipitation and temperature, it is possible to place major peatland types within a certain region of this space (Wieder & Vitt 2006; Yu, Beilman & Jones 2009; Yu *et al*. 2010). Within the boreal peatland region (Figure 2), at the coldest extreme of temperatures (annual mean temperature below 0°C) and lowest precipitation we find the peat plateaus in permafrost environments of Arctic tundra areas and palsa mires in subarctic areas. Palsa mires are characteristic of the zone of discontinuous permafrost, where ice lenses develop inside the palsa mounds and permafrost conditions are maintained by the thinner snow cover on the mounds (Seppälä 1986; Luoto, Fronzek & Zuidhoff 2004). At the opposite extreme, in climates with warmer annual mean temperatures (~5 to 10°C) but with extremely high precipitation all year round (>1000 mm), blanket bogs are found (Gallego-Sala *et al*. 2011). Blanket bogs are so-called because of their tendency to cover almost the entire landscape, developing even on sloping surfaces, which is only possible under conditions where the peat never dries out. Outside the boreal region, the temperature-precipitation space also can represent the climate constraints of peatland types. For example, tropical peatlands in wet and warm climates, including in Southeast Asia and Amazon, tend to dominate in areas with relatively high temperature and moderate precipitation. In southern high latitudes, such as in Patagonia and New Zealand, peatlands occur at high precipitation (up to 4 m/yr) with mild mean annual temperatures around 5˚C.

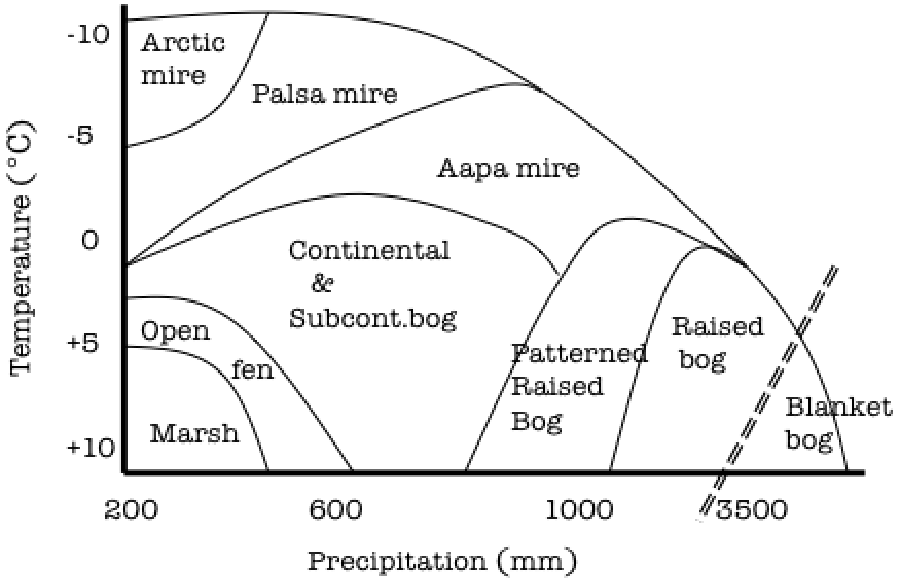

Figure 2. Relationship between climate (temperature and precipitation) and major peatland types in the boreal region. Climate diagrams show the seasonality of temperature and precipitation in different regions. Figure adapted from Wieder and Vitt (2006).

2.3 Climate control on ecosystem functioning

Warmer temperatures result in the lengthening of the growing season especially in high latitude peatlands that experience cold winters. A prolonged growing season increases plant production but at the same time warmer temperatures increase decomposition rates in peat soils (Dorrepaal *et al*. 2009). In certain nutrient-rich peatlands, the effect of a warmer, drier climate seems to increase both productivity and decomposition similarly (Flanagan & Syed 2011). However, carbon accumulation rates in peatlands have been shown to be most responsive to changes in the amount of photosynthetic active radiation (PAR) during the growing season (Charman et al, submitted. Thus, the length of the growing season is an important climatic control on carbon accumulation rate but so is the cloudiness, with very high cloudiness promoting peatland occurrence (because of low potential evaporation) while keeping carbon accumulation rates low (because of low incident PAR).

While taking up atmospheric CO_2, peatlands are net sources of the two other important biogenic greenhouse gases, methane and nitrous oxide. As long as the water table is maintained at a high enough level to maintain anoxia, the amount of methane produced under warmer temperatures and increased productivity will also be higher. However, if water tables fall, methane emissions are expected to decrease because oxygen can diffuse down into the aerated peat and decomposition to carbon dioxide becomes the most energetically favourable path of organic matter decay. Nitrous oxide fluxes are also elevated when the water table drops, especially in nutrient-rich peatlands (Martikainen *et al*. 1993).

Figure 3. Controls on peat C accumulation. The total C accumulated over the last 1000 years at 90 sites compared to A.) GDD0, B.) the ratio of precipitation to equilibrium evapotranspiration, and C.) PAR0. Adapted from Charman et al. 2011. Climate-driven changes in peatland carbon accumulation during the last millennium. Submitted. THIS FIGURE CANNOT BE INCLUDED UNTIL SUBMISSION TO NATURE HAS BEEN FINALISED.

3 What we know from peat-core records: past climates and peatlands

A unique feature of peatlands is that they record their own history and development via the accumulation of well-preserved organic remains of past plant communities and other organisms that can collectively be used to reconstruct the vegetation, hydrology, and geochemistry of the peatland. Many peat characteristics can also be used to infer changes in the past climate and broader areas of the landscape than the peatlands themselves. Several key points emerge out of a consideration of this evidence:

1. The initiation of peat growth has mostly been climatically determined, reflecting either prevailing climate conditions that have persisted over an extended period of time, or a change to a climatic regime more favourable to peat formation.
2. Peatland growth has resulted in continuous but variable sequestration of carbon dioxide in the world's peatlands, amounting to over 600 Gt C, almost as much as today's atmosphere. This valuable ecosystem service continues in pristine peatlands but is reversed in many damaged peatlands.
3. The development of northern peatlands over the postglacial period has influenced the atmospheric concentration of methane.
4. Peatland carbon sequestration has varied significantly over time as a function of both internal processes such as successional change and external factors such as climate and human disturbance.
5. Whilst peatlands are responsive to past climate change, in general the story is one of remarkable resilience to the natural changes that have occurred in the last 11,[illegible]00 years. The extent of this resilience is now challenged by more rapid future climate change and human disturbance.

