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Development, carbon balance and agricultural use of peatlands – overview and examples from Uppland Sweden

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Geological Survey of Sweden

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Summary

SKB is planning for a repository of radioactive waste at Forsmark situated along the coast of Uppland. The area is characterised by fast isostatic uplift and new wetlands and lakes are continuously formed in discharge areas for groundwater. It is plausible that radionuclides from the repository may reach the surface system in these areas. Layers of peat are successively accumulating in the wetlands and the properties of the accumulating peat changes as the vegetation develops through time. In many areas it is possible to ditch and cultivate peatlands and future human inhabitants can consequently be exposed to radionuclides through crops from the cultivated peat.

The peatlands in the present Forsmark area are young. The peat layers are thin and the prerequisite for cultivating peat covered areas are therefore generally not fulfilled. In the future when the thickness of the peat has increased there will be possibilities to cultivate some of the present wetlands.

To facilitate cultivation the groundwater level in the peatlands is lowered, whereafter the peat layers starts to subside. A peat covered area can consequently only be cultivated for a short period. Cultivation can, however, continue if the peat is underlain by deposits suitable for cultivation.

The aim of this report is to discuss conditions affecting accumulation of peat and the effects of cultivation. The report is especially focusing on the conditions that prevail today and will prevail in the Forsmark area.

The report includes results from a literature review concerning peat accumulation and the succession of peat types in wetlands. Additionally results from a corresponding study is presented, discussing the prerequisite for cultivation of peat and which factors that affect the subsidence of the peat layers that occur in connection with cultivation are included.

Peat data which was collected from peatlands in northern Uppland around 90 years ago, by the Geological survey of Sweden (SGU), is also included in the report. These data have been digitalised and data from new investigations has been added. The information was used to study accumulation rates of peat and the succession of peatlands in the vicinity of Forsmark.

The rate of peat accumulation in peatlands is dependent on the production of new organic material forming peat and the decay rate of that organic material. These factors are in turn controlled by factors such as type of vegetation, climate, nutrient status and hydrology. During the succession of mires the accumulation rate will change through time as vegetation, nutrient status and wetness changes. In a continental setting such as Uppland the peat accumulation initially is high but decreases with time.

Peat areas used for cultivation in the surroundings of Forsmark are most often characterised by fen peat rich in nutrients, while the less nutrient rich bog peat more infrequently is used for cultivation. Only a small proportion of the total peat areas in Uppland are used for cultivation. Compared to other parts of Sweden Uppland is characterised by a relative high proportion of cultivated *Bryales* peat, characterised by a high pH.

Due to compaction the subsidence is initially very fast in a peatland where the groundwater table has been lowered to facilitate cultivation. The rate of compaction decreases after a few years and oxidation becomes the dominating process causing subsidence. Also the rate of oxidation decreases as the most easily oxidised components disappear. Bog peat with a low degree of humification is characterised by a relatively fast rate of compactation after lowering the ground water table but by a relatively slow rate of oxidation. The opposite relation is characteristic of the subsidence of fen peat with a high degree of humification. The most important factors affecting the oxidation rate of peat during cultivation are depth of ditches, type of crop, type of peat and climate. There is a large span of rates of peat oxidation reported in the literature, and there are different opinions to what extent the factors mentioned above affect the rate of peat oxidation. The varying results are probably due to the effects of different peat properties and different time since the onset of cultivation. It is, however, clear that peat oxidation is a fast process which alone can cause subsidence rates of between 0.5 and 1 cm/year.

The study of data from SGUs peat archive shows that the peatlands in Uppland goes through different types of successions. Wetlands which are relatively old are often characterised by accumulation of *Sphagnum* peat, which has been proceeded by a stage with *Carex* peat accumulation. Around half of the studied peatlands have been preceded by a lake stage. At many sites peat accumulation started as primary peat initiation in wetlands directly after the sites were uplifted above the Baltic Sea. At some sites peat accumulation probably started due to a changed climate and was initiated several thousand years after the sites were uplifted. The data from the peat archive also revealed a clear connection between age of peatlands unaffected by land use and thickness of the peat layers. The rate of peat accumulation is on average between 0.5 and 1 mm/year. The rate of peat accumulation is fastest during the first thousands of years after peat initiation but decreases with time. A large proportion of the studied peatlands were cultivated when visited in the early 1900s. Around half of those peatlands were preceded by a lake stage whereas as the others started to accumulate in wetlands situated in the lowest topographical parts of the landscape. The cultivated peatlands are all underlain by fine-grained sediments, which may be cultivated when the peat has completely oxidised.

Sammanfattning

SKB planerar för ett djupförvar av använt kärnbränsle nära Forsmark vid Upplandskusten. Området kännetecknas av en snabb landhöjning där våtmarker och sjöar kontinuerligt bildas i utströmningsområden för grundvatten. I dessa områden är det tänkbart att radionuklider från ett framtida djupförvar kan nå ytsystemet. I våtmarkerna byggs successivt lager med torv upp, vars egenskaper kommer att förändras allteftersom våtmarkernas vegetation successivt förändras. I många fall är det möjligt att dika och odla upp torvmarker och framtidens människor kan följaktligen komma att exponeras för radionuklider via de grödor som skördas från före detta våtmarker.

I Forsmark är torvmarkerna ännu unga och torvlagren tunna vilket gör att förutsättningarna för uppodling av torv idag är små. Allt eftersom torv ackumuleras kommer det dock bli möjligt att odla upp vissa av dessa områden. För att möjliggöra odling dikas torvmarkerna varefter torvlagren relativt snabbt sjunker ihop. Det gör att torvmark endast kan odlas under en relativt kort tid. Många gånger är det dock möjligt att fortsätta uppodlingen om torven underlagras av jordarter lämpliga för odling.

Syftet med denna rapport är att redovisa förutsättningarna för ackumulation av torv och effekterna av uppodling. Rapporten fokuserar speciellt på de förhållanden som idag råder och i framtiden kan förväntas råda i Forsmarksområdet.

I rapporten redovisas resultat från en litteraturgenomgång av förutsättningarna för ackumulation av torv och successionen av olika torvslag i våtmarker. Dessutom redovisas resultat från en motsvarande studie av vilka förutsättningar som är nödvändiga för uppodling av torv samt vilka faktorer som påverkar den hopsjunkning av torvlagren som sker i samband med uppodling. I rapporten redovisas vidare data som Sveriges geologiska undersökning (SGU) samlade in för omkring 90 år sedan från torvmarker i norra Uppland. Dessa data har digitaliserats och kompletterats med resultat från nya undersökningar. Informationen har använts för att studera torvens ackumulationshastighet och succession av torvmarker i Forsmarks närområde.

Ackumulationen av torv i torvmarker beror på förhållandet av hur mycket nytt organiskt material som produceras och hur mycket av det materialet som i sin tur bryts ner. Produktionen och nedbrytningen är i sin tur beroende av en mängd faktorer som vegetation, klimat, näringsstatus och hydrologi. Allteftersom torvmarkerna utvecklas kommer även ackumulationshastigheten att ändras då vegetation, näringsstatus och blöthet förändras. I områden med ett mer kontinentalt klimat där torvmarkerna i huvudsak domineras av kärr som i Forsmarksområdet kommer torvackumulationen var snabb i början för att sedan minska med tiden.

De torvmarker som idag används för uppodling i Forsmarks närområde består i första hand av relativt näringsrik kärrtorv medan den mer näringsfattiga mossetorven endast undantagsvis odlas. Endast en liten andel av den totala torvarealen i Uppland är uppodlad och andelen har minskat under de senaste årtiondena. Specifikt för Uppland är den höga andelen uppodlad *Bryales* torv, som karaktäriseras av ett högt pH.

I en torvmark som nyligen dikats för uppodling är hopsjunkningen under de första åren mycket snabb och kompaktion är den dominerande processen. Efter några år avtar kompaktionen och oxidation blir den dominerande processen. Med tiden avtar oxidationshastigheten allt eftersom de mest lättoxiderade organiska föreningarna försvinner. Låghumifierad mossetorv kompakteras snabbt men oxiderar relativt långsamt medan motsatta förhållanden råder för den mer höghumifierade kärrtorven. De viktigaste faktorerna som påverkar hastigheten för den oxidation av torv som sker vid uppodling är dikningsdjup, typ av gröda, torvslag och klimat. De hastigheter för torvoxidation som rapporters i litteraturen uppvisar en stor variation och det finns olika uppfattning om i vilken utsträckning alla de faktorer som nämns ovan påverkar hastigheten för oxidation av torv. Resultaten varierar sannolikt till följd av att torven i studierna har olika egenskaper och har varit uppodlad under olika lång tid. Det är dock helt klart att oxidation av torv i uppodlade områden är en mycket snabb process som kan förorsakar en marksänkning på mellan 0,5 cm år^{-1} och 1 cm år^{-1}.

Studien av data från SGUs torvarkiv visar att torvmarkerna i Uppland följer olika typer av utveckling i sin succession. Våtmarker som är relativt gamla kännetecknas ofta av ackumulation av *Sphagnum* torv, som har föregåtts av en period med ackumulation av *Carex* torv. Ungefär hälften av de studerade torvmarkerna har föregåtts av ett sjöstadie. På många platser startade ackumulationen av torv direkt efter det att platsen genom landhöjningen nått ovan havets yta. På vissa platser började sannolikt ackumulationen av torv till följd av klimatförändringar som ägde rum tusentals år efter det att platsen lyfts ovan havsytan. Data från torvarkivet visar också på ett tydligt samband mellan av markanvändning opåverkade våtmarkers ålder och mäktigheten på torvlagren. Den genomsnittliga ackumulationen av torv är mellan 0,5 och 1 mm år^{-1}. Ackumulationen av torv är snabbast under de första årtusendena och visar en med tiden avtagande tendens. En stor andel av de studerade torvmarkerna är uppodlade och ungefär hälften av dessa har föregåtts av ett sjöstadie medan övriga utgörs av torv som bildats i våtmarker vilka uppstått direkt i låglänta delar av terrängen. De odlade torvmarkerna underlagras av finkorniga sediment vilka kan lämpa sig för odling även efter det att torven oxiderat bort.

Contents

1 Introduction

The Swedish nuclear waste management company (SKB) have planned for a geological repository for radioactive waste which will be situated close to Forsmark, in Uppland, at the coast of the Baltic Sea (SKB 2011). In SKBs safety assessment the potential future human exposure of radionuclides is modelled. In the future radionuclides may reach the surface system in discharge areas for groundwater. Food from these areas may consequently contain radionuclide from the repository. Modelling results show that the highest potential exposures for most radionuclides occur in discharge areas which are used as arable land (SKB 2010, Saetre et al. 2013).

Discharge areas for groundwater are often situated in peat covered wetlands. Peat is composed of dead organic material accumulated from vegetation at a certain site (i.e. not transported) and having an organic content of at least 30% (Joosten and Clarke 2002). In reality most peat has a considerably higher content of organic material. In Sweden the peat has an organic content of 90–98% (see Jeglum 2006). Soils formed in deposits rich in organic material (e.g. peat) are referred to as histosols. Peat may accumulate in either fens or bogs. A fen may be considered as a discharge area for groundwater. As peat continues to accumulate the fen can with time develop into a bog where the surface of the mire will become hydrologically almost independent of the landscape. At that point, the wetland has reached an ombrotrophic stage where the production of vegetation is all rain-fed (Charman 2002). Moreover, the potential accumulation in vegetation of radionuclides entering from below will level off as the bog plane rises. The properties and accumulation rate of the peat in a wetland changes through time as a consequence of changing environmental conditions. Especially in young fens the succession of different types of vegetation causes changes in peat properties. Also climatic variations may cause changes in accumulation rates and peat properties. Peat is often classified by the dominating vegetation that has accumulated to form the peat (e.g. *Carex*) and by the degree of decomposition of the peat (von Post and Granlund 1926, Granlund 1932). The degree of decomposition is classified according to a humification scale with ten classes, where a low humification is denoted by low values and vice versa. Bog peat is often characterized by a low degree of humification and the dominance of *Sphagnum* in the peat. Fen peat is dominated by other species and tends to have a higher degree of humification.

The present Forsmark area has recently been uplifted above the level of the Baltic Sea and the peat coverage is therefore generally too thin for cultivation (Hedenström and Sohlenius 2008, Fredriksson 2004). In the future the Forsmark landscape will change drastically as new land areas are uplifted and lakes are filled with sediments and peat. Due to the flatness of the landscape the land areas will increase relatively fast. In a landscape model SKB has predicted the future distribution of peatlands in the Forsmark area (Brydsten and Strömgren 2010, Lindborg 2010, Lindborg et al. 2013). The accumulation rate of peat used for the landscape model is based on the rate of in growth of *Phargmites* in former lakes situated in Uppland (e.g. Bergström 2001) that has been compiled by Brydsten (2004). In that model most peat areas are equivalent to areas covered by *Phragmites*. A large proportion of the peatlands in that model are consequently formed in areas proceeded by a lake stage. There are, however, several studies showing that peat is commonly formed in areas which have not been preceded by a lake stage (e.g. Rundgren 2008, von Post and Granlund 1926). Peat accumulation is likely to be initiated in areas with clays or other deposits with a low hydraulic conductivity.

Today the ground water table in many peat covered wetlands has been lowered to obtain arable land or to improve forest growth. In such areas the accumulation of peat has stopped and the peat is oxidizing and compacting due to dryer aerated conditions. Especially in peat areas used for agriculture, the peat layers are rapidly decreasing due to these processes. In SKB´s landscape model (Lindborg 2010) it is predicted that many future peat areas will be used as arable land in a later stage of the Forsmark area. Peat areas can, however, only be used for agriculture during a certain period of time, due to the fast oxidation and compaction of peat. These processes have been discussed in earlier SKB reports (Lindborg 2010). The subsidence rate of cultivated peat was obtained from literature presenting results from Swedish studies (e.g. Berglund 2008, Kasimir-Klemedtsson et al. 1997). There are, however, several studies from other countries, situated in boreal climate, dealing with these processes (e.g. Oleszczuk et al. 2008, Nieuwenhuis and Schokking 1997).

This report evaluates some of the processes important for SKBs safety assessment concerning accumulation of peat in wetlands and oxidation of peat in areas used for agriculture. Information was compiled both from the literature and from SGUs peat archive. The following questions were addressed:

1) In which environments are peat accumulation predominantly initiated, in former lakes or directly on wet ground?
2) How fast is peat accumulating in young peatlands and how long time does it take for a peat layer thick enough for cultivation to form?
3) Which succession of different types of peat can be expected in the future Forsmark area?
4) How fast is peat subsiding in areas used for agriculture, and for how long can an area with a certain peat thickness be used for cultivation?

These questions are discussed with the use of two methods:

1) Literature on peat accumulation and peat subsidence. Focus is put on results from areas having a climate similar to the present Forsmark area.
2) Studies of data from SGUs peat archive. These data were collected during the early 20th century and are used to study the thickness of peat and succession of peat types in wetlands of different ages. Additional data from new field studies conducted by SGU in Uppland are also discussed.

2 Peat accumulation

2.1 Introduction

The carbon accumulation in boreal and subarctic mires since the last glaciation has resulted in a carbon storage of 220–460 Pg of carbon in the Northern hemisphere peatlands (e.g. Gorham 1991, Lappalainen 1996). The present rate of the carbon sequestration in Boreal and Subarctic peatlands is estimated to 66 Mt C/yr (Turunen et al. 2002). The wide range of climatic settings has also resulted in a wide range of types of peatlands in the northern hemisphere. These peatlands haven't only been a formidable carbon sink where they hold 1/3 of the stored land carbon, on 3% of the earth's land surface, but do also represent important ecosystems.

The rate and nature of carbon accumulation and exchange of carbon with atmosphere and water in peatlands is a complex system depending on several different factors interacting with each other. The carbon accumulation in peatlands is directly controlled by the balance of the net primary production of the vegetation on the mire and the rate of decomposition of the produced material. These rates are in turn controlled by different factors and processes. Yu et al. (2009) have compiled a general image for factors controlling carbon accumulation and how they depend on each other (Figure 2-1). The five state factors control the production on the mire and the decomposition of material directly or through intermediate processes. The relative importance of the different state factors on the carbon accumulation change over time as the peatland develops. For example parent material and topography are more important in the early stages of the peatland development compared with later stages in the development. The relative importance of the factors and processes varies between regions but will also be dependent on factors such as stage of development and mire type.

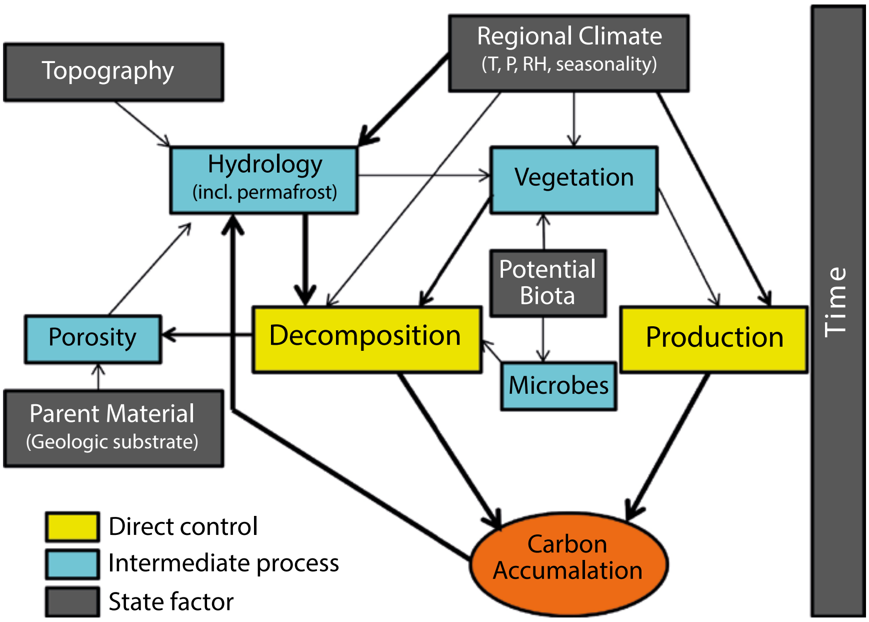


***Figure 2-1.** A model describing the state factors controlling the carbon accumulation rate in mires and the intermediating processes and how they depend on each other. The thickness of the arrows indicates the relative importance of control (Redrawn from Yu et al. 2009). The regional climate parameters in the figure are: T = temperature, P = precipitation and RH = relative humidity.*

2.2 The basic principle of carbon accumulation in mires

Mire systems are generally characterized by a comparably low net primary production (e.g. Campbell et al. 2000) but also a rather low net exchange of CO_2 and low soil respiration (e.g. Campbell et al. 2000). Thus the nature of the peatlands and their accumulation of peat can be ascribed to a low rate of decomposition rather than to a high net primary production. A fundamental fact in the nature of peatlands is that in the oxic zone in the uppermost part of the peat-profile, the so called acrotelm, the rate of decomposition is relatively fast and it is also here where the primary production takes place. When leaving the oxic zone of the acrotelm, often not deeper than 30–40 cm, and moving into the anoxic zone of the catotelm the overall activity significantly slows down and the rate of decomposition can be an orders of magnitude lower (e.g. Clymo 1984). The low rate of decomposition in the catotelm thus preserves the organic litter entering this anaerobic zone and thus the relationship between the net primary production and the decomposition rate in the acrotelm will to most extent be the determining factor of the carbon accumulation rate. A mire can thus be divided into two units; the high activity acrotelm at the surface and the low activity catotelm below the mean water table in the mire. Thus of major importance for the rate of carbon accumulation is the amount of material entering the catotelm from the acrotelm.

2.3 Different expressions of carbon accumulation in mires

LARCA/LORCA: Long-term (apparent) rate of carbon accumulation

This is equal to the long term apparent rate of carbon accumulation. By its simplest means it is calculated by dating the basal peat and taking the mass per unit and dividing it by its total age. When determining LORCA/LARCA it is apparent that mires of different age and of different types have different long-term accumulation rates (e.g. Clymo et al. 1998, Turunen 2003). As this method does not take into account the slow rate of loss of peat over time in the catotelm, LORCA tends to overestimate the true rate of carbon accumulation.

ARCA: Actual net rate of carbon accumulation

This is the rate of which a peatland accumulates carbon when taking into account both gains and losses over time. As ARCA also take into account the loss of peat from deeper peat layers as is not the case with LARCA/LORCA the values of ARCA is often around 2/3 of LORCA values (Tolonen and Turunen 1996). The rate of carbon accumulation decreases with the age of the mire if it has the same type of vegetation over time (Rydin and Jeglum 2006, Figure 12.8) when using ARCA. As ARCA take into account the fluxes both in and out of the peatland and the complexity of this system it is often described through different types of models (e.g. Clymo et al. 1998, Frolking et al. 2001)

RERCA: The recent rate of carbon accumulation

This is the carbon accumulation which has occurred during the period close to present and represents the fresh peat added to the peatland. RERCA can be obtained by dating the uppermost part of the peat and determining the bulk density of the peat. In contrast to ARCA, RERCA does not take into account the losses of peat from deeper layers. RERCA is often measured over a few decades up to 100 years.

2.4 Factors controlling carbon accumulation in mires

2.4.1 Climate

The requirement for the formation of peatlands is that the climate provides enough moist conditions in order to allow peat to form and accumulate over time. Traditionally the limiting factor for peat formation has been assigned to precipitation (Granlund 1932) but it is obvious that temperature and other climatic parameters are equal or more important (e.g. Clymo et al. 1998). Boreal and subarctic peatlands occur in a wide range of climatic settings with annual temperatures ranging from +6°C down to –12°C and with a precipitation between 200 and 1,000 mm (Yu et al. 2009). As peatlands are abundant at such a broad range of climate settings, other climate parameters than annual temperature and precipitation values are of importance for the formation and maintenance of peatlands. A suggestion is that annual evapotranspiration, relative humidity and climate seasonality could be of major importance as the distribution of northern peatlands is highly assigned to annual relative humidity values between 65% and 95% (Yu et al. 2009).

In a major regional scale, when comparing the carbon accumulation over climate regions, mires situated in colder climate regimes tend to have lower carbon accumulation rates compared with mires situated in areas with higher temperatures (e.g. Turunen et al. 2002). There is also indications of that the highest values of carbon accumulation is in areas with intermediate temperature and precipitation when comparing with the climate settings where peatlands are present. Thus the highest carbon accumulation is in areas with an annual temperature of 0°C to 2.5°C and a precipitation between 450 and 550 mm (Yu et al. 2009) i.e. in areas with a low evapotranspiration. This is supported by model studies of mire wetness in relation to carbon accumulation where the highest values are acquired at only moderately wet climate conditions (Swanson 2007). The reason for this is that the decomposition rate of the plant litter produced in mires increases with higher temperature due to higher microbial activity than in colder climate conditions (e.g. Clymo et al. 1998, Davidson and Janssens 2006) and that the mire microtopography becomes flattened out under these conditions (Swanson 2007). At lower temperatures the primary production will become lower and can be related to the number of degree days above zero (Clymo et al. 1998).

2.4.2 Vegetation

The nature of the vegetation is often important for the rate of carbon accumulation in peatlands. The vegetation is to a major extent dependent on the climate, hydrology and nutrient status of the mire. In general *Sphagnum* dominated peatlands have a higher carbon accumulation than other mires. The main reason for this is that *Sphagnum* has a high resistance to decay compared to other types of vegetation.

