The potential peatland extent and carbon sink in Sweden, as related to the Peatland / Ice Age Hypothesis

L.G. Franzén, F. Lindberg, V. Viklander & A. Walther

Department of Earth Sciences, University of Gothenburg, Sweden

SUMMARY

Peatlands cover approximately 65,600 km^2 (16 %) of the Swedish land area. The available areas suitable for peatland expansion are far from occupied after *ca*. 12,000 years of the present interglacial. We estimate the potential extent of peatland in Sweden, based on slope properties of possible areas excluding lakes and glaciofluvial deposits. We assume no human presence or anthropic effects, so the calculation is speculative. It may have been relevant for previous interglacials.

We calculate the potential final area of peatlands in three scenarios where they cover all available land with different maximum slope angles (1−3 º) using a Digital Elevation Model (DEM). The three scenarios yield potential peatland areas of 95,663 km^2 (21 % of total available area), 168,287 km^2 (38 %) and 222,141 km^2 (50 %). The relative increases from the present 65,600 km^2 are 46, 157 and 239 % respectively.

The slope scenarios give CO_2 uptake rates of 8.9−10.8, 18.1−22.4 and 24.6−30.5 Mt yr^{-1}. Under global warming conditions with isotherms moved northwards and to higher altitudes, following an increase of raised bog area, the CO_2 uptake rates might increase to 12.2−13.8, 24.4−27.7 and 33.5−37.9 Mt yr^{-1}; i.e. up to 4.3−4.9 vpb of atmospheric CO_2. If we make the speculative extrapolation from Sweden to all high latitude peatlands, and assume that all suitable areas with slope angle ≤ 3 ° become occupied, the global peatland CO_2 sink might approach 3.7 Gt yr^{-1} (about 2 vpm yr^{-1}) and potentially cause a net radiative cooling approaching 5 W m^{-2}.

KEY WORDS: carbon dioxide; DEM; Digital Elevation Model; GIS; lateral growth of peatland; P/IAH

INTRODUCTION

Study objectives

The Peatland/Ice Age Hypothesis (P/IAH) (Figure 1, Franzén 1994, Franzén *et al*. 1996, Franzén & Cropp 2007) offers an alternative or supplement to the generally accepted Milankovitch theory on periodic cooling of the Earth. Even though the longer Milankovitch cycles are a good fit to glacial cycles, they are considered to be too weak to account alone for the dramatic climate changes seen between glacial and interglacial periods. Other environmental forces must amplify the climate change that the Milankovitch Cycles initiate. The P/IAH postulates that, due to progressive lateral growth during an interglacial, peatlands may become such a large carbon sink that critically low atmospheric carbon concentrations result, and this in turn may lead to a new Pleistocene ice age.

The main objective of this study is to examine the areas of Sweden that could potentially be covered by peatlands during a hypothetical interglacial, ignoring anthropic effects. We also try to estimate the size of the carbon sink that would result from maximal peatland extent according to the constraints applied in our models, and how this may change in a warming climate. In the rest of this Introduction we establish a background for the study by describing and assessing the growth and spread of peatlands in Sweden.

Peatlands and the carbon cycle

Since the last glacial period, a quantity of organic carbon in the range of 270−455 Gt has accumulated in northern peatlands (Gorham 1991, Turunen *et al.* 2002, Joosten 2010). Peatlands constitute more than 30 % of the global store of soil carbon, and correspond to a potential source of 990−1674 Gt of CO_2 if suddenly oxidised or 127−215 vpm if released into the atmosphere. Various calculations suggest that the present annual carbon sequestration in northern peatlands amounts to between 70 Mt (Clymo *et al*. 1998) and 96 Mt (Gorham 1991). Franzén *et al*. (1996) estimated a sink of 97−160 Mt yr^{-1} growing with time over the Holocene, the lower value being valid for temperate peatlands. The temperate peatland CO_2 sink is presently about 0.033−0.045 vpm and the net radiative forcing of northern peatlands, accounting for both CO_2 uptake and CH_4 emission, is currently about -0.22 to -0.56 W m^{-2} (a cooling) (Frolking & Roulet 2007).

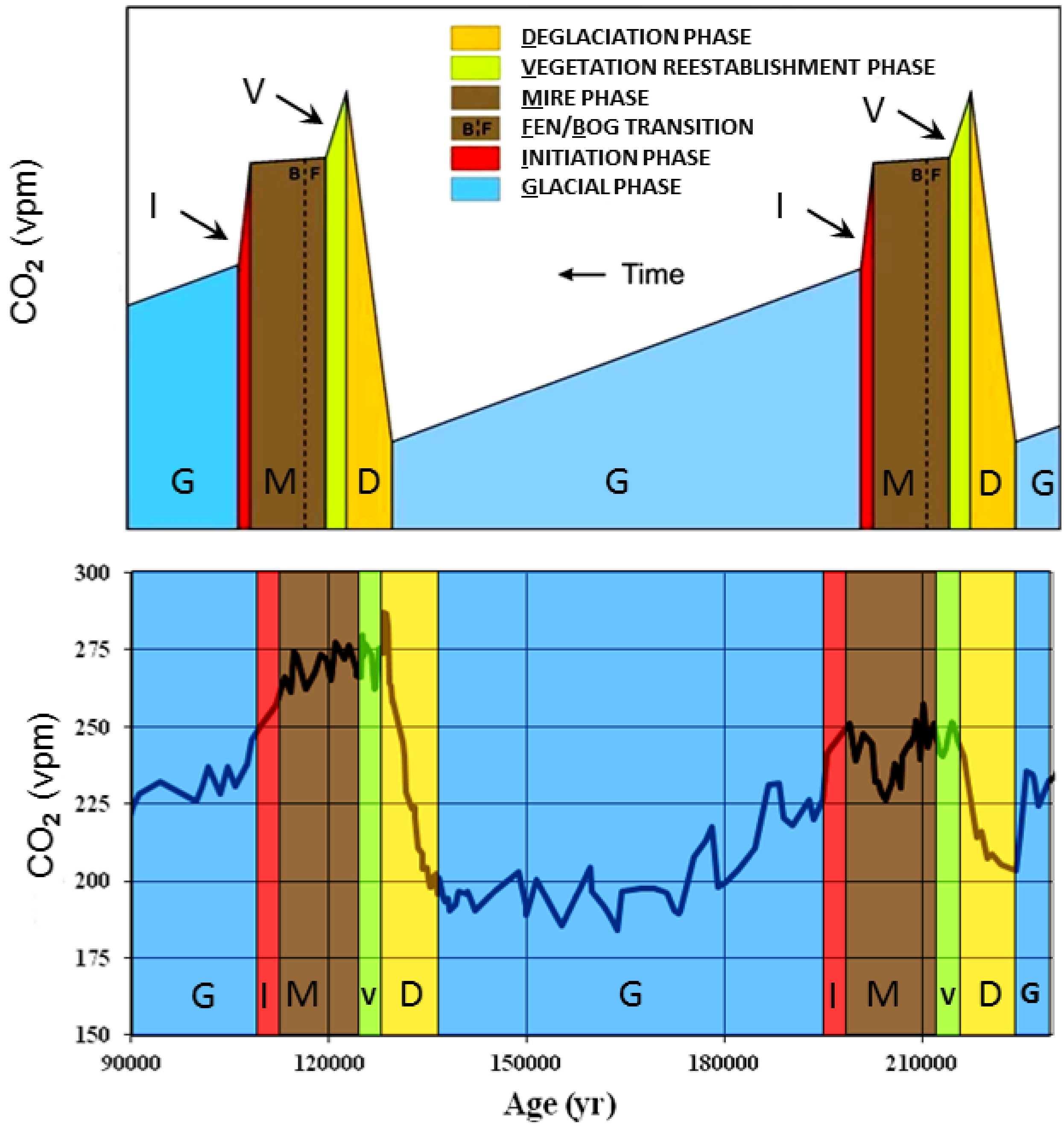

Figure 1. The idealised CO_2 development of age cycles according to the P/IAH (above) and applied to the CO_2 concentrations of 90−230 kyr from Antarctic ice cores (Petit *et al*. 1999, Monnin *et al*. 2001, Pépin *et al*. 2001, Raynaud *et al*. 2005) (below).

On a global scale, the occurrence of peatlands is strongly related to topography and climate, with the greatest abundance on flat land in cool and moist climates (Kuhry & Turunen, 2006). Peatlands are both sinks (CO_2) and sources (CH_4, N_2O) of greenhouse gases, and thus have both cooling and warming effects on climate through their influence on the atmospheric loadings of these gases (Frolking *et al*. 2006). Only a little is known about the variability of the carbon budget of peat over the present interglacial, and its response to climate variations (Moore *et al*. 1998). However, Frolking & Roulet (2007) consider it likely that peatlands caused net warming in the early Holocene due to high emissions of CH_4, but that they have caused net cooling for the past 8000−11,000 years.

According to the P/IAH, carbon sequestration by peatlands may be an important factor in climate regulation, and may even be a driving force for the Pleistocene shifts between glacials and interglacials.

Dynamics of peatlands

Traditionally, peatland scientists have recognised three main peatland formation processes, namely: infilling (terrestrialisation of lakes), primary peat formation over bare ground, and paludification (Rydin & Jeglum 2006). Areas with consistently or temporarily high groundwater tables will host hydrophilic vegetation and can subsequently develop into various types of wetlands. Under favourable conditions many types of primary wetlands can develop into peat-forming types e.g. fens, carrs and raised bogs. The initially formed peat may act as an effective hydrological seal over the substratum; hence a peatland, once formed, will transform into a hydrologically isolated unit where the quantity of water exchanged between the mineral soil and the overlying peat may be negligible. Due to the anoxic conditions in peatlands, peat will accumulate vertically at a rate determined by the balance between primary production and decay integrated over all depths.

Lateral growth of peatlands

Whenever the peatland surface is raised above the initial hydrological zero level (groundwater table), peatland water supplied by precipitation may flow from the peatland's interior towards the margin, where adjacent mineral soils may successively become waterlogged so that drier vegetation types are transformed into hydrophilic wetland types. Paludification can also be initiated by pedogenic processes, such as podsolisation and pan formation, promoting decreased soil permeability which causes wet and anoxic near-surface conditions that lead to *Sphagnum* invasion (Rydin & Jeglum 2006). Yet another cause for paludification is natural or human-related forest fires and forest clearing leading to decreased evapotranspiration—mainly loss of canopy interception and hence increase of precipitation reaching the ground, but also cessation of transpiration. This results in a wetter forest floor and favours the development of hydrophilic vegetation, e.g. *Sphagnum* (Rydin & Jeglum 2006). Long ago, Sernander (1910) claimed that charcoal was a common feature in the transition from substratum to peat layer, and inferred that forest fires were a cause of mire formation. Sernander's ideas were later confirmed from both Finland and Canada by the observation of numerous charcoal layers at the peat−mineral substratum contact (Ikonen 1993, Korhola 1996, Bauer 2002).