3.1 The history of carbon sequestration in peatlands

The initiation of peat growth marks the transition of the ecosystem to a net accumulator of carbon. Thus, we can learn something about the contribution of peatlands to the global carbon cycle simply by reconstructing the extent and initiation patterns of peatlands in the past. Radiocarbon dating of the deepest peat layers can be used to date the onset of peat accumulation and used to reconstruct large-scale changes patterns of peatland extent. In western Canada, patterns of peatland expansion followed known trends in millennial scale climate change, with initial peatland establishment in suitable areas following deglaciation, and expansion further into other regions as cooler conditions were established from about 6000 years ago (Halsey, Vitt &

Bauer 1998). In Siberia, peatlands expanded rapidly after the end of the last glacial period but continued to spread throughout most of the Holocene period (Smith *et al*. 2004). Across the whole of the circum-arctic region, peat shows a similarly rapid development early in the Holocene with new peatlands continuing to develop later as climatic and soil conditions became more suitable later (MacDonald *et al*. 2006). Changes in the extent of peatlands also have implications for methane emissions and several authors have suggested that the early Holocene rise in methane was partly driven by the development of northern peatlands (Smith *et al*. 2004; MacDonald *et al*. 2006). The later spread of peatlands following neoglacial cooling after about 5,000 years ago could also have contributed an additional pulse of methane to the atmosphere (Korhola *et al*. 2010).

3.2 Lessons from the record of carbon accumulation in peatlands

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Variations in the rate of peat accumulation over time are important in understanding the contribution of peatlands to global atmospheric CO_2 variations. If peat grows faster it will sequester more carbon from the atmosphere. Conversely, if it slows down or stops, it will be a smaller CO_2 sink or even a CO_2 source. Reconstructing changes in accumulation rates through time is not as straightforward as establishing the time of initiation, because the detection of rate changes is dependent on highly precise dating throughout the profile. Radiocarbon dating has inherent uncertainties and normally only a fairly small number of dates are available for individual profiles. Hence only the more significant rate changes can be resolved.

Studies at individual sites and over small regions show that changes in the rates of peat growth vary widely (e.g., Mäkilä 1997; Mauquoy *et al*. 2002; Jones & Yu 2010), but large-scale data compilations again reveal some basic patterns (Yu, Beilman & Jones 2009). In boreal peatlands, peat growth rates were fastest in the early Holocene, associated both with the early phases of peat growth and also warmer conditions. Regional differences are also apparent with very high rates in the very early Holocene for Alaska and generally lower rates elsewhere in the Arctic. These patterns were different for tropical peatlands (Yu *et al*. 2010) but the links with climate variability there are less clear. Further evidence for a broad-scale link between temperature and accumulation exists. Very well-dated individual sites suggest that peat growth was faster during short warm phases such as the 'Medieval Warm Period' when compared with the later Little Ice Age (Mauquoy *et al*. 2002). Spatial patterns in carbon accumulation for the last 2000 years across a north-south temperature gradient in Siberia also show faster rates of peat accumulation in warmer areas (Beilman *et al*. 2009).

There is thus a strong suggestion from palaeoenvironmental reconstructions that peat accumulation (and hence carbon sequestration) are higher under warmer climates, as long as there is sufficient moisture to maintain a high water table (Yu *et al*. 2011). This has important implications for future peatland response to climate change. Small increases in temperature may increase peat growth rates in the future in areas where productivity is limited by short growing seasons and low temperatures. There also seems to be scope for peatlands in more temperate regions to increase peat growth rates to some extent. This would provide a small but significant negative feedback to anthropogenic warming. However, projected climate changes for the next century are much greater than the small-amplitude, slow changes that peatlands have experienced in the past and the response of peatlands is likely to be non-linear. At some point, peat accumulation will likely reach a threshold and will decline as temperature rises, but we don't yet know what that threshold will be. Furthermore, natural fires are likely to increase, while human activities could exacerbate climatically induced pressures on accumulation rates.