In the *Sphagnum* group there are differences in the rate of primary production but also in their decay resistance. For example *Sphagnum* species occupying hummocks have a higher resistance to decay (e.g. Johnson and Damman 1991, Belyea 1996). This could be related to a higher content of uronic acids in hummock species (Clymo and Hayward 1982) and phenolic compounds in the plant tissue can also be of importance (Børsheim et al. 2001). These compounds make the environment more acidic and also inhibit microbiological activity (e.g. Verhoeven and Toth 1995).

2.4.3 Primary production

The primary production in boreal and subarctic peatlands is low compared with boreal forest ecosystems. Studies on primary production on mire vegetation have mainly focused on *Sphagnum* as *Sphagnum* is such an important group when it comes to the formation of peat. The net primary production of *Sphagnum* ranges between 8 to 1,450 g dw m^{-2} y^{-1} with a mean of 259 g dw m^{-2} y^{-1} (Gunnarson 2005). The net primary production of *Sphagnum* is highly dependent on climate factors and higher temperatures increase the production of *Sphagnum* (Gunnarson 2005) but the production can be hampered by increased nutrient supply (Gunnarson and Rydin 2000). For the different types of *Sphagnum* the production is highest in carpets, intermediate in lawns and lowest on hummocks (Gunnarson 2005) which shows that the production is highest in more moist conditions. For brown mosses it has been suggested the production is similar to that of *Sphagnum* (Vitt 1990) and records of the primary production ranges from 55 to 405 g dw m^{-2} y^{-1} (Busby et al. 1978, Vitt 1990, Thormann and Bayley 1997).

When considering other types of mire plants the role of underground production becomes more important but is not very well investigated (Wieder 2006). The above ground production in herbaceous plants is in the range of 8.5–302 g dw m^{-2} y^{-1} (Grigal et al. 1985, Szumigalski and Bayley 1996) and in a study from southern Finland the total production of *Carex* rostrata in a mesotrophic fen show that the above ground production was only 12% of the total production (Saarinen 1996) showing the importance of the below surface production.

The total net primary production when the total vegetation at one site is considered have been investigated at some sites in Northern America where the production in bogs ranged between 280 and 755 gdw/m^{2}yr^{-1} and in fens between 11–710 gdw/m^{2}yr^{-1} (Thormann and Bayley 1997). This study however don't take into account the below underground production which can be considerable in fens.

2.4.4 Decay rates

The rate of decomposition is the most important parameter controlling the carbon accumulation in mires. As shown in Figure 2-1 the decay rate is dependent on several different factors and intermediating processes. In Table 2-1 a summary is given for some of the important variables affecting the decay rate of the plant litter in mires. The highest decay rates are presumed to occur in mires with a high nutrient status with vegetation dominated by vascular plants and with moderately wet conditions. The annual temperature should not be too low as when temperature becomes lower the decomposition rate is hampered (e.g. Moore et al. 1999). This is especially important for the decay in the anaerobic zone as the methanogenesis process here is highly temperature dependent (Moore and Dalva 1993) compared with the decay in the aerobic zone (Segers 1998). The role of precipitation on the rate of decomposition can affect the acrotelm depth and the residence time of the material in the acrotelm. This has for example been recorded at the bog "Store Mosse", which is situated in south western Sweden (Malmer and Wallen 2004).

The importance of vegetation on the resistance against decay have been shown in experimental studies and among the major peat forming plant groups *Sphagnum* is most resistant to decay (Table 2-2). *Sphagnum* dominated peatlands generally have a lower productivity than peatlands dominated by vascular plants but has a high rate of carbon accumulation (Turunen 2003), as their rate of decomposition is lower (Thormann et al. 1999). The reason for the low decomposition rates for *Sphagnum* is its low content of nutrients but also different types of organic compounds inhibiting the microbial activity and lowering the pH (e.g. Painter 1991, Johnson and Damman 1993). The most important substances are Sphagnan, an uronic acid, and sphagnols, a phenolic substance, which both lower the pH, inhibiting microbial activities and makes the litter resistance to decay (Verhoeven and Liefveld 1997, Børsheim et al. 2001). When the mineral supply of N and P increases to *Sphagnum*-dominated settings the decay rate increased (Aerts et al. 2001) showing the effect of nutrient supply on decay rates.

Table 2-1. Some important conditions controlling the decay rate/decomposition rate of litter in peatlands.

Factor	Condition	Effect
Climate	Low temperature	Lower decomposition rates
	High temperatures	Higher decomposition rates
Microsites	Hummock	Lower decomposition rates
	Hollow	Higher decomposition rates
	Lawn	Low decomposition rates
Vegetation	Dominated by *Sphagnum*	Low decomposition rates
	Dominated by vascular plants	Higher decomposition rates
Position in relation to water table	Dry	Low/high decomposition rate
	Wet	Low decomposition rate
	Intermediate	High decomposition rate
Nutrient content (N,P)	High	Higher decomposition
	Low	Slower decomposition
pH	Neutral/high	Higher decomposition
	Acidic/Low	Lower decomposition

Table 2-2. Rate of decomposition based on mass loss measurements in Canadian peatlands (Moore and Basiliko 2006).

Rate of decomposition	Low							High
Type of material	Woody material	Hummocky *Sphagnum*	Hollow *Sphagnum*	Lawn *Sphagnum*	Tree needles	Tree leaves	Shrub leaves	Sedge

The most important abiotic factor controlling the decomposition is the position of the water table where a high decompositianal regime exists in the aerated zone above the water table. This is demonstrated by the fact that in drier microsites the decomposition is higher (Belyea 1996) while the decomposition becomes lower at wetter settings. However at the driest settings the decomposition is restricted by the lack of moisture (Laiho et al. 2004). The highest rate of decomposition is at the zone of water table fluctuation and becomes lower below this zone and above it (Beleya 1996). In moderately wet settings with a fluctuating water table the wetness conditions are suitable for decomposition but in total intermediate wet settings will have the highest rate of carbon accumulation while extremely dry and wet settings have lower rate (Belyea and Clymo 2001).

2.4.5 Mire type – bogs and fens

The carbon accumulation is generally lower in fens compared to bogs. The reason for this is the nature of the environment they consist of with higher nutrient status, higher pH, and a domination of vascular plants. These factors enhance microbial activities and the plant litter produced is also easier to degrade (e.g. Aerts et al. 1999). During the very early development of fens, the carbon accumulation can be particularly high (e.g. Yu et al. 2003). The reasons behind this could be that the production is high in the earliest fen stages due to the input of nutrient rich and well oxygenated water. Another important factor could be that the acrotelm is less well developed during this early phase of peat growth due to a high groundwater table and the plant litter produced will enter the catotelm fast. When the peat grows in height the peatland surface will become more isolated from the nutrient rich groundwater, the surface will become drier and the production is reduced while the decomposition rate increases (e.g. Damman 1986).

In continental bogs and in fens carbon accumulated through time can be illustrated by a curve with a convex shape with higher accumulation in the early part of the development (e.g. Yu 2006). This stands in contrast to the concave shape of corresponding curve from bogs in an oceanic setting (Clymo 1984) where the accumulation rate increases with time. As mentioned above the reason for the higher growth in the early phase of fens is that these young fens the acrotelm is not very well developed and they have a higher nutrient supply (e.g. Damman 1986) but the carbon accumulation in fens decreases with increased height of the peat column as the surface become drier (Yu et al. 2003). Bogs in more continental settings seem to be more sensitive to changes in the water balance of the climate (e.g. Kuhry and Vitt 1996, Turunen et al. 2001). The reduced peat accumulation rate over time can both be dependent on autogenic changes within the mire and external factors altering the hydrology. The reason for the concave curve of oceanic bogs is caused by a constant growth, due to wet conditions, in combination with an exponential decay of peat in the deeper peat layers (Clymo 1984).

2.5 Estimations of long-term carbon accumulation in boreal and subarctic mires

Some major regional investigations/compilations of the carbon accumulation in boreal and subarctic have been made for Northern America, Finland and in Siberia (e.g. Ovenden 1990, Zoltai 1991, Botch et al. 1995, Turunen et al. 2002). The carbon accumulation in these studies is in the range of 20–35 g $m^{-2} yr^{-1}$. The data in these studies is mainly from well developed deep mires and does not to a full extent take into account younger and shallower peatlands which makes the data-sets not fully representative for the northern hemisphere peatlands and especially not for the Forsmark area, which is characterised by young wetlands. Values of carbon accumulation from a range of studies are illustrated in Table 2-3. From this data a mean value for the carbon accumulation in boreal and subarctic mires of 19 g $m^{-2} yr^{-1}$ is achieved. A thorough review on carbon accumulation in northern peatlands is given in Turunen (2003). When examining the major studies and the ranges in carbon accumulation in the data-sets it is obvious that the between site variability in carbon accumulation is very high. These variations are due to different climate settings, differences in vegetation and different local conditions.

Table 2-3. A compilation of some studies made on carbon accumulation (in g C m^{-2} yr^{-1}) in boreal and subarctic mires. The data includes both individual studies and averages values from larger data-sets.

LORCA (g Cm^{-2} yr^{-1})	Geographical area and mire type	Reference
Global		
29	Global	Gorham 1991
21	Global	Clymo et al. 1998
Regional boreal		
30–35	Finland bogs	Turunen 2003
24	Finland bogs	Tolonen and Turunen 1996
19.8	Finland bogs average	Mäkilä and Goslar 2008
23	Finland average	Tolonen and Turunen 1996
36.3	Finland young mires average	Korhola et al. 1995
14–15	Finland fens	Tolonen and Turunen 1996
14–35	Western Boreal Canada	Kuhry and Vitt 1996
7.8–113	Boreal Canada fens	Yu 2006
25.5	Boreal Canada fens average	Yu 2006
25	Canada average	Gorham et al. 2003
8–40	Canada	Gorham et al. 2003
10–35	Canadian Boreal mires	Ovenden 1990
14.4–18.9	Canadian Boreal mires	van Bellen et al. 2011
19.4	Interior Canada	Vitt et al. 2000
72–80	Fens and marshes	Botch et al. 1995
Regional subarctic		
30	Former USSR average	Botch et al. 1995
12	Northern polygonal mires	Botch et al. 1995
10–85	Western Siberian mires	Borren et al. 2004
16.2	Western Siberian mires average	Borren et al. 2004
12.1–23.7	Russian raised string bogs	Turunen et al. 2001
14.6	Finland aapa mires average	Mäkilä and Goslar 2008
Minor/single site studies		
25	Degerö stormyr, Sweden	Oldfield et al. 1997
6.3	British Colutribia bog	Turunen and Turunen 2003
14–18	Swedish mires	Klarqvist 2001
16.7–22.3	Finland bog	Mäkilä 1997
4.6–67.5	Quebec bog	Loisel and Garneau 2010
18.5	Quebec bog average	Loisel and Garneau 2010
8	Finland aapa mire	Mäkilä et al. 2001

When it comes to climate conditions it is obvious that the long-term carbon accumulation rate is dependent on climate. Boreal mires have higher carbon accumulation than subarctic mires due to the difference in the vegetation season (Clymo et al. 1998) and in settings with a more oceanic climate the accumulation also becomes higher as in the case of Finland (Tolonen and Turunen 1996). This however stands somewhat in contrasts with the compilation by Yu et al. (2009) which suggests that the highest carbon accumulation occurs in areas with an annual temperature slightly above 0°C and moderately wet conditions which is more equal to subarctic conditions. What is obvious is though that the relative humidity and climate seasonality is of major importance to the carbon accumulation rate (Yu et al. 2009).

In more detailed studies of single sites the effect of climate on both the development of the mire and its carbon accumulation can be seen (e.g. Mäkilä et al. 2001, Yu et al. 2003, van Bellen et al. 2011) and major changes in carbon accumulation over time is common (e.g. Klarqvist 2001, Mäkilä et al. 2001, van Bellen et al. 2011).

2.6 Peatland initiation and mire succession

Peatlands started to form after the last glaciation and in Europe the onset of major peatland expansion started c. 12,000 years ago with the most intensive phase of peat initiation between 11,000 and 8,000 years ago (MacDonald et al. 2006). The intensive phase of establishment of peatlands was due to a warmer climate and that land areas suitable for peatland establishment was exposed as the ice sheet retreated. After 8,000 years ago the peat initiation declined but has continued until present.

There are three processes responsible for the development of new peatlands (Kuhry and Turunen 2006), namely paludification, primary peat formation and terrestrialization of lakes (see Table 2-4 for details). In most part of the world paludification and primary peat initiation is the dominant process but there are major regional differences. Peatlands formed through paludification are developed over previously vegetated mineral soil while peatlands formed through primary peat formation develop directly on mineral soil without any previous vegetation. In west-central Canada the majority of the peatlands are formed through paludification (cf. Kuhry and Turunen 2006) and in Finland the major part of peatlands are formed through paludification and primary peat initiation (Korhola and Tolonen 1996). Peatlands formed through paludification has been proceeded by a period with non peat forming vegetation such as wood or grassland while peat has been accumulated directly on mineral soil in peatlands formed through primary peat initiation.

The terrestrialization process is to a major extent a self going process where a lake basin is infilled with sediments and providing enough moisture to promote peat growth. The process of terrestrialization can be affected by changes in climate where a drier climate could promote terrestrialization as lake levels are lowered and the formation of peat starts (e.g. Svensson 1988, Korhola 1996). In contrast to terrestrialization the process of paludification and primary peat production is more dependent on prevailing climate conditions. In paludification also pedogenic processes like precipitation of iron and aluminium oxides can form impermeable layers creating sufficiently moist conditions. This is also the case with other pedogenic processes such as the formation of a surface humus layer (e.g. Hilbert et al. 2000). Large changes in vegetation due to human impact can also initiate peat formation as in Great Britain where peatlands started to form when a major part of the woods were cut.

2.6.1 Peatland initiation and climate

The single most important factor in the initiation of peatlands is different climate variables. In periods when the effective moisture (precipitation minus evaporation) increase either by increasing precipitation or lowering of the temperature or a combination of both peatland initiation is promoted. As peatlands are dependent on a wet climate, changes in climate can initiate formation of new peatlands and during periods when the climate has become wetter, more intensive peatland initiation have occurred (e.g. Campbell et al. 2000).

Table 2-4. Different processes for the development of new peatlands.

Type of peatland initiation	Process	Occurrence
Paludification	Formation of peat on previously vegetated mineral soil without any previous body of water.	Most common type
Primary peat formation	Formation of peat directly on bare mineral soil without any previous vegetation stage.	Previously glaciated areas
Terrestrialization of lakes	Infilling of shallow lakes through the formation of grounded or floating vegetation mats.	

Table 2-5. Effects of factors controlling different types of peatland initiation.

Ranking of importance	Paludification	Terrestrialization	Primary peat initiation
1	Climate	Geology/substrate	Geology/substrate
2	Topography	Biogeography	Topography
3	Biogeography	Topography	Climate

In west-central Canada and western Siberia peatlands started to form extensively at c 7000 BP (before present) as the climate before that was to warm and dry (Zoltai and Vitt 1990, Kremenetski et al. 2003). Further to the north the cooling of the climate during middle and late Holocene has instead lead to reduced formation of peatlands, and the change of peatlands from fens into Palsa mire types (e.g. Zoltai 1995). In more oceanic settings the amount of precipitation have been sufficient for the formation of peatlands, and basal dates of peats follow deglaciation and the emergence of new land due to isostatic uplift (e.g. Korhola 1994). However the lateral expansion and slower growth in these settings can occur due to drier and warmer climate. This is for example recorded from Finland for the period 7000 to 4500 BP (Korhola 1995). The peatland growth and initiation can also be hampered by a cooler climate as recorded in fens of western Canada (Yu 2006). A drier climate could also promote terrestrialization as lake levels are lowered (e.g. Svensson 1988, Korhola 1996). The dry climate situation in western Canada also have delayed the peat initiation for a long time and peat started to form at 3,000 yrs ago (Kuhry 1997).

In several areas with a subarctic climate, the peatlands were formed in a boreal climate during the Holocene climate optimum. With decreasing temperatures these peatlands have reduced their peat forming processes and transformed into peatlands with permafrost and formation of palsas. From both Canada and Siberia old radiocarbon dates are recorded from the upper peat layers in these areas (Zoltai 1995, Peteet et al. 1998). It is not necessary that the peat formation has completely stopped in these areas but it is possible that erosion has removed the uppermost part of the peat exposing older peat layers at the surface.

Table 2-6. Examples of peat initiation due to climate change.

Area	Timing BP	Mechanism	Reference
West-central Canada	C 7000 BP	The climate was to dry and warm during the previous period after the deglaciation.	Zoltai and Vitt 1990
Western Siberia south of 58N°	C 7000 BP	The climate was to dry and warm during the previous period after the deglaciation.	Kremenetski et al. 2003
Southern Finland	8000–7000 BP	Periods with wetter climate.	Korhola 1995
	4500–3000 BP		
Newfoundland	5000–6000 BP	Periods with wetter climate.	Davis 1984
	4000–2500 BP	Pedogenic processes.	

3 Drainage of peatlands for agricultural use

3.1 Introduction

Areas with peat are currently used for agriculture in most countries with significant peat areas (Strack 2008, Table 3-1). There are several examples from Sweden describing the draining of peat areas and the following effects of that process (e.g. Runefelt 2008, Mc Afee 1985). The cultivated peat soils have an organic content of at least between 20 and 30%, but the organic content is often considerably higher (80–90%). The cultivated deposits discussed here can consequently have a wide range of organic contents and thereby varying physical properties.

To meet the requirements of crops the groundwater level in peat covered wetlands must be lowered to make cultivation possible. Many peat areas can potentially be cultivated, but only a small proportion of the Swedish peatlands are presently used for that purpose (Strack 2008, Berglund et al. 2009). After draining the accumulation of peat stops and the peat layers are subsiding due to oxidation, shrinkage and compaction. It should be noted that shrinkage and compaction are two different processes, where shrinkage cause a decrease in volume due to shrinkage of the peat particles whereas compaction cause decrease volume due to a decreased proportion of pores within the peat. Several studies have shown that this subsidence is a fast process which may exceed 1 cm/year (e.g. Kasimir-Klemedtsson et al. 1997, Hutchinson 1980). A peat land can consequently only be used for cultivation for a certain period of time. Cultivation can, however be continued if the underlying soils are suitable and if it is possible to maintain the ground water table low enough.

SKB has modelled the future accumulation of peat and land use in the Forsmark area (Lindborg 2010). The resulting landscape model shows that there will be large areas with peat suitable for cultivation in the future. These results have been used by SKB to assess the potential exposure of radionuclides to humans consuming food from cultivated peat areas that has been exposed to long-term release from an underground repository of spent nuclear fuel (SR-Site, SKB 2010) or low-level waste (SKB, 2014). To be able to model the fate of peat when an area is drained and cultivated the following questions are addressed in this report:

1) How fast is the total subsidence of peat?

2) Which factors affect the rate of subsidence?

3) Is it possible to determine the relative contributions of oxidation and compaction/shrinkage to total peat subsidence?

3.2 Cultivation of peat in Sweden

In this report cultivated peat is defined as areas with peat where the groundwater table has been lowered to facilitate tillage, and grassland for grazing. In Sweden the areas with cultivated peat have decreased significantly during the last 60 years. Large peat areas in middle Sweden are, however, still used as arable land (Figure 3-1). According to Hjertstedt (1946) 12.3% of all areas with organic deposits in Sweden were used as arable land during the mid 20th century. This corresponded to 20% of all cultivated land. Most of these organic deposits were classified as peat (Table 3-2). Today, around 6% of the cultivated land area in Sweden is situated on peat deposits, which corresponds to 160,000 ha (Berglund et al. 2009). According to Oleszczuk et al. (2008) c. 5% of the total Swedish peat area is used for cultivation. That study assumes that much larger peat areas are used for cultivation than Berglund et al. (2009) assumed. The study by Berglund et al. (2009) is, however, the most thorough study made concerning the use of peat as arable land. That study was made by comparing SGU's maps of Quaternary deposits (QD) and the area used as arable land. The comparison also includes areas shown as a thin coverage of peat (< 0.5 metre) on SGU's maps. Since the quality of the QD maps is much higher now than 60 years ago, the estimation of cultivated organic deposits made by Berglund et al. (2009) is therefore probably better than the estimations made by Hjertstedt (1946) 60 years ago. The large difference between the estimates made by Hjertstedt (1946) and Berglund et al. (2009) is, however, a clear proof of decreased of peat covered areas use for cultivation. One reason for the decreased proportion of cultivated peat areas during the last 60 years may be that the peat layers have oxidised and many present areas with arable land have consequently once been covered by a layer of peat. It is also clear that large peat areas formerly used for cultivation have been abandoned (Berglund et al. 2009). Today it is generally not allowed to make new ditches in areas unaffected by ditches, and peat-covered wetlands are at present not converted to arable land in Sweden. Wetlands are instead restored to obtain and promote biological diversity and to achieve traps for nutrients and other emissions from anthropogenic activities. Also in Finland the areas with cultivated peat has decreased (Maljanen et al. 2007). However, further south in Europe a much larger proportion of the peatlands are currently used for agriculture, the great majority being used as meadows and pastures (Strack 2008, Table 3-1), which indicates that a larger proportion of the Swedish peatland could potentially be used for cultivation in the future. The high proportion of cultivated peat in, e.g. the Netherlands may be attributed to the dense population causing need for arable land. Some of the differences in the proportion of cultivated peatlands may, however, be an effect of different suitability for cultivation in different areas (e.g. peat quality and draining possibilities).

In eastern Uppland the proportion of peat used as arable land has decreased during the last decades (cf. Berg et al. 2006). The present proportion of cultivated peat deposits in the County of Uppsala (5.0%), where Forsmark is situated, is close to the Swedish average (cf. Berglund et al. 2009). Almost half of these areas are covered by a peat layer thinner than 0.5 metre. It is likely that many areas that today consist of postglacial clay or clay gyttja formerly were covered by peat layers, which now have oxidised (cf. Section 4.4.7). That is likely since these clay deposits have a low hydraulic conductivity and are often situated in discharge areas for ground water, where peat accumulation naturally would occur.

Only a small proportion of the present Forsmark area is covered by peat and these peat layers are generally not thick enough for cultivation (Hedenström and Sohlenius 2008). During the forthcoming thousands of years the peat thickness will increase in the Forsmark area and cultivation of peat areas will consequently be possible (Lindborg 2010). Cultivation is also possible in peat areas underlain by deposits, which can be used for further cultivation when the peat has oxidized. Most of the peat areas in the landscape model are situated in areas which are preceded by a lake stage.

Table 3-1. Peatland areas and proportion of the peatlands used for cultivation in some countries (Oleszczuk et al. 2008). The values shown in the table should be regarded as estimations, but it is clear that the proportion of Swedish peat areas used for cultivation is relatively small compared to the situation further south in Europe.

