Increased decomposition of subsurface peat in Swedish raised bogs: are temperate peatlands still net sinks of carbon?

L.G. Franzén

Department of Earth Sciences - Physical Geography, Göteborg University,
P.O. Box 460, SE-405 30, Göteborg, Sweden

SUMMARY

An increased rate of decomposition has been observed in a large number of raised bogs in southern Sweden and elsewhere since the 1970s. The effect is manifest as a discoloured and mucous subsurface peat layer, and there is associated subsidence of mire surfaces. This paper reports the results of a systematic investigation of the phenomenon in 14 raised bogs in southern Sweden, which was carried out between 1997 and 2005. Degree of decomposition, bulk density and ash content were measured and evidence of surface subsidence over recent decades was collected. Shallow peat layers of 'normal' appearance could not be found anywhere within the study sites, and all showed the same signs of secondary decomposition. In particular, the ombrotrophic parts of the Komosse Bog Complex appeared to have subsided by at least 150 mm over the last 35 years, i.e. at a rate of approximately 4.3 mm *per annum*, which is more than four times the average rate of peat formation in circumboreal raised bogs. The changes observed could have been caused by change in any one of a number of factors, e.g. climate, hydrology and rate of nutrient supply; or by a combination of such factors. However it seems most likely that they are attributable to the heavy modern nutrient load, e.g. of dust from anthropogenic sources. There is cause for concern that many high-latitude peatlands may consequently have switched over from being net sinks, to net sources, of atmospheric carbon.

KEY WORDS: anthropogenic dust, carbon balance, net CO_2 source, fertilizing, secondary decomposition.

INTRODUCTION

Peatlands are reservoirs of organic soils and peat, in which significant amounts of carbon have been accumulated since the last glacial retreat. Globally, they extend to approximately $5x10^6$ km^2, covering about 3.5% of the Earth's land surface. The greatest concentration of peatlands and the highest rate of peat formation occur in the cool, humid climates of the temperate belt of the Northern Hemisphere. Indeed, more than 95% of the total peat reserves of the world are concentrated here, most of the remainder being in the humid tropics.

Estimates of the amount of carbon stored globally in peatlands range from 120 to 400 Gt (Franzén 1994; Franzén *et al*. 1996; Ajtay *et al*. 1979; Sjörs 1980, 1982; Adams *et al*. 1990). In a recent report, Smith *et al*. (2004) estimate that peat makes up *ca.* 26% of all the terrestrial carbon accumulated since the Last Glacial Maximum so that it is one of the largest terrestrial carbon reservoirs. Thus, peatland may be crucially important as a long-term sink for atmospheric carbon dioxide. On the other hand, there is a concern it may become a net source of CO_2 due to climate change (Waddington *et al*. 1998), or due to other factors that influence peat formation.

The strength of the peatland carbon sink has changed during the Holocene. For a raised bog in Finland, Mäkilä (1997) estimated that carbon accumulation rates were at their all-time minimum in 1500–1000 BC when the climate was warm and dry, and that the highest rates occurred in 3050–2950 BC, 1950–1600 BC, 600–400 BC and 1100–2000 AD, coinciding with humid climatic phases. Peatlands were small and dominated by minerotrophic plant communities in the early Holocene, and many mid-latitude sites became ombrotrophic during periods of high humidity, e.g. around 4500 BC, 3000 BC, 2300 BC, 1700 BC, 1000 BC, 500 BC and 500 AD.

The area of most peatlands has increased by a cubic function since their initiation (Franzén *et al*. 1996), and calculations indicate that 50% of the pre-industrial peatland area could have been formed during the last 2,000 years. A few recent investigations involving ^{14}C dating of basal peat layers confirm the high rate of lateral expansion of peatlands, e.g. in Finland (Korhola 1992, 1994), Denmark (Aaby 1990) and Sweden (Almquist-

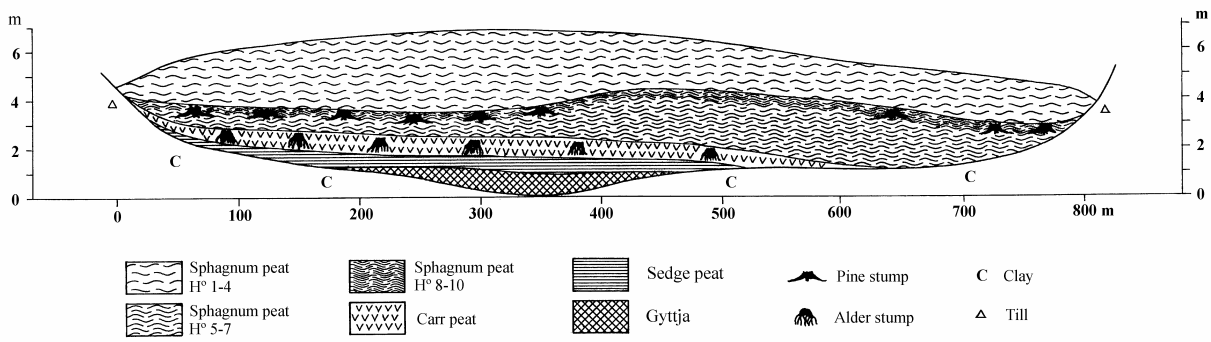


Figure 1. Section through Store Mosse, Nossebro, southwest Sweden (from Franzén 1985). The transition from little humified to well humified peat at 2−3 metres depth is generally known as Recurrence Surface III (Granlund 1932).

Jacobson & Foster 1995). However, during the last 100 years, the area of peatland in the industrialized countries has declined dramatically due to farming, forestry and peat extraction and hence has contributed to the increasing concentration of atmospheric carbon dioxide (Franzén *et al.* 1996). Waddington & Price (1999) report a net loss of 4.1 Gt C from the world's wetlands between 1795 and 1980 due to the effect of land use conversion on CO_2 exchange processes. In addition, marginal drainage (protective ditching) has temporarily halted the lateral expansion of most of the mires that remain more or less undisturbed.

The extent of wetland in Sweden is 93,000 km^2, of which approximately two-thirds is peatland. The uppermost 2−3 metres of most Swedish raised bogs consists of a more or less unbroken layer of weakly decomposed peat (Figure 1) which reflects the cool, moist climate that has prevailed throughout the Sub-Atlantic (the last *ca*. 2,500 years). The author has been investigating peat stratigraphy in Sweden since the early 1970s, and noticed a remarkable change in the appearance of the shallow subsurface layers of most bogs from that time up to the early 2000s. From the living superficial layer to 10−25 cm below the surface, the peat was discoloured and had a mucous consistency (Plate 1). This paper reports the results of a systematic follow-up investigation of the phenomenon at 14 raised bogs in southern Sweden.

Plate 1. A peat block cut from the mire surface at the Björnsjömossen sampling site on the Komosse Bog Complex (Site 6 in Figure 2). The dark peat horizon near the surface is the layer that has undergone secondary decomposition.

METHODS

Sites

Fourteen raised bogs in southern Sweden (Figure 2) were investigated within a larger study of peat accumulation and peat geochemistry carried out during the summers of 1997−2005. Of particular note is the Komosse complex (Plate 2, Sites 6 and 7 in Figure 2), one of the largest and best preserved virgin bogs in western Europe, which covers almost 50 km^2 of a high altitude bedrock plateau in central south Sweden. Komosse was described by Osvald (1923), and was one of the sites chosen for hydrological investigations during the International Hydrological Decade (IHD) 1965−74 (Johansson 1976).