Marginal paludification provides a mechanism which makes it possible for peatlands to grow not only vertically but also laterally. The rate of lateral growth depends on several factors such as humidity, the composition of the substratum and the slope of the adjacent terrain. Hence, high-humidity fine-grained sub-soils (or bare bedrock) and flat land (low relief) would favour the spread of peatland; whereas low-humidity coarse soils (or bare fissure-rich bedrock) and steeply upward-sloping adjacent terrain may inhibit peatland initiation and restrict lateral growth. Flat relief is usually (but not always) correlated with a large percentage of peatland. The agricultural plains of coastal Sweden and in the vicinities of Lakes Vänern, Hjälmaren and Mälaren are obvious exceptions. It is scarcely possible to determine how and to what extent these areas would have been peat-covered if they had not been subjected since the Iron Age or earlier (Sjörs 1983) to grazing, haymaking, woodcutting and agriculture. Although most of the mires in the world are found on plains and in valley bottoms, soligenous mires such as blanket bogs have developed even on steep slopes in extremely maritime environments such as those of western Norway, Ireland and Scotland. McVean & Ratcliffe (1962) recorded mean surface gradients in Scottish blanket bogs between 50 and 250 ‰ (3−14 º), with maximum gradients as great as 470 ‰ (26 º). Steeply sloping (soligenous) mires also occur in terrain with steep gradients at more continental sites. In most cases, such mires are minerotrophic (fens) and associated with distinct (springs) or diffuse outflow of groundwater.

Whereas the vertical accumulation of peat is accepted and well confirmed, the extent of lateral growth has been debated for over a century. In Sweden, Tolf (1893) was convinced of the threat of expanding mires by a sighting of Komosse (Box 1); but decades later the issue was still 'live'—the two main disputants during the hottest year of debate being Von Post (1927) and Malmström (1932). However, with the application of ^{14}C datings, the evidence made it clear that quite rapid spreading of peatlands over the surrounding mineral ground can occur, caused by marginal paludification. According to Sjörs (1983) and Rydin & Jeglum (2006) it seems likely that the larger part of the world area of peatland has been formed by the paludification of originally less wet land usually carrying forest. Paludification occurred extensively in the early (until about 6500 BP) and middle (after about 4800 BP) parts of the Holocene. Most of the paludified areas in the north and south-west of Sweden had previously been forests and woodland, though in many cases the woodlands may have been swampy from the beginning. Beaver damming, once widespread in Sweden, not only created ponds that were later invaded by hydrophilic vegetation but also caused true paludification above the actual flooding level. Much of this paludification started

BOX 1

Even if the bog Komosse is not of the same size as the bog Storemosse in Käfsjö and Åker parishes, it still was a more than usually dreary sight, that appeared to my eyes when I, on a dark and rainy day stood at the north-eastern edge of this wasteland, prepared to take a walk across it. I have had the opportunity to see many raised bogs, equal in size to Komosse, and I have often been attracted by their waste and wild beauty. I have admired the wonderful display of colours of the mires of northern Sweden on a bright summer day, which is beyond all description; I have actually been stunned at the sight of a heather bog, glowing like a sea of purple at sunset – but I have never seen a mire having a, so to speak, scoundrelly appearance as this one. Lacking all trees worth speaking of, with the vast grey-brown surface frequently broken by holes and grooves filled with black mud and numerous ponds in which water a lead grey sky was reflected, without sign of advanced animal life, it just lay there like an enormous, repulsive polyp, stretching out its dreadful arms and intruding in all directions. It is an open, constantly fretting cancer wound to its district and the private enterprise stands perplexed and vain against this evil spreading over its surroundings. The warm-hearted person, now deceased, that once proposed that the government should take immediate steps to drain all larger bogs, had he needed new impulses to raise this question again – indeed he couldn't have got them better than at the edge of Komosse." Robert Tolf

(Tolf 1893)

from existing mires in valley bottoms and expanded upslope through bottom sealing and edge damming (Malmström 1923). In cases of gradual expansion, a wet minerotrophic stage advanced outwards from the mire's edge. On slopes flushed with seepage, paludification may have occurred simultaneously across the whole slope. Studies indicate that both slow and rapid phases of lateral growth have occurred during the Holocene depending mainly on the topography of the mineral substrate (Korhola 1994, Mäkilä 1997). The fastest expansion is usually associated with peatlands having confining layers such as clays, whereas slow expansion is typical for peatlands on more permeable soils (Foster *et al*. 1988, Korhola 1994, Korhola 1996, Turunen & Turunen 2003). On sand plains and other highly permeable soils, paludification was often by a "dry" sub-type of bog vegetation dominated by dwarf shrubs directly replacing the similar understorey of a dry pine forest on podsol (Sjörs 1983). Paludification may occur not only in northern conifer forests, but also in grasslands, cool temperate heathlands, arctic or alpine tundra, or even bare rock areas (Rydin & Jeglum 2006).

More constant lateral expansion rates have also been recorded (Foster & Jacobson 1990, Foster & Wright 1990). Some studies have measured rates of annual radial spread in metres per year (e.g. Aaby 1990, Kuzmin 1994) whereas others have claimed a more moderate growth averaging around 10 cm per year (Almquist-Jacobsen & Foster 1995, Lode *et al*. 2001, Lode 2002). From Finnish studies, Korhola (1992, 1994, 1995) found at some periods in mire history "… the mire front advancing several metres a year—indicating that mire ecosystems are by nature exceptionally expansive elements." The peatland expansion was mostly related to the topography of the mineral substrate. A period of overall slow paludification between 7000 BP and 4500 BP was ascribed to drier climate. The peatlands also expanded slowly over the last 2–3 millennia due to steepening of the bottom gradients at the margins of bogs. From a study at the southern margin of the boreal region of West Siberia, Peregon *et al*. (2009) concluded that the rate of lateral expansion varied widely from 2.3 to 791.7 cm yr^{-1}, was most rapid during the initial stage of mire development, and slowed to 9.9−15.4 cm yr^{-1} over the last 2000−3000 years. On the other hand, taking the large Bakchar Bog in Western Siberia as typical, Neustadt (1984) suggests that lateral spreading has continued fairly rapidly up to the present time.

To compare these observations with south Swedish conditions, a similar investigation was performed at the Komosse bog complex by Franzén & Cropp (2007), who used 53 calibrated (Stuiver & Reimer 2000) ^{14}C-datings (Ua-12461−12464, Ua-12589−12613 and Ua-14061−14084) of basal peat layers to demonstrate a mean lateral growth rate, since the mire was initiated some 7500 years ago, of 10.6 cm yr^{-1}. The annual lateral growth rates in

500-year intervals are shown in Figure 2. Sampling co-ordinates are given in Franzén & Cropp (2007, Table 1: 5a, 5b) and may be viewed e.g. in Google Earth™).

During the last three centuries, the increased population demanded more agricultural areas and many peatlands, mainly fens, were drained and used for farming. In the 1950s about 10 % of the Swedish agricultural area was on drained wetlands (Franzén 1985), but the late 20th century saw changes in agricultural methods which reduced the total area required. The former wetlands were abandoned first, because they typically required more attention and incurred higher costs e.g. ditch clearing and larger amounts of fertilisers. These sites, situated in lowland areas, are also more prone to frost.

In many populated areas lateral growth has effectively been terminated or restricted by marginal drainage, mainly for forestry purposes. While forest drainage was previously subsidised to increase forest productivity, it is forbidden by newer legislation, mainly because of the revaluation of wetlands as important biotopes.

According to Maltby & Immirzi (1993) the extent of peatlands in Sweden that have been drained or otherwise altered for forestry and agriculture is 13,500 km^2. In less densely populated areas such as northernmost Sweden ditching has been less common (Gunnarsson & Löfroth 2009) and lateral growth has continued undisturbed. Thus, many peatlands—such as those in undulating terrain in northern Sweden—may already have reached their maximum lateral extents owing to steep adjacent up-slopes. On the other hand, peatlands in flatter terrain still have vast surrounding areas to conquer, or the potential to reoccupy disused agricultural areas.

Peat accumulation rates

Vertical peatland growth is controlled by the balance between primary production and decay. Peat is formed in the upper aerobic zone, the acrotelm, in which the decay rate is normally high. The thickness of the acrotelm depends on humidity but it normally extends 10−50 cm below the surface. The rate of decomposition of dead plant material depends on

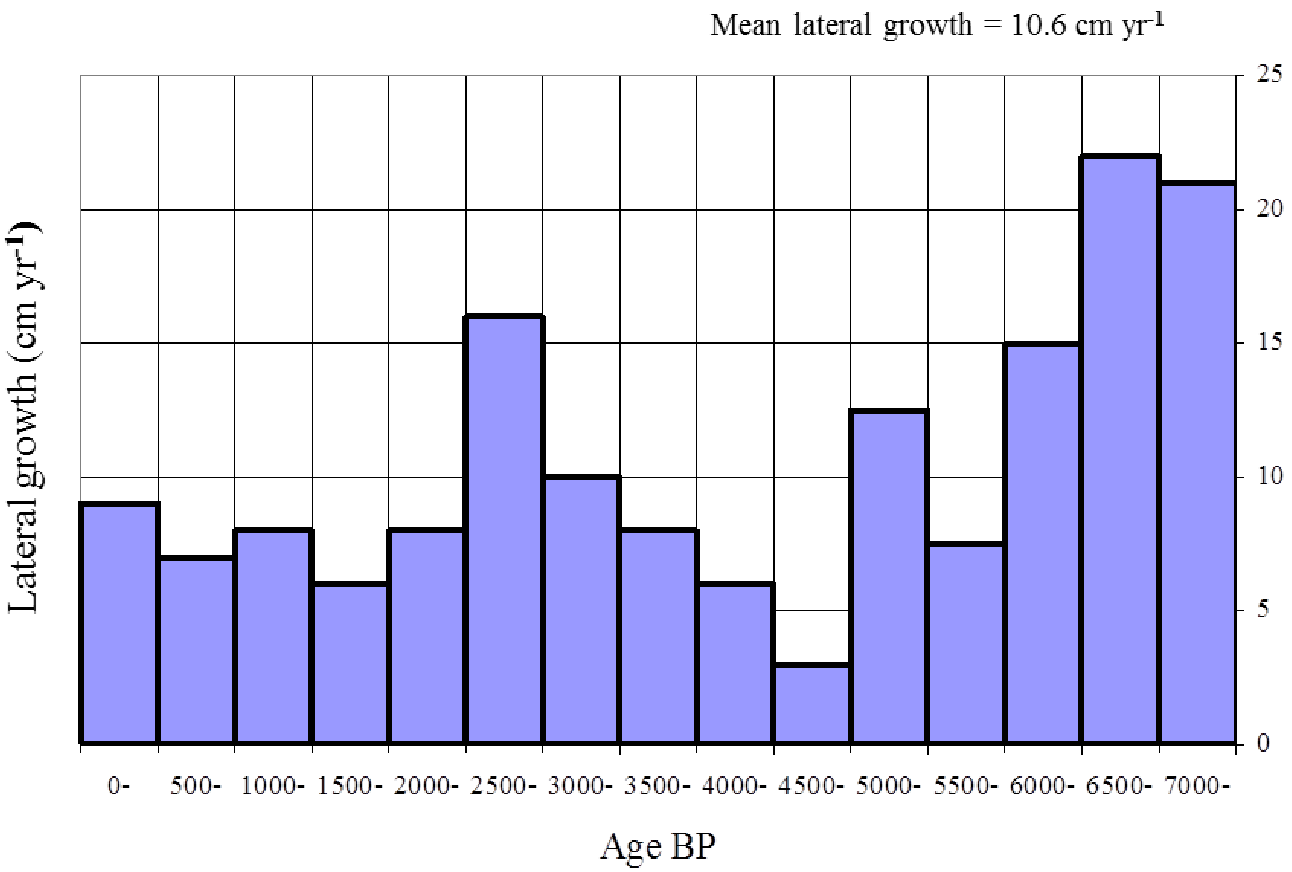

Figure 2. Annual lateral growth at Karsbomossen, part of Komosse raised bog complex, south-west Sweden, as calculated from 53 cal.^{14}C datings of basal peat (after Franzén & Cropp 2007).