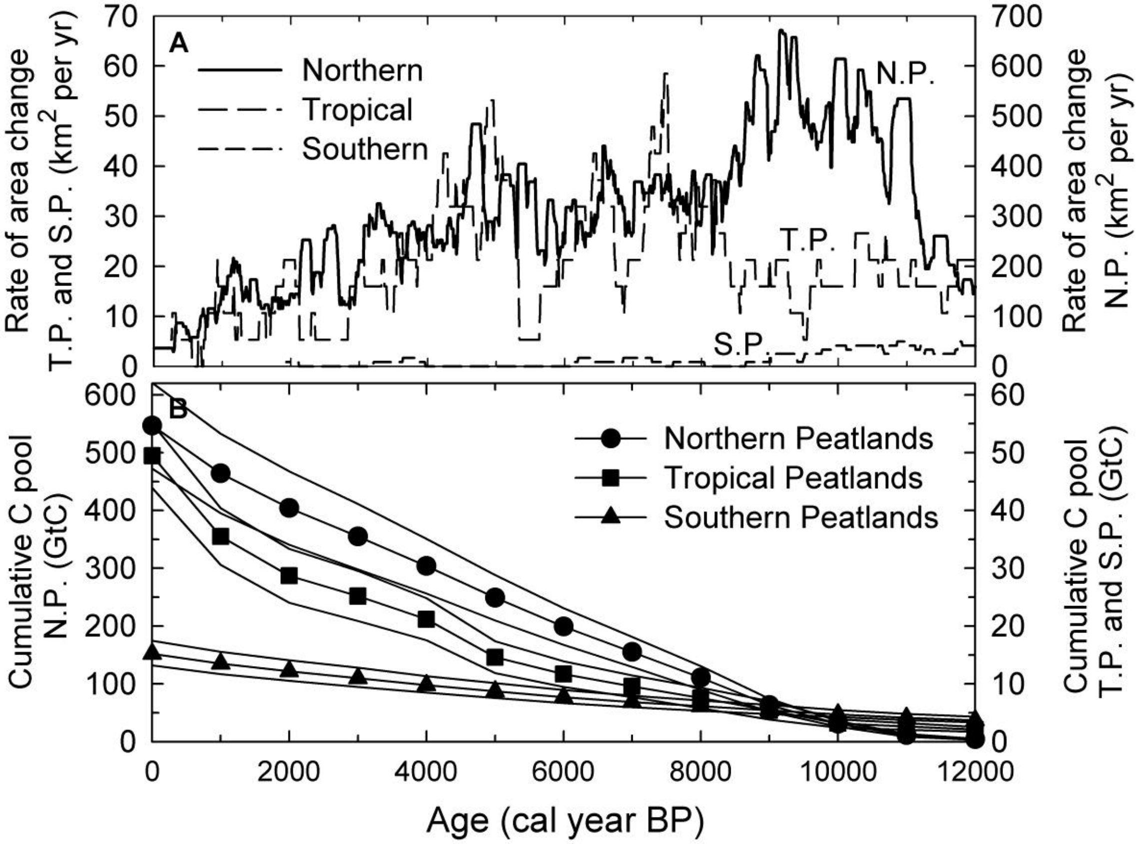

Figure 4. Changes in the rate of global peatland expansion and size of the cumulative peatland carbon pool divided into northern, southern and tropical regions (Yu *et al*. 2010). The changes in extent are estimated from basal peat ages and an assumed linear expansion since inception. The change in the size of the cumulative pool is based on accumulation rates from multiple ages in peat cores.

4. Future climate change and peatlands

4.1 Predicted climatic changes

There is universal scientific agreement that continued greenhouse gas emissions will cause further warming and changes in the climate of the Earth during the 21st century (IPCC 2007). The

Intergovernmental Panel for Climate Change's Fourth Assessment Report (AR4) predicts a warming of 0.2˚C per decade for the next two decades, then further warming depending on the emission scenario, with the warming being greater (a) at high latitudes and (b) over land (Trenberth *et al*. 2007). As a result, the snow cover will decrease and the thaw depth of permafrost regions, including the vast expanses covered in boreal peat, will decrease, both these trends have already been identified by satellite observations during the last 40 years for the Northern Hemisphere (Lemke *et al*. 2007). Precipitation patterns are expected to change, with increases at high latitudes and decreases in subtropical regions. In addition, climatic extremes, such as heat waves and heavy precipitation events, are also likely to increase. All these changes are anticipated to affect peatland regions particularly, since boreal, tropical and mountains regions have been highlighted as being especially vulnerable to the predicted climatic changes (IPCC 2007).

4.2 Changes in the global extent of peatlands.

Since climate largely determines the extent of most peatlands, we can asssume that changes in the climate will result in changes in the overall extent of these ecosystems. Information from ice cores and pollen analysis suggests that wetlands expanded during the Little Ice Age, when the climate was cooler (Finkelstein & Cowling 2011). This finding implies a shrinking of the global extent of wetlands if the mean land temperatures keep increasing in the future, although this effect may be offset by the high carbon accumulation rates during warm periods as suggested in many other studies, including Charman et al. (submitted, note: references to Charman et al may not be possible until we have an answer from Nature). In agreement with this study, bioclimatic models at the regional scale also predict that the suitable bioclimatic envelope for peatlands will retreat towards higher latitudes in the future due to climatic changes (Gignac, Nicholson & Bayley 1998; Clark *et al*. 2011; Gallego-Sala *et al*. 2011). This retreat is mainly driven by increases in temperature. Equally, peatland ecosystems at lower latitudes may not be well adapted to survive the more frequent extreme heat waves predicted in Europe and North America as part of climate change (Meehl & Tebaldi 2004; Bragazza 2008).

As well as temperature, precipitation patterns are likely to change in the future and affect peatland extent. Future precipitation predictions are more uncertain and present more regional variation, so the effect on peatlands will be more localised. For certain peatlands, precipitation increases may counterbalance the effect of higher temperatures on evapotranspiration, but the effects will be dependent on local factors, including mire type (Parish et al. 2008). For example, future climate changes, particularly increased climate variability, may lead to peatland expansion rather than shrinking in kettlehole basins, which are common in previously glaciated environments (Ireland & Booth 2011). For most peatlands, changes in the distribution of rainfall towards more frequent extreme events, i.e., drought and/or flooding, is likely to exacerbate the effect of increased temperatures and become a further stress on peatlands, making them vulnerable to peat erosion.

The tree line, i.e. the boundary for tree growth, which is usually controlled by growing-season temperatures, is likely to also advance towards higher latitudes and altitude where there might have been peatlands before, leading to a decrease in albedo (Parish *et al*. 2008). The effects may depend on peatland type and for example in the case of northern oceanic peatlands, it has been proposed that they may be increasing in area, due to a retreat of the tree-line and an ecological succession towards bogs where there were previously forests (Crawford, Jeffree & Rees 2003). Although oceanic mires may in the future expand towards mountainous and northern areas, their present location may still be under threat from increasing summer and annual temperatures (see Case Study 2). Again, it is important to remember that in the past, peatlands have been able to survive periods of climatic changes, and that these ecosystems can be are resilient to environmental change.

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CASE STUDY 2 Are Blanket bogs under threat?

Blanket bog is a distinctive type of mire that is very rare at the global scale, and almost restricted to the fringes of continental land masses in mid-to high latitudes. Blanket bog requires the highest year-round rainfall of all peatlands, combined with low summer temperatures (but no permafrost), a combination that effectively restricts the distribution of this mire type to the hyperoceanic regions of the world. Blanket bogs are ombrotrophic (rain-fed) mires that cover the landscape with a blanket of peat broken only by the steepest slopes. Because by definition, it is not limited to particular topographic situations, it is a peatland type suitable to bioclimatic modelling. A simple process-based bioclimatic model, PeatStash, was used with climate-change projections from seven global climate models to study the fate of blanket bogs globally (Gallego-Sala & Prentice, in preparation). The results (Figure 5) show dramatic shrinkage of its bioclimatic space with only a few, restricted areas of persistence. However, shrinkage of the bioclimatic space for blanket bog does not necessarily entail complete or swift disappearance of these peatlands and the associated loss of the accumulated carbon to the atmosphere. The resilience of peat to environmental changes has been highlighted previously (Hogg, Lieffers & Wein 1992; Lindsay 2010b) and rapid carbon losses may be avoidable, especially if vegetation cover is maintained. Nevertheless, regions falling outside the envelope will be under stress from climate change and unlikely to continue growing and acting as carbon sinks. There will be further differentiation of vulnerable zones within blanket bogs. Small parts of the blanket bogs in flatter topographic areas may be more likely to continue growth, effectively changing to raised bogs, and the very large areas of peatland on slopes and summits will be more vulnerable. For this reason, good management is necessary on these threatened areas and cost-effective ways to safeguard the multiple ecosystem services provided by blanket bogs. Protection of these mires, including good water management and fire and grazing control is critical to preserve these rare peatlands and mitigate the effects of a changing climate on blanket bogs (Parish *et al*. 2008).