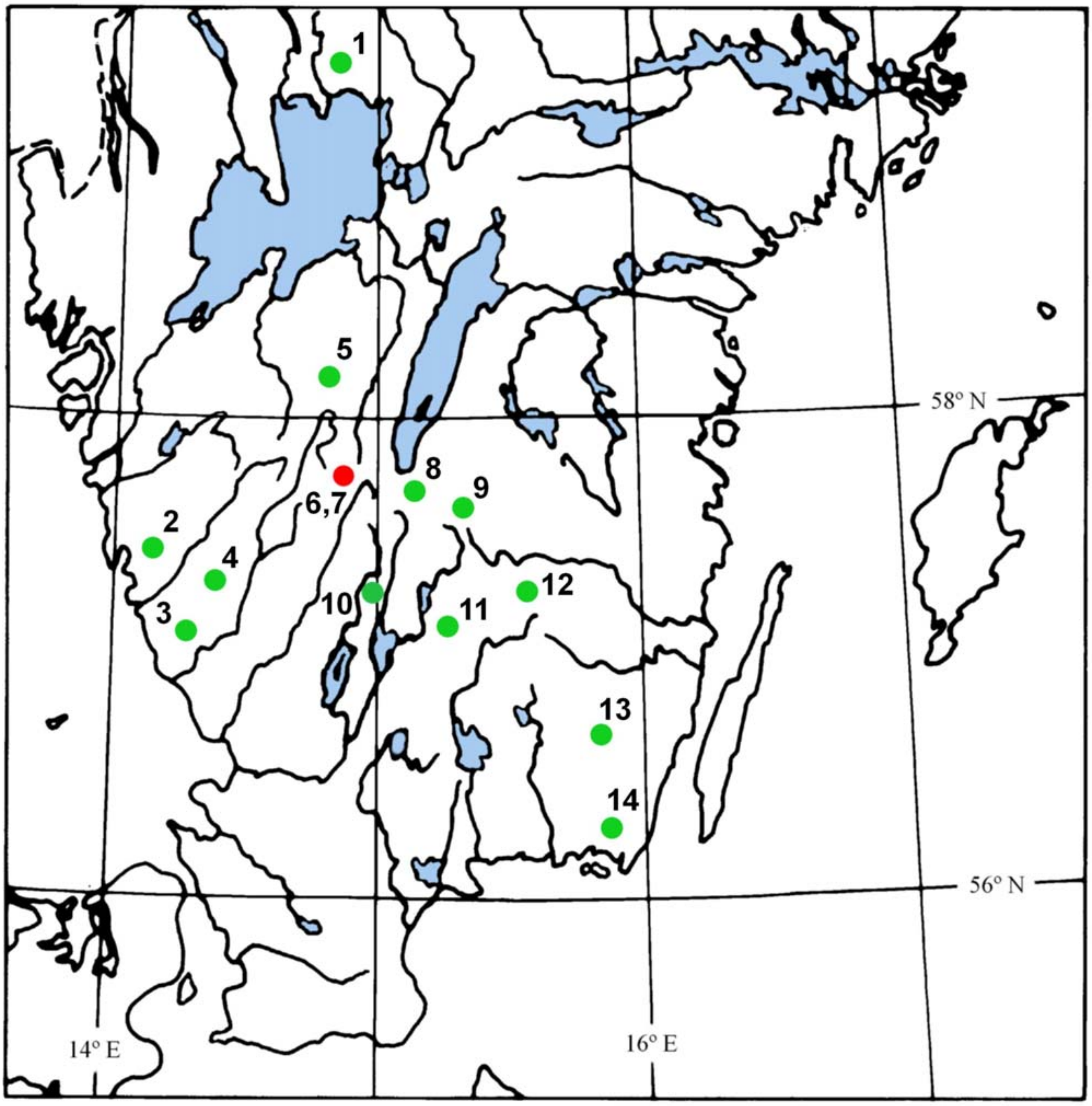


Figure 2. Sampling sites (and sampling years) in southern Sweden. 1: Dömle Mosse (1997); 2: Lyngmossen (1997); 3: Gällseredsmossen (2003); 4: Store Mosse Öxabäck (2003); 5: Hjortemossen (1998); the Komosse Bog Complex sites 6: Björnsjömossen (2005) and 7: Karsbomossen (2003); 8: Konungsömossen (1998); 9: Fallamossen (1998); 10: Store Mosse Kävsjö (2002); 11: Bråtarna (2002); 12: Vildmossen (2001); 13: Torstamåla Fly (2001); and 14: Store Mosse Kallinge (2000).

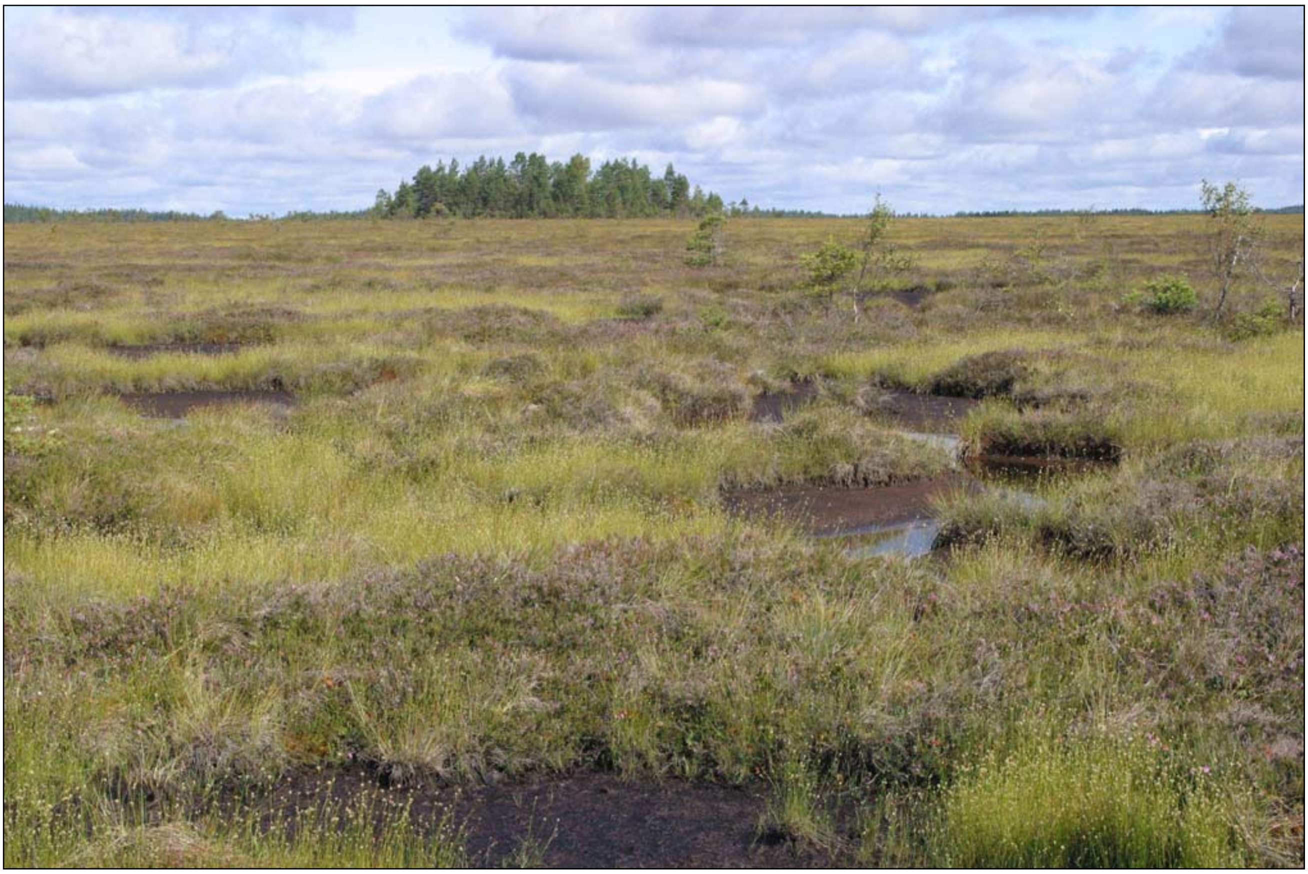


Plate 2. Overview of part of the Komosse Bog Complex, looking northwest from the Björnsjömossen (6) sampling site.