Country	Total peat land area (km^2)	Peat land area used for cultivation (km^2)	(%)
Europe			
Belarus	23,967	9,631	40
Estonia	10,091	1,300	13
Finland	94,000	2,000	2
Germany	14,200	12,000	85
Great Britain	17,549	720	4
Iceland	10,000	1,300	13
Ireland	11,757	896	8
Latvia	6,691	1,000	15
Lithuania	4,826	1,900	39
Netherlands	20,350	2,000	85
Norway	23,700	1,905	8
Poland	10,877	7,620	70
Russia	568,000	70,400	12
Sweden	66,680	3,000	5
Ukraine	10,081	5,000	50
North America			
Canada	1,114,000	170,000	15
USA	611,000	61,000	10
Asia			
Indonesia	200,728	42,000	20
Malaysia	25,890	8,285	32
China	10,440	2,610	25

There are, however, also large low lying areas with clay which in the future maybe covered by peat and thereafter cultivated (Hedenström and Sohlenius 2008). In fact in the present Uppland peat is often underlain by clay gyttja (cf. SGUs QD maps and Chapter 4), a sediment which is deposited in shallow bays of the Baltic Sea, implying that the initiation of peat formation was not preceded by a lake stage alternatively only a short lake stage. As a consequence, the landscape model probably underestimates the future areas potentially covered with peat. Furthermore, the QD maps show that peat presently used as arable land is almost always situated in areas bordering areas with sand or clay. That suggests that the cultivated peat to a large extent is underlain by minerogenic fine-grained deposits, e.g. clay or sand, which can be used as arable land when the peat has oxidised. Also, analysis of data from SGUs peat archive (see Chapter 4) shows that around half of 47 cultivated peatlands are underlain by clay and the other half by gyttja i.e. lake sediments (von Post and Granlund 1926). The properties of cultivated peatlands in the north-eastern parts of the Uppland are further discussed in Chapter 4.

Table 3-2. The proportional distribution of organic deposits at sites used for cultivation (from Hjertstedt 1946). The values for the County of Uppsala are shown with an black font. Undetermined % represents peat which not has been possible to determine due to a high degree of degradation. The proportions of cultivated peat types can obviously have changed slightly since 1946.

		LS[2]	Fen peat					Bog peat		
County[1]	N	Gyttja (%)	*Phragmites* peat (%)	*Carex* peat (%)	*Bryales* peat (%)	*Sphagnum-Carex* peat (%)	Woody sedge peat (%)	Forest bog peat (%)	*Sphagnum* peat (%)	Undetermined (%)
Stockholm	327	15	2	20	14	6	28	2	4	9
Uppsala	**527**	**7**	**1**	**24**	**24**	**3**	**18**	**1**	**3**	**19**
Södermanland	383	20	1	17	8	7	31	2	3	11
Östergötland	555	13	1	15	2	7	37	3	7	15
Jönköping	504	18	2	29	3	8	12	2	10	16
Kronoberg	386	31	2	17	–	7	19	3	11	10
Kalmar	604	24	–	16	3	4	18	1	5	29
Gotland	207	8	–	25	16	1	1	–	–	49
Blekinge	497	30	5	19	–	2	22	–	6	16
Kristianstad	227	11	3	19	3	2	34	3	5	20
Malmöhus	218	11	1	15	4	3	41	5	4	16
Halland	137	17	1	21	1	4	20	2	29	5
Göteborg and Bohuslän	39	8	–	16	–	–	30	–	28	18
Älvsborg	319	8	5	24	7	7	14	2	12	21
Skaraborg	531	6	3	35	11	3	14	1	11	16
Värmland	208	16	1	18	–	14	17	3	14	17
Örebro	592	10	1	12	2	9	40	7	4	15
Västmanland	337	12	1	20	10	19	19	3	9	7
Kopparberg	633	4	–	43	11	12	15	2	10	3
Gävleborg	342	6	–	30	5	9	20	2	7	21
Västernorrland	357	3	–	36	10	18	17	3	8	5
Jämtland	1,125	2	–	36	29	12	10	1	4	6
Västerbotten	1,111	5	–	40	14	17	5	3	13	3
Norrbotten	258	4	–	57	15	9	6	1	4	4
The whole country of Sweden	10,524	11	1	28	10	9	19	2	7	13

[1] The division of Sweden into different counties has change slightly since 1946.

[2] LS = Lake sediment.

3.3 Genesis of peat in areas used for cultivation

Peat properties are of importance when cultivating a peat covered wetland. The properties of peat accumulating in a wetland vary through time as a consequence of the succession stages a mire experience from a young fen to an open bog (see Section 4.4.3).

Osvald (1937) made one of the most thorough discussions regarding cultivation of Swedish peat covered wetlands. Bog peat is characterized by low pH and low contents of nutrients and is consequently not suitable for cultivation without amelioration. The bog peat is also characterised by a high water content and low stability, making cultivation problematic. It is, however, possible to cultivate bog peat after adding sand and clay. Fen peat is generally more often suitable for cultivation, since the pH and contents of nutrients are relatively high. Fen peat also has physical properties suitable for cultivation. After the groundwater table has been lowered nitrogen and phosphorus bound in the fen peat can be successively available for plants during the first years of peat mineralization.

The proportional distribution of different peat types and gyttja, which were used for cultivation during the mid 20th century, is summarised in Table 3-2 (from Hjertstedt 1946). These proportions may have partly changed since that time, since today a much smaller proportion of the arable land is situated on peat soils (cf. Berglund et al. 2009). In general a low proportion of nutrient poor peat which has been formed in bog environments (*Sphagnum* peat and forest bog peat) was cultivated during the mid 20th century (Table 3-2). In the County of Uppsala, where Forsmark, is situated the proportion of cultivated bog peat is smaller than the Swedish average. However, one reason for the low proportion of cultivated bog peat in the County of Uppsala might be that there are other more favourable deposits available for cultivation. South western Sweden has a higher proportion cultivated bog peat, which can be explained by the high abundance of that peat type in that area due to a relatively high precipitation. It cannot be ruled out that an increased demand for arable land in the Forsmark area could cause an increase in cultivation of peat, including bog peat.

According to Hjertstedt (1946) the most commonly cultivated peat types in the County of Uppsala are *Carex* peat and *Bryales* peat. Both *Carex* and *Bryales* peat are classified as fen peat and are commonly occurring in the area. That is reflected by data from SGUs peat archive, which is presented in Chapter 4. Compared to other parts of Sweden a relatively large proportion of *Bryales* peat is cultivated in the County of Uppsala (Table 3-2). *Bryales* is governed by a high pH, which probably is an effect of the abundance of lime rich soils, causing a high pH in many fens. Many of the peatlands in the County of Uppsala has recently been uplifted above the sea level and the succession of different peat types will consequently continue in many wetlands. In the future other peat types will be more common (e.g. woody sedge peat from fens), which also might be reflected in the future properties of cultivated peat. In other parts of Sweden a higher proportion of forested fen peat is cultivated and that peat type is well suitable for cultivation according to Hjertstedt (1946).

Figure 3-1. *A cultivated peat area situated in the County of Västmanland. An area which have a similar geological setting as Forsmark with surroundings. The peat soils are recognised by a characteristic black colour (Photo: Henrik Mikko SGU).*

The cultivation of the peat covered "Bälinge Mosse" (Mc Afee 1985) was one of the largest drainage projects in the County of Uppsala. Before cultivation the peat at that site was a fen peat with a high degree of humification, which was rich in mosses and *Carex*, i.e. similar to the peat commonly cultivated in the region (cf. Hjertstedt 1946).

The proportion of cultivated *Phragmites* peat is low throughout Sweden (Table 3-2). Northern Sweden lacks cultivated *Phragmites* peat completely probably due to a lower frequency of *Phragmites* as a consequence of the colder climate. Stratigraphical studies from the County of Uppsala (see Section 4.4) show that the layers of *Phragmites* peat often are thin, explaining the low proportion of cultivated *Phragmites* peat.

3.4 Cultivation of peat – practical aspects

The practical aspects of peat cultivation have been discussed by several authors (e.g. Mc Afee 1984, Osvald 1937). According to Osvald (1937) it is technically possible to convert all types of wetlands with peat layer thick enough to arable land, but it is not always economically feasible to do so. During the early 20th century cultivation of bog peat was feasible when there was a large demand for arable land and no alternatives where at hand. What is economically feasible change, however, through time, which is reflected by the present situation when large areas of arable land recently have been abandoned.

There are several peat properties which must be considered during the conversion of a peat area to arable land. The hydraulic conductivity of peat decreases with increasing degree of humification. The distances between the ditches must consequently be adapted to the peat types. The capillarity of peat is in some cases low which may cause dry conditions at the ground surface. In addition peat can hold large amounts of water which is strongly bound and not available for the crop. To avoid drought problems the groundwater table must consequently not be lowered deeper than necessary. In peat with a high degree of humification the roots can easily penetrates down to the groundwater table (Osvald 1937). In peat with a low degree of humification the roots can only develop in the uppermost tilled part of the cultivated soil and the roots can consequently not reach the groundwater if situated too deep below the tilled layer. Crops growing on peat types with a low degree of humification, e.g. *Sphagnum* or *Phragmites* peat, are therefore sensitive to drought if the groundwater is situated too low below the ground surface (cf. Osvald 1937).

Peat soils are characterised by low heat capacity and in the spring peat can consequently be frozen when other soils are free of ice (Osvald 1937). That is however favourable during the spring tillage, since the ice causes a high stability of the otherwise unstable peat soils. In northern Sweden, where the growing season is short, the low heat capacity can be a problem since the peat soils are partly frozen during a large part of the snow free period.

Osvald (1937) never discussed how thick the undrained peat layer must be to make cultivation possible. Ivitsky (1975) made recommendation for the depth of ditches needed for cultivation of peat in the former Soviet union, and recommended depths of between 60 and 120 cm depending on peat thickness and type of crop (Table 3-3). It is, however, clear that the values presented by Ivintsky (1975) are deeper than what is necessary to make cultivation possible. According to studies in Finland by Valmari (1977) depths of 50–60 cm below the surface are suitable water table depths for many crops and plants can tolerate a water table depth of 20–40 cm for a period. However, farming is problematic when the water table is less than 30–40 cm below the ground surface, since the wet conditions cause unstable ground conditions. Berglund (1996a) studied six sites where organic soils were cultivated. At these sites the groundwater level was situated between 0.5 and 1 metre below the ground surface, indicating that the groundwater level often is situated more than 0.5 metres below the ground surface. The peat subsides considerably when the groundwater table is lowered (see below) and the original peat layer must therefore be considerably thicker than the cultivated layer to make cultivation possible. In Chapter 4 data from SGUs peat archive is presented, showing that all studied cultivated peat areas in the County of Uppsala constitute of fen peat, which most often is underlain by fine grained deposits, i.e. not till.

Table 3-3. Recommended depth (cm) to the groundwater table for different crops (Ivitsky 1975).

	Thin peat	Thick peat
Pasture	60–70	80–85
Cereals	80–90	100–110
Potatoes, sugar beet	90–110	110–130
Food roots, cabbage	85–100	110–120

3.5 Subsidence of peat in areas used for agriculture

There are numerous studies showing a significant subsidence of cultivated peat as a consequence of a lower groundwater table (e.g. Mc Afee 1985, Kluge et al. 2008). The subsidence is caused by several factors:

1) Oxidation as a consequence of oxidising conditions in the uppermost drained peat.
2) Compaction as a consequence of lowering of the groundwater table and by the weight of machines.
3) Shrinkage of the peat as a consequence of lower water content.
4) Erosion by wind and water.

Subsidence of peat has been studied for two reasons: 1) The oxidation of peat causes emissions of greenhouse gases which may cause a warmer climate, 2) The subsidence of the ground surface decreases the depth of the groundwater table, which may cause conditions too wet for cultivation demanding further deepening of the groundwater level. The processes which are causing subsidence of peat are discussed in the text below. Erosion is not further discussed since that process is commonly not of large importance in Sweden (cf. Berglund 2008). There are, however, examples from Skåne and Gotland where wind erosion of peat soils has been a problem (Osvald 1937).

3.5.1 Total subsidence of peat over time

The most important factors determine the subsidence, in a newly drained peatland, are shrinkage and compaction (e.g. Berglund 1996b, Figure 3-2, Figure 3-3, Table 3-4). Compaction is caused by the increased gravitational pressure on the peat layers, which is caused by a lowering of the groundwater table. Shrinkage on the other hand refers to the decreased irreversible volume of the organic material which is an effect of drying. The shrinking causes the formation of macro pores where oxygen can make its way into the soil. The peat starts consequently to oxidize (see Section 3.5.2) and the soil becomes successively more humified and fine grained.

After lowering the groundwater table compaction and shrinkage also cause an increase in dry bulk density and decrease in porosity (Berglund et a. 1989), which is demonstrated in Figure 3-4 where the dry bulk densities in a peat profile before and after drainage are compared. The increase in bulk density decreases with increased depth below the ground surface (Table 3-5 from Stenberg 1936). The compaction takes place both above and below the groundwater table and the magnitude of this process increases with thickness of the peat column (Berglund 1989). The largest subsidence occurs in the uppermost peat horizons. However, deeper peat layers below the ground water level are also subject to compaction (Table 3-5, Figure 3-4, Table A1-2 in Appendix 1).

The relative importance of oxidation increases with time (Figure 3-2) after drainage. As the subsidence continues the groundwater level will successively be situated closer to the ground surface. It will then be necessary to lower the ground water level again. That action will cause a new period characterised by fast subsidence, which is caused by compaction and shrinkage (cf. Hutchinson 1980).

Peat type is important for the subsidence behaviour of peat over time. The relationship between dry density and degree of humification in peat samples from undrained mires is illustrated in Figure 3-5.

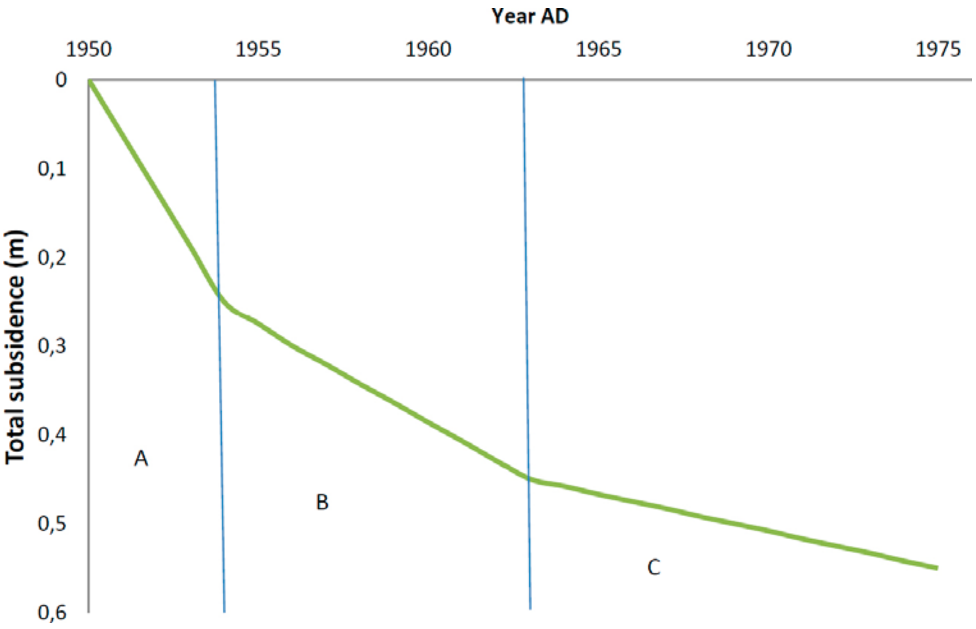


Figure 3-2. *The subsidence of peat after the draining of a wetland in southern Sweden (Lidhult) for cultivation (modified from Berglund 1989). The first initial period (A) after the peatland was drained is characterised by a fast subsidence where compaction is the main contributor to the subsidence. The compaction continues after the initial period but at a lower rate (B). After 10–15 year oxidation is the main contributor to subsidence (C). Oxidation occurs throughout the illustrated period and is not decreasing during the first decades after the draining. Over a longer period of time rate of oxidation can, however be expected to decrease since the amount of fast degradable organic material will decrease.*

Table 3-4. Subsidence of peat on arable land that is used for two types of cultivation (Berglund 1989). Data was obtained from a cultivated peatland in southern Sweden (Lidhult) that was drained in 1950. The data from the eastern part of the peatland is also shown in Figure 3-2. The lower subsidence rates in the areas with grass can be attributed to lower oxidation rates in peat areas used for that crop.

	Measured periods				
	1950–1954	**1954–1956**	**1956–1964**	**1964–1976**	**1950–1976**
Eastern part – mostly grass					
Total (cm)	27	6	14	8	55
Yearly (cm)	6.8	3.0	1.8	0.7	2.1
Western part – arable land					
Total (cm)	42	10	13	14	79
Yearly (cm)	10.5	5.0	1.6	1.2	3.0

Peat with a low degree of humification is characterised by high water content and will consequently compact significantly if drained. *Sphagnum* peat (bog peat) is characterised by high water content and will consequently compact fast after a lowering of the ground water table (Figure 3-3). That peat type is, however, not easily oxidised and the subsidence rate of *Sphagnum* peat is therefore low after the initial subsidence phase has finished. Fen peat on the other hand is characterised by lower water content and will therefore be subjected to lower initial subsidence rates than *Sphagnum* peat. Oxidation of fen peat is, however, much faster than that of bog peat, which constitutes *Sphagnum* peat (Figure 3-3).

Peat with a high degree of humification is more subjected to the shrinkage, caused by dryer conditions, than *Sphagnum* peat with a low degree of humification, i.e. bog peat can be expected to shrink less than fen peat (cf. Oleszczuk et al. 2008). The relatively large subsidence of bog peat shown in Figure 3-3 indicates, however, that compaction is a quantitatively more important contributor to subsidence than shrinkage.

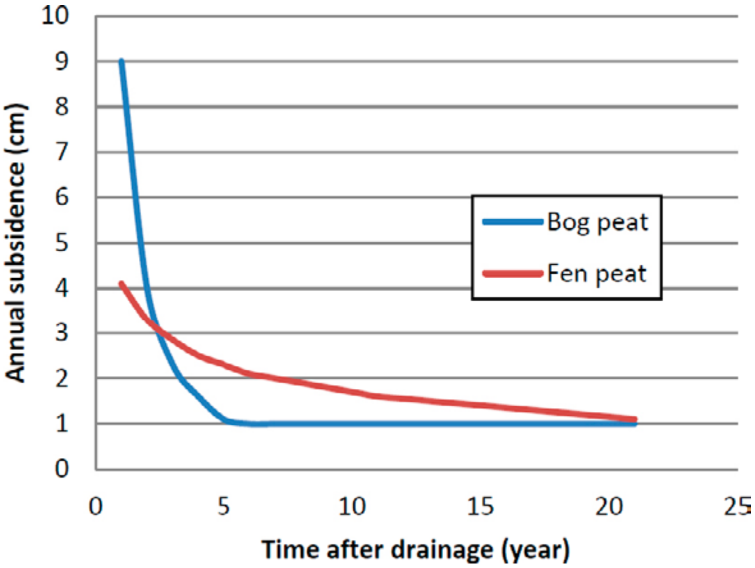


Figure 3-3. *Subsidence rate of cultivated peatlands in northern Poland (modified from Jurczuk 2000). The bog peat (Sphagnum peat) is characterised by a fast initial subsidence due to compaction and shrinkage followed by a much slower subsidence caused by oxidation. The fen peat (alder peat) is characterised by a slow initial subsidence followed by a faster oxidation. The bog peat has an initial thickness of 2.75 metre and the fen peat an initial thickness of 3.60 metre. The ground water levels are on 0.55 and 0.6 metres below the ground surface, respectively.*

The oxidation of peat causes a successively increased content of minerogenic particles, which further increases the dry bulk density of the uppermost soil. Kechavarzi et al. 2010 studied the properties in two peat profiles from England (Table A1-3 in Appendix 1). The high relatively ash content (%) in the uppermost samples in these profiles is an effect of the ongoing oxidation of organic matter, which mainly takes place in the uppermost soil horizon. The property of the peat is also changed due to the mineralization process which causes increased degree of humification and the development of a fine grained structure of the peat. The increased degree of humification causes a degradation of the soil structure and a reduction in hydraulic conductivity and water holding capacity (Kechavarzi et al. 2010).

The physical properties of cultivated peat varies, which is illustrated by the data from Finland (Table A1-4 in Appendix 1 from Maljanen et al. 2007). That data can be further compared with data from other studies (e.g. Table A1-2 and Table A1-3 in Appendix 1), showing the large variability in physical properties of cultivated peat. Also data compiled by Berglund (1996a, Table 3-6) shows a large span of densities for cultivated fen peat, the most commonly cultivated peat type. The variability of peat properties (e.g. ash content and degree of humification) are likely to affect the rates of peat oxidation discussed below. A high content of minerogenic particles in the uppermost part of many soils can be suspected to be associated with relatively low rates of oxidation (Section 3.5.2).

SKB has analysed the bulk density of peat at five cultivated sites in the north-eastern Uppland (Sheppard et al. 2011). The dry bulk density of the uppermost soil varied between c. 0.2 and 0.3 g dw cm^3. When compared to dry bulk density data from studies from e.g. Finland (Table A1-4 in Appendix 1), the data from Sheppard et al. (2011) show relatively low dry bulk density of the uppermost cultivated peat. On the other hand the cultivated peat in “Bälinge mossar” (Table A1-2 in Appendix 1) shows similar dry bulk density as the data from Sheppard et al. (2011). The soils studied by Sheppard et al. (2011) and Mc Afee (1985) have not been cultivated long enough for developing a significant enrichment of minerogenic particles in the top soil, which is reflected by the low density. If cultivation continues at these sites the density and ash content in top soil will probably increase, and the rates of peat oxidation will probably decrease (see Section 3.6). The dry bulk density of drained peat in Uppland (Sheppard et al. 2011, Mc Afee 1985) can be compared with corresponding data from undrained peat (Figure 3-5). That shows that the fen peat with a relatively high degree of humification, that may be cultivated, can be expected to compact in thickness with as much as a factor 3 if drained and cultivated (Grolander 2013).

Thick layers of peat are problematic to cultivate due to the fast subsidence caused by compaction of the peat after drainage (Figure 3-2 and Figure 3-3). It is, however, possible to cultivate peat areas where the peat layer is several metres thick (cf. Mc Afee 1985). From Sweden there are several long time series showing the rate of subsidence through time (e.g. Agerberg 1956, Berglund 1989, se Figure 3-4). Theses studied show all relatively fast subsidence during the first years of cultivation.

One long-term empirical estimate from an area with peat north of the city of Uppsala ("Bälinge mosse") shows that the ground surface had subsided 1.5 metres or more on large parts of the former mire during approximately 80 years of cultivation (Mc Afee 1985). The bog was drained in 1908 followed by fast subsidence of the ground surface. In 1938 the groundwater was lowered further as a consequence of the subsiding ground surface. Measurements from 1984 show that the total thickness of peat in "Bälinge mosse" had decreased with more than 70% during almost 80 years of cultivation (Table 3-7). The fastest rates of subsidence were recorded at sites with the thickest layers of peat. Average rates of peat subsidence have at some sites been larger than 2 cm/year during the 80 years of cultivation (Table A1-1 in Appendix 1).

Agerberg (1956) studied the lowering of the ground surface in a cultivated area with fen peat in the County of Norrbotten. The study lasted for more than 40 years after the area was cultivated. During that time the ground surface subsided c. 0.8 metre. The original thickness of the peat was 2.6 metres.

Berglund (1989) studied the lowering of the ground surface in a cultivated area with bog peat in Lidhult in Småland, which is located in southern Sweden (Table 3-4 and Figure 3-2). The study lasted for almost 30 years and during that time the ground surface subsided almost 0.8 metre. The original thickness of the peat layers was 3.4 metres.

Hutchinson (1980) studied a site in East Anglia, Homer Post, where the subsidence has been observed for 130 years. At that site a total subsidence of almost 4 metres has been recorded. The rate of subsidence was extremely fast during the first 10 years after drainage, almost 2 decimetre each year. Today the subsidence at Homer Post is around 1 cm each year. There are several studies reporting that fast subsidence rates may continue long after drainage. From the Netherlands, Hoogland et al. (2012) reports fast subsidence rates in an area with cultivated peat that was drained more than one hundred years ago.