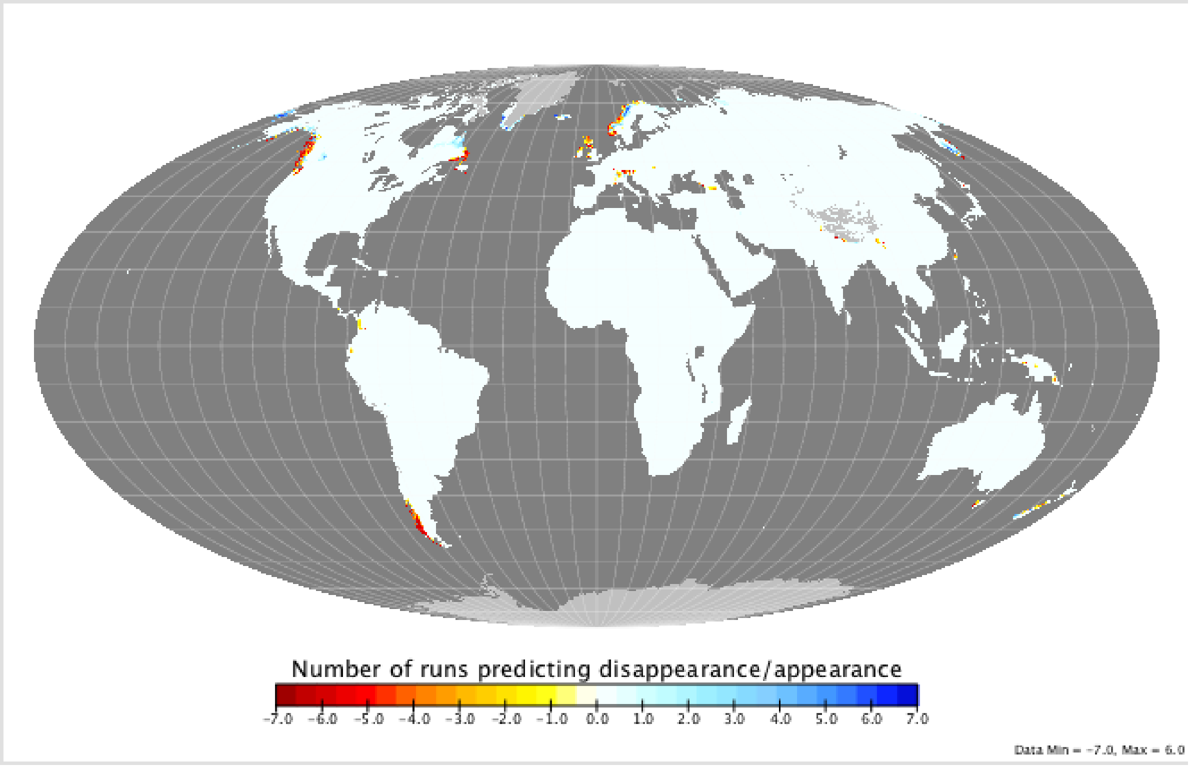

Figure 5. Projected changes to blanket bog bioclimatic space for seven climate change scenarios compared to the standard period. The scenarios were derived by pattern scaling, assuming a 2K warming by 2050, resulting in a warming of 3.9 to 4.5K over land during 2070-2099. The colour scale represents number of climate models predicting new appearance (blue) or disappearance (red) of blanket bog bioclimatic envelope area. Adapted from Gallego-Sala and Prentice, in preparation. TO BE CHANGED: Black and white and only show some of the more relevant regions. As it is difficult to show both disappearance and appearance wihout using colour…. Perhaps the thing to do is to make a "cartoon" version, ringing the area where there is a change and labelling the ringed area with plus or minus signs?

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4.3 Changes in carbon accumulation rates

Peat accumulation depends on the balance between plant productivity and the decomposition processes that happen in the peat matrix. The annual carbon accumulation rate by northern peatlands has been estimated to be around 0.076 Pg C y^{-1} (Gorham 1991). The rate at which carbon is sequestered in peat is dependent on climate, because both of these processes depend on climatic conditions. Plant productivity generally increases with temperature (up to a point), length of the growing season, and PAR. PAR varies with latitude and also with cloudiness, i.e. it too is climate-dependent. How fast plant material is decomposed in the soil is highly dependent on hydrology, which acts as an on-off switch: if the water table is high, then anoxia sets in and decomposition slows down dramatically, while if the water table is low, oxygen can diffuse into the peat matrix and this speeds up decomposition. On the other hand, temperature is also an important environmental control on decomposition rates for the same hydrological conditions.

Since higher temperatures increase both productivity and decomposition, future rates of peat accumulation could be higher or lower depending on which of these processes' rate increases most in a future warmer climate. Evidence from field manipulation experiments has been used to suggest major future carbon losses from increased decomposition in peatlands (Dorrepaal *et al*. 2009), but these projections assume no change in productivity due to increased temperatures and growing season length, which could increase carbon sequestration. A recent study in a forested Canadian fen found a warmer drier climate increased both productivity and decomposition similarly (Flanagan & Syed 2011). On the other hand, studies of past peat accumulation rates have shown that peak carbon accumulation occurred in northern peatlands during warmer climate periods. Although they have very different plant communities, peat accumulation also tends to be much higher in the tropics (Dommain, Couwenberg & Joosten 2011). Northern peatlands could therefore act as a small negative feedback to climate change in the future (Yu *et al*. 2011). However, the main factor affecting accumulation rates is PAR (see section 2.2) and how PAR may change in the future is more uncertain, as precipitation and cloud patterns are less well defined in model predictions. Thus, the overall future contribution of peatlands to the global carbon cycle feedback is still not known with any precision (Parish *et al*. 2008).

Changes in vegetation composition resulting form climate change will also influence future peat accumulation rates as different plants have different potential for productivity and decay. Currently there is a large scale pattern of dominat peat forming plant types in the world varying from mosses in the Arctic to Boreal zones, via grasses and sedges in the temperate and subtropic areas, to trees in the tropics. Changes in vegetation composition could be brought about by climate change, but internal feedbacks may mean that change is slow and the outcome is still uncertain.