Stratigraphy

Stratigraphical samples were collected between 1997 and 2005, using a 50 mm diameter Byelorussian peat corer. Since a bog normally starts to develop in a moist depression, from which the mire grows upwards and expands laterally (Franzén 1994, Franzén *et al*. 1996), the samples were collected from a *Sphagnum* lawn at the centre of each site in order to obtain the longest possible record. They were extracted as 50 mm layers, giving a temporal resolution of *ca*. 50 years (peat accumulation rate *ca*. 1 mm *per annum*). The sampling year for each site is given in the legend to Figure 2.

Degree of decomposition was determined using a Minolta Chroma Meter, which measures the reflectivity and colour of air-dried peat samples. This system of colour determination, developed by the Commission Internationale de l'Eclairage, provides an objective indication of the degree of decomposition; a strongly decomposed peat has a low reflectance, i.e. a dark colour, and *vice versa*. The degree of decomposition (H°1−10) according to von Post (1927) was calculated as a linear function of reflectance.

Dry bulk density was calculated from the sample volume (40 cm^3) and the dry weight after oven drying (12 hours at 108°C). The peat samples were then ashed at 700°C and ash content was calculated as a fraction of dry weight. Dry peat consists of combustible organic material and mineral matter deposited during peat formation. Peat ash is generally composed of *ca*. 90% soluble salts, mainly Ca (Fredriksson 1996), together with insoluble particles such as microscopic mineral (mostly quartz) grains deposited as condensation nuclei, volcanic ash (Pilcher & Hall 1992) and silicon-rich phytoliths from peat forming plants in some stratigraphical layers. The ash concentration in natural ombrotrophic peat is *ca*. 0.5−1%, whilst in fen peat the ash content can reach 15% or even more (Fredriksson 1996).

In a concurrent project focusing on the growth dynamics of the same raised bogs, more than 100 calibrated (Stuiver & Reimer 1993) AMS ^{14}C dates were obtained for both vertical profiles and horizontal transects established to investigate the lateral expansion of the bogs. Additional dates were obtained using tephrochronology (Pilcher & Hall 1992) and geochemical signal levels e.g. for lead (Renberg *et al*. 2000, 2001); and individual tephra horizons identified using SEM-EDX were investigated geochemically using the Inductively Coupled Plasma Mass Spectrometer (ICP-MS) technique. Additional information was obtained using the less reliable 'constant bulk density' method. This method is based on the assumption that the mire has been growing at the same rate over its whole surface ever since peat growth began, so that all the peat at a specific level has the same bulk density (Ilomets 1984; Lode *et al*. 2001); it could also be extrapolated between different mires within a restricted geographical region if they have similar developmental histories. Whilst this method gives no information on exact timing, it can indicate the approximate time of formation of individual stratigraphical layers, enabling rapid location of e.g. tephra horizons.

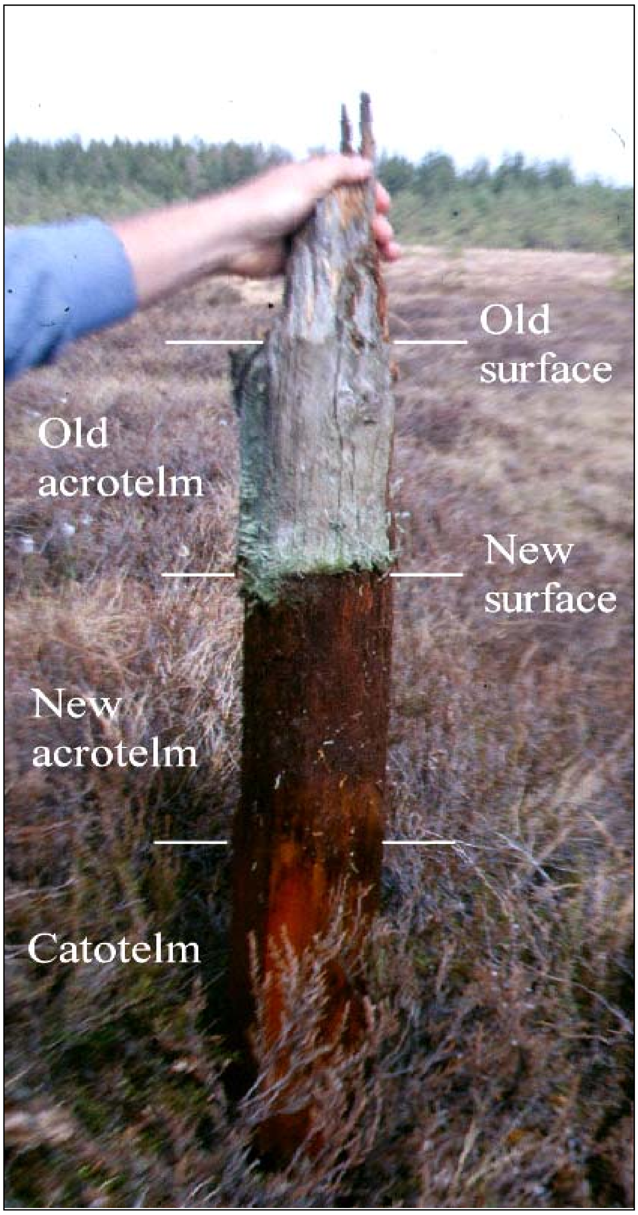


Plate 3. Wooden post which was pulled out from the surface of Björnsjömossen in the Komosse Bog Complex (Site 6 in Figure 2), approximately 20 m from the steel tube shown in Plates 4 and 5. The zonation visible on the post supports the hypothesis that the mire surface has subsided.

Plate 4. Demonstration of the measurement procedure for the IHD steel tubes on the Komosse Bog Complex. This and all the other IHD tubes were visited and re-measured five times between 1996 and 2005.

Surface subsidence

At most of the sites, changes in surface level were inferred by examination of old wooden boundary marker and fence posts, which offer the advantage over telegraph and power-line poles that they can be pulled out for inspection. Such posts are normally driven into peatland surfaces to a depth of 0.5–1 m. As time passes, the part of the post that is exposed to the atmosphere decomposes but the part that is buried in peat is preserved. Thus, when such a post is pulled out, the part that has rested in the catotelm looks much newer than the acrotelm part. At each bog visited, such poles were sought, pulled out, and the zonation they displayed was recorded (Plate 3).

Komosse and the International Hydrological Decade (IHD) investigation

At Komosse (Figure 2, Sites 6 and 7), a legacy of the IHD investigation offered a unique opportunity to assess surface subsidence. During the winter of 1969/70, 54 perforated galvanised steel tubes were driven through the peat and 0.5 m into the underlying mineral soil (till), in order to facilitate the study of fluctuations in water table and mire surface level at a network of locations across the mire (Plate 4). After installation, the altitudes of the top of each tube and the adjacent mire surface were surveyed to 1 mm precision, in compliance with RAK (Swedish General Map) standards. The protruding length of each tube was measured regularly during the currency of the IHD project, using a solid plate (30 x 40 cm) with a slot to allow it to fit round the tube to define the mire surface. The regular measurements ceased at the end of the IHD project in 1974 but the tubes were not removed. All the “tube sites” were re-examined twice in 1996 (February and July), once in 2001 (September), once in 2003 (March) and once in