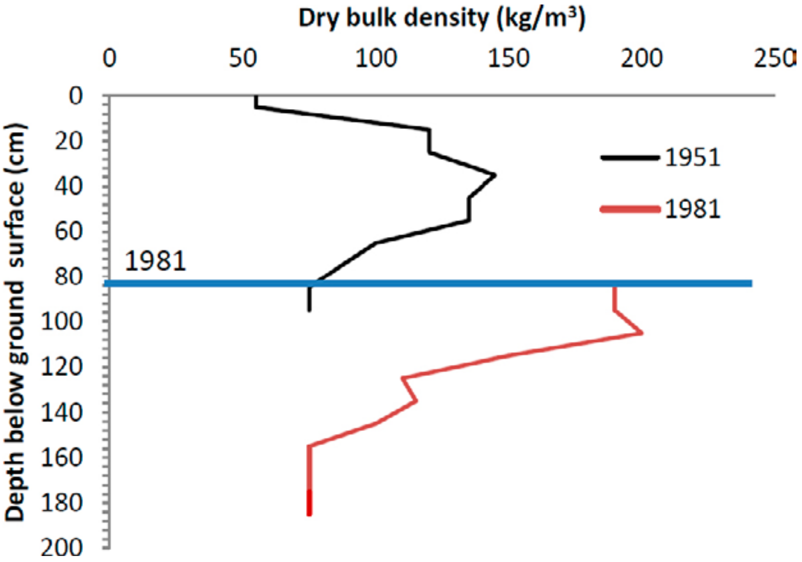


***Figure 3-4.** The effect of subsidence caused by compaction and oxidation due to thirty years of cultivation of a peat area (Lidhult) in Småland, which is located in southern Sweden (from Berglund 1989). The depth value refers to the ground surface 1951 and the blue line to the ground surface 1981. The ground has consequently subsided more than 80 cm during this period. It is obvious that the bulk density of the uppermost peat layers have increased significantly, which implies decreased porosity in the upper soil horizon. Data from the same peatland is shown in Figure 3-2 and Table 3-4.*

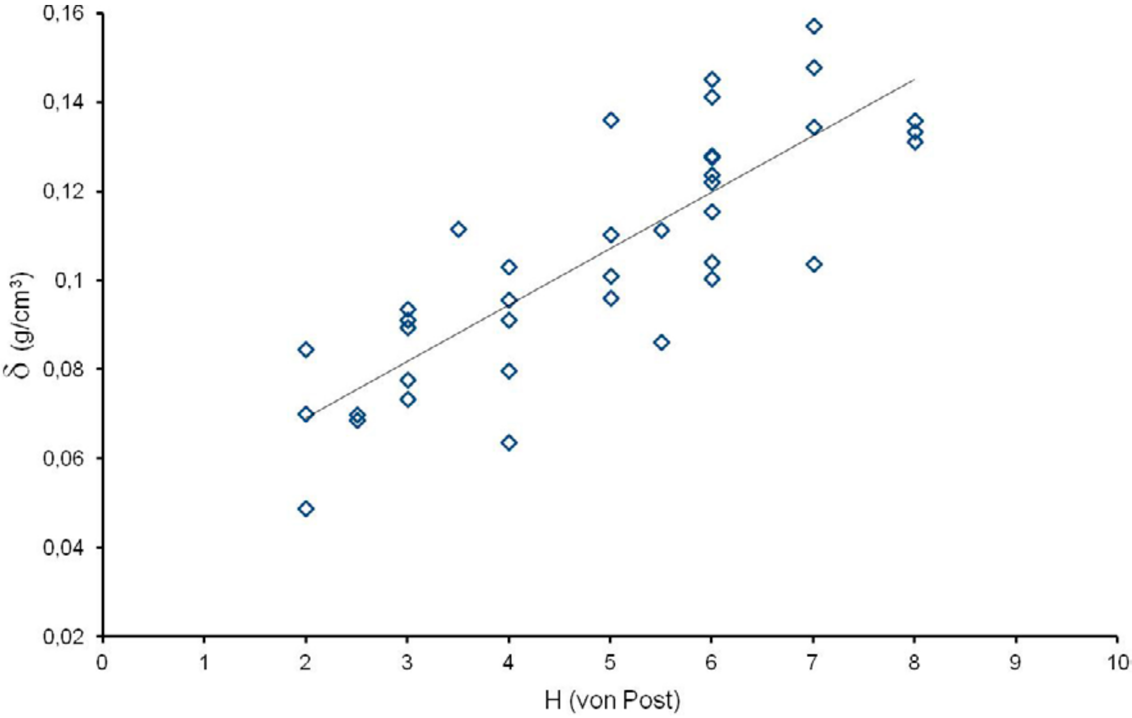


***Figure 3-5.** The dry bulk density (δ) of undrained peat (g cm^{-3}) as a function of humification = H (as defined by von Post and Granlund 1926). The densities increase with increasing degree of humification. The data in the figure comes from northern part of Uppland, close to Forsmark, and is further discussed in Schoning (2014). It is clear that peat with a low degree of humification (mostly bog peat) has a low dry bulk density and is consequently characterised by a high water content, explaining why bog peat is considerably compacted if the groundwater table is lowered.*

Table 3-5. The average decrease of peat thickness during the first ten years (1922–1932) after cultivation of a peatland in northern Sweden (from Stenberg 1936). The decrease of thickness is mainly due to compaction. The uppermost layers have also subsided due to shrinkage.

Original depth of peat (cm)	Subsidence (cm)	The subsidence in % of the original peat depth
0–50	14	43.0
60–100	20	24.0
110–150	24	18.3
160–200	27	15.4
210–250	33	14.2
260–300	38	14.2
> 300	41	12.4

Table 3-6. Physical characteristics of cultivated organic soils. The lower values represent deposits, which are not significantly affected by compaction and the higher values represent the compacted uppermost part of the cultivated soils (from Berglund 1996a).

Deposit	Dry bulk density (g/cm³)	Porosity (% by volume)
Moss peat	0.07–0.2	85–95
Fen peat	0.1–0.6	70–91
Gyttja	0.2–0.4	81–89
Clay gyttja	0.3–0.8	69–84
Gyttja clay	0.5–1.1	60–78

Table 3-7. Subsidence as a function of original peat depth at "Bälinge mosse", a bog that is located in the County of Uppsala. The data represents 80 years of cultivation and the fastest subsidence rates were recorded at the sites with the largest original peat depth (from Mc Afee 1985).

Studied point	Original peat depth (cm)	Total peat subsidence (cm)	Subsidence (cm year^{-1})	Subsidence as % original peat depth
1	180	130	1.71	71.2
2	250	200	2.60	80.0
3	250	198	2.60	79.2
4	250	190	2.50	76.0
5	300	210	2.76	70.0
6	300	255	3.22	85.0
7	300	225	2.96	75.0

3.5.2 Oxidation of peat

Oxidation of peat in areas used for cultivation has been studied by many researchers, since these areas emit a significant amount of green house gases (GHG) to the atmosphere (Nykänen 2003, Kasimir-Klemedtsson et al. 2000, Maljanen et al. 2004, 2007, 2010, Berglund and Berglund 2010, Eggelsmann 1976). In fact, considering GHG fluxes agriculture is climatically the most unfavourable land use for managed peat soils (cf. Maljanen et al. 2004, 2007, 2010). Drainage, ploughing and fertilization cause a high decomposition rate of peat leading to high emissions of CO_2 but also considerable amounts of N_2O are emitted from these soils (Table 3-8). In contrast to many wetlands, arable land is not a source for methane (CH_4), and may instead act as a sink for that gas.

Several important factors affecting the rate of peat oxidation have been identified:

1) Depth of drainage

2) Type of management and crops

3) Type of peat (degree of humification)

4) Climate

There are different opinions of the relative importance of the factors listed above, which is discussed in the text below. The factors affecting rate of peat oxidation from cultivated soils has also been discussed in a literature review by Norberg et al. (2012). Peat areas drained to obtain improved forest growth are also subjected to oxidation and Laiho (2006) discusses the effect of lowering of groundwater table on the rate of peat oxidation depend on several factors such as peat type, temperature and nutrient availability. There are several publications (e.g. Maljanen et al. 2007, Norberg et al. 2012) discussing how the fluxes of GHG from cultivated areas can be decreased and which factors that control the emission rates of these gases. Van Huissteden et al. (2006) argue that restoring wetlands is one way to decrease the total emissions of GHG from areas with cultivated peat.

Table 3-8. Fluxes of green house gases (GHG) from different types of cultivated peatlands in Finland (compiled by Sarkkola 2007).

	Average cropland	Grass	Cereal	Fallow	Abandoned
CO_2 g/m^2/yr					
Average	2,072	1,485	1,760	2,971	1,188
Min–max	290–4,033			2,167–4,033	–330–3,300
CH_4 g/m^2/yr					
Average	0.42	1.27	–0.43	0.41	–0.22
Min–max	–0.49–0.91	0.11–0.91	–0.49–0.51	–0.35–4.00	
N_2O g/m^2/yr					
Average	1.74	0.85	1.74	2.63	1.29
Min–max	0.17–5.81	0.17–1.56	0.85–3.79	0.60–5.81	

Methods to determine the emissions of CO_2 from arable land

The rate of oxidation can be estimated with several approaches. Several studies reports results from direct measurements of GHG fluxes from arable land (e.g. Berglund and Berglund 2011), while other studies are focused on the long term subsidence taking place during several decades (e.g. Mc Afee 1985). Measurements of gas fluxes are often conducted during one or a few years and it is therefore difficult to use these data to evaluate the long term oxidation rates of cultivated peat. Furthermore photosynthesis and respiration of the roots also affect the CO_2 balance and must be separated from CO_2 emitted from peat oxidation. Nykänen et al. (1995) compared cultivated peat with and without plants and concluded that 38% of the CO_2 emissions were caused by fresh organic material. Long term subsidence studies may be used to estimate average oxidation rate, but it can be difficult to separate subsidence caused by oxidation from that caused by compaction and shrinkage.

Several attempts have been made in order to separate oxidation from the other factors causing subsidence (Eggerman 1976, Armentano and Menges 1986). According to Armentano and Menges (1986), the oxidation contributes to a factor 0.33–0.67 of the total subsidence, and according to Eggelsmann (1976) 70% of the long-term subsidence can be attributed to oxidation. That factor can only be used when the initial subsidence, mainly caused by compaction and shrinkage, has ceased. There is no consensus regarding which factor that should be used. Berglund and Berglund (2010) used a factor 0.35 when calculating the total emissions of CO_2 from cultivated arable land in Sweden, whereas Kasimir-Klemedtsson et al. (1997) used the factor 0.7 from Eggelsmann (1976).

Some examples of the methods used to estimate oxidation rates:

1) The most commonly used micrometeorological method is the eddy covariance (EC) method, where the gas flux is determined from the high-frequency measurements of gas concentration, wind and scalar atmospheric data series (Hendriks et al. 2007).
2) Chamber techniques determine the gas fluxes from the change in gas concentration in a chamber (Berglund and Berglund 2011, van den Bos and van de Plassche 2003).
3) Subsidence through time. There are several long time series showing the rate of subsidence over time (Hutchinson 1980, Mc Afee 1985). The total subsidence is an effect of several factors (section 3.5) and it is then necessary to separate oxidation from these other factors.
4) Climatic site data (temperature and precipitation) can be used to estimate oxidation (Eggelsmann 1976).
5) The ash content in the top soil and underlying soil can be compared to estimate the enrichment of minerogenic matter caused by peat oxidation (Grønlund et al. 2008).
6) Several paper reports results from modelling of the future and past subsidence of peat (Kluge et al. 2008, van Huissteden et al. 2006). Historical and field data are used as input to these models.

Total emissions of CO_2 from arable land

Results from a number of studies where the oxidation rates of cultivated peat have been determined, including rates of subsidence caused by oxidation are summarised in Table 3-9 and Table 3-10. The latter values can be compared with values of total subsidence, including shrinkage, compaction and oxidation, which are shown in Table 3-11. The total subsidences in Table 3-11 are generally larger than the values in Table 3-9 , and some of the data presented in the two tables are from the same studies (see Eggelsmann and Bartels 1975). The three studies of oxidation rates from cultivated bog peat (Table 3-10), show slightly lower oxidation rates than the average rates from studies of cultivated fen peat (Table 3-9). Also results from Jurczuk (2000) indicate lower oxidation rates of bog peat (*Sphagnum* peat) than of fen peat (Figure 3-3), which is due to the commonly high content of waxes and resins, and high C/N ratio in bog peat (cf. Oleszczuk et al. 2008). The low number of data from bog peat reflects the fact that this peat type is not commonly cultivated. Even though the rates of CO_2 emissions varies between the studied sites it is clear that peat oxidation from cultivated peat is a fast process, and the rate of subsidence caused by oxidation of fen peat are generally between 0.5 and 1.0 cm year^{-1}. These rates have been calculated based on an assumed bulk density of the peat of 0.2 g cm^{-3}. In many cultivated peat soils the density is, however, higher (see e.g. Table 3-16) and the rate of subsidence caused by oxidation may at some sites consequently be lower than indicated in Table 3-9 and Table 3-10.

Table 3-9. Emission of CO_2 and subsidence of cultivated fen peat, which is caused by peat oxidation. The subsidence rate cm/year is calculated by assuming that the peat has a density of 0.2 g/cm^3 and an organic content of 100% (an overestimation since peat always contains some minerogenic material). The C-content of the organic material is assumed to be 58%. The total subsidence may be considerably larger (Figure 3-2 and Figure 3-3) since the values in this table only represent subsidence caused by oxidation. Density and organic contents vary however considerably between different sites (see Table 3-6, Table A1-2, Table A1-3 and Table A1-4 in Appendix 1), which may be one reason for the varying results. Most of the data has been recalculated from a table in Oleszczuk et al. (2008). Nd = no data.

Emission (g C m^2/year)	Oxidation (cm/year)	Area	Land use	Reference	Method
286–668	0.24–0.57	NE Germany	Nd	Mundel (1976)	Measurements of CO_2 fluxes from bare soils
1,120	0.95	Poland	Arable land	Okruszko (1989)	Subsidence
1,060–1,650	0.90–1.40	NW Germany	Arable land	Eggelsmann and Bartes (1975)	Subsidence
660–990	0.56–0.84	S Germany	Arable land	Schuch (1977) recalculated by Höper (2002)	Subsidence
845–1,690	0.72–1.44	Sweden	Cereals	Berglund (1989)	Subsidence
409–845	0.34–0.72	Sweden	Grassland	Berglund (1989)	Subsidence
1,690–2,509	1.44–2.13	Sweden	Row crop	Berglund (1989)	Subsidence
545	0.46	Sweden	Cereals	Kasimir-Klemedtsson et al. (1997)	Measured CO_2 flux assuming 38% root respiration
409	0.35	Sweden	Grassland	Kasimir-Klemedtsson et al. (1997)	Measured CO_2 flux assuming 38% root respiration
210–829	0.18–0.70	Finland	Barley	Maljanen et al. (2007)	Chamber measurements
690–1,100	0.59–0.93	Finland	Fallow	Maljanen et al. (2007)	Chamber measurements
79–750	0.07–0.64	Finland	Grassland	Maljanen et al. (2007)	Chamber measurements
191	0.16	Canada	Varying but not so large differences in C emission	Glenn et al. (1993)	Measurements on CO_2 fluxes from bare soils
412	0.35	NW Germany	Grassland	Meyer et al. (2001)	Measurements on CO_2 fluxes from bare soils
401–750	0.34–0.64	NW Germany	Grass and barley	Meyer et al. (2001)	Measurements on CO_2 fluxes from bare soils
790	0.67	Western Netherlands	Arable land	van den Bos (2003)	Micro metrological
1,120	0.95	Western Netherlands	Drained but no other information	van den Bos (2003)	Micro metrological
690	0.59	NE Germany	Grassland	Kluge et al. (2008)	Soil profile and incubation
580	0.49	NE Germany	Grassland	Augustin (2001)	Micro metrological
860	0.73	Norway	Mostly grass	Grønlund et al. (2008)	Change in mineral content
800	0.68	Norway	Mostly grass	Grønlund et al. (2008)	Subsidence rate
600	0.51	Norway	Mostly grass	Grønlund et al. (2008)	CO_2 flux measurements

Table 3-10. Emission of CO_2 and subsidence of cultivated bog peat, which is caused by peat oxidation. The subsidence is calculated by assuming that the peat has a density of 0.2 g/cm^3 and an organic content of 100%. The C-content of the organic material is assumed to be 58%. The data has been recalculated from a table in Oleszczuk et al. (2008).

Emission (g C m^2/year)	Oxidation (cm/year)	Area	Land use	Reference	Method
746	0.37	NW Germany	Arable land	Eggelsmann and Bartels (1975), Höper and Blankenburg (2000)	Subsidence
821	0.41	NW Germany	Grassland	Kuntze (1992)	Subsidence
593	0.30	Sweden	Grassland	Hillebrand (1993)	Measurements on CO_2 fluxes from bare soils

Table 3-11. A compilation of studies showing the subsidence rates, caused by oxidation, compaction and shrinkage, of cultivated peat (from Kluge et al. 2008). The higher subsidence rates from arable land compared to meadows indicate higher oxidation rates from the former land use type. Nd = no data.

Decrease of peat thickness (cm/yr)	Land use	Mean groundwater table depth (cm)	Time period	Location	Authors
2.0–3.0	Arable land	40–70	Nd	Germany	Eggelsmann (1976)
2.7 1.6	Arable land	130 65	1962–1974	Northwest Germany	Eggelsmann and Bartels (1975)
0.6	Meadow	20–50	1877–1975	Netherlands	Schothorst (1977)
0.7–1.0	Meadow	Nd	1963–1985	Northeast Germany	Weinzierl (1997)
0.1 0.6 0.7–0.8	Meadow	–100 100–200 > 260	1951–1990	Poland	Ilnicki (2002)
0.5	Meadow	Nd	1961–1996	Northeast Germany	Eggelsmann (1976)
0.3 0.6 1.1	Meadow	40–60 60–100 100–120	1903–1969	South Germany	Eggelsmann and Bartels (1975)

However, the results obtained from the different methods used to measure CO_2 emissions, mentioned above, varies, which may be due to several reasons (Table 3-12 and Table 3-13). It is clear that the values calculated from subsidence rates are generally higher than those obtained from direct measurements of CO_2 emissions (Table 3-12 and Table 3-13).

Kasimir-Klemedtsson et al. (1997) compared results from different methods for determining oxidation rates of peat. The subsidence measurements give different rates depending on type of crop. The oxidation part of total subsidence was calculated by assuming that 70% of the subsidence was caused by oxidation (from Eggelsmann 1976). The annual precipitation and average temperature was also used to calculate peat oxidation and the result gives consequently no difference between crops (Eggelsmann 1976). When calculating CO_2 from peat oxidation it was assumed that 38% of the CO_2 was produced from the plants growing on the fields and remaining parts from oxidation of peat (Nykänen et al. 1995). There are only data from a few CO_2 measurements available, which all give lower oxidation rates than the other two methods.

Grønlund et al. (2008) used three methods, subsidence rates, ash content and measured CO_2 fluxes, to estimate oxidation rates of peat on arable land in Norway (Table 3-12). The ash content was calculated by subtracting Mg and Ca components, which were assumed to emanate from lime and fertilizer. It was concluded that the direct measurements of CO_2 fluxes underestimates the rates of long term peat oxidation. One reason for that might be that that the oxidation rates have decreased since the studied sites were drained for cultivation. The differences between the results obtained from the methods used by Grønlund et al. (2008) are, however, relatively small and it can be concluded that all results implies fast subsidence rates (cf. Table 3-9).

As mentioned above, Kasimir-Klemedtsson et al. (1997) calculated the oxidation from subsidence by assuming that 70% of the subsidence is due to oxidation, whereas Grønlund et al. (2008) assumed that 38% of the subsidence is due to oxidation. These different approaches obviously give different resulting oxidation rates. Berglund and Berglund (2010) assumes that 35% of the subsidence can be attributed to oxidation (Table 3-15), which consequently gives CO_2 emissions that are half as large as the values calculated by Kasimir-Klemedtsson et al. (1997). If the calculations of oxidation are based on subsidence obtained from the period shortly after drainage it is likely that the rates of oxidation will be overestimated since the early subsidence to a large part is caused by compaction and shrinkage. Kasimir-Klemedtsson et al. (1997) may consequently overestimate the long range oxidation rates of peat since these data are based on the data from Berglund (1989) where the initial phase of peat subsidence is included.

Furthermore, difficulties in measuring GHG emissions may explain some of the varying results presented in Table 3-9. One problem when interpreting results from these measurements is the difficulty to separate CO_2 emanating from peat oxidation and CO_2 emanating from plant respiration.

There are also differences in CO_2 emissions between the studied sites which may be due to varying soil and land use properties. These properties are further discussed in the text below. One important factor is probably that the organic content varies between the studied sites. When comparing the dry bulk densities presented in Table 3-16 (from Kluge et al. 2008), Table A1-4 (from Maljanen et al. 2007), Table 7-3 (from Kechavarzi et al. 2010) and Table A1-2 (from Mc Afee 1985) it is obvious that the properties of cultivated peat varies widely (Appendix 1). The relatively high densities at some sites reflect relatively low organic carbon contents. That in turn probably affects the rate of oxidation negatively, which can be supposed to decrease with lower organic content in the soil.

It is in conclusion not possible to evaluate exactly why the results in e.g. Table 3-9 show such varying values of CO_2 emissions. All results show, however, that oxidation of cultivated peat is a fast process and that cultivation of peat is not sustainable over a long period of time.

Several attempts have been made to model the rate of peat subsidence and oxidation (e.g. Kuikman et al. 2003, van den Akker et al. 2008, Kluge et al. 2008). The empirical relationships from 30 years of studies between ditch water and groundwater levels and subsidence were used by van den Akker et al. (2008) to calculate the total emissions of CO_2 from Dutch agriculture soils. Kluge et al. (2008) used historical data together with field studies and laboratory measurements as input to a model which was used for calculating past and future emissions of CO_2 from a cultivated peat area in northern Germany. Temperature and soil moisture are of considerable importance for the oxidation rates and were therefore also used in the model. The resulting model shows how the rate of peat oxidation will increase in the future due to the global warming. In the future it will consequently be more difficult to take action that will decrease oxidation of cultivated peat. The results from the modelling also suggest that the rate of oxidation increases with increasing depth to groundwater. By comparing data from a historical study with new field data Kluge et al. (2008) also showed that oxidation of peat mainly occurs in the uppermost decimetres of the soil (Table 3-16).

Table 3-12. Rates of peat oxidation from cultivated peat soils in Norway determined with three methods (from Grønlund et al. 2008).

Method	Hypothesis	Sources of errors Underestimating oxidation rate	 Overestimating oxidation rate	Oxidation rate (g C/m^2/year)
Enrichment of minerals	Homogenous peat. The oxidation takes place in the plough layer. Only mineral addition from lime and fertiliser.	Oxidation also in deeper peat horizons.	Inhomogeneous peat with respect to mineral content. Deposition of mineral particles from the air.	860
Subsidence	Compaction is insignificant a few years after drainage. Constant rate of oxidation through time. Oxidation does not change bulk density.	Oxidation is faster during the first years after the drainage.	Compaction continuous also long after the drainage.	800
CO_2 flux	Oxidation with a constant rate through time. Photosynthesis can be estimated with the help of data from yields and literature.	Oxidation is faster during the first years after drainage.		600

Table 3-13. The yearly loss of CO_2 (t/ha/yr) determined with three different methods (modified from Kasimir-Klemedtsson et al. 1997). Nd = no data. I) Long term subsidence which to 70% is assumed to be caused by oxidation (Eggelsmann 1976). II) Calculated from climatic data (temperature and precipitation). III) Measured CO_2 fluxes (38% of the flux was attributed to root respiration and remaining flux to peat oxidation.)