4.4 Climate models and the carbon cycle

Changes in the atmospheric concentration of CO_2 are the primary driver of contemporary climate change, but climate change also influences the amount of CO_2 in the atmosphere by affecting plant productivity and decomposition processes in soils. The carbon cycle, climate and atmospheric carbon dioxide concentration form a feedback loop (Friedlingstein *et al*. 2006). Earth system model results and observations of interannual and historical variability in CO_2 concentration point to a positive climate-carbon feedback, whereby climate change results in a larger fraction of anthropogenic carbon dioxide emissions remaining in the atmosphere, further warming the climate (Friedlingstein & Prentice 20[illegible]0). However, the strength of this feedback is highly uncertain, indeed it is now one of the largest uncertainties in climate change science (Gregory *et al*. 2009). The terrestrial carbon cycle feedback is both the dominant term (over the ocean carbon cycle feedback) and the least well quantified (Friedlingstein *et al*. 2006; Matthews *et al*. 2007).

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CASE STUDY 3: Peatlands as part of carbon cycle models

Until recently, models have completely ignored the potential contribution of peatlands, even though they contain 530-694 GtC (Yu *et al*. 2010), i.e. almost as much as the total amount of carbon in the atmosphere. Yet, with the widespread acknowledgement that peatland ecosystems play an important role in the carbon cycle comes an increasing interest in representing peatlands in terrestrial carbon models. Some initial efforts have already been made to include peatlands in global models:

- A methane emissions model for northern peatlands within the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-WHyMe) has been developed which includes permafrost dynamics and peatland vegetation and hydrology (Wania, Ross & Prentice 2009). Simulations runs using this model predict an increase in methane emissions in the future.
- A model that uses a topographic index to calculate inundation as a proxy for peatland/wetland extent has been developed as part of ORCHIDEE, the Institut Pierre-Simon Laplace land surface scheme (Ringeval *et al*. 2011). This model also calculates methane emissions and their role in the climate-carbon cycle feedback.
- A land surface scheme, the MOSES-LSH, coupled to the Met Office climate model uses a topographic index to assess the extent of peatlands and can also calculate methane emissions (Gedney, Cox & Huntingford 2004). This model's results suggest that global wetlands response to climate change will amplify the total anthropogenic radiative forcing at 2100 by about 3.5–5% via increases in methane emissions.
- The McGill Wetland Model is being developed from previous peat accumulation models (e.g., the Peat Decomposition model, (Frolking *et al*. 2001)) in order to be coupled with the Canadian Centre for Climate and Model Analysis (CCCma) coupled general circulation model (St-Hilaire *et al*. 2008). This latter model has already been applied at the regional scale to a raised bog in Canada, and it predicts low sensitivity of the net carbon balance to variations in water table because of opposing responses in plant productivity and decomposition. On the

other hand, the net carbon balance of this particular bog in Canada was extremely sensitive to temperature increases that could switch the balance from a sink to a source of carbon (St-Hilaire *et al*. 2008).

- The climate model of the Institute of Atmospheric Physics of the Russian Academy of Sciences (IAP RAS CM) has also been coupled with a model of soil thermal physics and the methane cycle, and initial results predict an increase in methane emissions from wetland ecosystems under all future IPCC scenarios, together with a decrease in the area covered by permafrost (Eliseev *et al*. 2008).
- Finally, a simple wetland distribution and methane emissions model have been incorporated within the Goddard Institute for Space Studies (GISS) GCM (Shindell, Walter & Faluvegi 2004). Simulations using this model under carbon dioxide levels double that of the pre-industrial time show an increase in annual average wetland methane emissions from 156 to 277 Tg/yr, a rise of 78%.

Most of these peatland models are able to make predictions of how methane emissions from wetlands or peatlands may change in the future, but are not advanced enough yet to give us a clear picture of the overall role of peatlands in the carbon cycle. For example, they can't predict yet how carbon accumulation rates may change under a warmer climate, whether the radiative forcing of peatlands will vary, or whether peatlands extent may change. There are many challenges ahead for the peat modelling community, some of which will involve developing modules able to calculate the extent of peatlands dynamically, better representation of the hydrology of peatlands as distinct from mineral soils and improved representation of the biogeochemical processes that occur in peat. The small-scale heterogeneity and self-regulation of northern peatlands is particularly problematic to build into models (Baird *et al*. 2009). A further particular challenge is to develop models that are capable of simulating the long-term responses of peatlands to climate change observed in the past record (section 2).

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4.3 Changes in fire frequency

Analysis of sedimentary charcoal records has revealed that there is a close correlation between large-scale temperature trends and biomass burning (Marlon *et al*. 2008). One implication is that global warming is very likely to increase fire frequency, and several modelling studies have made this prediction, globally or for specific regions (e.g. Scholze *et al*. 2006; Lavorel *et al*. 2007; Girardin & Mudelsee 2008; Balshi *et al*. 2009). On the other hand the effect of climate change on fire is unlikely to be spatially uniform and some regions could see reduced fire risks due to increasing rainfall (Krawchuk *et al*. 2009; Pechony & Shindell 2010). Rising CO_2 is expected to increase fire risks by promoting increased fuel loads in semi-arid regions where fuel supply is limiting to fire (Scholze *et al*. 2006). Peatlands are flammable when the water table drops and fires can in principle occur on any peatland, although less is known about the history and potential future risks of peat fires.

In tropical peatlands, especially in Indonesia, the compound effects of drought, deforestation and fire have been responsible for tremendous loses of carbon to the atmosphere in recent years. It has been calculated that ~1.45 Mha of peatlands were burnt in Indonesia in 1997 alone, an El Niño year, releasing 0.81-2.57 Pg C to the atmosphere: equivalent to 13%-40% of the global annual CO_2 emissions from fossil fuel burning (Page *et al*. 2002). Drainage and deforestation are continuing to give way to palm oil and other biofuel crops in the region, which in addition to the predicted increase in the frequency of extreme weather events, drought and heat waves is likely to increase the fire frequency (Page *et al*. 2002; Miettinen, Shi & Liew 2011). Therefore, unless there is a clear management change in these peatlands, involving major mitigation, restoration and rehabilitation programmes, the impact of fires on ecosystem services is likely to escalate in the future (Refer to chapter 13 tropical peat swamps).