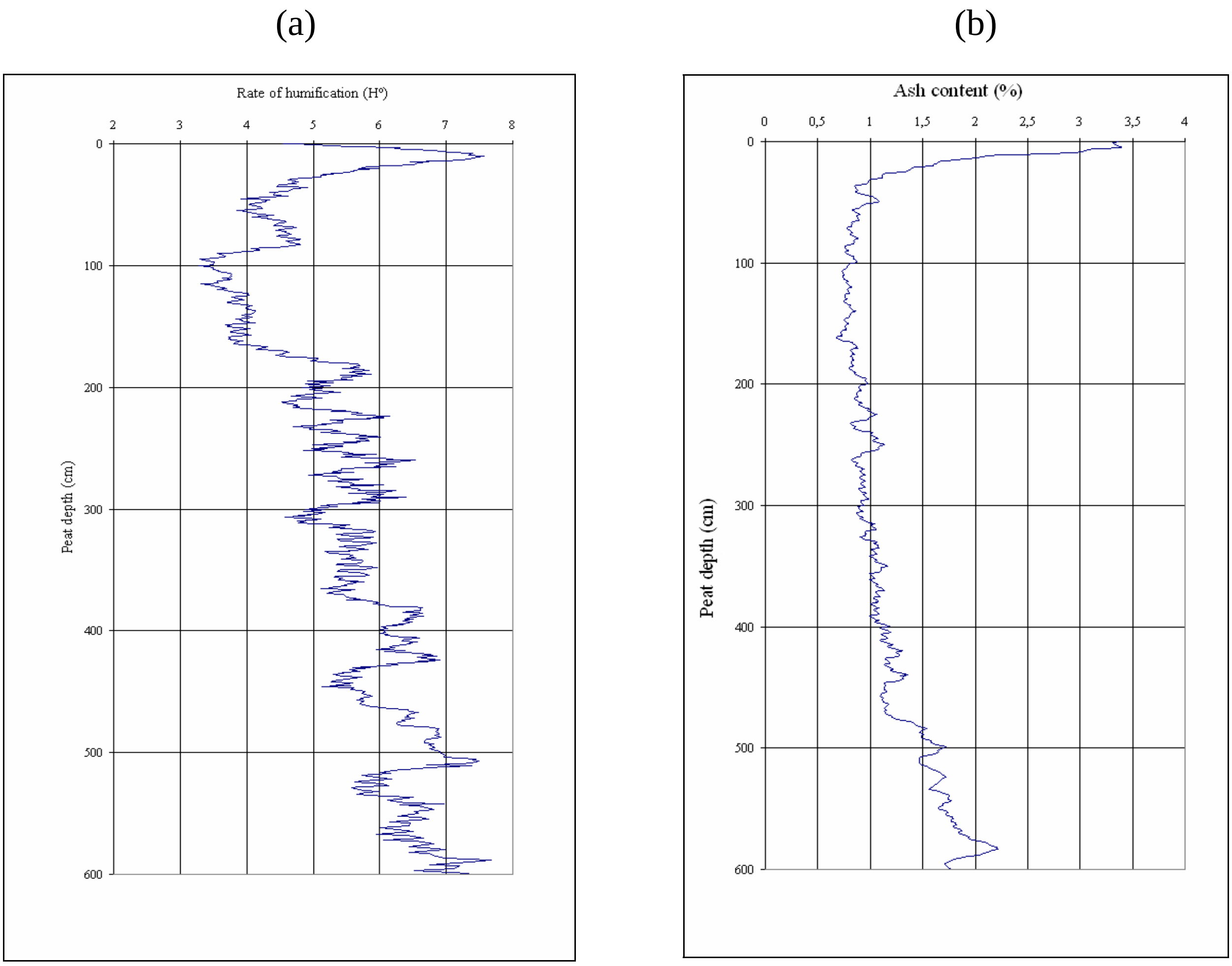


Figure 3. Characteristics of the peat profile at Lyngmossen (Site 2 in Figure 2), a typical south Swedish raised bog: (a) profile of humification, measured as the reflectance of dried peat using a Minolta Chroma Meter, at 1 cm depth intervals; and (b) profile of ash content. The higher ash concentrations near the base of the profile reflect the presence of basal minerotrophic peat (see Figure 1) and the high surface concentrations result from anthropogenic activities. All the other bogs investigated exhibited similar stratigraphical patterns.

2005 (July) in order to establish whether the mire surface level had changed. At these times, the vertical distance from the top of each tube to the upper surface of the plate was measured and the thickness of the plate was added to the measurement, as during the IHD surveys.

RESULTS

Stratigraphy

The field examination of peat stratigraphy confirmed that no shallow peat of 'normal' appearance could be found at any of the study sites, i.e. that they all exhibited the same signs of secondary decomposition (e.g. Plate 1). A more objective evaluation is provided by the measurements of reflectance (degree of decomposition) and dry bulk density.

Example profiles of humification and ash content are shown in Figure 3. The uppermost 20-30 cm of all of the raised bogs investigated show high humification (Figure 3a) and a very high concentration of minerals (i.e. high ash content) (Figure 3b). However, high ash content in the surface layers could be a self-enhancing artefact, in that the high influx of airborne particles due to human activity may improve the supply of mineral nutrients, promoting decomposition and loss of organic matter and thus passively increasing the concentration of the mineral (ash) fraction.

The dry bulk density data, re-calculated as the total annual dry substance accumulation for all the bogs in the study over the period since peat formation began, are shown in Figure 4. This analysis eliminates 'noise' arising from differences in the annual increment of peat thickness (mm yr^{-1}) between sites. All of the 14 raised bog profiles studied showed similar characteristics, with high annual dry bulk mass accumulation around 4000 BC, followed by a decline to around 30 g m^{-2} yr^{-1} *ca*. 2000 BC, a pronounced peak between 600 BC and 200 AD, a trough centred around 500 AD and another peak centred around 1100−1300 AD. The thin peak at 1700 AD and the very thin peak just below the surface are probably artefacts, as discussed above.

Figure 5 shows profiles of dry bulk density and reflectance (degree of decomposition) for the uppermost metre of each bog, and overall mean values are shown in the last diagram. In this case, no correction is made for variations in annual peat increment between different bogs, but even so, the sub-surface peak of high peat density and low reflectance (high degree of decomposition) is striking for all of the bogs investigated. In general,