temperature, time spent in the acrotelm, and supply of nutrients for micro-organisms (Franzén 2006). Hence, the thinner the acrotelm, the more weakly decomposed is the peat and *vice versa*. Other factors that can affect net peat production are peat fires, wind abrasion, and thermocarst erosion in permafrost zones (Kuhry & Turunen 2006). In the zone below the acrotelm, known as the catotelm, decomposition is much slower due to the anoxic conditions. Only ~5−10 % of the biomass produced on the surface is incorporated into the catotelm as peat (Clymo 1984, Gorham 1991, Warner *et al*. 1993), but the slow anaerobic processes here result in only minor losses as gas. Some dissolved organic material can also be lost through the basal layers if hydrological exchange takes place between the peat and its substratum (Kuhry & Turunen 2006).

The long-term rate of carbon accumulation (LORCA) is a function of the peat formation rate and time since the onset of peat accumulation. Bog plant communities generally have a higher net rate of peat accumulation than minerotrophic mires because *Sphagnum* has higher resistivity to decay than *Carex*. Hence, a raised bog that has developed from a fen may have accumulated more peat carbon as a bog than during a similar period as the preceding fen. Another decisive factor is length of the vegetation period, which is shorter in the colder fen-dominated higher altitudes and latitudes. During warmer and drier periods when the mire water table is lower, the residence time of biomass in the acrotelm will be longer, hence carbon loss will be higher and the resulting peat more decomposed. Changes in climate regimes are normally visible in the stratigraphy of peat as so-called “wet shifts”, i.e. transitions from strongly to weakly decomposed peat associated with climatic deterioration, and the opposite “dry shifts”, e.g. the recurrence surfaces described by Granlund (1932) (Barber 1981, Barber *et al*. 1998, Charman *et al*. 1999, Vorren *et al*. 2012). An analysis of 1302 dated peat cores from Finland gave a LORCA of 18.5 g m^{-2} yr^{-1} for the entire undrained peatland area in Finland (Turunen *et al*. 2002, Kuhry & Turunen 2006). In western Sweden, Russian Karelia, western Siberia and west-central Canada the LORCA for the whole Holocene is estimated at 13−20 g m^{-2} yr^{-1} (Kuhry & Turunen 2006). From eight raised bogs in southernmost Sweden, Franzén (2002) reported a mean dry matter accumulation rate of 40.9 g m^{-2} yr^{-1} for bog peat formed since 6500 BP, which corresponds to about 20.5 g C m^{-2} yr^{-1}. The maritime western bogs accumulated 20−25 g C m^{-2} yr^{-1} whereas the more continental eastern bogs had mean accumulation rates of 15−20 g C m^{-2} yr^{-1}. The distribution over time is shown in Table 1.

Table 1. Average carbon deposition rates since bog peat formation started, for eight raised bogs in southernmost Sweden. From Franzén (2002).

Age range (BP)	Approximate rate of carbon deposition (g m^{-2} yr^{-1})
6500−3500	10−20
3500−2500	20
2500−2000	20−40
2000−1000	10−20
1000−500	20−25
500–present	25−60

METHODS

Carbon characteristics of Swedish peatlands

Sweden can be divided into two major areas with different peatland development (Figure 3). The boundary between them is the so-called *Limes Norrlandicus* (*LN*). This corresponds roughly with the present mean annual temperature isotherm of 4 ºC, but also largely coincides with a rather sharp geomorphological transition from lowland plains (with a few exceptions) in the south to a more undulating broken landscape with generally higher altitudes in the north and with a general change from broad-leaved trees to conifers. Whereas the south is dominated by ombrotrophic mires (raised bogs) and flat minerotrophic mires (topogenous fens in the plains), the north is characterised by mixed mires, i.e. mosaics of bog and fen elements, which are mainly found in valley bottoms and other low terrain forms. Fen elements are found in both flat and gently sloping (soligenous) landscapes. A transect from south to north in the northerly area shows an ever-increasing proportion of fens as one moves northwards. In the lowland plains of the far north, most mires are of the aapa type with well-developed strings and flarks.

The mean peat thickness in Sweden as calculated by Franzén (1985) is 1.69 m, with 1.52 m in the district of Norrland (north Sweden), 1.94 m in the district of Svealand (south-central Sweden) and 2.26 m in the district of Götaland (south Sweden). The country’s total peat volume was calculated as 106,540 million m^3 and the total amount of carbon presently stored in peatlands as 5 Gt (Franzén 1992). The latest estimate of carbon stored in

Swedish peat is 6.7 Gt (Joosten 2010). The regional distribution of peat growth shows a similar pattern to that of mire depth. For the growth of southern bogs, we can use a linear growth rate of 1.0 mm yr^{-1} for *Sphagnum* peat (Franzén 2002). For sedge peat in the northern mires, a good approximation is 0.3−0.4 mm yr^{-1} (Franzén 1985). Using these values we can calculate the annual accumulation of dry matter as 0.81 Mt in the south and 1.5−2.1 Mt in the north. The mean carbon proportion of Swedish peats by mass is 50−55 % (Franzén 1985, Franzén 1992). After reduction for peat ash, this means that the annual sequestration of carbon is 1.2−1.5 Mt. The annual fixation of carbon dioxide in peat by Swedish mires is thus 4.2−5.3 Mt.

Present peatland area

The reported peatland area of Sweden has changed substantially with every new inventory. There are several reasons. One is variations in the way that peatland is defined. Whereas the Geological Survey maps peat of minimum thickness 50 cm, the National Forest Survey uses a peat thickness threshold of 30 cm to define wetland unsuitable for forestry. Swedish soil scientists record organic soil of depth > 30 cm as peat, provided there are no mineral grains included; and botanists define a wetland as an area that is dominated by hydrophilic vegetation. The latest estimate of peatland area in Sweden is 65,600 km^2 (Joosten 2010) and we have used this figure for the calculations here. The map of present peatland extent in Sweden (Figure 7a) is based on the *Swedish Wetland Inventory* (Gunnarsson & Löfroth 2009) and does not include wetlands outwith the area covered by the inventory, as shown in Figure 4.

Potential peatland area

To estimate the potential extent of peatland expansion in Sweden during a hypothetical interglacial with no human interference, we have applied a model using the following simple criteria:

- peatland formation impossible where lakes larger than 1 ha are located;
- peatland formation impossible on coarse glaciofluvial deposits; and
- peatland formation possible only on slopes ≤ 3 º.

Exceptions to these criteria are possible, of course; for example the terrestrialisation of shallow lakes, initial peat forming a seal on coarse substrata during high humidity periods, and soligenous mire formation on steeper slopes in high humidity areas. This is further discussed below. Three different slope criteria were used; ≤ 1°, ≤ 2° and ≤ 3°.

Future distribution of peatland types

With increased annual temperature due to climate change the *LN* will be moved northwards and minerotrophic mires in the southern parts of north Sweden may consequently transform into raised bogs, with associated changes in their rates of vertical growth. Having estimated the potential extent of peatland expansion in an interglacial without human influence, we superpose the effect of climate change by moving the *LN*. Figure 3 shows the present *LN*, which is practically identical to the 4 ºC annual isotherm, and the future *LN* after a projected 4 ºC temperature rise becoming coincident with the present 0 ºC isotherm.

Spatial data

To estimate the potential coverage of peatlands during an interglacial in Sweden, a number of national spatial datasets and data sources were used. To obtain topographical properties (slopes) of geomorphological variables important for peatland development we applied a Digital Elevation Model (DEM), i.e. a gridded dataset of spatial resolution 50 m (Lantmäteriverket 2011a). Two different data sources were used for information about relevant land cover classes. First, digital versions of the *Map of Sweden* (Lantmäteriverket 2011b) and the *Soil Map of Sweden* (SGU 2011) were used to identify, respectively, water bodies and glaciofluvial deposits (Figure 5). The *Map of Sweden* was also used to define the Swedish land territory. Finally, a geo-database of current peatland cover was obtained from the *Swedish Wetland Inventory* (Gunnarsson & Löfroth 2009). All spatial data in this article are referenced to the horizontal co-ordinate system SWEREF99 TM and the altitude data use the vertical co-ordinate system of RH70.