Type of crop	Method	Finland	Sweden	Netherlands
Grassland	I	Nd	15–31	8–30
	II	20	60	115
	III	15	15	11±3
Cereals	I	Nd	31–62	Nd
	II	20	60	115
	III	Nd	20	Nd
Row crop	I	Nd	62–92	Nd
	II	20	60	115
	III	Nd	Nd	Nd

Table 3-14. Subsidence of peat on arable land that is used for different types of cultivation at Flahult in southern Sweden (Agerberg 1961). Data was obtained from a cultivated peatland in southern Sweden and represents the period 1901–1960.

	Peat depth before draining (m)	Total subsidence (cm)	Yearly subsidence (cm)
Intensive cultivation	2.0	105	1.8
Mostly grass	2.9	122	2.1
Area used for grassing	2.7	55	0.9

Table 3-15. The proportional distribution and carbon losses from different types of Swedish agricultural soils (Berglund and Berglund 2010). The calculations are based on the distribution of thin (< 0.5 m) and thick (> 0.5 m) layers of peat shown on SGUs maps of Quaternary deposits. Bulk densities of 0.2 g/cm^3 and (0.3 g/cm^3, within brackets) were used for the emission calculations. It was assumed that 35% of the subsidence was caused by oxidation.

Cultivation intensity (crop type)	Subsidence rate (cm/year)	C loss (Mg ha^{-1} yr^{-1})	Area (ha)	Total C loss (Gg yr^{-1})
Row crops	2.5	8.8 (13)	3,536	31 (46)
Annual crops except row crops	1.5	5.2 (7.9)	60,113	310 (470)
Managed grasslands	1.0	3.5 (5.2	91,179	320 (470)
Extensive land use inclusively trees	0.5	1.8 (2.6)	96,483	170 (250)
Total			251,311	831 (1,236)

Table 3-16. Changes in peat properties during 40 years of cultivation of a peat area in northern Germany (Kluge et al. 2008). Each line corresponds to a specific peat layer, e.g. the uppermost layer (0–0.2 m in 1963) is only 5 cm thick in 2003. The total subsidence was in average 1 cm/year. The carbon losses from different soil horizons were estimated and it is clear that the largest losses occurred from the uppermost horizon. The corresponding horizons from 1963 are also shown for 2003 although the thicknesses of the horizons have decreased significantly. Totally 27.5 kg carbon was lost from the profile during 40 years of cultivation. BD = Bulk density.

1963				2003			
Depth (m)	BD (kg/m^3)	C_{org} (kg/kg)	C_{org} (kg/m^2)	Depth (m)	BD (kg/m^3)	C_{org} (kg/m^2)	C_{org}loss (kg/m^2)
0–0.2	300	0.33	19.9	0–0.05	550	6.7	–13.2
0.2–0.35	300	0.33	15.0	0.05–0.10	550	6.7	–8.3
0.35–0.7	370	0.19	24.7	0.10–0.35	580	2.0	–3.7
0.7–0.9	160	0.44	14.3	0.35–0.45	270	1.0	–2.3
Total			73.9			46.4	–27.5

Factors affecting the oxidation rate of cultivated peat

Type of crops

The effects of crop types on the rate of peat oxidation are discussed in several papers (Kasimir-Klemedtsson et al. 1997, Kluge et al. 2008, Norberg et al. 2012), but it is not fully clear how cultivation intensity and type of crop affect the oxidation rate. Different types of crops demand different types of tillage and it can be assumed that an intensive tillage causes higher oxidation rates. Reicosky and Archer (2007) have shown that CO_2 losses from loam soil where tillage has been applied is several times higher than from corresponding soils where tillage not has been applied. Results from some of the studies made on cultivated peat soils are compiled in Table 3-9 and Table 3-11. Results from several studies indicate that the rate of peat oxidation is faster in peat areas used as arable land than in those used as grassland (Table 3-14 and Table 3-15, Eggelsmann 1990, Okruszko 1993, Zeitz and Velty 2002, Ilnicki and Okruszko 2002, Couwenberg 2009). There are also data indicating that peatland used for roots vegetables give the highest losses of peat due to oxidation (Kasimir-Klemedtsson et al. 1997). The effects of crop types are, however, somewhat inconclusive. Maljanen (2003) presents data showing higher rates of CO_2 emissions from grassland compared to cereals. In another report Maljanen et al. (2007) present data indicating somewhat higher CO_2 emissions from areas with barley than from those with grass. Large amounts of CO_2 are also emitted from peat areas during fallow and from peat on abandoned arable land. In fact, the emissions remain at the same high level also after cultivated peat areas have been abandoned (Maljanen et al. 2007, 2012). Data presented in Kasimir-Klemedtsson et al. (1997) is mainly based on data from Berglund (1989) and shows that the total subsidence in cultivated peat areas is around 5 mm/year for areas used for grassing, 10 mm/year for cereals and 20–30 mm/year for root vegetables. Accordingly, high management intensity may cause a subsidence as large as 1.5 m during a 50 year period. As mentioned above, Kasimir-Klemedtsson et al. (1997) may however overestimate the long range oxidation rate of peat since these data are based on the data from Berglund (1989) where the initial phase of fast peat subsidence is included. In contrast to several other studies Norberg et al. (2012) concludes that the crop type has little effect on the emissions of GHG and that differences mainly can be attributed to differences in properties between the studied sites. It cannot be excluded that different types of peat are used for different types of crops giving rise to different oxidation rates, which are related to peat type and not crop. Several studies show, however, that peatlands with grass cultivation (arable grassland) emit less CO_2 than peatlands used for cereals (Table 3-9, Table 3-11 and Table 3-12) and it is therefore likely that the crop cultivation system has an effect on the oxidation rates.

Properties of the peat

The property of the peat is one factor that can be assumed to affect the rate of peat oxidation. As mentioned above there are studies showing lower oxidation rates from cultivated moss peat than for fen peat (Figure 3-3). A literature study presented in Oleszczuk et al. (2008) indicates lower oxidation rates from cultivated bog peat than from fen peat, which is apperant from comparing Table 3-9 and Table 3-10. This is because *Sphagnum* peat has a high resistance to decay due to its content of uronic acids and phenolic compounds (see Section 2.4.2). That is also in line with observations from Minkkinen et al. (2008) who have shown that *Sphagnum* peat is oxidising with a slow rate in peat areas drained for forestry. Forested areas with such peat can even act as a sink for CO_2, when drained to improve forest growth (Minkkinen et al. 2007). Unfortunately peat properties are not thoroughly described in most papers discussing oxidation of cultivated peat. Prasad et al. (2000) showed that the rate of peat oxidation increases with increasing pH. The use of fertiliser and lime can also increase the rate of peat oxidation. That is probably one of the reasons for the high oxidation rates from cultivated peat. In a study by van den Bos and van de Plassche (2003) it was concluded that the rate of peat oxidation is not significantly influenced by differences in peat composition. It is, however, not clear how much the peat properties of that study varied.

The high oxidation rates of peat with a high pH are of special interest when discussing oxidation of peat in cultivated areas at the future Forsmark site, where naturally calcareous fens with a high pH are common. Today *Bryales* and *Carex* peat are the most commonly cultivated in the County of Uppsala (Hjertstedt 1946**)** and it is likely that these areas are characterised by relatively fast oxidation rates. Peat that potentially will be cultivated in the future Forsmark area can consequently be expected to be characterised by fast rates of oxidation.

The peat properties changes with time due to the ongoing oxidation. Increasing content of minerogenic particles decreases the amount of organic material in the topsoil, probably causes decreasing rates of oxidation with time. Furthermore, the proportion of organic material which easily can be oxidized decreases with time causing decreasing oxidation rates. The data from Swedish cultivated peat are from peatlands that were cultivated during the first half of the 20th century (e.g. Mc Afee 1985). It is possible that some of the studied peatlands from e.g. Germany and the Netherlands has been cultivated for longer periods than the soils studied by e.g. Berglund (1989), which is indicated by both higher bulk densities and contents of minerogenic particles (e.g. Kluge et al. 2008),compared to the Swedish data. According to van den Bos and van de Plassche (2003), large peat areas in the Netherlands was cultivated already during the 10th to the 14th century, supporting the relatively old age of some cultivated peat areas. Results from SKBs studies (Sheppard et al. 2011) in the Forsmark neighbourhood show that the cultivated peat has relatively low bulk density and high content of organic carbon. It is therefore likely that the fast oxidation and subsidence rates recorded from other cultivated peat soils in other parts of Sweden are valid also for peat which at present is cultivated in the area close to Forsmark (se also results from Schoning 2014). The exceptionally high subsidence rates at "Bälinge mosse" (in some cases more than 2 cm/year, see Table 3-7 and Table A1-1 in Appendix 1 from Mc Afee 1985) are, however, attributed to the large original peat depth at that site. The subsidence rates of around 1 cm/year (Berglund 1989) and from Poland is regarded as a more likely scenario of subsidence rates, which takes place 15–20 years after the drainage. However, in the future the cultivated peatlands close to Forsmark will probably obtain properties more similar to the peat studied in the Netherlands (van den Bos and van de Plassche 2003),

Climate

Both annual rainfall and temperature has an effect on the rate of peat oxidation. Eggelsmann (1976) showed some examples of annual height loss caused by oxidation in relation to climate. The highest rates were found in semiarid environments, i.e. places with low precipitation and high temperature. In one such area, northern Greece, over 50 mm annual height loss of peat has been recorded. In colder and wetter areas such as Finland considerably lower rates of height losses (around 10 mm/year) were recorded. Several other paper reports results showing that the rate of CO_2 emissions increases with increasing temperature (Berglund et al. 2010).

The effect of CO_2 production caused by peat oxidation in relation to temperature is illustrated in Figure 3-7 from Oleszczuk et al. (2008). It is, however, not possible to see any effects of climate when studying the compilation of subsidence data presented in Table 3-9. These data represent a smaller span in climate compared to the dataset studied by Eggelsmann (1976). It is also clear that other parameters affect the rate of oxidation, e.g. peat properties.

It is not only the air temperature that determines the rate of peat oxidation. Observations from northern Finland have shown faster oxidation rates of forested peat in northern Finland compared to the southern part of that country. These results have been attributed to longer periods of snow in northern Finland, which isolate the soil and give rise to higher soil temperatures and peat oxidation also during the winter (Minkkinen et al. 2007).

Too dry conditions may cause lower rates of oxidation. A soil moisture content of around 60% by volume gives the maximum rate of oxidation (Szanser 1991). A dry summer may consequently decrease the rate of peat oxidation in the top soil.

Depth of drainage

Peat oxidation mainly takes place in the top layer (0–30 cm) of the peat soil (van den Bos and van de Plassche 2003, Kluge et al. 2008) and the groundwater level is often situated far below that level. Never the less there is a clear correlation between lower groundwater level and increase rate of peat oxidation (cf. Wessolek et al. 2002, Oleszczuk et al. 2008, Kluge et al. 2008). According to Oleszczuk et al. (2008) peat oxidation is most intense when the groundwater table is 90 cm or deeper below the soil surface whereas a deeper groundwater level does not affect the oxidation rate.

Field studies by Renger et al. (2002) indicate that the rate of peat mineralization and CO_2 emission increases distinctly with a deeper groundwater level (Figure 3-6) and that peat oxidation can be reduced by as much as 30–40% of the maximum by a groundwater level closer to the ground surface. In studies from the Netherlands, van der Akker et al. (2008, 2012) concluded that high ditch water levels is one way to decrease peat oxidation and the authors suggest that subsurface irrigation may be used to raise the groundwater levels and reduce oxidation rates and thereby GHG emissions. The results showed that it was possible to reduced CO_2 emissions with 50% by decreasing the depth between the ground surface and the groundwater table. Also Regina and Myllys (2009) suggested that raising the groundwater level can be used as a tool to decrease the emissions of GHG from cultivated peat soils. Van den Bos (2003), Freibauer et al. (2012) and Hendriks et al. (2007) argue that restoration of wetlands is one way to decrease the emissions of GHG. Maljanen et al. (2012) showed that GHG emissions from formerly cultivated soils can be avoided if the groundwater level is kept at a high level. Another way to decrease CO_2 emissions from cultivated peat soils is afforestation which leads to a decrease in CO_2 emissions (Maljanen et al. 2007, Hytönen et al. 2007).

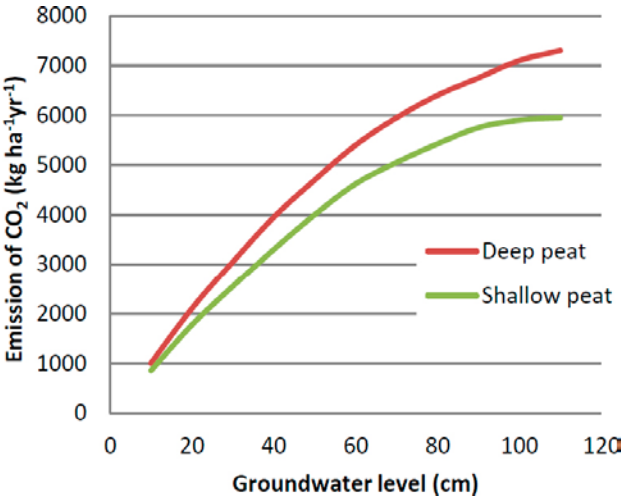


Figure 3-6. *Emission rates of CO_2 from cultivated peat in relation to groundwater levels (Renger et al. 2002). A shallow groundwater level is obviously causing lower emissions of CO_2 than a deep groundwater level. Deep peat = a total thickness of cultivated peat of 1 m or more, shallow peat = a total thickness of cultivated peat of 0.5 m or less.*

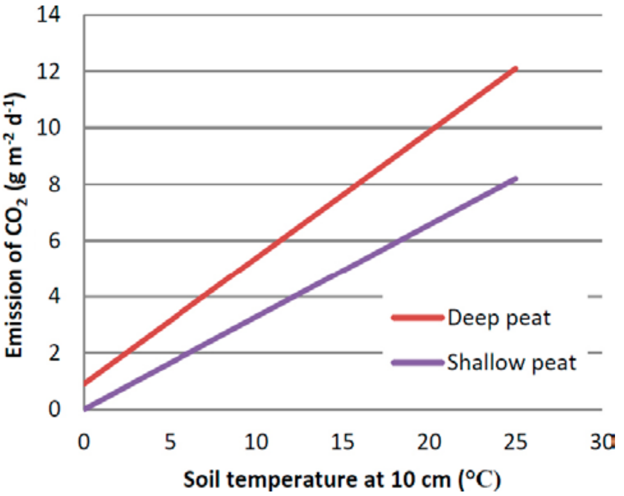


Figure 3-7. *The predicted emissions of CO_2 as a function of soil temperature (Oleszczuk et al. 2008). An increased soil temperature obviously increases the rate of CO_2 emission. Deep peat = a total thickness of cultivated peat of 1m or more, shallow peat = a total thickness of cultivated peat of 0.5 m or less.*

Results from a study of gas flux measurements in undisturbed soil columns (Berglund and Berglund 2011) has, however, shown that the rate of CO_2 emissions may decrease with increasing depth of the groundwater table. In that study, lowering the water table from 40 cm depth to 80 cm depth decreased the CO_2 emissions from two soils with contrasting soil properties. That may be an effect of dryer conditions in the topsoil when the groundwater level is too low, which may decrease the rate of oxidation. As mentioned above too dry condition may decrease oxidation rates (Szanser 1991), and the lower CO_2 emissions from soils with a low groundwater table recorded by Berglund and Berglund (2011) can be explained by dryer conditions in the uppermost soil horizon. As mentioned above, oxidation of peat occurs mainly in the uppermost decimetres of the soil. That can explain why a deeper groundwater level not necessarily causes increased oxidation. There are, however, results from several studied showing that deeper groundwater levels cause increased oxidation of peat (Renger et al. 2002). It could therefore be concluded that deeper groundwater levels generally cause a higher rate of peat oxidation.

Berglund and Berglund (2011) used their observation to conclude that restoring cultivated peatlands to wetlands is not a way to decrease emissions of CO_2. That must, however, be regarded as a too far going conclusion since it is the lowering of the groundwater table that cause the fast oxidation rates of cultivated peat.

Priming

The occurrence of roots may increase the oxidation rate due to the effect of priming. Several mechanisms have been suggested (Kuzyakov et al. 2000):

1) Metabolism of the peat substrate with root exudates.

2) Fertilization of the microbial population by exudates.

Studies of CO_2 emissions from bare soils may consequently give values too low when attributed to cultivated areas, and Huissteden et al. (2006) argues that laboratory incubation tests gives too low emissions of CO_2 due to the absence of roots.

3.5.3 The effects of cultivation of peat areas on peat properties and subsidence – summary

Lowering the groundwater table in wetlands for cultivation of peat causes fast changes of peat properties giving rise to rapid subsidence rates, which during the first years after draining can be several cm each year. Subsidence rates are often around 1 cm/year 10–15 years after drainage, but in a longer time perspective decreasing rates can be expected as the content of minerals and slowly oxidizing organic material increase in the top soil. The subsidence is caused by shrinkage compaction and oxidation. Depth of the ground water level, peat properties and climate are probably the most important conditions affecting the rate of these processes.

There are numerous studies concerning subsidence and especially oxidation of peat as an effect of cultivation. However, different peat properties and land use history gives different results and problems in comparisons. Studies of subsidence from Swedish sites deals with peat which was drained during the mid 20th century and are still characterized by fast rates of subsidence. These peatlands have similar properties as peat that at present is cultivated in the Forsmark surroundings. Subsidence calculations from recently drained peatlands, e.g. the Swedish studies, are regarded as useful to predict the development of cultivated peat in the present and future Forsmark area. Fen peat is the most commonly cultivated peat type due to a high nutrient status and in the Forsmark region fen peat dominated by *Carex* and *Bryales* has historically been frequently used for cultivation.

4 Peat accumulation and succession of wetlands in northern Uppland

The patterns in peat accumulation and mire succession of wetlands in northern Uppland were studied using data from SGUs peat archive. In the study the properties of drained and cultivated mires were distinguished from undrained mires and the general patterns in peatland development for these two groups were evaluated together with patterns in peat accumulation. This is of interest for understanding the properties of peatlands in the future landscape and the nature of possible future peatlands used for cultivation. The results from this study can be used for estimating the peatland properties and peatland development in the future Forsmark area but also the consequences of possible future cultivation of these peatlands.

4.1 Data from SGUs Peat archive

SGUs peat archive comprises peat data that has been collected during a period of almost 100 years. The data gives information about the thickness and properties of peat but also contain information concerning, mire type, land use and composition of the vegetation and peat type. Most of the information is from the southern half of Sweden and was to a large extent made for evaluating the amount of peat available for energy production, but some studies were conducted to determine the possibility to drain peatlands for agriculture. This chapter demonstrates how peat data collected by SGU can be used to study the development of peatlands where the archive data was used to evaluate rates of peat accumulation, succession of young wetlands and the effects of cultivation of peatlands.

The most homogeneous data set in the SGU peat archive is the SGU line inventory (Figure 4-1), which was conducted in 1917–1923 with the purpose to quantify the peat resources in Sweden (von Post and Granlund 1926). Most of the data from the line inventory is in the form of hand written field diaries, field maps and sections through peatlands (Figure 4-2 and Figure 4-3).

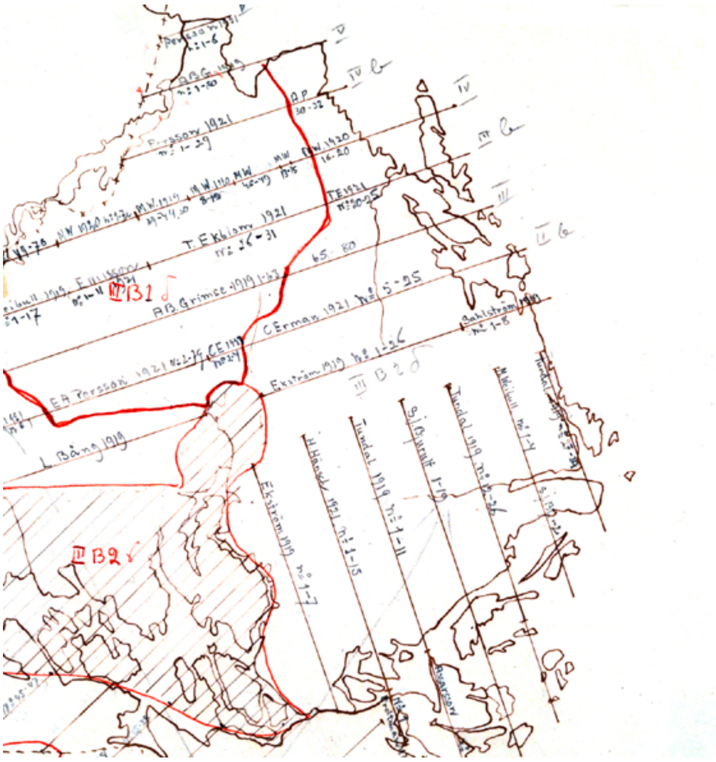
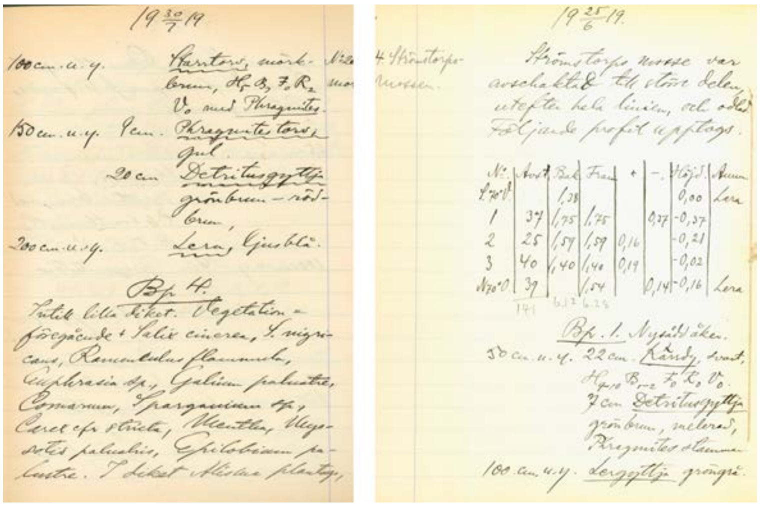


Figure 4-1. An overview of inventory lines in Uppland surveyed between 1917 and 1923 in order to quantify the areal coverage and quality of peat in the southern part of Sweden (von Post and Granlund 1926).



19$\frac{30}{7}$19

100 cm. u.y. Starrtorv, mörkbrun, H_5 B_3 F_0 R_2 V_0 med Phragmites.

150 cm. u.y. 9 cm. Phragmitestorv, gul

20 cm Detritusgyttja grönbrun – rödbrun,

200 cm. u.y. Lera, Ljusblå.

Bp. 4.

Inuti lilla diket. Vegetation = föregående + Salix cinerea, S. nigricans, Ranunculus flammula, Euphrasia sp., Galium palustre, Comarum, Sparganium sp., Carex cfr stricta, Mentha, Myosotis palustris, Epilobium palustre. I diket Alisma plantago,

19$\frac{25}{6}$19.