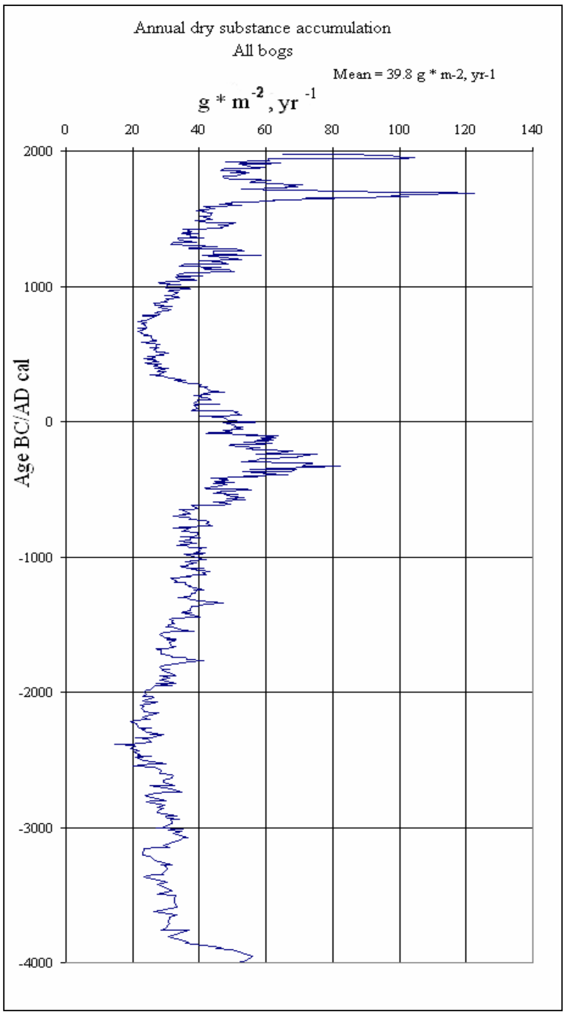


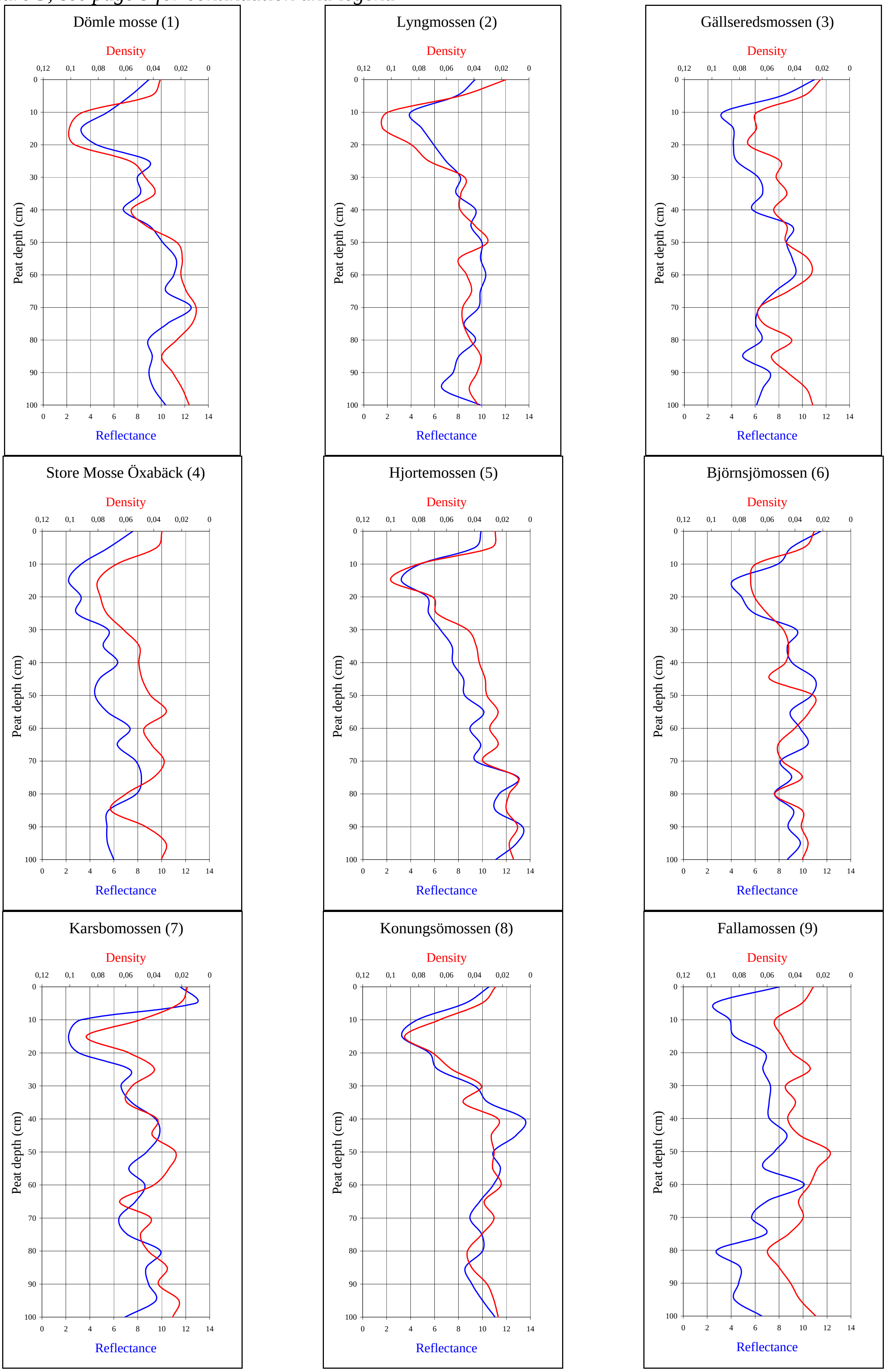
Figure 4. The variation of total annual dry bulk accumulation with peat age for the 14 bogs investigated in this study.

the peak is centred some 10-25 cm below the surface. From a geographical point of view, the peaks tend to be quite shallow in westerly sites (e.g. Lyngmossen ≈ 10 cm) and at greater depths in the east (e.g. Torstamåla Fly ≈ 25 cm). This tendency is consistent with the general pattern of humidity and mire water table depth in southern Sweden, where precipitation and water tables are higher in the west than in the east.

The data used to construct Figure 5 are re-worked as a plot of reflectance (rate of humification) *vs*. dry bulk density in Figure 6.

All of these data indicate unequivocally that a subsurface layer of peat is decomposing more rapidly than the underlying (and overlying) peat. Its dark colour reflects the high degree of humification and mineralization; and its dry bulk density is 2−3 times higher, its reflectance 2−3 times lower and its ash content 3−4 times higher than that of the peat immediately below.