Data processing

The spatial analysis tools used are visualised in Figure 6. All geoprocessing and spatial analysis was performed in ArcGIS 10. To derive gentle slopes suitable for peatland expansion we applied a slope algorithm. The algorithm calculates the maximum rate of change between each DEM cell and its neighbours, for example the steepest descent for the cell (the maximum rate of change in altitude over the distance between the cell and any of its eight neighbours). Every cell in the output Digital Terrain Model (DTM) had a slope value which was classified as peat or not, based on the criteria set (e.g. slope ≤ 1 °). The *Map of Sweden* was used both to derive a mask of the Swedish mainland and islands and to select lakes larger than 1 ha. The *Soil Map of Sweden* was used to derive areas of glaciofluvial deposits. The *Swedish Wetland*

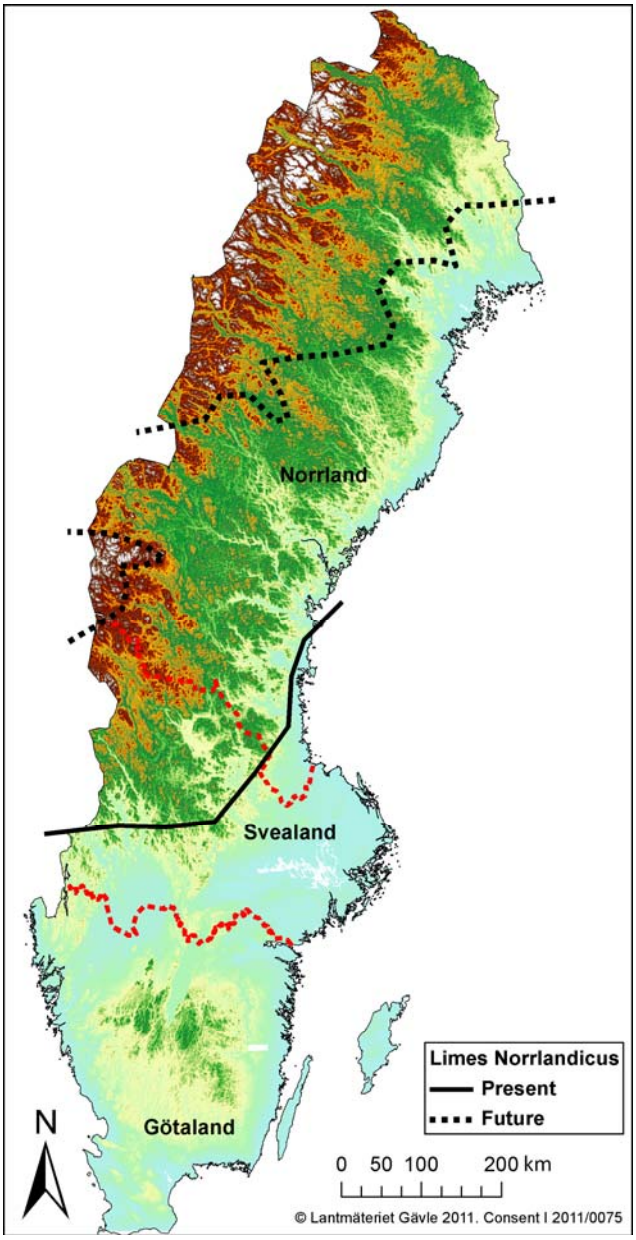

Figure 3. Map of Sweden showing the districts of Götaland, Svealand and Norrland separated by dashed (red) lines, and the present and expected future *Limes Norrlandicus*.

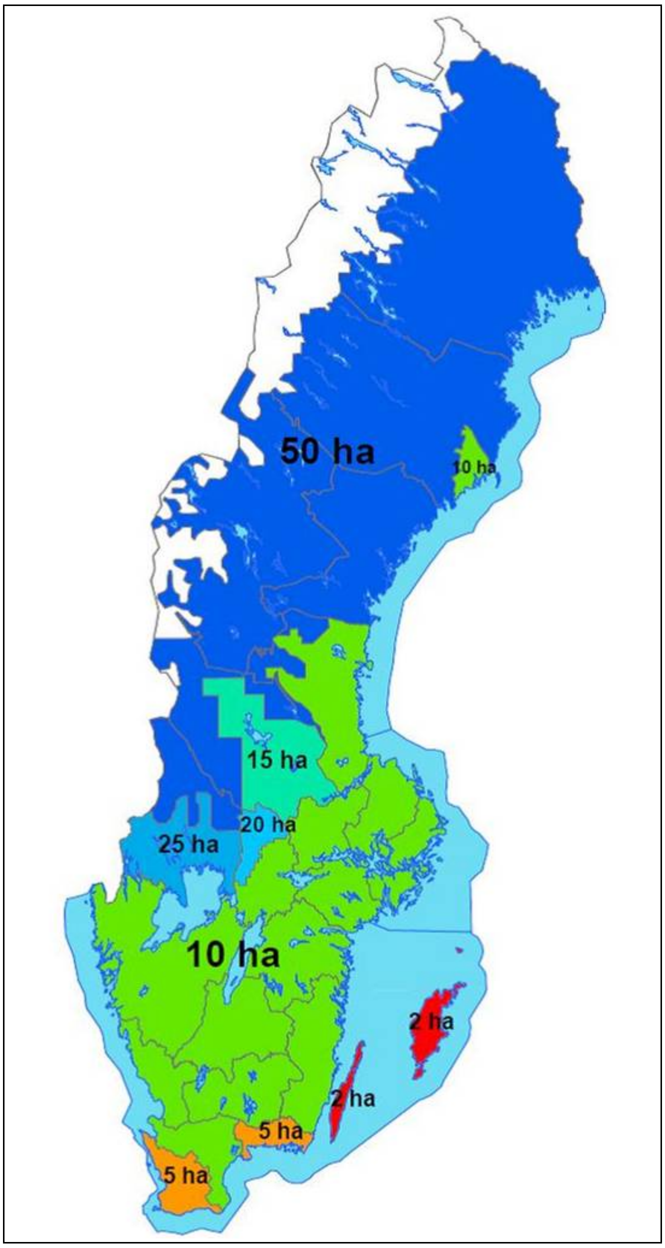

Figure 4. Smallest areas used in the *Swedish Wetland Inventory*, from Gunnarsson & Löfroth (2009). The white areas were not surveyed.

Inventory was already available as vector polygons and ready for analysis. The three latter geodata layers were used to remove areas unsuitable for peatland expansion from the land mask using the Erase tool in ArcMap. Finally, an overlay function (Clip) was used between suitable slopes and the land mask to identify areas where potential peatland expansion might occur.

Sources of error

A number of errors must be considered. As a very large area is involved (~450,000 km^2), the issue of scale becomes important. Both the *Soil Map of Sweden* and the *Map of Sweden* at this national level are produced at 1:1,000,000 scale, causing generalisations that may affect the result. Regarding the altitude data the spatial resolution of 50 m is probably satisfactory, even if small depressions and variations in altitude within this coarse-grid resolution could affect the result. Also the altitude data are made up of tiles that could result in edge effects in some parts of the study area. However, since the tiles are large, the edge effect has no overall influence on the final result. The *Swedish*

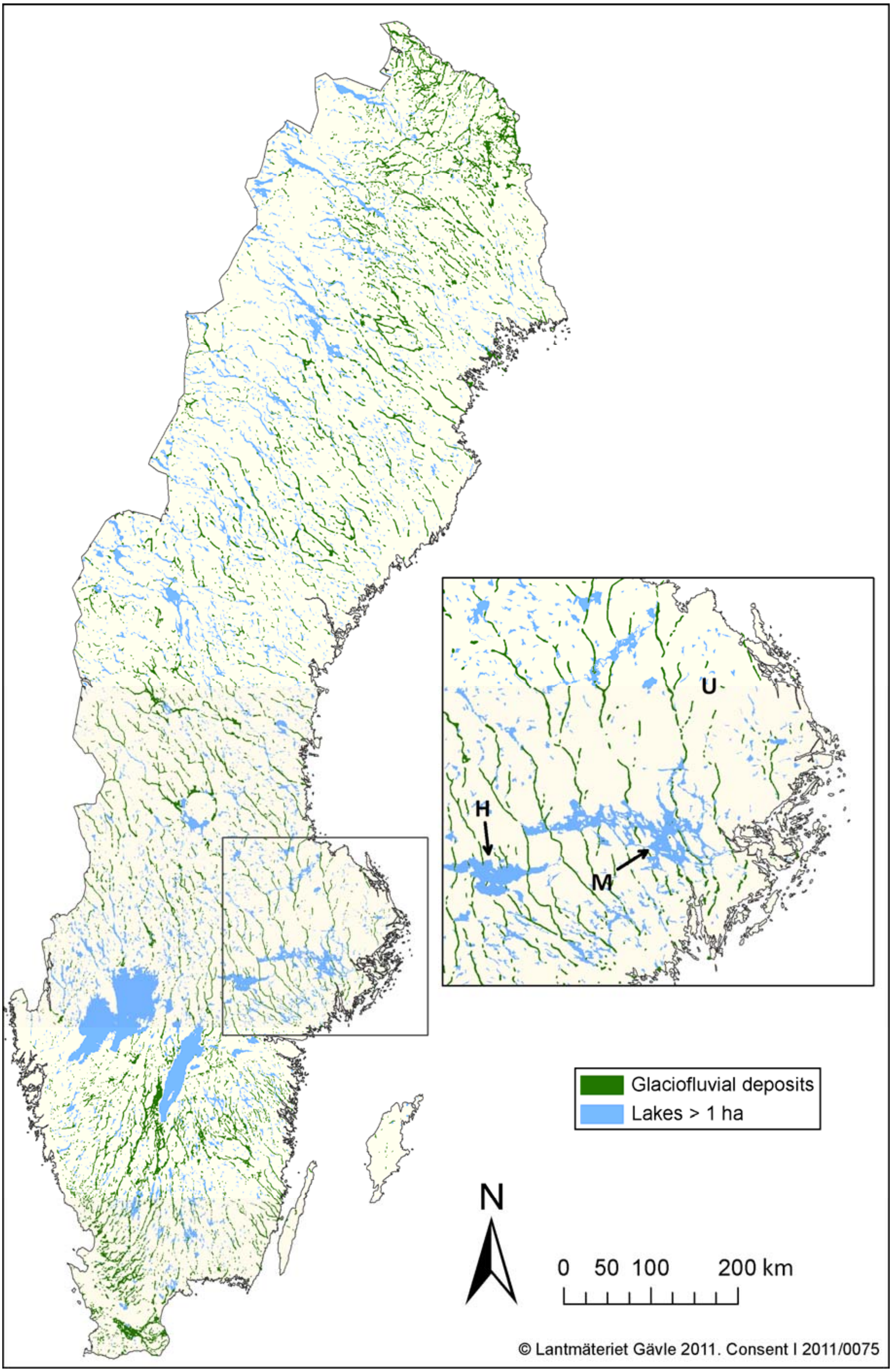

Figure 5. Lakes and glaciofluvial deposits. Inset: Eastern Svealand with labels indicating the lakes Hjälmaren and Mälaren, and the Upland plain.