4. Strömstorps-mossen.

Strömstorps mosse var avschaktad till större delen utefter hela linien, och endast följande profil upptogs.

Nº.	Avst.	Bak	Fram	+	–.	Höjd.	Anm.
S70°V.		1,38				0,00	Lera
1	37	1,75	1,75		0,37	-0,37	
2	25	1,57	1,59	0,16		-0,21	
3	40	1,40	1,40	0,19		-0,02	
N70°O.	39		1,54		0,14	-0,16	Lera

141 6,12 6,28

Bp. 1. Nysådd åker.

50 cm. u.y. 22 cm. Kärrdy, svart, H_{9-10} B_{1-2} F_0 R_0 V_0.

7 cm Detritusgyttja grönbrun, melerad, Phragmitesstammar.

100 cm. u.y. Lergyttja gröngrå.

Figure 4-2. Examples of field diary notes from the line inventory of peat, which was carried out 1917–1923 (von Post and Granlund 1926). This diary was written by Martin Ekström in 1919 and shows results from a peatland in Uppland. The surveyor describes the vegetation and peat stratigraphy (left) and the distance between the cored sites and their relative height difference (right).

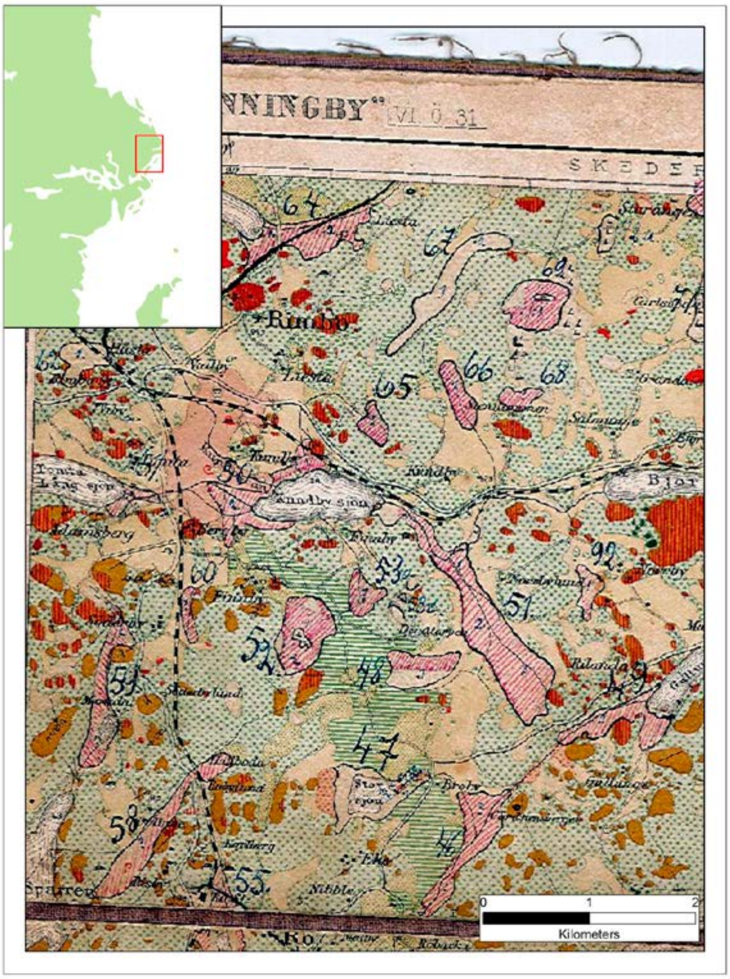


Figure 4-3. An example of a field map from the SGU qualitative peat survey 1917–1923. Each studied peatland is marked with a number and a handmade raster. Results from that survey were used in the present study for evaluating the relationship between peatland age and peat thickness. The map shows some of the peatlands in Uppland from which data is presented in this report. The studied peat areas are marked on SGUs map of bedrock and Quaternary deposits from the late 19th century.

The advantage of this material is the well described methodology (von Post and Granlund 1926) and the standardized investigation procedures, including information on peat properties as well as vegetation and land-use, which gives the possibility to compare the present conditions with the conditions in the early 1900s. The classification of peat types was done in the field by identifying the plant remains building up the peat. In some cases the plant remains were identified with microscope. The peat types were denoted according to a system described by von Post and Granlund (1926)

Recent studies have shown that the data from the line inventory has a high quality and that it is possible to identify sites that were sampled almost 100 years ago (James 2010, Schoning et al. 2012, Lundgren and Modig 2013). These studies conclude that some of the sites investigated during the line inventory have changed into drier and more nutrient-rich condition peatlands, during the last 90 years. Furthermore, the peat thickness was reduced during that period most likely due to peat compaction as a consequence of wetland drainage.

4.2 The studied area

The studied area (Figure 4-4) is situated in the province of Uppland, eastern middle Sweden, which is characterized by a flat bedrock surface intersected by narrow valleys. The county was completely covered by the Baltic Sea after the last deglaciation, taking place c. 11,000 years ago. As a consequence of the disappeared pressure from inland ice there is a resilience of the land surface position indicated by successive land uplift since the deglaciation (Påsse and Andersson 2005). That is an ongoing process and at present the land is rising with a rate of 5–6 mm each year. Due to the flatness of the landscape the land area is rapidly increasing and new peatlands have been continuously formed.

The highest topographical areas are dominated by till and exposed bedrock, whereas the lower areas are dominated by fine grained water laid deposits, which in some areas are covered by peat (Persson 1985, 1986). Peatlands of the area are often small and bogs tend to be covered with pine forest. A large proportion of the county is situated at low altitudes, especially close to the coast, and the wetlands in these areas are consequently young (Schoning 2014).

The glacial clay and till along the coast of northern Uppland area are rich in $CaCO_3$, which during the glaciations was transported to the area from a limestone area existing at the floor of the Bothnian Sea (Persson 1985, 1986). The chemistry and vegetation in many wetlands are affected by the presence of lime, and many of the wetlands along the coast are characterized as rich fens.

4.3 Material and methods

In this study, data from the peat archive has been used to investigate pathways of peatland succession. The data was also used to compare peat thickness and peat types with the ages of the wetlands. Data from altogether 138 peatlands located in the north-eastern parts of Uppland was used (Figure 4-4, Appendix 2). Additional data (18 sites) from a recent study, was also used (Schoning 2014). In that study carbon accumulation in young coastal mires of northern Uppland was evaluated. That was done by comparing results from radiocarbon dates with peat thickness. The peatlands in the data-set are on distances from 50 km northwest to 100 km south of Forsmark (Figure 4-4) and at an altitude between 1.5 and 60.5 metres above sea level (m.a.s.l.). That represents a time span of isolation from the Baltic Sea from c. 300 BP (BP = before present) to almost 8000 BP. A flow chart demonstrating the key components that were used for a model illustrating peat accumulation in the Uppland area is shown in Figure 4-5.

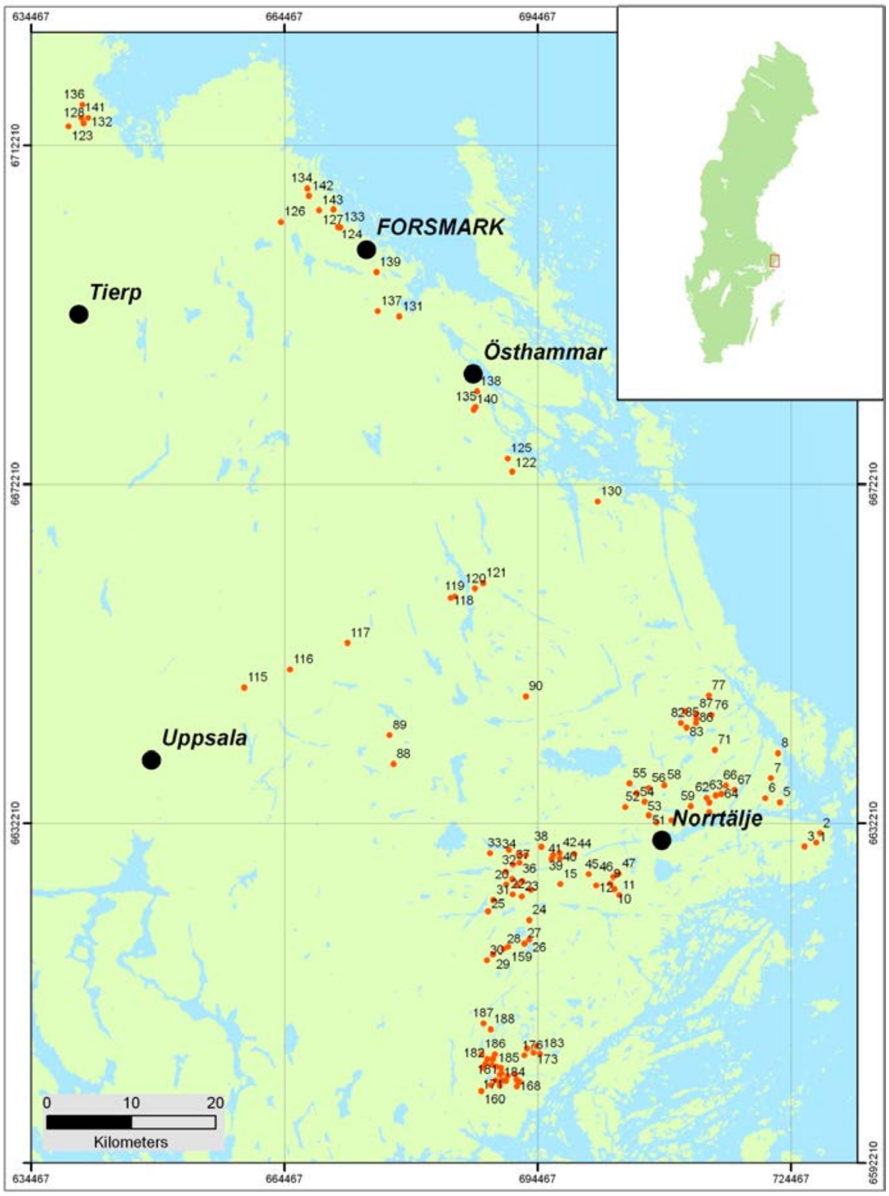


Figure 4-4. Geographical location of sites with data from SGUs surveys studied in the early 20th century, and used in this report. The majority of the sites are situated along the coastal area of Uppland at altitudes below 30 metres above sea level. The sites found close to Forsmark and Östhammar as well as the sites north of Tierp were sampled in a recent study (Schoning 2014). Sites 115–121, north east of Uppsala, were first sampled during the SGUs line survey 90 years ago, but were recently revisited and sampled by James (2010).

4.3.1 Processing of archive data

The initial phase of the work was to digitalize material from the SGU line inventory, a task that partly was carried out within a student work (Lundgren and Modig 2013). Information on peat stratigraphy, peat properties and land-use were transferred from the field diaries to excel sheets. The peat properties and stratigraphy provided information on peatland development and peat depth (Figure 4-5). Based on the information from the diaries the sites were classified into different peatland types (Figure 4-5) with preferences on peatland vegetation (e.g. pine bog, tall-sedge fen), peatland formation (terrestrialization, paludification and primary peat formation) and land-use and influence on peatland hydrology (e.g. cultivated, pristine, intensively ditched). The positions of the investigated sites were identified by comparing the field maps (Figure 4-3) with modern maps. The original field maps were rectified into a geographical information system (GIS) (ESRI 10.0) and points that were used to mark out each coring site on the original map were superimposed onto the GIS map. SGUs modern maps of Quaternary deposits were used to confirm the occurrence of peat at the earlier investigated sites. The identified peatlands were represented in the GIS map as point shape files (Figure 4-4).

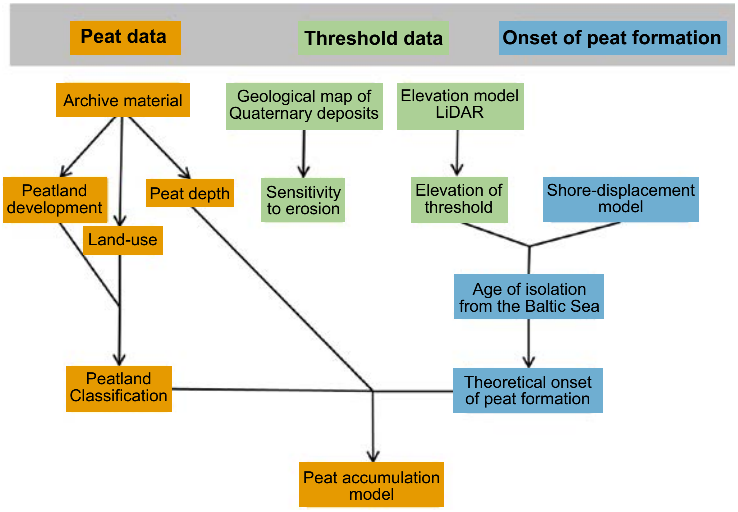


Figure 4-5. *Flow chart showing the three main components for a model illustrating peat accumulation; peat data, threshold data and onset of peat formation essential to know for developing the peat accumulation model for the study area. The threshold data describes the properties and altitude of the thresholds, which are found at the outlets of the peatland.*

4.3.2 Defining the basin threshold level

The altitudes of the peatlands basin threshold were defined as the threshold over which the outflow from the peatland occurs. This altitude corresponds to the level at which the peatland was isolated from the Baltic Sea due to the isostatic land upheaval. The threshold level for each site were determined using a raster file from Lantmäteriets National Elevation Model (NNH 2 m), based on laser data (LiDAR), that visualize elevation information to a horizontal resolution of 2 m and a vertical error of only ±0.2 m. This high resolution allows a measurement of the altitude of threshold with a high precision for each peatland (Figure 4-7). At many sites the thresholds have been eroded during and after the isolation from the Baltic Sea. SGUs maps of Quaternary deposits were therefore used for controlling the presence of erosion-sensitive soils at the threshold, which indicates the occurrence of erosion after isolation. The altitude of the thresholds at the time of isolation was determined after estimating how deep water courses have eroded the thresholds.

4.3.3 Determining the onset of peat formation

The identified threshold level was further transferred into a calendar age for the isolation of the peatland basin from the Baltic Sea using SGUs model for shoreline displacement (Påsse and Andersson 2005) (Figure 4-6). The shoreline displacement curve is mainly based on ages determined from radiocarbon dates. Since the concentration of ^{14}C in the atmosphere has varied through time the radiocarbon ages have been calibrated to correspond to true years (calendar years). The age of a threshold represents the age when a certain wetland or lake was isolated from the Baltic Sea and gives a maximum age for the onset of peat accumulation. However at some sites peat accumulation was preceded by a lake stage and peat accumulation started consequently some time after the sites were isolated from the Baltic Sea. Furthermore, peat accumulation could to some extent have been initialized already in shallow bays of the Baltic Sea.

4.3.4 Determining peatland initiation type

Peat which is underlain by gyttja is interpreted as having formed in wetlands proceeded by a lake stage, i.e. these wetlands have formed by terrestrialization. That interpretation is based on the fact that gyttja is commonly deposited in lakes. Peat underlain by other deposits is interpreted as having formed due to primary peat initiation or paludification. Sites with a very low peat depth relative to the age of the peatland threshold have been assigned to as have been formed through paludification. These wetlands have commonly woody peat as the lowermost peat, indicating relatively dry conditions before the onset of peat formation. A large proportion of the studied peat layers formed in wetlands through primary peat initiation and paludification are underlain by clay gyttja/gyttja clay. These deposits are commonly deposited in bays of the Baltic Sea, and indicate that the wetlands have not been preceded by a lake stage. Clay gyttja is often occurring in the lowest topographical area where the groundwater table is situated close to the ground, something that can initiate peat formation. The other wetlands formed through primary peat initiation and paludification are underlain by glacial or postglacial clay, which was deposited at the floor of the Baltic Sea thousands of years before peatland initiation.

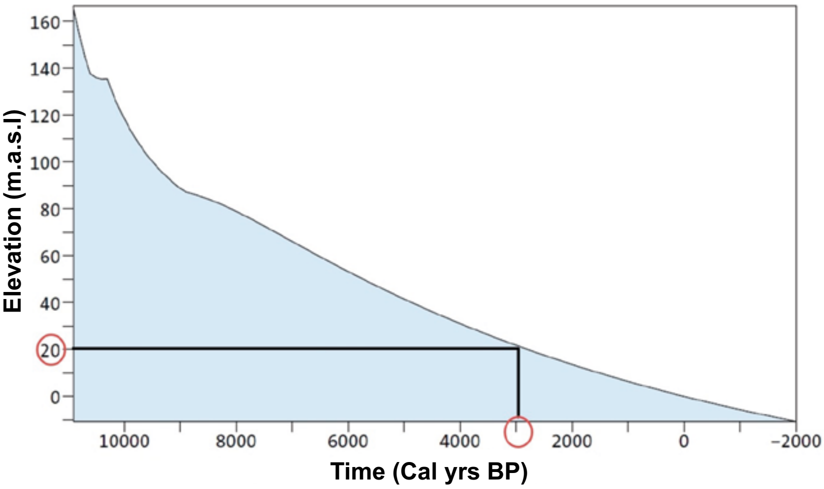


Figure 4-6. *The curve shows the shoreline displacement in northern Uppland. The blue area in the figure delimits the altitude (m a. s. l.) above the present sea level which was situated below the Baltic Sea surface since the time of deglaciation until present. Shortly after the deglaciation the shoreline was situated more than 150 m above the present sea level and Uppland was consequently completely covered by water. Note that the curve also predict the shoreline displacement during the forthcoming 2,000 years. An example of determining the theoretical time for onset of peat formation is shown in the figure. In this example a peatland with a threshold level of 20 m a. s. l. was isolated from the Baltic Sea approximately 2900 calendar years BP.*

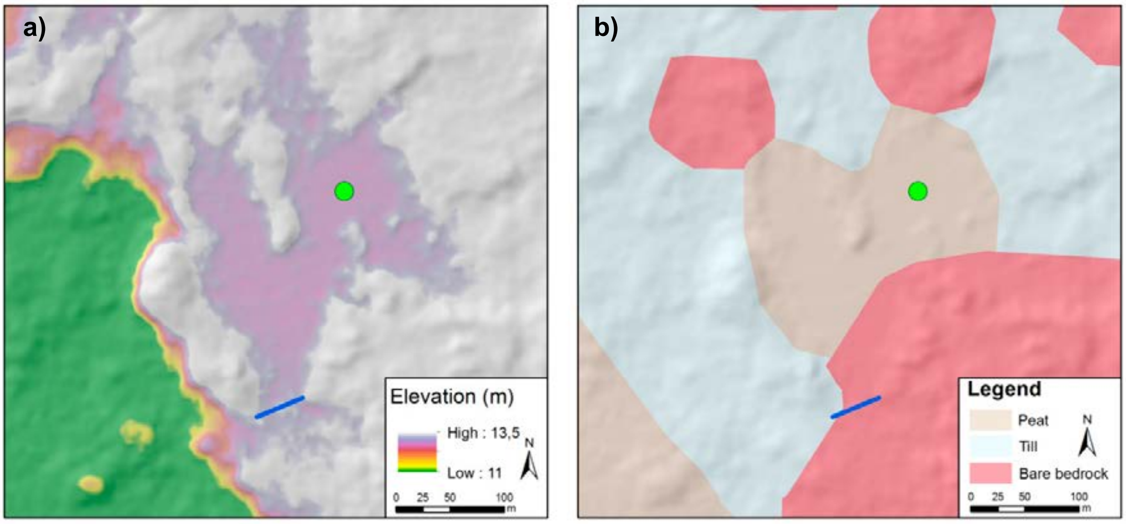


Figure 4-7. *a) The altitude of the thresholds for the peatlands was determined with the New National Elevation Model (NNH 2 m) from Lantmäteriet. The blue line represents the identified threshold for the peatland. The elevation is expressed as the level above the present sea level. It was possible to determine when the threshold was uplifted above the sea by using a shoreline displacement curve (Figure 4-6, Påsse and Andersson 2005). b) SGUs map of Quaternary deposits for the same peatland. The green point represents the site investigated by SGU during the early 20th century. The cored sites are often situated in the central parts of the peatlands (brown colour). The threshold shown here is situated in an area dominated by bare bedrock and till and has probably not been affected by erosion. However, the map of Quaternary deposits shown above is presented in a much smaller scale than intended when the map was produced. The delineation of bare bedrock and peat does therefore not completely correspond with the actual occurrence of these constituents, which is obvious when comparing with the NNH data.*

4.4 Results and discussion

Data from in total 156 mires in Uppland (Figure 4-4) were studied and a main part of the data is from SGUs line inventory performed in the 1910s and 1920s. A minor part of the data (18 sites) is from a recent study on young mires (500–2,500 years old) in the northern part of Uppland (Schoning 2014). The data was used for determining the general characteristics of the peatlands, the properties of the peat and the wetland successions. The data was also used to make a model for peat accumulation rates and to study the effects of cultivation.

4.4.1 Properties of the non-cultivated mires

Altogether 76 of the 156 mires sampled during SGUs line inventory were regarded as not being used for cultivation neither today or when the mires were investigated in the early 1900s. However most of these mires are not entirely pristine and unaffected by human activities today but are to a various degree affected by ditching. A major part of this drainage of the landscape was made during the mid to late 1900s due to extensive forestry activities. Thus, most of the data used here was collected before this period of extensive ditching reflecting a situation with more limited human impact. This interpretation is also supported by the results in James (2010) and Schoning et al. (2012) who compared the peatland properties of today with data from the line inventory.

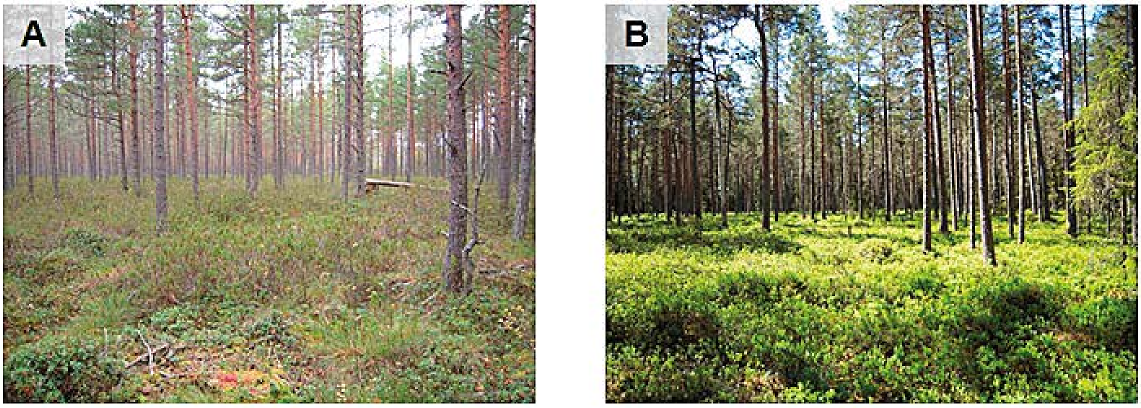
The mires in the data-set are of highly variable types but a general picture is that relatively young mires situated at an altitude equal to an age of 1,500 years or less reflect different types of fen environments while older peatlands situated at higher altitudes are of both bog and fen types. Typical examples of mire environments in the non-cultivated mires are illustrated in Figure 4-8. The mean peat depth in the data-set is around 140 cm for the non-cultivated peatlands (Table 4-1). This rather low medium peat depth is a consequence of the young age of the wetlands which mainly have formed during the last few thousand years, but is probably also affected by the climatic setting, where the rather low annual precipitation does not favour intense peat growth.