Figure 5; see page 9 for continuation and legend



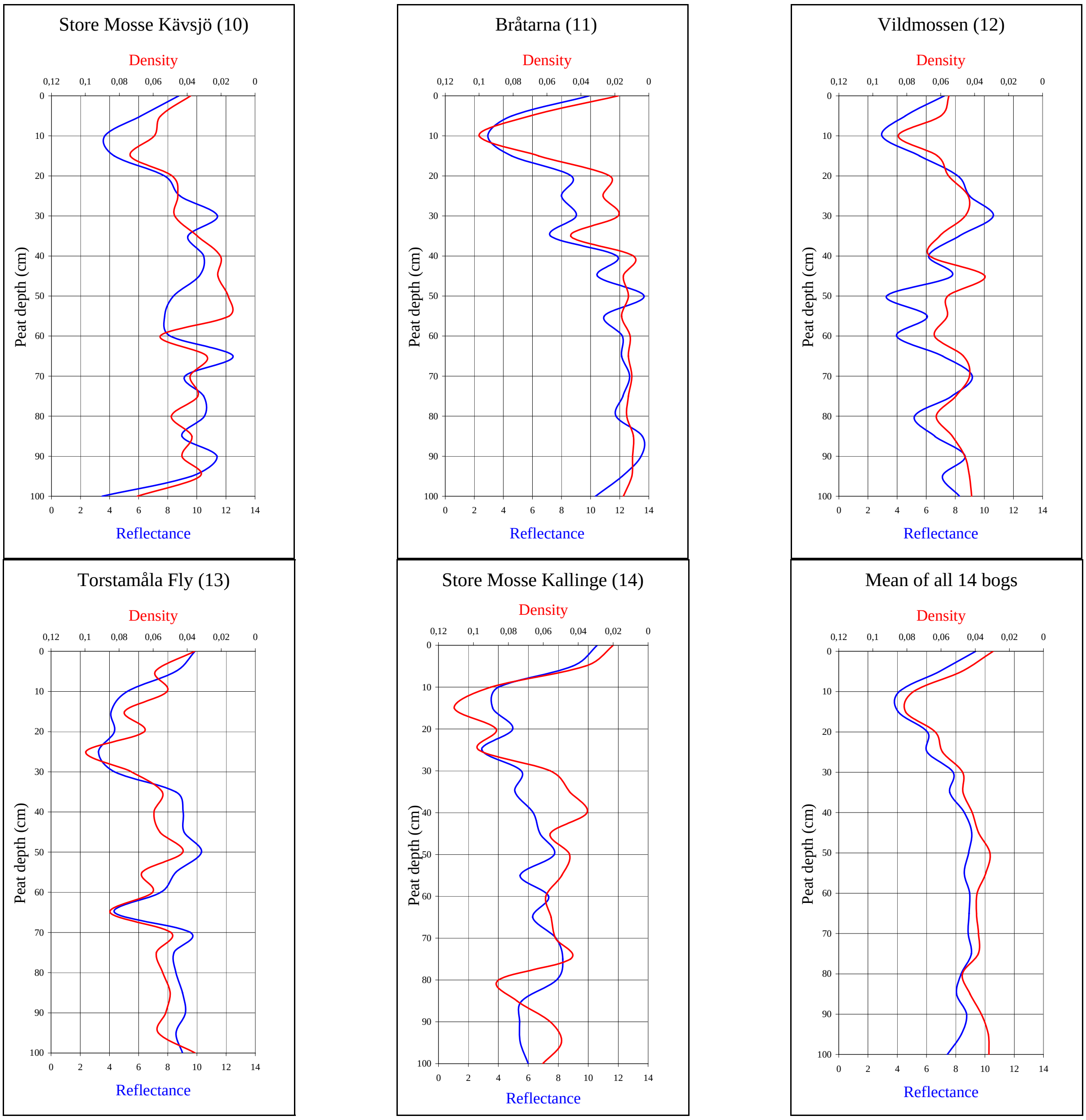


Figure 5. Profiles of dry bulk density and reflectance (degree of decomposition) in the superficial layers (0–1 m below the surface) of the 14 bogs investigated, and overall mean values. The increase in dry bulk density and degree of decomposition (lowered reflectance) from a depth of ≈10–20 cm towards the surface is visible in all cases.

Surface subsidence

There is little doubt that the direct observations of wooden posts and the Komosse steel tubes show that there has been subsidence. Only a small number of wooden posts were found, but all displayed similar features; namely a catotelm zone at the bottom, an acrotelm zone above, and an old acrotelm zone at the top which had become exposed above the bog surface. At the very tops of some posts, there were remains of core wood that had not disappeared (Plate 3).

While the ages of the wooden posts were unknown, the installation date of the Komosse steel tubes was well known. For these, the most obvious indication of change was the position, relative to the current mire surface, of the sharp transition between the preserved zinc coating on the upper part of each tube and the rusty surface of its lower part, which had lost the coating (Plates 4, 5). The distances between the transitions and the tops of the tubes agreed well with the initial (1969/70) measurements of ‘tube top to mire surface’ distance. The five re-measurements (1996–2005) confirmed that the ombrotrophic part of the mire surface (i.e. true

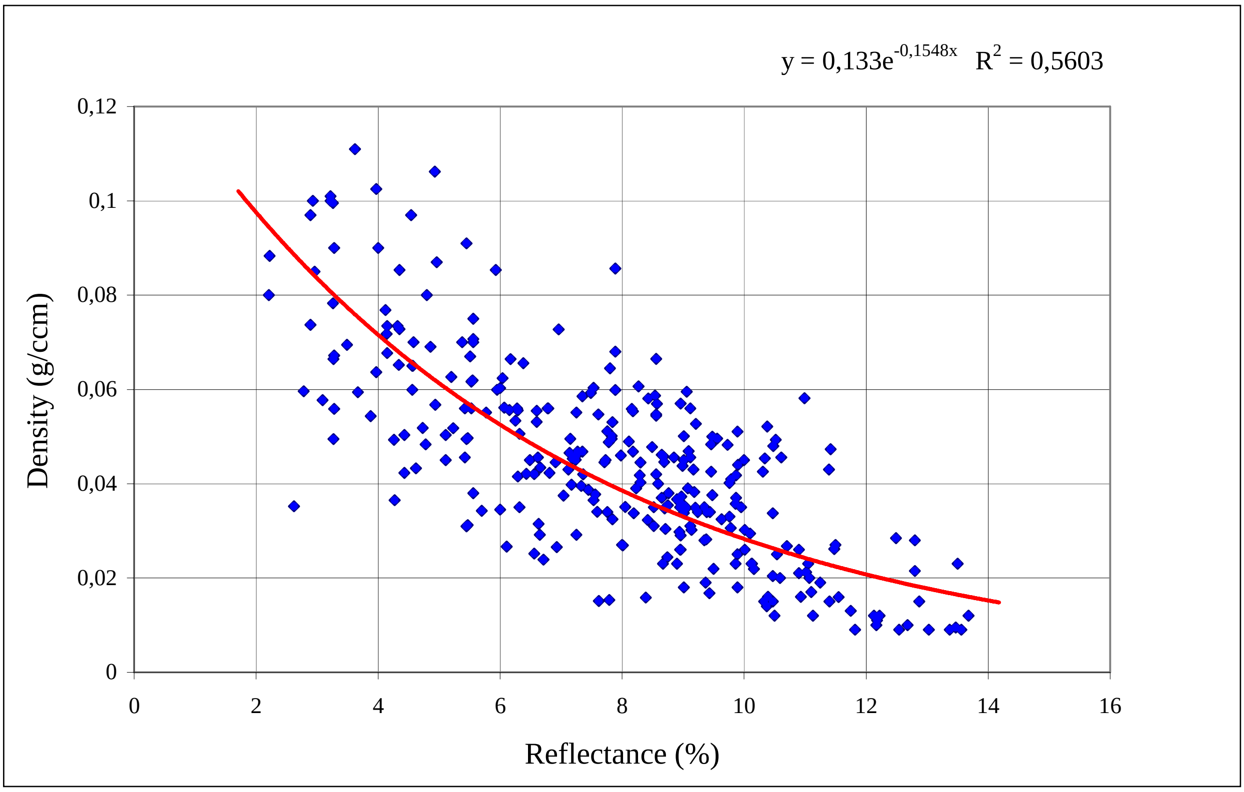


Figure 6. Reflectance *versus* dry bulk density for the surface peat samples (0-1 m) from all 14 raised bogs. An exponential function provided the best fit to the data.