Model predictions suggest the areal extent of extreme fire danger risk is also likely to increase in boreal regions (Stocks *et al*. 1998). The intensification of extreme weather events, in particular drought and heat waves, have already resulted in the number of wildfires escalating on boreal regions (Riordan, Verbyla & McGuire 2006). The proliferation of fires in this region can also affect peatlands. For example, unprecedented drought conditions, combined with an extended heat wave, resulted in widespread forest and peatland fires in western Russia during the summer of 2010 that burned hundreds of thousands of hectares (Stocks et al. 2011). Some areas of Russia are extremely fire prone due to drainage for peat mining in the past and abandonment since the beginning of the 1990s.

Mid-latitude peatlands are not exempt from fire risk. It has been suggested that at a global scale, temperate peatland fires may emit up to 0.32 Pg C during drought years (Poulter, Christensen & Halpin 2006). As drought frequency is predicted to increase in the future, then fires from mid-latitude peatlands could also become more frequent, continuing to release a significant amount of carbon to the atmosphere. For example, in the UK, moorland fires are like to increase due to changes in the climate and increased visitor access to peatland areas. The pattern of fires is likely to be concentrated in time, so that management of these wild fires will be challenging and will require additional resources in the UK and other countries where fire risk was lower in the past (McMorrow *et al*. 2009).

Fires in peatlands have considerable consequences in terms of ecosystem services. They release large amounts of carbon into the atmosphere in the form of carbon dioxide, carbon monoxide, methane and other volatile organic compounds together with nitrous oxide (Yamada *et al*. 2010). In this way, they are a large point-source of greenhouse gases and contribute to climate change. Vegetation is lost after fire, this loss may be long-lasting depending on the type of vegetation, its regeneration capabilities and the depth and intensity of the fire. The loss of vegetation may lead to erosion, dissolved organic carbon losses, peat subsidence and/or an increase in surface waters because of decreased evapotranspiration (Charman 2002). Soil organisms are also affected, especially in deep fires. The surface layer of peat may be lost, slowing the rate of peat accumulation. There is a release of bioavailable nutrients after fire in the form of ash, although at the same time, there may be losses in the form of nitrogen and sulphur gases (Charman 2002). All these changes are likely to modify the characteristics of the peatland, and depending on the severity of the fire, some of the changes may be irreversible.

Both humans and climate play a role in determining fire patterns, especially in peatland-rich regions, where mires that have been artificially drained are most at risk. Considering the economic and natural losses involved in large-scale peat fires, fire prevention in peatland regions is a cost-effective mitigation strategy. For example, the Russian authorities, in conjunction with Wetlands International Russia, have been working on the Meschera National Park in the Vladimir province, where 2000 ha of degraded peatland has been rewetted as a fire prevention measure (http://russia.wetlands.org/). Other restoration projects are in place in tropical peatlands, for example one in the Central Kalimantan province in Indonesia, which has involved the blocking of drains. Regeneration of peatlands through rewetting and revegetation is a complex and lengthy process, but the benefits are worthwile, since they result in a reduction of fire risk and subsequent reduction in carbon dioxide emissions, a reduction of peat subsidence and a decrease of dissolved organic matter in run-off waters and an increase of biodiversity plus benefits to the local communities (Parish *et al*. 2008). (Refer to chapter 13)

4.4 Changes in water table and the greenhouse gas exchange (ref to chapter 4)

To a degree, the limited hydraulic conductivity and large storage coefficient of peat allow it to maintain the water table at a certain level, although inevitably the water table in peatlands is greatly affected by rainfall and groundwater inflow. The water table level controls the oxic-anoxic boundary in the peat soil, and plays an essential role in controlling methane and carbon dioxide fluxes from peatlands. Future changes in precipitation will impact the water table level and therefore have far reaching effects on all microbial processes occurring in peatlands. The predicted precipitation changes will be different depending on the region. Annual precipitation is predicted to increase in higher Northern latitudes while summer precipitation will decrease in mid Northern latitudes, while tropical regions may experience an increase of precipitation (Amazon) or a decrease (Indonesia) depending on the area. In general, lowering the water table increases the rate of carbon dioxide emission and decreases the emission rate of methane in the long term (Daulat & Clymo 1998; Blodau, Basiliko & Moore 2004; Strack & Waddington 2007). In South East Asia, drained peatlands experience subsidence and have become large sources of CO_2 due to peat oxidation, this source being larger than that from peatland fires in the region, while methane fluxes become negligible when water tables are lowered (Couwenberg, Dommain & Joosten 2010). Similarly, drained peatlands in Europe are also negligible sources of methane, and large sources of carbon dioxide (Couwenberg *et al*. 2011). However, the effect of the water table is not always straightforward. In a water table drawdown experiment, lowering of the water table resulted in peat subsidence, an increase in vascular plant cover and decreased methane fluxes, but did not have a significant effect on carbon dioxide fluxes (Strack and Waddington, 2007). The effect of the water table level seems to be dependent, to a certain degree, on the microtopography and type of vegetation. However, generally peatlands that experience increased precipitation and higher water table level in the future are likely to produce and emit more methane. On the other hand, those peatlands with lower water table levels in the future will release more nitrous oxide, which is also a greenhouse gas (Martikainen *et al*. 1993). Finally, peatlands that experience a lowering of the water table level are likely to become more forested, while peatlands with increasing water table level may become deforested (Parish *et al*. 2008).

4.5 Changes in permafrost

Peatlands at high latitudes have experienced warming over the past decades that have led to a lengthening of the growing season, an increase of the potential evapotranspiration and warming and/or melting of permafrost (Riordan, Verbyla & McGuire 2006). An increase of the thickness of the snow pack and an early establishment of the snow cover also enhances permafrost melting because of the insulating properties of snow (Zhang, Barry & Haeberli 2001). Permafrost degradation can have a number of different ecological consequences, depending on the terrain, soil characteristics and hydrology. It can result in conversion of forests to peat forming ecosystems, or to improvement of drainage in upland areas (Jorgenson & Osterkamp 2005). In fact, there have been studies showing markedly different effects of permafrost melting on peatlands, for example, Alaskan remote sensing observations since the 1950s have shown drying of lakes and wetlands of the discontinuous permafrost region which was thought to be mainly due to an increase in evapotranspiration and improved drainage (Riordan, Verbyla & McGuire 2006). A more recent study offers an alternative explanation to the observed drying of lakes in Alaska: terrestrialization, i.e. the formation of peatlands on previously existing lakes (Roach *et al*. 2011). A study of subarctic peatlands in Canada during the same period based on long-term ecosystem monitoring found that rapid melt of permafrost due to increase snow thickness favoured the rise of water tables, with subsequent formation of thermokast lakes and expansion of fens and bogs (Payette *et al*. 2004). The overall effect on peatlands may vary with peatland type and topographic characteristics, but certain mires, for example palsa mires, which contain peat mounds that are permanently frozen, are likely to be threatened by the increasing temperatures and the area occupied by these mires is likely to decrease (Fronzek, Luoto & Carter 2006).