The fens of younger age are mainly of wetter types with either an open vegetation of *Carex* (Sedge) and *Sphagnum* (moss) or *Carex* and *Bryales* (moss). Additionally fens with a high proportion of *Phragmites* (reed) are known from the coastal areas of Uppland (Löfgren 2010). Fens older in age are often characterised by drier conditions and sometimes have tree layer vegetation, mainly alder and birch. The bog types in the data-set are to a high extent presently covered with pine forest and have a dense dwarf shrub vegetation of *Rhododendron tomentosum* (Labrador tea) and/or different species of *Vaccinium sp*. Some of the bogs were visited in 2011 or 2012 and all show up a dry bog surface and most of them are affected by recent forestry activities and ditching (Schoning et al. 2012).

4.4.2 Peatland initiation of the non-cultivated mires

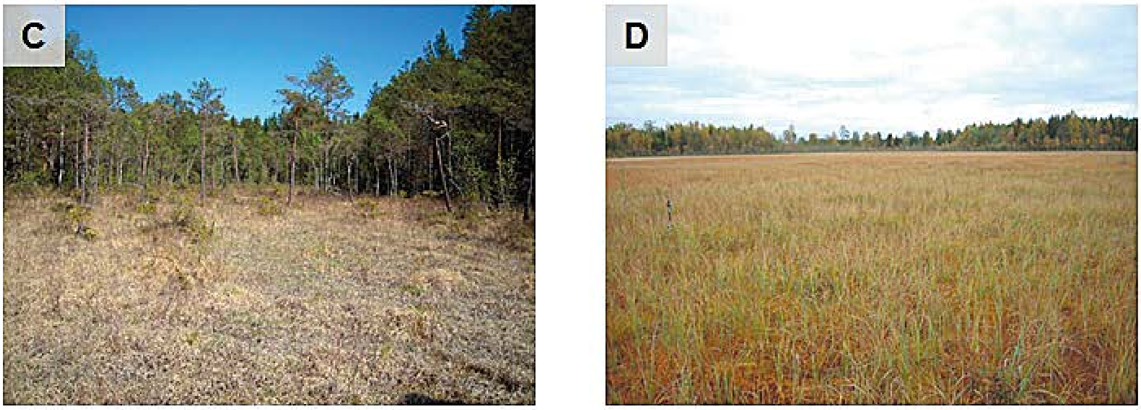
About an equal number of the non-cultivated peatlands in the data-set were formed through primary peat initiation and paludification as through terrestrialization (Table 4-1). This is in accordance with results presented by von Post and Granlund (1926) but with somewhat higher values for the group primary peat initiation and paludification. This can possibly be explained by the fact that the term primary peat initiation not was used by von Post and Granlund (1926) and peatlands underlain by clay gyttja/gyttja clay (i.e. sediments that have deposited in bays of the Baltic Sea), might have been interpreted as sites preceded by a lake stage.

It is somewhat difficult to distinguish peatlands formed through primary peat initiation from those formed through paludification. There is however a cluster of peatlands with a rather low peat depth situated at altitudes that were isolated from the Baltic Sea between 6,000 and 3,500 yrs ago (Figure 4-10). The low peat thicknesses in these peatlands indicate that the peat started to form much later than would have been the case if peat accumulation started directly when the sites emerged from the Baltic Sea. At these sites the accumulation of peat would thus have been initiated at a later stage through paludification. These sites more often contain woody sedge peat than the sites formed through primary peat formation. Paludification is further discussed below.



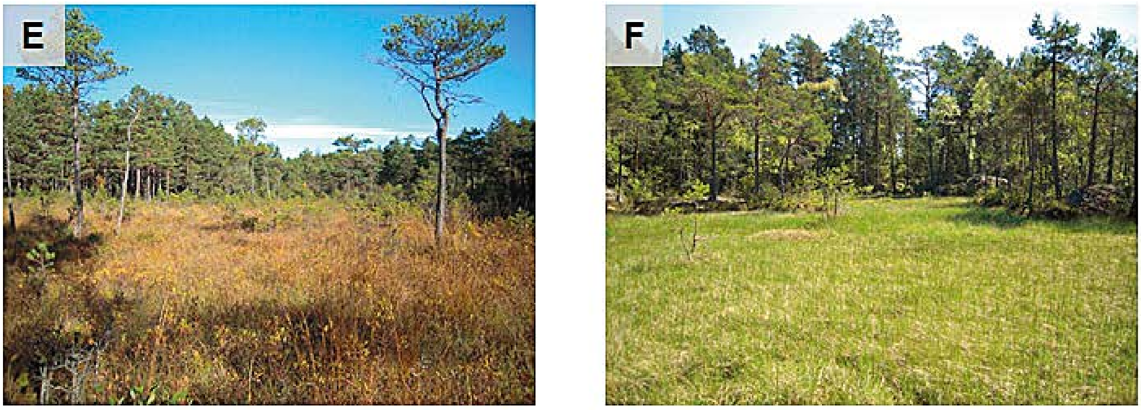
Pine bog with a dominance of Rhododendron tomentosum and a relatively dry surface with accumulation of Sphagnum peat.

Pine bog with dwarf shrub vegetation dominated by Vaccinium myrtillus and with a dry surface with accumulation of Sphagnum peat.



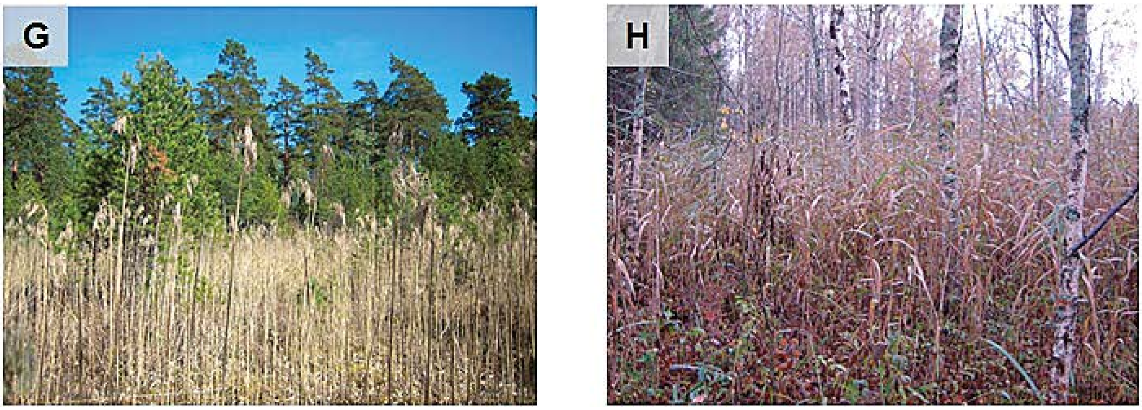
Bryales – Carex fen with a moderately wet surface with accumulation of Bryales-Carex peat

Carex – Sphagnum fen with a very wet surface with accumulation of Carex-Sphagnum peat



Carex-Bryales fen with Myrica gale and a very wet surface with accumulation of Carex-Bryales peat.

Carex fen with a wet surface with accumulation of Carex peat.



Phragmites-Sphagnum fen with pines and a moderately wet surface with accumulation of Phragmites-Carex peat.

Birch fen with Phragmites and Filipendula ulmaria and moderately wet surface with accumulation of woody sedge peat

Figure 4-8. *Examples of different mire environments with typical vegetation at some of the studied sites in the north-eastern Uppland (Photos, Kristian Schoning/SGU).*

Table 4-1. Properties of studied non-cultivated peatlands.

	Primary peat initiation and paludification*	Terrestrialization
Number of sites	37	39
Mean depth of peat (cm)	141	139
Mean threshold age	3,400	3,170
Type of peat (upper layer)		
Bryales-Carex	2	1
Woody Sedge	14	4
Carex	6	19
Sphagnum	15	11
Phragmites		3
Highly decomposed peat		1

*10 of these sites were considered as formed through paludification.

4.4.3 Succession of the peatlands

When considering typical successions and development of the peatlands in the data-set there are some major pathways present. In Figure 4-9 the presence of typical mire environments, as indicated by the peat stratigraphies, are shown and the thickness of the arrows in the figure is proportional to the number of peatlands in the data-set following a specific path. In Appendix 2 the peat successions and ages of the studied wetlands are shown. Accumulation of *Sphagnum* peat is the final stage of the successions, but due to the young age of the landscape most wetlands have not reached that stage. As the successions in the mires are highly dependent on local factors, the network of developmental paths is complex. However some major pathways can be distinguished. It should be noticed that even though all pathways in Figure 4-9 ends with *Sphagnum* peat this does not necessary imply that all mires will reach an ombrotrophic stage.

About an equal amount of the sites in the data-set were formed through primary peat initiation or paludification as through terrestrialization. Notable is that none of the peatlands formed through primary peat initiation or paludification were directly underlain by till or other coarse sediments but were all underlain by glacial clay or clay gyttja. The peatlands formed through primary peat initiation were mainly underlain by clay gyttja indicating initiation of peat formation directly after shallow bays of the Baltic Sea appeared above the sea-level. Only a few sites were clearly assigned to paludification. Paludification may, however, cause a significant increase in the future areal coverage of peatlands in Uppland. Franzén et al. (2012) has made calculations indicating that a large proportion of the landscape in the future may be covered with peat assuming a wetter climate. Even though these calculations include large uncertainties it is plausible that wetter conditions may cause large lateral expansion of peatlands in the flat landscape of Uppland which is characterised by a high proportion of clays with low permeability. The sites that were interpreted to have been formed through paludification were all initiated by wetlands with an alder/birch fen stage, an example of this environment is seen in Figure 4-8 H. That peat type indicates that initiation of peat accumulation in drier environments compared with the sites formed through primary peat initiation. In similar geological settings of young age in Finland the proportion between the different initiation processes indicate that 60% of the mires were formed through primary peat initiation and only 10% through terrestrialization (Huttunen and Tolonen 2006).

For the sites formed through terrestrialization there are only a few mires that have a phase with *Phragmites* (Figure 4-8 G). The presence of *Phragmites* is though probably underestimated in this study (Figure 4-9) because *Phragmites* is often present together with *Carex* in the early fen stages. Peat accumulating in such environments often contains remnants of *Phragmites* but is often classified as *Carex* peat. Furthermore, most sampling points are situated in the centre of the peatlands where *Phragmites* peat is less common compared to the borders of the basin.

The two far most common path of succession in the data-set is an initial *Carex* phase (Figure 4-8 C–F) followed by an ombrotrophication with a dominance of *Sphagnum* mosses (Figure 4-8 A–B)(Figure 4-9). The other common developmental path starts with a birch/alder fen environment (woody sedge peat) followed by *Bryales* or *Carex* and finally ombrotrophication with *Sphagnum* mosses. The wetlands in this region with accumulation of *Sphagnum* peat is characterized by pine forest (Figure 4-8 A–B), and are still in an early stage of bog formation, and can in some cases be regarded as nutrient-poor fens.

Most of the peatlands in the data-set have not reached far in their succession and are only in early stages of different fen environments. This is a consequence of the young age of the peatlands in the area and is reflected in Figure 4-9 by the thinning of the arrows upwards in the figure. Most of the peatlands are today in a stage/environment dominated by *Carex* either in an open fen environment or together with birch and alder. Only a limited number of the peatlands has reached an ombrotropic setting dominated by *Sphagnum*. The tendency in the development is towards less nutrient rich environments and this is the classical development of mires, that ultimately ends in a bog. This kind of development of the mires has also been recorded in Finland (Huttunen and Tolonen 2006).

The exact timing of the succession pathways illustrated in Figure 4-9 is difficult to determine. As mentioned above bog peat with *Sphagnum* peat is only found in wetlands which has been uplifted for at least 1,500 years (Figure 4-10). It is therefore suggested that it takes at least that time for a wetland to reach its final stage with *Sphagnum* peat accumulation (Figure 4-9). However, sites with that peat type can probably be found locally in nutrient-poor fens of younger age. It can also be concluded that during the forthcoming thousands of year most of the studied peatlands will be covered with *Sphagnum* peat. Furthermore the ombrotrophication of the mires presently covered by *Sphagnum* peat will continue and the surface of the bogs will consequently continue to rise.

The results presented in Figure 4-9 indicate that an initial mire formation with *Bryales* is not a very common path. However, fens initiated by accumulation of *Bryales* peat are probably more common in reality since fens dominated by *Bryales* together with *Carex* are frequent along the coast today (Schoning 2014). One reason for the expected underestimation of *Bryales* peat, in the young wetlands studied here, is that highly humified peat is often only assigned to as fen peat in diaries from the Line inventory. In our reclassification we have put this type of peat into the *Carex* path.

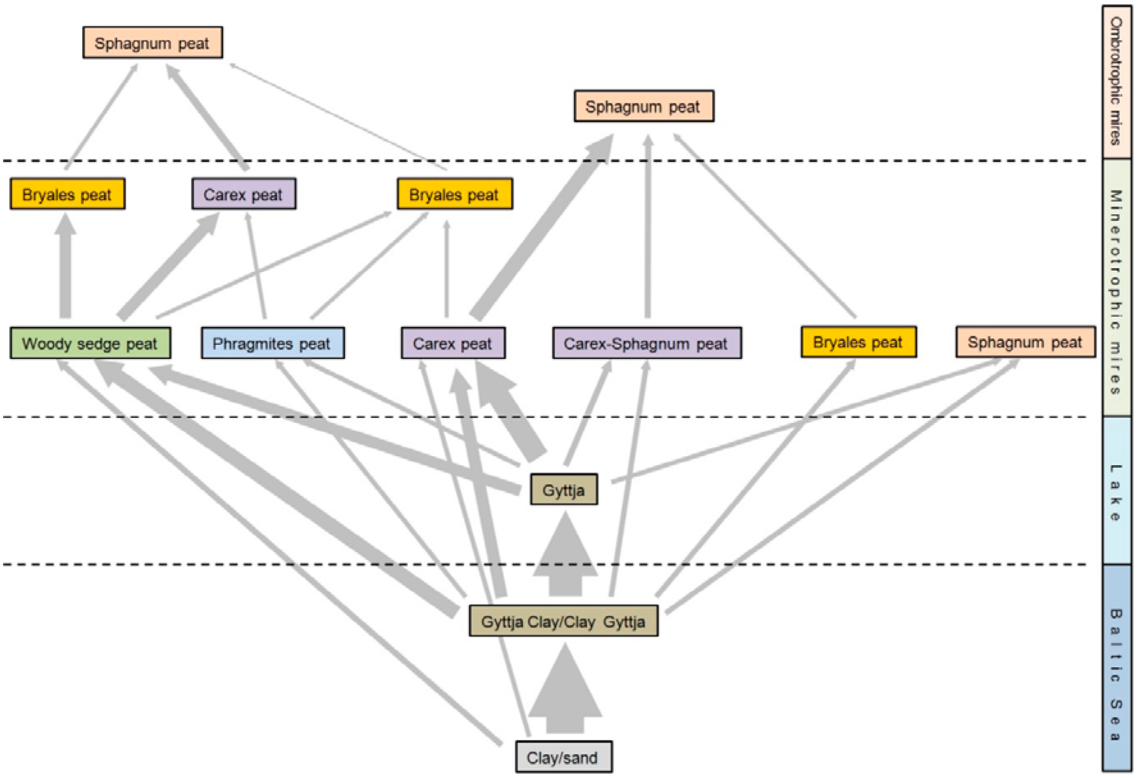


Figure 4-9. *The registered peatland succession in the data-set (both pristine and cultivated peatlands, Appendix 2). The thickness of the arrows in the figure is proportional to the number of peatlands following a specific path. As can be seen a large proportion of the peat is formed after a lake stage with gyttja accumulation, but primary peat initiation and paludification on other fine grained deposits are also commonly occurring. The arrows are generally thinner in the upper parts of the figure reflecting that many wetlands are in an early stage of succession.*

However, some of that peat is probably consisting of a combination of both *Carex* and *Bryales*. The vegetation in the most initial phase of mires in land uplift areas of Finland is dominated by different *Carex* species (Havas 1967). The presence of *Bryales* far up in the development of the mires is a consequence of the, compared to Finland, high nutrient level with high pH in the Uppland coastal area. The conditions specific for the area studied here is the presences of lime in the soils surrounding many of the wetlands, which causes a high pH in many fens. That lime is, as mentioned above, emanates from a limestone area situated at the floor of the Bothnian Sea north of the studied area.

4.4.4 A model for the peat accumulation rate

As earlier described the theoretical earliest time for the onset of peat initiation was calculated by determining the age of isolation from the Baltic Sea, using the shore displacement model by Påsse and Andersson (2005) together with the altitude of the threshold of the basin where the peat is accumulating. By combining this theoretical highest age for the peatland with the total peat depth from the stratigraphical information an empirical function for peat accumulation in the investigation area was developed. This empirical model describes the general pattern of peat accumulation over time in the peatlands of the area but does not take into account peatland type and effects of changes in climate.

Only peatlands without a preceding lake stage and clearly not affected by ditching was used in order not to bias the relationship using sites with a delayed onset of peat formation due to the presence of a lake stage. The best fit of the data is achieved with a slightly convex peat accumulation model (Figure 4-10) indicating a higher peat accumulation rate during the earlier stages of the mire development compared with the later stages in the development. This pattern is supported by radiocarbon dates from mires in northern Uppland (Schoning 2014). Younger peatlands in the area of Uppland thus have a higher rate to peat accumulation 0.5 to 1.3 mm /year compared with peatlands of a higher age which generally have accumulation rate around 0.5 mm/yr. It should be noted that these values represent the average rates since the onset of peat accumulation.

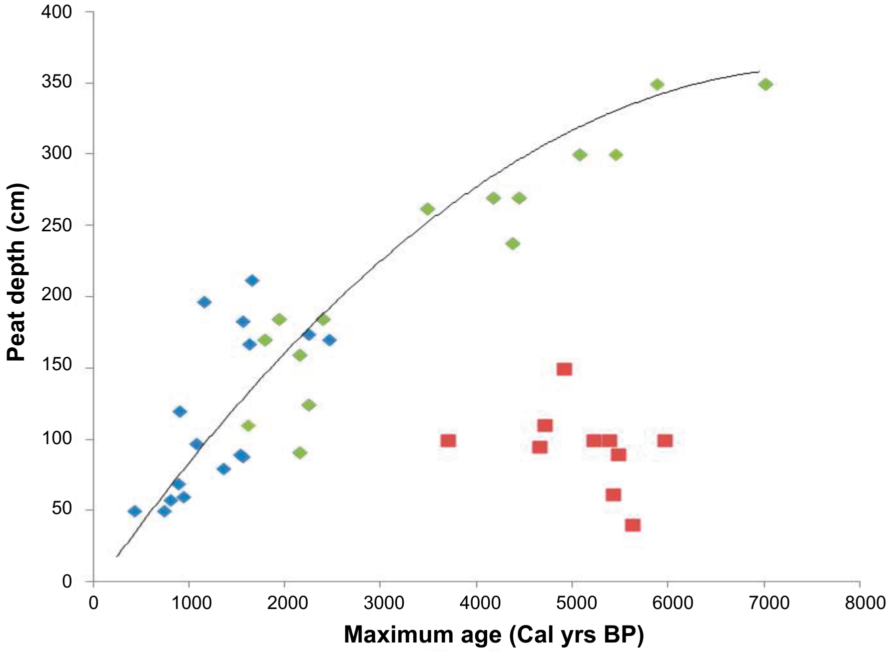


Figure 4-10. *Diagram showing the peat depth as a function of threshold age in peatlands unaffected by draining activities. At all sites the peat is interpreted to have formed through primary peat initiation or paludification. The blue data points represent mires formed through primary peat initiation when the mires were emerged from the Baltic Sea and green diamonds represents peatlands formed through primary peat initiation with Sphagnum as top peat layer. Data represented by the blue and green points were used for making the peat accumulation model which is illustrated by the black line. The red data points are interpreted as representing mires formed through paludification long after the sites emerged from the Baltic Sea.*

The rate of accumulation at a certain point in time differs from that value. This is in concordance with what has been recorded in fens but also bogs situated in a more continental setting (cf. Yu et al. 2009). The highest accumulation rate in peatlands is recorded from the mires youngest in age. That is evident in Figure 4-11 where the accumulation rate expressed as total peat thickness divided by the age of the mire (blue curve) clearly demonstrates high rates of peat accumulation in the youngest wetlands. The actual rate of peat accumulation for each time slice of 50 years is also show in Figure 4-11, and this curve shows a linear decrease in accumulation rate with time. The initial period with high accumulation is due to formation of a loose peat, which is not compacted. After this initial phase there is a steady decline in peat accumulation partly due to compaction but mainly due to reduced rate of peat formation, and height increment of peat ceases when a mire reach an age of 8,000 years. The mire studied here have, however, not yet reached the stage of ceased peat formation. Peat accumulation can of course proceed for longer periods if the future climate changes. The reason for the decreased accumulation rate with increasing age could be an effect of the climate setting in the area of Uppland is rather continental and the bogs present in the area have dry surface where the present peat accumulation probably is low. The effect of this climate setting would thus also be that when the peat column grows in thickness there will be limited possibilities for the mire to withstand a high water level and the peat growth will slow down due to higher decomposition rates. The decreased increment rate may also be partly due to weight compaction of the increasing peat column.

The peat accumulation model achieved here gives a probable picture of how the pattern of peat accumulation through time generally looks like in the peatlands of Uppland. In more detail the pattern of peat accumulation rate over time is more complex as climate changes over time and different development paths of peatlands occurs. Schoning (2014) has studied the rate of peat accumulation in the study area after interpreting results from ^{14}C dated peat cores. The results indicate higher rates of accumulation in *Sphagnum* peat compared to fen peat. The mean peat accumulation rate for peatlands dominated by *Sphagnum* peat is 1.0 ± 0.39 mm/yr (mean ± SD) and 0.89 ± 0.30 mm/yr for peatlands dominated by fen peat. This is somewhat higher than recorded from data in the peat archive but the interpretations from radiocarbon ages are based on less data and these sites are all young in age. The mean accumulation rate for correspondingly young wetlands from the peat archive is 0.82 ± 0.10 mm/yr thus very similar to the radiocarbon dated fens.

One possible distinguishable climate effect on the formation of peat in the investigation area is the fact that several peatlands situated at an altitude corresponding to an age of isolation from the Baltic Sea between c. 7000 BP and 3500 BP have thinner peat layers than predicted by the peat accumulation curve (Figure 4-10). All of these peatlands are interpreted as formed through paludification without a preceding lake stage and probably long time after the sites emerged from the Baltic Sea.