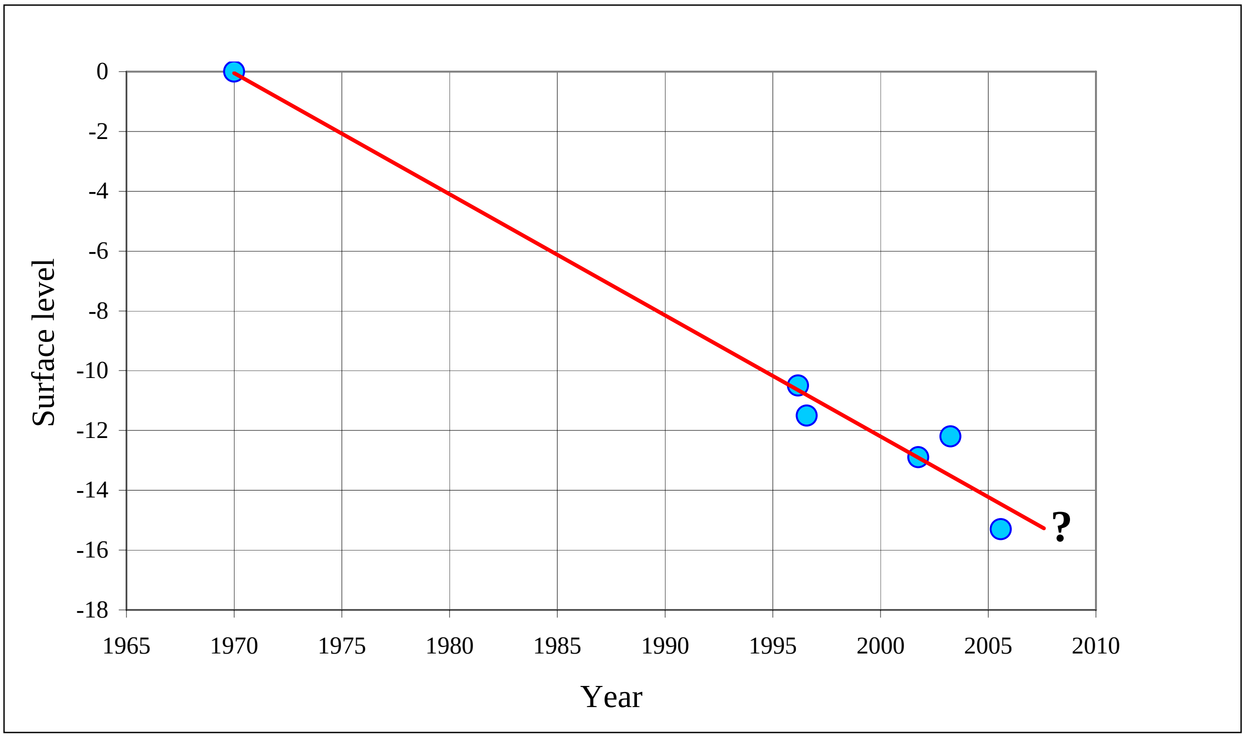


Figure 7. Mean level of the ombrotrophic mire surface at the Komosse Bog Complex on five occasions in 1996−2005, expressed (in cm) relative to its position in 1969/70. Data derived from measurements made at the IHD tube sites.

Plate 5. Close view of the IHD steel tube shown in Plate 4, at Björnsjömossen (Site 6 in Figure 2) in the Komosse Bog Complex. The sharp boundary between corroded and non-corroded tube galvanization shows the former position of the bog surface, and the length of the rusty section gives a rough indication of the amount of subsidence that has occurred since 1970.

raised bog) at Komosse had indeed subsided significantly. The mean subsidence since 1970 for all sites was -12.8 cm, and individual values ranged from +18 to -43 cm. In shallower minerotrophic areas (fens), some tubes indicated no changes and the surface had risen at others. All the posts with positive values were in minerotrophic locations (soaks and lagg fens). For truly ombrotrophic situations, mean subsidence amounted to -15.3 cm or *ca*. 4.5 mm yr^{-1} between 1969/70 and July 2005. Assuming a mean growth rate for the topmost peat layers of 1 mm yr^{-1} (*ca*. 2.5 cm in 35 years), the total subsidence of the bog since installation of the tubes could, therefore, be as much as -17.8 cm, or *ca*. 5 mm yr^{-1}. The progress of subsidence from 1969/70 to July 2005 is shown in Figure 7.

DISCUSSION

Absolute measurements of small changes in peatland growth and subsidence rates are not readily obtainable. Even thousands of thorough descriptions of peatland stratigraphy from southern Sweden dating back to the early 20th century would be of little help in this context unless the sampling sites could be precisely re-located, and this would be impossible unless durable markers had been placed at the time of recording. An attractive alternative, in theory, would be to assess changes by comparing historical and modern maps; but in practice the resolution of older maps is generally too low to allow detection of sufficiently subtle differences in surface altitude. Fortunately, there are other ways to trace changes, for example by examining old wooden posts as described in this paper. Although we might anticipate that peat growth would eventually bury such posts, the converse seems to be true at the present time; in fact, peat shrinkage is progressively exposing them (e.g. Plates 3 and 5).

It might be argued that the subsidence of peat around the IHD tubes could be due to disturbance of the sensitive mire surface during the installation and subsequent measuring operations. However, the mire surface shows no discontinuities near the tubes and does not lie below the general surrounding surface. Also, the subsidence measurements at the tube sites are very similar to those recorded at wooden posts in undisturbed areas.

An alternative interpretation of the results from the two types of poles is that they have been lifted gradually by winter frost heave. However, we might reasonably anticipate a greater frost heave effect for wooden posts buried to a depth of 0.5–1 m than for much heavier steel tubes driven through the full thickness of peat. And yet the wooden post shown in Plate 3 indicated less subsidence (23−25 cm) than the steel tube *ca*. 20 metres away (32−34 cm; Plate 4). Moreover, it seems highly unlikely that heavy steel tubes in relatively dry bog areas would be lifted more than the tubes situated in wetter soak and lagg fen sites.

It is obvious that something has happened, and is still happening, to the surface layers of mid- and high-latitude bogs. Even though the observations to date are few and scattered, they provide strikingly consistent evidence of increased decomposition, compaction, subsidence and, most probably, loss of carbon. Moreover, the phenomenon of strongly decomposed peat and high ash content in the surface and subsurface layers of mires is not restricted to southern Sweden. The author observed similar features in several raised bogs in Ireland and Northern Ireland during 2000; in some south-central Norwegian bogs in 1999−2002; and in palsa bogs in Tunguska, central Siberia, in 2001. On the other hand, the pure *Sphagnum magellanicum* bogs of Tierra del Fuego (Argentina) showed no signs of secondary decomposition in 2004; nor did they display high surface concentrations of ash.

Most of the peatlands in Sweden have been affected by increased exposure to pollutants during recent decades. This is especially pronounced in the southern and central parts of the country. The increase in nitrogen deposition means that the environment for mire plants has changed dramatically, especially in bog and poor fen systems which naturally provide extremely nutrient-poor conditions. In south Swedish bogs, it seems that this has resulted in increased growth of trees and bushes, the decline of other plant species, and some new invasions (SNV Naturvårdsverket 1994).

How an increased influx of nitrogen would influence net production of these bryophyte-dominated ecosystems is a matter of debate. Ombrotrophic mires can be expected to exhibit the greatest sensitivity to nitrogen inputs because they are dominated by the highly specialised bog *Sphagna* which, being naturally adapted to very nutrient-poor conditions, may grow more slowly or even die of over-nutrition (Press *et al*. 1986). Malmer (1988, 1990) considers that additional nitrogen deposition in ombrotrophic sites should increase production because nitrogen is naturally a limiting factor; but others claim that further deposition in systems that already have high nitrogen loads would not increase productivity because phosphate would become limiting (Hogg *et al*. 1994). Some workers even suggest that productivity would decline under high nitrogen loads (Press *et al*. 1986) and that the system would thus change from being a carbon sink into a carbon source (Aerts *et al*. 1992). However, Hogg *et al*. (1994) observed no differences in rate of decomposition between bogs with different nitrogen loads although they did find differences within the same mire area.

Many studies converge towards the opinion that high nitrogen loading does not raise *Sphagnum* productivity because the N/P ratio has already increased due to a rise in N influx combined with a decline in P influx. In Sweden, the N/P ratio is <6 in the north and 34 in the south (Aerts *et al*. 1992). As their optimal N/P ratio is 10–14, southern Swedish mires are thus tending to become P-limited systems. Gunnarsson and Rydin (2000) studied the effect of increased nitrogen influx on *Sphagnum* growth over a period of three years in mires located in two areas with different rates of airborne N deposition. They found that *Sphagnum* growth declined with increased N and postulated an effect on the carbon balance, again tending to convert mires from carbon sinks into sources. Nordin & Gunnarsson (2000) reported similar results after a two-year experiment involving simulated N deposition.

Regarding other substances, a 60-year field trial on cultivated raised bog by Kuntze *et al*. (1990) indicated that the supply of elements that raise the pH, such as most of the major base cations, caused more intense humification than did acid fertilizing.

Yavitt (1994) measured the carbon dioxide flux from different types of wetlands (swamp, marsh and bog) in the Appalachian Mountain Region of West Virginia and western Maryland, and concluded that the surface carbon balance was negative at all the sites investigated. Similar results were obtained by

Wickland *et al*. (2001), who investigated CO_2 and CH_4 exchange between the atmosphere and a subalpine wetland in Colorado. The wetland was a net source of carbon gases to the atmosphere during all three years of measurement.