The consequences of permafrost degradation seem to be different depending on local characteristics, but even then, they are likely to affect the provisioning and climate regulation services provided by peatlands that currently lie on permafrost areas (Riordan, Verbyla & McGuire 2006). The disappearance of permafrost and subsequent variations of the water table could have profound consequences for provisioning services. For example, in Alaska, where water tables may lower, the breeding grounds of many wild animals would be affected, especially waterfowl and shorebirds, and the subsistence lifestyles of indigenous people would also be impacted (Riordan, Verbyla & McGuire 2006). In Fennoscandia, the shrinking of the area covered in palsa mires would have devastating consequences on the biodiversity of sub-arctic mires, since these especial mires are characterised by a rich diversity of bird species and are considered high-priority in terms of conservation (Fronzek, Luoto & Carter 2006).

In terms of climate regulation services, future climatic changes may favour carbon sink conditions in subarctic peatlands because of the rising of water table levels leading to an expansion of peatlands and to rapid peat accumulation (Vitt, Halsey & Zoltai 2000; Payette *et al*. 2004). However, the capture of carbon dioxide may be offset by large increases of methane emissions once discontinued permafrost peatlands have melted (Turetsky, Wieder & Vitt 2002). The net effect of permafrost melting in terms of "global warming potential" is a still a matter of debate, but one prediction is that future changes in climate in the next decades will result in an increase in organic matter accumulation of 11% due to expansion of peatlands on to previously forested landscapes (Vitt, Halsey & Zoltai 2000). At the same time, increases in methane emissions are likely, and field measurements in areas of disappearing permafrost in Canada suggest these increases may be as large as 30-fold locally (Turetsky, Wieder & Vitt 2002).

4.6 Changes in sea level: inundation of coastal peatlands

Due to thermal expansion and glacial and ice sheet melting, sea level is projected to rise by between 0.20 m and 0.35 m by the end of this century, depending on the emission scenario (Bindoff *et al*. 2007), with some experts predicting significant risk of a much larger rise due to the rapid melting of the Greenland icesheet (Gregory, Huybrechts & Raper 2004; Overpeck *et al*. 2006). Sea-level rise will have unavoidable consequences for coastal peatlands. Worldwide, as much as 150,000 km^2 of low-lying coastal peatlands may be vulnerable to sea level rise (Henman & Poulter 2008). These peatlands may suffer from shoreline erosion, salt-intrusion and/or inundation. When coastal peatlands are inundated by seawater, there is vegetation die-off, peat subsidence and a shift from methane production to sulphate reduction in the decomposition process. Inundation of coastal peatlands is likely to be a positive feedback to climate change, because the combination of factors is likely to release the carbon store to the atmosphere (Henman & Poulter 2008). In certain areas, sea intrusion will cause forest retreat and replacement by salt marshes (Williams et al. 1999) in others freshwater peatlands may become saltmarshes. An added issue is that in many cases, human populations are concentrated on these coastal peatlands, which have been drained to give way to agriculture and grazing. Drainage of peatlands in coastal areas leads to subsidence with a lowering of the surface that is much faster than the expected rise in sea water level. In this way former and current drainage of coastal peatlands accelerates the local rate of sea-level rise (Borger 1992). This is a serious problem in many populous countries, e.g.the Netherlands, Germany, UK and also in US (Gulf coast) and Indonesia (Kalimantan, Sumatra).

4.7 Changes due to CO_2 fertilisation

Plant life is not only being exposed to climatic changes but also to the direct physiological effects of an increase in the atmospheric concentration of CO_2, which has risen from 280 ppm in preindustrial times to the current 390 ppm (Forster *et al*. 2007). The continuing CO_2 concentration increase is likely to affect vegetation photosynthetic rates and water-usage efficiency. The combined effect on plants, also called the CO_2 fertilisation effect, seems to be variable dependent on a series of factors that may limit its extent, such as temperature, nitrogen availability and plant type. A number of FACE (free-air CO_2 enrichment) experiments have been carried out on peatland vegetation to study the CO_2 fertilisation effect on these ecosystems. The prevalence of mosses, especially *Sphagnum* sp., and other bryophytes coexisting with vascular plant species such as sedges, grasses and rushes means that the composition of peatland vegetation is unique and there is no clear reason *a priori* to expect that the response to CO_2 would be the same as in e.g. forests or grasslands; although it might be anticipated that strong nutrient limitations in ombrotrophic peatlands would constrain the magnitude of the CO_2 effect. Some experiments have found no effect on *Sphagnum* moss biomass growth (Berendse *et al*. 2001) but an increase of *Sphagnum* moss height, which may give it an advantage over lower-lying plants (Heijmans *et al*. 2001). One study measured markedly increased plant productivity under CO_2 enrichment, especially in more nutrient-rich sites, and a slight shift towards vascular flora and loss of mosses (Freeman *et al*. 2004). A study of bogs in Finland found no CO_2 fertilisation effect on either above- or below-ground productivity and attributed this to nutrient limitations (Hoosbeek *et al*. 2002), although the statistical power of this study to detect a change was limited. In any case higher CO_2 atmospheric concentrations may well enhance the growth of vascular flora of nutrient-rich peatlands. The limited available evidence suggests that CO_2 fertilization is likely to be less significant for *Sphagnum* than for vascular plants.