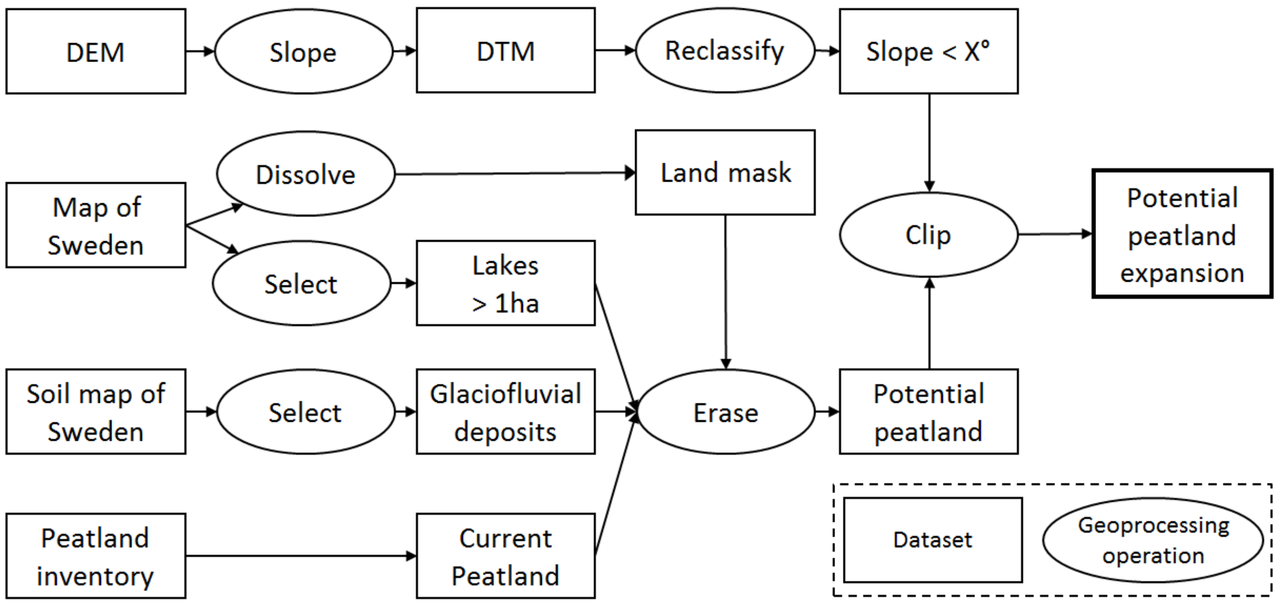

Figure 6. Geoprocessing scheme. The Dissolve function in ArcGIS 10 is used to aggregate all the various land cover classes within the *Map of Sweden* into one land mask representing the whole area of Sweden.

Wetland Inventory was made in administrative units (counties) between which the minimum areas for recording differed. For example, a 10 ha limit was commonly used in southern Sweden whereas 50 ha was used for west-central Sweden and the largest part of the north (Figure 4). However, the *Swedish Wetland Inventory* has high detail and the resulting errors are small compared to those from other sources such as scale issues of the *Map of Sweden*. It would be possible to use other DTMs such as the Topographic Wetness Index (TWI) to estimate the probability of peat formation; we did not do this because we were interested in the final extent of peat after a long time (i.e. a full interglacial).

RESULTS

Figures 7 a–d show the present mire extent and the potential extent of peatland with the three different slope limits; Table 2 summarises the statistics. For the present extent of mire we have used the most recent data from Joosten (2010) i.e. a total of 65,600 km^2. The resulting values for the ≤ 1 °, ≤ 2 ° and ≤ 3 ° experiments for Sweden as a whole are 95,663, 168,287 and 222,141 km^2. The relative share of the total Swedish land area in the three experiments is 21 %, 38 % and 50 %. The relative increases from the present 65,600 km^2 are 46 %, 157 % and 239 % respectively.

If we use the *Limes Norrlandicus* (*LN*) to divide Sweden and use our results for ≤ 1 °, ≤ 2 ° and ≤ 3 ° slope angles we find that the resulting mire share in southern Sweden is 34,725, 67,314 and 87,978 km^2 respectively, the increases being 190 %, 463 % and 639 % from the present mire area. Corresponding values for areas north of the *LN* are 60,938, 100,973 and 134,163 km^2, the respective increases from the present being 14 %, 88 % and 150 %. It is obvious that the major share of peatland addition would take place in southern Sweden. This implies that most suitable areas for peatlands in the more broken terrain of the north are already occupied and that existing mire edges must climb at a slower rate against more steeply sloping terrain.

The present rate of carbon uptake in Swedish peatlands is estimated at 1.2–1.5 Mt yr^{-1} and the rate of carbon dioxide fixation at 4.2–5.3 Mt yr^{-1}. If all areas with slope angles ≥ 1 °, ≥ 2 ° and ≥ 3 ° were covered by peatlands under the present climate, the respective rates of carbon uptake would be 2.4–2.9, 4.9–6.1 and 6.7–8.3 Mt yr^{-1}. Corresponding rates of CO_2 uptake would be 8.9–10.8, 18.1–22.4 and 24.6–30.5 Mt yr^{-1}. In the scenario with the *LN* moved northwards to follow the present 0 °C isotherm, the total rate of carbon sequestration would be 3.3–3.7, 6.6–7.5 and 9.0–10.3 Mt yr^{-1} for the three slope angle cases; and the corresponding rates of CO_2 uptake would increase to 12.2–13.8, 24.4–27.7 and 33.5–37.9 Mt yr^{-1}.

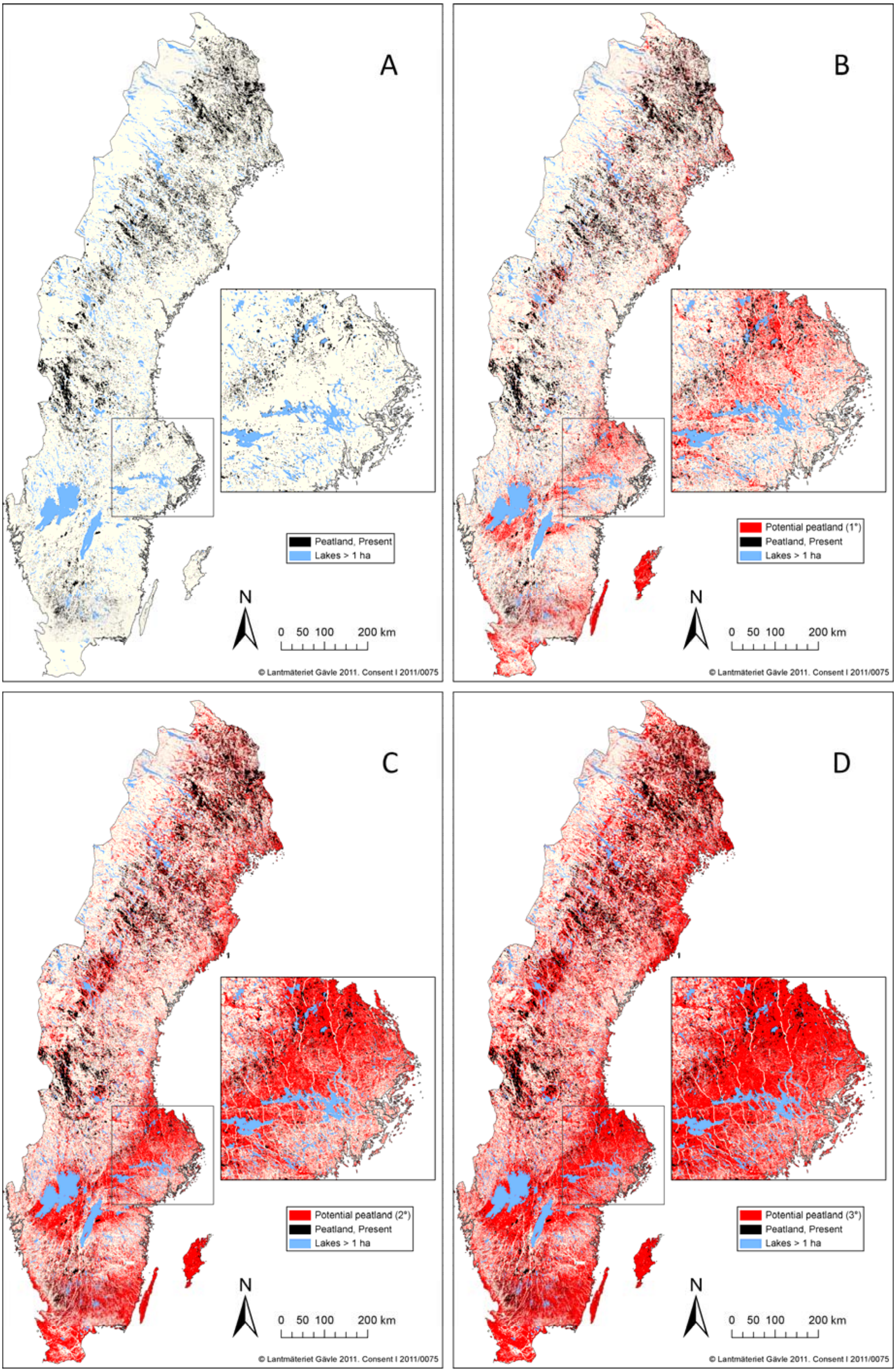

Figure 7. Present extent of mires in Sweden (A) and as projected in the three scenarios ≤ 1 º (B), ≤ 2 º (C) and ≤ 3 º (D). Inset: Eastern Svealand.

Table 2. Areas of peatland in Sweden, at the present time and in the three slope angle scenarios described in the text, under present and future climate regimes. For both climate regimes, four statistics for the corresponding Swedish peatland sink are calculated for each slope angle scenario. *LN* is *Limes Norrlandicus*.

			Total areas	Extent of peatland			
				Present	All slopes ≤ 1°	All slopes ≤ 2°	All slopes ≤ 3°
	Whole of Sweden	area (km^2)	449,964	65,600	95,663	168,287	222,141
		% of total		14.6	21.3	37.5	49.5
		% increase			45.8	156.5	238.6
PRESEN TCLIMAT E	Sweden south of present *LN*	area (km^2)	158,223	11,960	34,725	67,314	87,978
		% of total		7.6	22.0	42.7	55.8
		% increase			190.0	462.8	635.6
	Sweden north of present *LN*	area (km^2)	291,741	53,640	60,938	100,973	134,163
		% of total		18.4	21.0	34.7	46.1
		% increase			13.6	88.2	150.1
	Swedish peatland sink	Annual dry substance (Mt)		2.3−2.9	4.8−5.3	9.8−11.0	13.3−15.0
		Annual carbon (Mt)		1.2−1.5	2.4−2.9	4.9−6.1	6.7−8.3
		Annual CO_2 (Mt)		4.2−5.3	8.9−10.8	18.1−22.4	24.6−30.5
		Annual atmospheric vpb		0.5−0.7	1.1−1.4	2.3−2.9	3.2−3.9
FUTURE CLIMATE	Sweden south of future *LN*	area (km^2)	334,933	44,448	74,100	133,702	177,945
		% of total		13.3	22.1	40.0	53.1
		% increase			99.6	260.1	377.9
	Sweden north of future *LN*	area (km^2)	115,031	21,152	21,563	34,585	44,691
		% of total		18.4	18.7	30.1	39.2
		% increase			22.0	95.7	152.9
	Swedish peatland sink	Annual dry substance (Mt)		3.1−3.9	6.6−6.8	13.2−13.6	18.1−18.6
		Annual carbon (Mt)		1.6−2.0	3.3−3.7	6.6−7.5	9.0−10.3
		Annual CO_2 (Mt)		5.7−7.2	12.2−13.8	24.4−27.7	33.5−37.9
		Annual atmospheric vpb		0.7−0.9	1.5−1.8	3.1−3.6	4.3−4.9