Measurements of carbon dioxide fluxes in peatlands by Bubier *et al*. (1999) indicated that these ecosystems may switch from net sinks to net sources of carbon over short timescales in response to small changes in soil temperature or water table position. Malmer & Wallén (1999) suggest that bogs no longer act as sinks for carbon because, in contrast to their former condition, their surfaces are no longer covered entirely by the *Sphagnum* mosses that provide litter for peat formation, so that the rate of carbon sequestration per unit area now only just balances losses in CH_4 and CO_2. They attribute the underlying changes in vegetation to either climate change or autogenic processes. Gunnarsson *et al*. (2002) describe remarkable vegetation changes at the Åkhultsmyren in central south Sweden which indicate drying of the mire surface and an increase in nitrogen availability over the period 1947–1997. The observed spread of trees may have triggered further changes in the plant cover.

Belyea (1996) emphasizes the role of the water table, and concludes that mass loss decreases with depth for peat decaying in its natural position in hollows and lawns and in the oxic layer of *Sphagnum* hummocks. Silvola *et al*. (1985) found that lowering of the water table by *ca*. 0.5 m was followed by a 2.5-fold increase in soil respiration and that the rate of decomposition increased considerably more than the rate of production of new organic material. Application of fast-dissolving PK or urea leads to a rapid increase in soil respiration and decomposition at nutrient-poor sites. In another study from Sweden, Gustafsson (2001) observed significant carbon losses from peat after drainage for forestry. In some cases the annual carbon loss was almost 40 times the average accumulation for an undrained northern peatland.

Rapid historical changes in rate of decomposition within ombrotrophic peat deposits are well known phenomena. These transition zones, which are known as *recurrence surfaces* (see Figure 1), have generally been attributed to marked climate shifts during the Holocene. Since climate is a decisive factor for peat growth, we cannot rule out climate change as a causative or additional factor contributing to the present surficial changes. Robinson & Moore (1999) claimed that low and variable summer precipitation may contribute to low carbon accumulation rates through decreased plant production and/or increased aerobic decomposition. The results of field experiments in Scotland led Chapman & Thurlow (1998) to conclude that a rise in mean annual temperature of 5°C could potentially increase CO_2 emissions by a factor of 2–4 times and at low temperatures (0–5°C), small changes in temperature could have a much more marked effect; so that the temperature increase predicted for the next 50 years may bring about a significant increase in peat decomposition rates. Other experiments on mires in the Arctic tundra of Alaska show similar results (Billings *et al*. 1982), so that warming of the tundra climate could change this ecosystem from a sink for atmospheric CO_2 to a source.

CO_2 itself is also a possible cause of the observed changes. Various carbon dioxide enrichment experiments have been carried out. After a 3-year study in four European sites (Finland, Sweden, the Netherlands and Switzerland) with free air carbon dioxide enrichment (FACE) and N deposition, Berendse *et al.* (2001) and Hoosbeek *et al.* (2002) concluded that elevated CO_2 and N deposition alone had no effect on primary production or on decomposition rates of *Sphagnum* and vascular plant litter. They stressed the importance of limiting factors such as potassium and phosphorus and stated that net primary production of raised bogs that are at or close to steady state is regulated by input of nutrients through atmospheric deposition.

It is not clear whether the phenomenon observed in Swedish bogs is due to climate change, lowered water table or the increased deposition of nitrogen or other fertilizers. One factor that supports the fertilizing hypothesis is the high concentration of mineral compounds in surface peat reflected by the high ash content (Figure 3b). This surface peak is quite abnormal in the context of the deeper stratigraphy of ombrotrophic (bog *Sphagnum*) peat, where ash content is normally in the range 0.5–1.5% regardless of the degree of decomposition. No transition from weakly to strongly decomposed peat (or *vice versa*) associated with such a marked change in ash concentration is found anywhere except at the mire surface. Another observation favouring the fertilizing hypothesis is the fact that rapid stratigraphical transitions from weakly decomposed peat below to strongly decomposed peat above are rare, the opposite being much more common. Thus it seems that the highly humified peat in deeper layers is a ‘primary product’, formed gradually during periods of warm, dry climate (the little-decomposed peat being formed during colder and moister periods), whereas the highly humified peat near the surface has arisen through secondary decomposition.

For the future, there is a risk that peat subsidence will be self-perpetuating. Lowering of the mire surface may lead to lowering of the (absolute) water table, which re-exposes layers of the catotelm to oxygen causing secondary decomposition of peat. This in turn concentrates and releases stored nutrients which promote a further increase in decomposition. Such a mechanism could lead ultimately to total collapse of the ombrogenous dome. There are known examples from Sweden where bog fires have led to collapse, creating 'bowl-form' bogs or returning the systems to minerotrophic/aquatic development phases. Similar peat collapses have been observed in tropical and mid-latitude peatlands (e.g. DeLaune *et al*. 1994, Ellery *et al.* 1989).

From a historical perspective, the following scenario for subsidence of the bog peat is proposed:

1. From the 19th century, influx of excess plant nutrients as dust generated in agricultural areas, which were expanding rapidly following rapid population growth. Large areas of the highly sensitive ombrotrophic *Sphagnum* communities on bogs might thus have been killed through over-fertilization. This suggestion is consistent with the view of Malmer & Wallén (1999) that large areas of peat-accumulating vegetation on bogs have been lost; with the outcome of the reconstruction of mire history for the Teltow ground moraine plateau near Berlin by Brande & Huehn (1988), where anthropogenic eutrophic-ation has forced oligotrophic *Sphagnum* mires to retreat since Mediaeval times; and with the expansion of mud-bottom hollows on an Estonian raised bog (Karofeld & Toom 1999).
2. In the 20th century, agricultural activity continued to increase. Other atmospheric compounds were increasingly added from traffic (exhaust products and road dust), industry, heating and waste combustion (exhaust gases and dust) before measures to reduce emissions were applied. The deposited dust, and gases dissolved in precipitation, contained major and minor elements; some of these, such as nitrogen, phosphorus and potassium may have promoted microbiological activity in the acrotelm, leading to accelerated decomposition.

CONCLUSIONS

1. Observations on raised bogs throughout southern Sweden and at a few locations in Ireland, Norway and Siberia indicate unequivocally that near-surface ombrotrophic peat is undergoing secondary decomposition.
2. The most likely cause is the change in nutrient supply associated with the deposition on mire surfaces of airborne substances such as dust, gases and aerosols generated by anthropogenic activity. This explanation is supported by the absence of the phenomenon from bogs in Tierra del Fuego, where air pollution is minimal.
3. The secondary decomposition of surface peat indicated by increased dry bulk density and subsidence, the loss of peat-forming vegetation reported in several studies, and the net release of carbon indicated by the few available measurements of CO_2 and CH_4 fluxes at mire surfaces all suggest that peatlands may have switched from being net carbon sinks to net carbon sources, at least in areas with substantial human influence.
4. The size of the peat carbon reservoir is such that the prospect of widespread secondary decomposition in northern hemisphere peatlands, coupled with the loss of their carbon sink function, is a cause for concern because the potential contribution to atmospheric CO_2 loading, and thus to the 'greenhouse effect', is significant.

ACKNOWLEDGEMENTS

This study was supported by: the Geological Survey of Sweden (SGU), the Swedish Research Council (VR), the Swedish Peat Research Foundation (SST), the Royal Society of Science and Literature in Göteborg (KVVS) and the Swedish Foundation for International Cooperation in Research and Higher Education (STINT).

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Received 04 Oct 2004, final copy received 25 Nov 2005
Editor: Olivia Bragg

Author for correspondence: Lars G. Franzén, Department of Earth Sciences - Physical Geography, Göteborg University, P.O. Box 460, SE-405 30, Göteborg, Sweden.
Tel: +46-31-7731958; Fax: +46-31-7731986; E-mail: lars@gvc.gu.se *or* komosse@hotmail.com