5. Implications for peatland management

The changes in climate are expected to have an effect on many of the ecosystem services that peatlands currently provide. Biodiversity, water quality and regulation, and carbon storage are all likely to be affected, and good management of existing peatlands will be essential to mitigate the impacts of these changes. On the other hand, it is important to highlight that peatlands are resilient ecosystems and they have survive past changes of climate and therefore have the potential to retain provision of vital ecosystem services and even buffer against extreme weather events such as flooding. Peatlands are the last remnants of wilderness in many regions of the world and they may also serve a function in the future as temporary shelters for non-peatland species displaced by climate change in their migratory paths to northern latitudes (Ref to Chapter 3) (Parish *et al*. 2008).

Bioclimatic models (Gignac, Nicholson & Bayley 1998; Parviainen & Luoto 2007; Clark *et al*. 2011; Gallego-Sala *et al*. 2011) predict shrinking of the geographical distribution of peatlands, with some peatlands falling outside their bioclimatic envelope in the future, especially those in the Southern bounderies of the present distrubution. These peatlands will be at risk in the future and will require a more carefully considered management to abate the effects of climatic changes. It is worth noting that even assuming no further carbon sequestration, the loss of carbon to the atmosphere is likely to be slow and it would take in the order of millennia to deplete all the stored carbon in blanket bogs (Billett *et al*. 2010). Bioclimatic envelope models provide a useful insight into the fate of peatland types in a changed climate but only as a tool to inform policy and management so that these ecosystems and their services to society can be preserved (Pearson & Dawson 2003; Heikkinen *et al*. 2006; Billett *et al*. 2010). The fate of peatlands at risk depends not just on pressures stemming from climate change, but on management practices and policy, and therefore good water, fire and grazing management is key to mitigating the effects of climate change on peatland extent.

Coastal peatlands will be exposed to the consequences of sea level rise due to climate change, including inundation and/or erosion. In some cases, these effects maybe compounded by population pressures and peat surface subsidence due to drainage. The fate of coastal peatlands will be determined by the interactions of climate and the response of humans, in aspects such as resource exploitation, pollution, and water use (Michener *et al*. 1997).

Peatlands can play an important role in aiding society mitigate and adapt to climate change due to their carbon and water regulation functions. At the same time peatlands are susceptible to changes in the climate, especially if they exist in a degraded state. In terms of carbon regulating functions, a recent report by Wetlands International gives a global estimation of carbon loss from peatland degration of 1.3 Pg C yr^{-1} in 2008, an increase of 20% since 1990 (Joosten 2010), compared to the estimated carbon sink from Northern peatlands (not including tropical peatlands) of 0.076 Pg C yr^{-1} (Gorham 1991) and a total store of 547 Pg C (Yu *et al*0). These figures further support the case for peatland conservation and restoration. Rewetting of peatlands has been highlighted as a potential measure in the REDD+ initiative (www.reddpluspartnership.org) and the Land Use, Land-Use Change and Forestry (LULUCF) inventory sector of the United Nations Climate Change Secretariat. Rewetting can help reduce global greenhouse emissions from degraded wetlands, even when taking into account CH_4 emissions increases with higher water tables, which may partly counteract the benefits of CO_2 drawdown (Joosten 2010).

6. Conclusions

Climate change is expected to have far-reaching consequences for peatlands and the ecosystem services they provide. Peatland geographical distribution is likely to change, the area currently covered in peatlands may shrink and migrate northwards but at the same time, the melting of the permafrost is likely to increase the area covered in peatlands at the northern boundary. There is some evidence to suggest that they may accumulate carbon faster in the future, but overall, their role in the carbon cycle in a warmer climate remains uncertain. The uncertainty is compounded by the fact that the fire risk in peatlands worldwide is predicted to increase and the projected future increases in methane emissions will also contribute to the climate feedback of peatlands.

All these unknown effects make it clear that there are challenges ahead for the peatland research community, which could help inform peatland managers of which maybe the best way to deal with the impacts of climate change. There are large peatland areas that have received less interest and have not been the focus of many studies to date (e.g. tropical and remote regions of the Hudson Bay lowlands and East Siberia). These areas should be targeted by new projects based on their relevance to providing evidence on the effect of climate on peatland ecosystem services (Yu *et al*. 2011). To profit fully from the richness of information contained in the peat record, a more concerted effort should be made to integrate paleo and contemporary observations (Yu *et al*. 2011). Also of importance to peatland ecosystem management is long-term monitoring to obtain first a high-quality baseline and then data that clarify the main drivers of change (Bonn, Rebane & Reid 2009). Finally, efforts to include the complexity of peatland dynamics into Earth System models should continue so that more reliable predictions of the future contribution of peatlands to the carbon cycle can be taken into account.

Although climate change will impact peatlands, management can accelerate or mitigate its effect. The management practices currently applied to peatlands are often unsustainable and must be adapted to cope with pressure stemming from a changing climate as well as an increased population (Parish *et al*. 2008). There is a need to generally increase and improve knowledge exchange and promote increased awareness of the value of peatlands in the public (Bonn, Rebane & Reid 2009). First priority should be the preservation of those peatlands that are still intact;

preservation of existing peatlands is a highly cost-effective way of controlling their greenhouse gas emissions (Parish *et al*. 2008; Bussell *et al*. 2010). Next priority should be to restore or improve the conditions of degraded peatlands. Peatlands in many parts of the world have been drained for their exploitation for peat extraction, agriculture, grazing or forestry. Drainage leads to peat subsidence, oxidation and a higher risk of peatland fires. Furthermore, drained and damaged peatlands lose resilience and are more vulnerable to climate or environmental changes (Anderson, Buckler & Walker 2009). Certain strategies such as water management and wild fire control can improve the condition of degraded peatlands and help retain ecosystems services. Water management, such as drain blockage, has been shown to be an effective adaptation strategy to maintain biodiversity (Carroll *et al*. 2011), especially during extreme drought events which are predicted to become more frequent in the future (Meehl *et al*. 2007). It is also an effective strategy in terms of carbon storage, although increased water tables also increase methane emissions (Bussell *et al*. 2010; Worrall, Bell & Bhogal 2010). New management strategies, such as wet agriculture or paludiculture, addressed by the Vorpommern Initiative Paludiculture at the University of Greifswald, should be promoted as an alternative to drainage to generate sustainable productivity from peatlands without encroaching in the ecosystem services they provide. Adaptation will also be necessary to cope with the increased fire risk in both intact and especially drained peatlands (Parish *et al*. 2008). Further national expenditure on fire prevention and control will be necessary in order to prevent catastrophic carbon losses, such as those seen in recent years in Southeast Asian and Russian peatlands.

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