DISCUSSION

The present extent of peatlands in Sweden

The dynamics of lateral growth of peatlands are still largely unknown because there have been few investigations, mainly due to the large number of expensive ^{14}C dates required. Existing studies in Sweden and elsewhere have mainly been made on raised bogs, whereas the lateral expansion history of northern fenlands and aapa mires has hardly been investigated. It appears that most peatlands in northern Sweden have already reached their maximum extents, mainly due to steep slope angles at their edges. According to Peregon *et al*. (2009) the rate of lateral growth appears to have decreased (down to 9.9 cm yr^{-1}) between about 2200 and 550 cal. yr BP, but slightly increased again thereafter (up to 15.4 cm yr^{-1}). These variations may result from undulations in the topographical profile of the mire basin. From a north-central Finnish aapa mire, Mäkilä *et al*. (2001) reported that the lateral expansion was fastest at the beginning of paludification (i.e. before 8000 cal. BP) and 84 % of the present mire areas were already paludified by *ca.*

4000 BP. More recently, steepening of the bottom slope has retarded further lateral expansion.

In densely populated south Sweden, peatlands have been much more exploited than in the north; most fenlands have been drained for agriculture and many peatlands have been cut over for fuel, cattle husbandry and horticulture (Figure 7a inset). In the forested areas of the south most peatlands have been ditched at their margins to halt further paludification, and former carrs and wet forests have been drained. In fact, the Swedish Wetland Inventory reports that 40 % of the mires studied are affected by various drainage operations (Gunnarsson & Löfroth 2009). Christensen *et al*. (2010) estimate that about 10 % of the total wetland area of Sweden is influenced by drainage. Without human interference the natural peatland area in southern Sweden would be much larger than it actually is today. As early as 1783 the Royal Swedish Academy urged the growing rural population to exploit peatlands for agriculture and fuel (Fleichner 1783), and the 10 % loss of former mire area to forestry, agriculture and peat cutting claimed by Maltby & Immirzi (1993) is probably a gross under-estimate.

According to Granlund (1932), the distribution of raised bogs *versus* fens is mainly determined by topography and precipitation, the precipitation range for raised bogs in southern Sweden being 460–1000 mm yr^{-1}. In areas receiving less than 460 mm yr^{-1}, no raised bogs developed through paludification or transition from fens; and where precipitation exceeded 1000 mm yr^{-1} soligenous (blanket) bogs started to dominate. Granlund (1932) further suggested that the absence of raised bogs and the abundance of soligenous mires north of the *Limes Norrlandicus* is mainly controlled by topography and excess precipitation. The large Baltic limestone islands of Gotland and Öland become totally covered by peatlands in our scenarios. Large areas of their surface limestones are drained through karst fissures, and their thin topsoils have a high buffering capacity that would inhibit acid peat formation. But the existing topsoils of most parts of both Gotland and Öland are thick clayey tills or other fine-grained glacial and marine sediments that would effectively seal off the underlying karst. Besides, peatlands and other wetlands are present on these islands and it seems likely that there was much more peatland before human occupation. Similar conditions exist on some Cambrosilurian table mountains in south-west Sweden and within some sedimentary rock areas of Scania in the south. Estonia, in the eastern Baltic, has similar Phanerozoic sedimentary rocks and is about 25 % covered by peat.

Peatlands and the climate in future

The signal of future climate change across Sweden is strongest for the winter season and in the northern parts of the country, for both temperature and precipitation. Lind & Kjellström (2008) investigated the future climate change signal across Sweden derived from a large ensemble of coupled atmosphere−ocean general circulation models (AOGCMs) used in IPCC AR4. Some of the GCMs were used to downscale the climate signal with regional climate models in order to obtain more detailed information at the regional scale. Across different emission scenarios, for northern Sweden in winter the mean temperature rise is projected to be around 6 °C and precipitation is projected to increase by 25 %. For southern Sweden the corresponding figures are 4 °C and 11 %. For summer, the estimated changes are more moderate but have a similar tendency. Chen *et al*. (2007) estimated future changes in seasonal precipitation totals and extremes, and reported a clear tendency towards wetter and slightly more extreme conditions. In general an increase in precipitation intensity and amount is anticipated for all seasons, but especially for winter and spring. In summer a decrease in the number of rain days is expected, albeit still accompanied by more frequent extremes and higher intensities. Given the projected changes, peatlands are likely to be affected in different ways. Increased temperature could lead to decreasing peat accumulation due to lowered peatland water tables and hence a longer residence time in the acrotelm for the dead plant material. On the other hand an increased rate of precipitation would have the opposite effect, tending to keep water tables high and thus counteract the first effect, especially if falling during the season with the highest decay rate. A higher humidity with increased precipitation could lead to primary or increased marginal paludification and hence increased peatland area.

With an increased annual mean temperature as projected (Lind & Kjellström 2008) the climatological boundary *Limes Norrlandicus* (*LN*) will be moved towards higher latitudes and altitudes. The present limit is practically identical to the 4 ºC annual isotherm. In Figure 3 we have marked the present *LN* and the future *LN* at a projected 4 ºC temperature rise, i.e. the present 0 ºC isotherm. Both *LN* limits have been set rather coarsely for data processing reasons. Due to increased temperatures many minerotrophic mires in the southern parts of north Sweden may consequently transform into raised bogs with decreased methane production and increased carbon accumulation due to the shift from *Carex* to *Sphagnum* dominated plant communities. Hughes

(2000) stated that very abrupt mire-wide species turnover at the fen-to-bog transition and the "dry" character of a number of pioneer raised bogs in Great Britain and Ireland suggests that an allogenically driven fall in the water table could be responsible for an initial shift to ombrotrophy, one of the possible reasons being climate change towards reduced effective precipitation i.e. humidity. According to Hughes (2000) all that is required to create ombrotrophic conditions is the isolation of the growing surface from mineral-rich water. In fens, lowering of the groundwater level would lead to perching of the surface peat mass above the water table, and it could then fill with meteoric water (Wiegers 1986). Increased aeration of the surface peat would also lead to increased peat decomposition and structural collapse. According to Granath *et al*. (2010), the rich fen−bog transition generally occurs in two steps, namely:

(1) acidification of the rich fen by *Sphagnum* species leading to poor fen; and

(2) bog formation through peat accumulation (ombrotrophication, i.e. isolation from the influence of water flowing in from surrounding mineral soil).

The process includes feedbacks favouring *Sphagnum* species over vascular plants and other mosses by producing acids and decay-resistant litter. Granath *et al*. (2010) further conclude that the switch from rich fen to bog is a unidirectional ecosystem shift driven by strong positive feedbacks, and that changes in precipitation or the hydrology of the surroundings are vital for the rich fen−bog transition. Whereas some authors see the fen−bog transition as a primarily autogenic process, mostly influenced by local conditions, others stress the influence of allogenic factors such as climate variations. One view (Eckstein *et al*. 2011) is that peat accumulation intensifies under cool and moist climates; another is that the transition to ombrotrophy is promoted by dry conditions, i.e. a falling water table resulting in decrease of groundwater influence at the mire surface favouring ombrotrophic plants. Hughes *et al*. (2000) and Hughes & Dumayne-Peaty (2002) have argued that *Eriophorum vaginatum* plays an important role in the fen−bog transition and seems to facilitate the transition to true *Sphagnum*-dominated raised bog communities, the *Eriophorum* peat being an ideal substrate for *Sphagnum* species and *Eriophorum vaginatum* hummocks providing favourable microclimatic conditions for bog *Sphagna* (Eckstein *et al*. 2011). Regarding carbon sequestration *versus* climate, Yu *et al* (2011) reported that multi-year C balance measurements (CO_2, CH_4 and dissolved organic carbon), available from a few northern peatlands, showed a large weather-driven inter-annual variability from weak carbon sources to strong carbon sinks, responding to hydrological and temperature conditions. The present net carbon balance of about 25 g m^{-2} yr^{-1} was 2−3 times the rate of the last several millennia (≤ 10 g m^{-2} yr^{-1}). However, it was unclear if this high rate was a response to recent climate change and/or raised CO_2 concentration, or just the result of limited sampling. The recurring Swedish Forest Survey has reported on an increased coverage of *Sphagnum girgensohnii* in forests of southern Sweden, an observation also confirmed by Dr. Tomas Hallingbäck at the Swedish Species Information Centre, Swedish University of Agricultural Sciences (SLU), Uppsala (personal communication) (Franzén 2002). Precipitation amounts over southern Sweden have increased over the last century (Busuioc *et al*. 2001, Temnerud & Weyhenmeyer 2008, Chen *et al* 2007) and the increased emergence of *Sphagnum* in the forests of southern Sweden could be the first sign of neo-paludification. For south-west Sweden, where humidity is already near or above the limits for soligenous mire development (Granlund 1932), an increase in precipitation could lead towards development of conditions like those in western Ireland, Scotland and Norway which support the formation of blanket bogs. In areas dominated by fens, such as eastern south Sweden, it would be likely to promote ombrotrophication. The larger amount of nutrient-poor rain and snowmelt water would isolate the central parts of poor and intermediate fens from solutes, favouring the invasion of oligotrophic plants such as *Sphagnum* that would form growing patches of bog, finally transforming the whole surface into raised bog. In the north again, increased temperatures would extend the vegetation period and most flat and gently sloping mixed mires at low altitudes would increase their internal share of bog-like conditions; certainly, many formerly fen-dominated mires would turn completely into ombrotrophic types.

Peatland extent scenarios and the carbon cycle

In landscapes without human influence such as those existing during the last interglacial, our study shows that peatlands could potentially invade almost half the area of Sweden if the topographical (slope) limit is set at ≤ 3 º. Given higher precipitation than at present, peatland might in addition cover even steeper slopes to form blanket mires, especially in the maritime areas of the south-west and other presently high-humidity areas. Depending on mire type, carbon sequestration will differ from south to north. The largest addition of mires to the present distribution will take place in the so-called Middle Swedish Lowlands (Olvmo 2010)—which extend north-eastwards from Gothenburg across the basins of the Väner, Hjälmare and Mälare lakes to Stockholm—and the Upland Plain (Figure 5 inset). The present rate of carbon uptake in Swedish peatlands has been estimated at 1.2−1.5 Mt yr^{-1} and the rate of carbon dioxide fixation at 4.2−5.3 Mt yr^{-1} (Table 2). If all areas with slope angles ≤ 1 º, ≤ 2 º and ≤ 3 º were covered by peatlands under the present climate, and all mires retained their present trophic status, the rate of carbon uptake would be 2.4−2.9, 4.9−6.1 and 6.7−8.3 Mt yr^{-1} respectively. Corresponding rates of CO_2 uptake would be 8.9−10.8, 18.1−22.4 and 24.6−30.5 Mt yr^{-1}. In the global warming scenario with isotherms moved northwards and towards higher altitudes (Figure 3), carbon uptake would be likely to increase the number of mires transformed into raised bogs. For the three slope angle cases under consideration, the total rate of carbon sequestration would increase to 3.3−3.7, 6.6−7.5 and 9.0−10.3 Mt yr^{-1} respectively and the rate of CO_2 uptake to 12.2−13.8, 24.4−27.7 and 33.5−37.9 Mt yr^{-1}. The latter maximum rate of sequestration corresponds to about 4.3−4.9 vpb of atmospheric CO_2 (Table 2, lower part).

In a global perspective the projected final carbon sequestration ability of Swedish peatlands would rise from about 1.2−2.3 % to 9.4−14.7 % of the present global uptake as estimated by Gorham (1991) and Clymo *et al*. (1998). A calculation similar to ours on a global scale would be possible if and when a complete densely gridded global altitude database is available. If, as a highly speculative approximation, we apply the potential growth figures of Sweden to all peatlands, the annual peatland carbon sink in an idealised interglacial where all suitable areas with slope angle ≤ 3° are occupied, might approach 1 Gt (about 2 vpm). This is a little more than half the present exchange capacity (1.7 ± 0.5 Gt yr^{-1}) of the deep/surface ocean interface (Prentice *et al*. 2001). The production of $CaCO_3$ in oceans is about 0.4 Gt yr^{-1} but only about 0.2 Gt yr^{-1} is exported as deep-sea sediments (Milliman 1993). On a CO_2 basis the estimated global peatland carbon sink could potentially cause a net negative radiative warming (i.e. cooling) approaching -5 W m^{-2}. Hence, when added to other terrestrial and marine sinks, the final peatland sink might be a decisive factor in lowering the atmospheric CO_2 concentration to the critical threshold level required for neoglaciation, according to the P/IAH.

Methane

The above calculations are based on the assumption that peatlands are solely net carbon sinks with the re-emission of carbon-containing and other greenhouse gases ignored. However, Mäkilä *et al*. (2001) suggested that under present climatic conditions the northern circumpolar wet mires i.e. minerotrophic fens and mixed mires, are significant sources of greenhouse gases such as methane. Methane emission is a negative feedback from a P/IAH point of view, since sequestered CO_2 is transformed into a much more potent but shorter-lived greenhouse gas. In addition to high methane production, northern aapa mires have lower carbon accumulation rates than more southerly raised bogs. The annual production of methane from Swedish mires has been estimated at 0.2−1.1 Mt yr^{-1} (Nilsson *et al*. 2001). If we apply this value to the potential additional area of minerotrophic mires in the north for the 1−3 º slope scenarios, the methane production might rise by a factor of 1.5. Since most mires start as minerotrophic fens the initial emission of CH_4 in the south would be even higher.

In the global warming scenario, temperature would have no direct effect on the emission of methane but would influence it indirectly (Professor Mats Nilsson, SLU, Umeå, personal communication). The connection between temperature and the total water balance would play a more central role, in that higher temperatures and drier conditions would lead to increased evapotranspiration and lowered water tables, and *vice versa*. Because the unsaturated upper part of the peat stratigraphy is the part that is most exposed to short-term temperature variations, the increased temperature would above all lead to increased decomposition and hence reduced emission of CH_4. Another aspect is that if decomposition in the acrotelm increases (with no methane production) the remaining plant substance reaching the catotelm for anaerobic processing is reduced. This would lead to reduced emissions since the availability of fresh plant material is the major factor in methane production; old (recalcitrant) peat plays only a subordinate role (Couwenberg 2009, Couwenberg & Fritz 2012). A shift towards warmer and drier climate could lead to a transition from minerotrophy to ombrotrophy in northern mires, i.e. from fens to raised bogs. Hence the uptake of carbon dioxide would increase and the production of methane would decrease over time. In the parts of northernmost Sweden with sporadic and discontinuous permafrost, global warming would most likely lead to the release of additional methane, in amounts that are difficult to estimate.

CONCLUSIONS

Our study shows that the potential area of peatland in Sweden is more than three times the present area; i.e. that the extent of peatland could increase from about 65,600 km^2 to about 222,000 km^2. Whereas the present rate of CO_2 uptake by peatland has been calculated as 4.2–5.3 Mt yr^{-1}, in our maximum peatland extent scenario the CO_2 uptake would be 33.5–37.9 Mt yr^{-1}. Thus, on a global scale, carbon sequestration in peatlands may have had important climate cooling effects towards the ends of previous interglacials as proposed by the P/IAH. It cannot be ruled out that similar effects would be seen in a hypothetical Holocene lacking human presence.

ACKNOWLEDGEMENTS

We thank the editor and two anonymous reviewers for comments and suggestions that greatly improved our work.

REFERENCES

Aaby, B. (1990) Geologi og mosedannelse i Store Vildmose området (Geology and peatland formation in the area of the Great Wild Bog). In: *Landet og loven (Country and the Law)*, Miljöministeriet (Ministry of Environment) (in Danish).

Almquist-Jacobson, H. & Foster, D.R. (1995) Towards an integrated model for raised-bog development: theory and field evidence. *Ecology*, 76, 2503–2516.

Barber, K.E. (1981) *Peat Stratigraphy and Climatic Change: a Palaeoecological Test of the Theory of Cyclic Peat Bog Regeneration*. A.A. Balkema, Rotterdam, 219 pp.

Barber, K.E., Dumayne-Peaty, L., Hughes, P., Mauquoy, D. & Scaife, R. (1998) Replicability and variability of the recent macrofossil and proxy-climate record from raised bogs: field stratigraphy and macrofossil data from Bolton Fell Moss and Walton Moss, Cumbria, England. *Journal of Quaternary Science*, 13, 515–528.

Bauer, I.E. (2002) *Internal and External Controls over Holocene Peatland Development in Boreal Western Canada*. PhD Thesis, University of Alberta, Edmonton, Canada, 242 pp..

Busuioc, A., Chen, D. & Hellström, C. (2001) Temporal and spatial variability of precipitation in Sweden and its link with the large-scale atmospheric circulation. *Tellus,* 53A, 348–367.

Charman, D.J., Hendon, D. & Packman, S. (1999) Multiproxy surface wetness records from replicate cores on an ombrotrophic mire: implications for Holocene palaeoclimate records. *Journal of Quaternary Science*, 14, 451–463.

Chen, D., Achberger, C., Postgård, U., Walther, A., Liao, Y. & Ou, T. (2007) *Using a Weather Generator to Create Future Daily Precipitation Scenarios for Sweden*. Report C75, Department of Earth Sciences, University of Gothenburg, 81pp.

Christensen, P., Eriksson, Å., Glimskär, A., Hedblom, M., Sandring, S. & Svensson, J. (2010) Estimations of peatland surface areas in Sweden. http://habistat.vgt.vito.be/modules/Downloads/workshop2010/Poster_Christensen.pdf

Clymo, R.S. (1984) The limits of peat growth. *Philosophical Transactions of the Royal Society of London B*, 303, 605–654.

Clymo, R.S., Turunen, J. & Tolonen, K. (1998) Carbon accumulation in peatland. *Oikos*, 81, 368–388.

Couwenberg, J. (2009) *Methane Emissions From Peat Soils (Organic Soils, Histosols). Facts, MVR-ability, Emission Factors.* Wetlands International, Ede, The Netherlands, 14 pp. http://www.imcg.net/media/download_gallery/climate/couwenberg_2009b.pdf

Couwenberg, J. & Fritz, C. (2012) Towards developing IPCC methane 'emission factors' for peatlands (organic soils). *Mires and Peat*, 10(03), 1–17.

Eckstein, J., Leuschner, H.H. & Bauerochse, A. (2011) Mid-Holocene pine woodland phases and mire development – significance of dendroecological data from subfossil trees from northwest Germany. *Journal of Vegetation Science*, 22(5), 781–794.

Fleichner, E. (1783) *Åkerbruks Cateches eller Handbok och Underwisning uti Lant-Hushållningen* (*Farming Catechism or Manual and Textbook of Agricultual Husbandry*) Kungliga Vetenskapsakademin (Royal Swedish Academy of Sciences), Stockholm, 137 pp. (in Swedish).

Foster, D.R. & Jacobson, H.A. (1990) The comparative development of bogs and fens in central Sweden: Evaluating the role of climate change and ecosystem development. *Aquilo, Serie Botanica*, 28, 15–26.

Foster, D.R. & Wright, H.E. (1990) Role of ecosystem development and climate in bog formation in central Sweden. *Journal of Ecology*, 71, 450–463.

Foster, D.R., Wright, H.E., Thelaus, M. & King, G.A. (1988) Bog development and landform dynamics in central Sweden and south-eastern

Labrador, Canada. *Journal of Ecology*, 76, 1164−1185.

Franzén (1985) Peat in Sweden – a method to calculate the resources. *GUNI Report* 21, Department of Physical Geography Thesis, University of Gothenburg, Sweden, 1−239.

Franzén, L. (1992) Can Earth afford to lose the wetlands in the battle against the increasing greenhouse effect? *Proceedings of the Ninth International Peat Congress*, Volume 1, IPS, Uppsala, Sweden, 1−18.

Franzén, L.G. (1994) Are wetlands the key to the ice age cycle enigma? *Ambio*, 23(4−5), 300−308.

Franzén, L. (2002) Tillväxtdynamik hos några myrar i södra Sverige - samt några noteringar om torvmarker som arkiv över atmosfärshändelser under holocen (Growth dynamics of some bogs in southern Sweden - with some notes on the peatland archive of atmospheric events during the Holocene). *Stiftelsen Svensk Torvforskning Projektrapport*, 47, 1−43 (in Swedish).

Franzén, L.G. (2006) Increased decomposition of subsurface peat in Swedish raised bogs: are temperate peatlands still net sinks of carbon? *Mires and Peat*, 1(03), 1–16.

Franzén, L.G., Chen, D. & Klinger, L.F. (1996) Principles for a climate regulation mechanism during the late Phanerozoic era, based on carbon fixation in peatforming wetlands. *Ambio*, 25(7), 435−442.

Franzén, L.G. & Cropp, R.A. (2007) The peatland/ ice age hypothesis revised: adding a possible glacial pulse trigger. *Geografiska Annaler*, 89A(4), 301−330.

Frolking, S. & Roulet, N.T. (2007) Holocene radiative forcing impact of northern peatland carbon accumulation and methane emissions. *Global Change Biology*, 13, 1079−1088.

Frolking, S., Roulet, N. & Fuglestvedt, J. (2006) How northern peatlands influence the Earth's radiative budget: Sustained methane emissions versus sustained carbon sequestration. *Journal of Geophysical Research*, 111, G01008, doi: 10.1029/2005JG000091.

Gorham, E. (1991) Northern peatlands: role in the carbon cycle and probable responses to climate warming. *Ecological Applications*, 1, 182−195.

Granath, G., Strenbom, J. & Rydin, H. (2010) Rapid ecosystem shifts in peatlands: linking plant physiology and succession. *Ecology*, 91(10), 3047−3056.

Granlund, E. (1932) De svenska högmossarnas geologi (Geology of Swedish raised bogs). *Sveriges Geologiska Undersökning/Swedish Geological Survey (SGU),* Ser. C, 373, 1−193 (in Swedish with an extended German summary).

Gunnarsson, U. & Löfroth, M. (2009) *Våtmarksinventeringen – resultat från 25 års inventering. Nationell slutrapport för våtmarksinventeringen (VMI) i Sverige* (*Wetlands Inventory – Results from 25 Years of Inventory. National Final Report for Wetland Inventory (VMI) in Sweden*). Naturvårdsverket Rapport 5925, 120 pp. (in Swedish).

Hughes, P.D.M. (2000) A reappraisal of the mechanisms leading to ombrotrophy in British raised mires. *Ecology Letters*, 3, 7−9.

Hughes, P.D.M. & Dumayne-Peaty, L. (2002) Testing theories of mire development using multiple successions of Crymlyn Bog, West Glanmorgan, South Wales, UK. *Journal of Ecology*, 90, 456−471.

Hughes, P.D.M., Mauquoy, D., Barber, K. & Langdon, P.G. (2000) Mire-development pathways and palaeoclimatic records from a full Holocene peat archive at Walton Moss, Cumbria, England. *The Holocene*, 10, 465−479.

Ikonen, L. (1993) Holocene development and peat growth of the raised bog Pesänsuo in southwestern Finland. Bulletin 370, Geological Survey of Finland, Espoo, 58 pp.

Joosten, H. (2010) *The Global Peatland CO_2 Picture. Peatland Status and Drainage Related Emissions in all Countries of the World*. Wetlands International, Ede, The Netherlands, 36 pp. http://www.wetlands.org/LinkClick.aspx?fileticket=o %2bd %2bTaPldLI %3d&tabid=56

Korhola, A. (1992) Mire induction, ecosystem dynamics and lateral extension on raised bogs in the southern coastal area of Finland. *Fennia*, 170, 25−94.

Korhola, A. (1994) Radiocarbon evidence for rates of lateral expansion in raised mires in southern Finland. *Quaternary Research*, 42, 299−307.

Korhola, A. (1995) Holocene climatic variations in southern Finland reconstructed from peat-initiation data. *The Holocene*, 5, 43–58.

Korhola, A. (1996) Initiation of a sloping mire complex in southwestern Finland: Autogenic versus allogenic controls. *Écoscience*, 3, 216−222.

Kuhry, P. & Turunen, J. (2006) The postglacial development of Boreal and Subarctic peatlands. In: Wieder, R.K. & Vitt, D.H. (eds.) *Boreal Peatland Ecosystems*, Ecological Studies, Vol. 188, Springer-Verlag, New York, 25−46.

Kuzmin, G.F. (1994) *To the Balance of Peat Winning and Recreation*. Internal Report 8, All-Union Research Institute for Peat Industry, St. Petersburg, Russia.

Lantmäteriverket (2011a) GSD-Terrain Elevation Databank, 1:1,000,000. Gävle, Lantmäteriet. The Swedish mapping, cadastral and land registration authority. Accessed 2011-06-01 at: http://butiken.metria.se/digibib/info.html

Lantmäteriverket (2011b) Maps of Sweden, 1:1,000,000. Gävle, Lantmäteriet. The Swedish mapping, cadastral and land registration authority. Accessed 2011-06-01 at: http://butiken.metria.se/digibib/info.html

Lind, P. & Kjellström, E. (2008) Temperature and precipitation changes in Sweden, a wide range of model-based projections for the 21st century. *SMHI Reports Meteorology Climatology*, 113, 1−66.

Lode, E., (2002) GIS estimation of mire massif development. Natural mire hydrology in restoration of peatland functions. *Studia Forestalia Suecica*, 205, 30.

Lode, E., Sagris, V. & Ilomets, M. (2001) GIS estimation of mire massif development. In: Lode, E. *Natural Mire Hydrology in Restoration of Peatland Functions*. Doctoral thesis, Acta Universitatis Agrivuturae Sueciae, *Silvestria*, 234.

McVean, D.N. & Ratcliffe, D.A. 1962 *Plant Communities of the Scottish Highlands*. H.M.S.O., London, 455 pp.

Mäkilä, M. (1997) Holocene lateral expansion, peat growth and carbon accumulation on Hakkasuo, a raised bog in southeastern Finland. *Boreas*, 26, 1−14.

Mäkilä, M., Saarnisto, M. & Kankainen, T. (2001) Aapa mires as carbon sink and source during the Holocene. *Journal of Ecology*, 89, 589−599.

Malmström, C. (1923) Degerö Stormyr. *Meddelanden från Statens Skogsförsöksanstalt*, 20, 1−206 (in Swedish).

Malmström, C. (1932) Om faran för skogsmarkens försumpning i Norrland (The risk of forest soil paludification in Norrland). *Meddelanden från Statens Skogsförsöksanstalt*, 26, 1−126 (in Swedish).

Maltby, E. & Immirzi, P. (1993) Carbon dynamics in peatlands and other wetland soils. Regional and global perspectives. *Chemosphere*, 27(6), 999−1023.

Milliman, J.D. (1993) Production and accumulation of calcium carbonate in the ocean - budget of nonsteady state. *Global Geochemical Cycles*, 7, 927−957.

Monnin, E., Indermühle, A., Dällenbach, A., Flückiger, J., Stauffer, B., Stocker, T.F., Raynaud, D. & Barnola, J.-M. (2001) Atmospheric CO_2 concentrations over the last glacial termination. *Science*, 291, 112−114.

Moore, T.R., Roulet, N.T. & Waddington, J.M. (1998) Uncertainty in predicting the effect of climate change on the carbon cycling of Canadian peatlands. *Climate Change*, 40, 229−245.

Neustadt, M. (1984) Holocene peatland development. In: Velichko, A. (ed.) *Holocene Peatland Development, the Late Quaternary Environments of the Soviet Union*, University of Minnesota Press, Minneapolis, Minnesota, USA, 201−206.

Nilsson, M., Mikkelä, C., Granberg, G., Sundh, I., Svensson B. & Ranneby, B. (2001) Methane emission from Swedish mires: National and regional budgets and dependence on mire vegetation. *Journal of Geophysical Research*, 106 (D18), 20847−20860.

Olvmo, M. (2010) *Review of Denudation Processes and Quantification of Weathering and Erosion Rates at a 0.1 to 1 Ma Time Scale*. Report TR-09-18, Swedish Nuclear Fuel and Waste Management Company, Stockholm, 56 pp.

Pépin, L., Raynaud, D., Barnola, J-M. & Loutre, M.F. (2001) Hemispheric roles of climate forcings during glacial−interglacial transitions as deduced from the Vostok record and LLN-2D model experiments. *Journal of Geophysical Research*, 106(D23), 31885−31892.

Peregon, A., Uchida, M. & Yamagata, Y. (2009) Lateral expansion in *Sphagnum* mires along the southern margin of the boreal region, Western Siberia. *Environmental Research Letters*, 4, 1−7.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Benders, M., Chappellaz, J., Davis, M., Delayque, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E. & Stievenard, M. (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, 399, 429−436.

Prentice, I.C., Farquar, G.D., Fasham, M.J.R., Goulden, M.L., Heimann, M., Jaramillo, V.J., Khegesi, H.S, Le Quéré, C., Scholes, R.J. & Wallace, D.W.R. (2001) The carbon cycle and the atmospheric carbon dioxide. In: Houghton, J.T. *et al*. (eds.) *Climate Change 2001 – the Scientific Basis*. IPCC, Cambridge University Press, 183−237.

Raynaud, R., Barnola, J.M., Souchez, R., Lorrain, R., Petit, J.R., Duval, P. & Lipenkov, V.Y. (2005) Revisiting the Vostok record, the CO_2 paradox of marine isotopic stage 11. *Nature*, 436, 39−40

Rydin, H. & Jeglum, J. 2006 *The Biology of Peatlands*. Oxford University Press, 343 pp.

Sernander, R. (1910) Ausstellung zur Beleuchtung der Entwicklungsgeschichte der Schwedischen Torfmoore (An elucidation of the development history of Swedish peatlands). *Compte Rendue XIme Congrès Géologique International*, 203 (in German).

SGU (2011) Maps of Quaternary Deposits, 1:1,00,000, Ak series. © Geological Survey of Sweden.

Sjörs, H. (1983) Mires of Sweden. In: Gore, A.J.P. (ed.) *Ecosystems of the World 4B. Mires, Swamp, Bog, Fen and Moor, Regional Studies*. Elsevier, Amsterdam-Oxford-New York, 69−94.

Stuiver, M. & Reimer, P.J. (2000) CALIB rev. 4.3© http: //depts.washington.edu/qil/dloadcalib/

Temnerud, J. & Weyhenmeyer G.A. (2008) Abrupt changes in air temperature and precipitation: Do they matter for water chemistry? *Global Biogeochemical Cycles*, 22, GB2008, doi: 10.1029/2007GB003023

Tolf, R. (1893) Komosse. *Svenska Mosskultur-föreningens Tidskrift* 1893, Jönköping, 531–537 (in Swedish).

Turunen, J., Tomppo, E., Tolonen, K. & Reinikainen, A. (2002) Estimating carbon accumulation rates of undrained peatlands in Finland, application to boreal and subarctic regions. *The Holocene*, 12, 69−80.

Turunen, C. & Turunen, J. (2003) Development history and carbon accumulation of a slope bog in oceanic British Columbia, Canada. *The Holocene*, 13, 225−238.

Von Post, L. (1927) Beskrivning till översiktskarta över södra Sveriges myrmarker (Key to the overview map of peatlands in southern Sweden). *Sveriges Geologiska Undersökning Ser Ba* 11 (in Swedish).

Vorren, K.-D., Eldegard, Jensen, C. & Nilssen, E. (2012) Climate changes during the last c. 7500 years as recorded by the degree of peat humification in the Lofoten region, Norway. *Boreas*, 41, 13−30.

Warner, B.G., Clymo, R.S. & Tolonen, K. (1993) Implications of peat accumulation at Point Escuminac, New Brunswick. *Quaternary Research*, 39, 245−248.

Wiegers, J. (1986) Succession in fen-woodlands in the Dutch Haf district. In: Fanta, F. (ed.) *Forest Dynamics Research in Western and Central Europe*, Proceedings of the IUFRO workshop of subject group SI.01-00 ecosystems, Centre for Agricultural Publishing and Documentation, Wageningen, The Netherlands, 135−144.

Yu, Z., Beilman, D.W., Frolking, S., MacDonald, G.M., Roulet, N.T., Camill, P. & Charman, D. (2011) Peatlands and their role in the global carbon cycle. *EOS* 92(12), 97−98.

Submitted 13 Feb 2012, final revision 30 Aug 2012
Editor: R.S. Clymo

Author for correspondence:
Professor Lars G. Franzén, Physical Geography, Department of Earth Sciences, University of Gothenburg, P.O. Box 460, SE-405 30 Göteborg, Sweden.
Tel: +46-31-7861958; Fax +46-31-7861986; E-mail: lars@gvc.gu.se