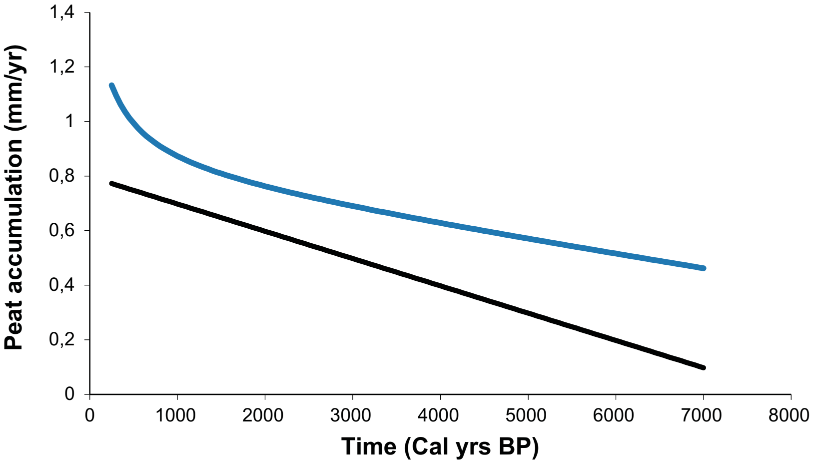


Figure 4-11. *Diagram showing two different aspects of the peat accumulation rate as a function of peatland age. The black straight line shows the derivative (* $\frac{\Delta y}{\Delta x}$ *) of the function f(age) = y(peat depth) shown in Figure 4-10. The derivative gives the accumulation rate for every 50 year time slice and show up a decreasing trend and the model suggests that the peat accumulation ceases at 8000 yrs BP. The blue line represents the* $f(x) = \frac{\text{total peat thickness}}{\text{Peatland age}}$ *and shows a highest peat accumulation rate > 1.1 mm/yr during the earliest stage of mire development.*

Initiation by paludification is supported by an initial stage with accumulation of woody sedge peat. It is thus possible that the climate during the period when these land areas emerged from the Baltic Sea was unfavourable for peat formation and when a climate change occurred peat started to form at these places. A similar period with limited peatland initiation has been recorded in southern Finland across the Baltic Sea during approximately the same time period (6500 and 4000 BP) (Korhola 1996) and a drier and warmer climate compared to the present conditions prevailed during this period of time in northern Europe (cf. Wanner et al. 2008).

4.4.5 The carbon accumulation

Accumulation rate of peat expressed as mm yr^{-1} is not the only factor of interest when it comes to peat accumulation, but the rate of carbon accumulation is also of interest. In a recent study of young mires in the Forsmark area the average accumulations since initiation of peat formation (long-term carbon accumulation rate) was estimated from some radiocarbon dated sites (Schoning 2014). The youngest mires in this study have a lower carbon accumulation rate than the mires of higher age (1,000–2,000 cal yrs old) but for the oldest sites in this study (older than 2,000 years) the carbon accumulation decreases again. There are only three mires older than 2,000 years included in the study by Schoning (2014) and it is consequently difficult to use the results from that study alone for making conclusions regarding the accumulation rates for carbon in mires older than 2,00 years. However, in Finland the Long-term apparent rate of carbon accumulation (LORCA) has been determined for more than thousand of mires (Turunen et al. 2002). That study shows that LORCA decreases from values of 30–40 g C m^{-2} yr^{-1} to 20 g C m^{-2} yr^{-1} after 2,000–3,000 years of peat accumulation which is in line by the resuls from the mires in the Forsmark area studied by Schoning (2014).

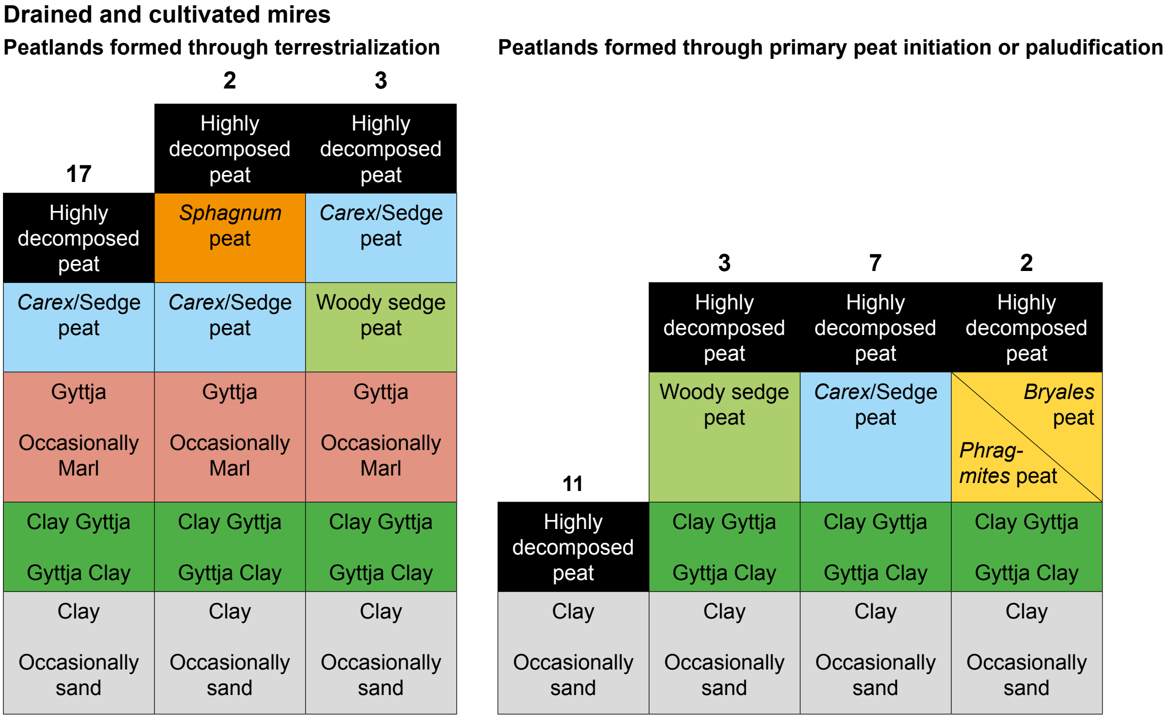
For the mires studied by Schoning (2014) the pattern of the carbon accumulation stands in contrast to peat accumulation expressed as mm/yr. The initial phase of the peatland development is characterized by a high peat accumulation rate (mm yr^{-1}), while the carbon accumulation is rather low (c. 20 g C m^{-2} yr^{-1}) during this period. This is an effect of the very low density of this initial peat which is reflected by a low rate of carbon accumulation. The following phase with higher carbon accumulation (c. 40 g C m^{-2} yr^{-1}) can probably be assigned to more favourable conditions for peat preservation: high water level but lower oxygen influence and still good nutrient status. The decrease of the carbon accumulation at the oldest sites is a consequence of drying up of the peat surface when the peat column grows and there will be limited possibilities for the mire to withstand a high water level and the peat growth will slow down due to higher decomposition rates. Here the anaerobic decay in the catotelm also can have an effect on the long term carbon accumulation.

4.4.6 Properties of the cultivated peatlands

In the data-set 45 sites were clearly identified as cultivated peatlands when they were investigated in the early 1900s. The main part of these cultivated peatlands are situated at rather low elevations and were isolated from the Baltic Sea during the last 4,000 years. The mean peat depth in the cultivated mires was 90 cm (Table 4-2) when they were investigated in the early 1900s and peat depths larger than 150 cm were rare. As in the case of the non-cultivated peatlands there is an even distribution between peatlands formed through primary peat initiation and paludification and peatlands with a preceding lake stage (Table 4-2).

The classification of the uppermost peat was used to determine during which stage in the wetland succession the peatlands were cultivated. The absolute majority of the cultivated peatlands has not reached a bog stage in their succession, when claimed for agricultural purposes. The cultivated sites were instead preceded by different types of fen stages. The uppermost peat layers at the cultivated sites was made up by different type of sedge peat but also highly decomposed peat not possible to classify was commonly occurring (Table 4-2).

The successions of the cultivated peatlands are fairly similar to the pattern of the non-cultivated peatlands. In Figure 4-12 typical mire environments, as indicated by the peat stratigraphies, are shown. Cultivated peatlands formed through terrestrialization generally have relatively large peat depth (Table 4-2) and these peatlands occasionally show up more stages in their development compared to the peatlands formed through primary peat initiation and paludification. Notable is that none of the cultivated peatlands are directly underlain by till but are underlain by different types of clay or gyttja.



Drained and cultivated mires

Peatlands formed through terrestrialization

17	2	3
	Highly decomposed peat	Highly decomposed peat
Highly decomposed peat	*Sphagnum* peat	*Carex*/Sedge peat
Carex/Sedge peat	*Carex*/Sedge peat	Woody sedge peat
Gyttja Occasionally Marl	Gyttja Occasionally Marl	Gyttja Occasionally Marl
Clay Gyttja Gyttja Clay	Clay Gyttja Gyttja Clay	Clay Gyttja Gyttja Clay
Clay Occasionally sand	Clay Occasionally sand	Clay Occasionally sand

Peatlands formed through primary peat initiation or paludification

11	3	7	2
	Highly decomposed peat	Highly decomposed peat	Highly decomposed peat
	Woody sedge peat	*Carex*/Sedge peat	*Bryales* peat *Phragmites* peat
Highly decomposed peat	Clay Gyttja Gyttja Clay	Clay Gyttja Gyttja Clay	Clay Gyttja Gyttja Clay
Clay Occasionally sand	Clay Occasionally sand	Clay Occasionally sand	Clay Occasionally sand

Figure 4-12. *The peatland succession in the cultivated peatlands. The deposits are successively younger towards the top of each column. In the generalization of environments peat consisting of carex only and peat with a high carex-content (sedge peat) are grouped together. Each column represents one path of succession. The numbers of peatlands following each developmental path are shown at the top of each column. Around half of the cultivated peatlands have been preceded by a lake stage (Terrestrialization), which is indicated by the presence of lake sediments (Gyttja) below the peat. Marl is gyttja with a high content of* $CaCO_3$.

Table 4-2. The properties of the cultivated peatlands, which were investigated during SGUs Line survey 90 years ago. The sites characterized as terrestrialization were preceded by a lake stage, whereas the peat at the other sites was initiated in wetlands with no former lake stage. The uppermost peat is highly decomposed at all the studied sites, and it was assumed that the decomposed peat corresponds to underlying peat. At 11 sites there was no other peat type below the highly decomposed peat layer.

	Primary peat initiation and paludification	**Terrestrialization**	**All sites**
Number of sites	23	22	45
Mean depth of peat (cm)	71	110	90
Mean threshold age	3,400	2,840	3,130
Type of peat (uppermost layer)	**No.**	**No.**	**No.**
Phragmites	1		1
Bryales	1		1
Woody Sedge	3	3	6
Carex/Sedge	7	17	24
Sphagnum		2	2
Highly decomposed peat	11		11

The cultivated peatlands in this study have a mean size of c. 32 ha but there is a wide size distribution. Most of the cultivated peatlands are between 10 and 50 ha (Figure 4-13). In comparison with the pristine mires the cultivated sites are generally larger and the pristine mires in the data-set rarely exceed 25 ha. The reason for this is that the pristine mires often fill up minor basins in forested areas while the cultivated peatlands are associated to the larger flat areas with fine grained sediments suitable for cultivation. The smallest cultivated peatlands are thus situated in association to fine grained sediment and it is possible that these peat areas have been larger but have decreased in size due to oxidation caused by the farming activities.

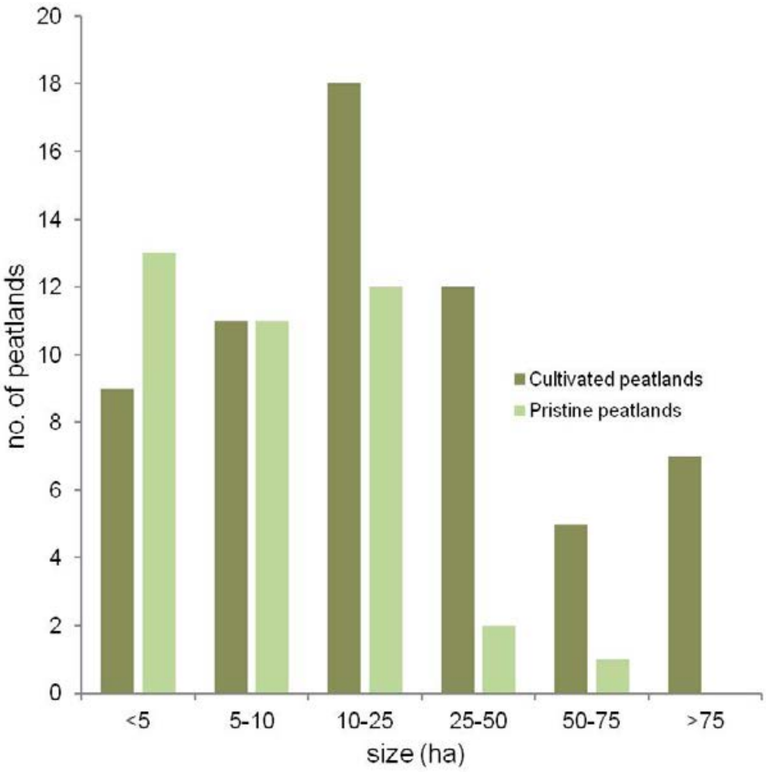


Figure 4-13. *Size distribution of the peatlands that either are used for cultivation or are unaffected by draining activities. The cultivated peatlands are generally larger in size while the pristine mires rarely exceed 25 ha in size.*

4.4.7 Indications of compaction and oxidation of peat

The relationship between the age of the isolation of the peat basins and the depths of peat at the cultivated sites are illustrated in Figure 4-14. The black line represents the expected peat accumulation in unaffected mires at the studied sites (Figure 4-10). All of the cultivated sites are situated to the right of this line showing that they have a smaller peat depth than they should have in unaffected peatlands where the peat has accumulated since the isolation from the Baltic Sea. This implies that the peat at these sites have compacted and oxidized as an effect of cultivation. These processes are explained and discussed in Chapter 3. Some of the cultivated sites had peat depths below 50 cm although the sites were isolated several thousand years ago. However, some of the cultivated peatlands had similar peat depth as the unaffected mires of the same age possibly reflecting that the threshold level was not correctly identified or that the peat depth was overestimated in the line inventory survey. Peatland used for cultivation has threshold that has been affected by human activities in connection with the drainage of the wetland and the correct altitude of the threshold can therefore be hard to determine. Furthermore, in some diaries from the line inventory material, many sites underlain with gyttja have had their peat depth adjusted to lower values after peat samples were analyzed in the laboratory (Schoning 2014). The sites with peat depths larger than expected are all underlain by gyttja and it is possible that coarse detritus gyttja have been interpreted as peat at these sites which thus give too high peat depths.

Oxidation of peat is a fast process (cf. Chapter 3) and a few of the peatlands cultivated 90 years ago are not peatlands any more according to SGUs modern map of Quaternary deposits. The peat has thus oxidized during the almost 100 years since the sites were investigated in the line inventory. Instead the map shows clay or gyttja clay but sometimes there is some peat areas left associated to these cultivated land. Schoning et al. (2012) has revisited a few peatlands that were cultivated during the line inventory and found that the peat had decreased in thickness with 19–45 cm since the line inventory in the early 1900s, some of these sites were, however; not used for cultivation today. At some sites peat was not present any more.

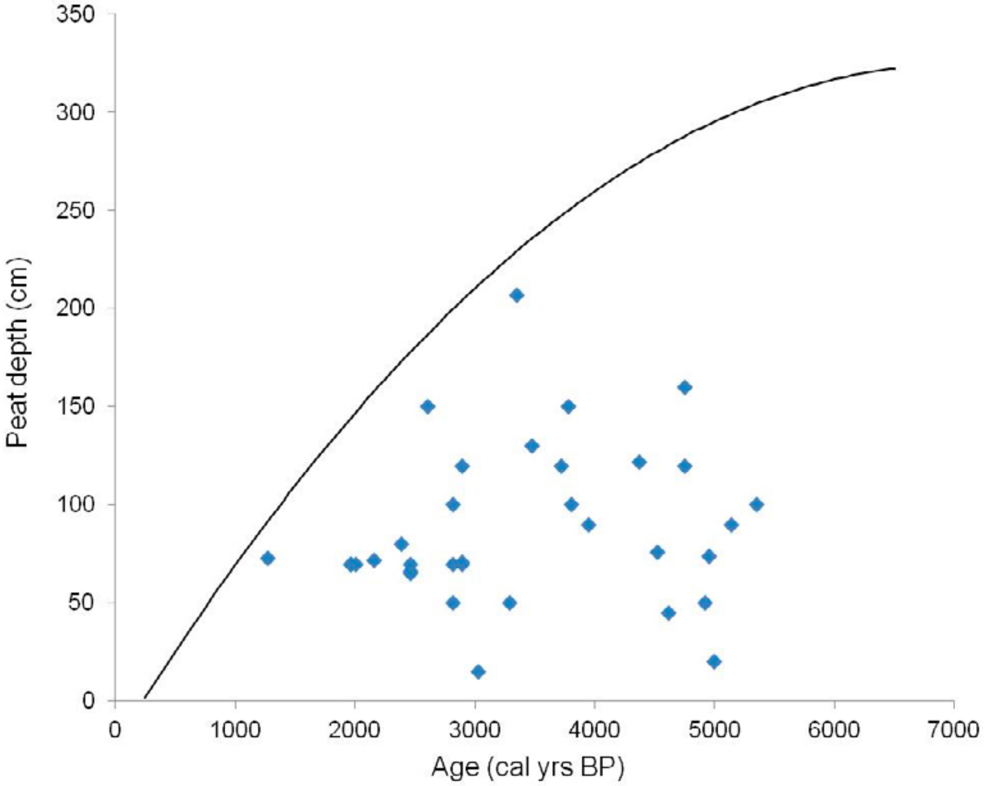


Figure 4-14. *Age–peat depth relationship of the sites used for cultivation. All cultivated sites has a peat thickness which is below the peat accumulation curve (black line) derrived from undrained wetlands (Figure 4-10). That difference is an effect of the subsidence taking place after draining peat for cultivation. The blue diamonds in the figure represents cultivated sites without preceding lake-stage.*

5 Conclusions

- The rate of peat accumulation in peatlands is dependent on the production of new organic material forming peat and the decay rate of that organic material, which in turn is controlled by factors such as type of vegetation, climate, nutrient status and hydrology.
- During the succession of mires the peat accumulation rate will change through time as vegetation, nutrient status, the height of the peat column and wetness changes. In a continental setting such as Uppland the peat accumulation initially is high but decreases with time.
- Peat areas used for cultivation in the surroundings of Forsmark are most often characterised by fen peat. Both data from literature and SGUs peat archive confirmed that cultivation of *Sphagnum* peat is uncommon in the area, and cultivation of bog peat has consequently not been common. The low proportion of cultivated *Sphagnum* peat can partly be explained by the relatively young age of the landscape, since that peat type is more commonly occurring in older wetlands.
- Subsidence is initially very fast in a peatland where the groundwater table has been lowered to facilitate cultivation. The rate of compaction decreases after a few years and oxidation becomes the dominating process causing subsidence. Peat oxidation in cultivated peat areas is a fast process which alone causes subsidence rates of between 0.5 and 1 cm/year. The most important factors affecting the oxidation rate during cultivation are depth of ditches, , type of peat and climate. Type of crop is an additional factor that may affect the oxidation rates.
- The study of data from SGUs peat archive shows that wetlands which are relatively old are often characterised by accumulation of *Sphagnum* peat, which has been proceeded by a stage with *Carex* peat accumulation. Approximately half of the studied peatlands have been preceded by a lake stage and in a third of the wetlands peat accumulation started through primary peat initiation directly after the sites were uplifted above the Baltic Sea. Only a minority of the sites were formed through paludification and in those peatlands peat accumulation probably started due to a change climate and was initiated long after the sites were uplifted.
- The data from the peat archive also revealed a clear connection between age of peatlands unaffected by land use and thickness of the peat layers. The rate of peat accumulation is in average between 0.5 and 1 mm/year. The fastest peat accumulation rates were recorded during the initial phases of the peatlands up to the age of c. 2,000 years. Thereafter the rate of peat accumulation decreases.
- Around half of the studied cultivated peatlands (from the peat archive) in Uppland were preceded by a lake stage and at the other sites with cultivated peat accumulation started in wetlands situated in the lowest topographical parts of the landscape, directly on marin sediments.
- The cultivated peatlands are all underlain by fine-grained sediments, which may be cultivated when the peat has completely oxidised. Some of the relatively large areas with cultivated fine grained postglacial sediments, in the present landscape, are most likely former wetlands that have been covered by peat.

References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at www.skb.se/publications.

Aerts R, Verhoeven J T A, Whigham D F, 1999. Plant-mediated controls on nutrient cycling in in temperate fens and bogs. Ecology 80, 2170–2181.

Aerts R, Wallén B, Malmer N, de Caluwe H, 2001. Nutritional constraints on Sphagnum-growth and potential decay in northern peatlands. Journal of Ecology 89, 292–299.

Agerberg L S, 1956. Brännbergsmyrens sättning. Uppsala. (Statens jordbruksförsök 77). (In Swedish.)

Agerberg L S, 1961. Några studier av nivåförändringar på myrjord. Grundförbättring 14, 141–176. (In Swedish.)

Armentano T V, Menges E S, 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. Journal of Ecology 74, 755–774.

Augustin J, 2001. Emission, Aufnahme und Klimarelevanz von Spurengasen. In Succow M, Joosten H (eds). Landschaftsökologische Moorkunde. 2nd ed.. Stuttgart: Schweizerbart'sche Verlagsbuchhandlung, 28–40.

Belyea L R, 1996. Separating the effects of litter quality and microenvironment on decomposition rates in patterned peatland. Oikos77, 529–539.

Belyea L R, Clymo R S, 2001. Feedback control of the rate of peat formation. Proceedings of the Royal Society B: Biological Sciences 268, 1315–1321.

Berg J, Jansson U, Wästfelt A, 2006. Landscape history and people in a geographical perspective. Studies of land-use, settlement and livehood in Oskarshamn and Forsmark. SKB R-06-37, Svensk Kärnbränslehantering AB.

Berglund K, 1989. Ytsänkning av mosstorvjord. Sammanställning av material från Lidhult, Jönköpings län. Report 89:3, Swedish university of Agricultural Sciences. Department of Soil Sciences. (In Swedish.)

Berglund K, 1996a. Cultivated organic soils in Sweden: properties and amelioration. Uppsala: Swedish University of Agricultural Sciences, Department of Soil Sciences. (Reports and dissertations 28)

Berglund K, 1996b. Agricultural improvement of cultivated organic soils II. Effects of liming and deep cultivation on soil properties and root development. Soil Use and Management 12, 176–180.

Berglund K, 2008. Torvmarker en resurs i jordbruket igår, idag och även imorgon? In Runefelt L (ed). Svensk mosskultur: odling, torvanvändning och landskapets förändring 1750–2000. Stockholm: Kungliga skogs- och lantbruksakademien, 483–498. (Skogs- och lantbrukshistoriska meddelanden 41.) (In Swedish.)

Berglund K, Miller U, Persson J, 1989. Gyttjejordar, deras sammansättning och egenskaper. The composition and properties of gyttja soils. Report 160, Swedish university of Agricultural Sciences, Department of Soil Sciences. (In Swedish.)

Berglund Ö, Berglund K, 2010. Distribution and cultivation intensity of agricultural peat and gyttja soils in Sweden and estimation of greenhouse gas emissions from cultivated peat soils. Geoderma 154, 173–180.

Berglund Ö, Berglund K, 2011. Influence of water table level and soil properties on emissions of greenhouse gases from cultivated peat soil. Soil Biology and Biochemistry 43, 923–931.

Berglund Ö, Berglund K, Sohlenius G, 2009. Organogen jordbruksmark i Sverige 1999–2008. Rapport 12, Swedish university of Agricultural Sciences, Department of Soil Sciences. (In Swedish.)

Berglund Ö, Berglund K, Klemedtsson L, 2010. A lysimeter study on the effect of temperature on CO_2 emission from cultivated peat soils. Geoderma 154, 211–218.

Bergström E, 2001. Late Holocene distribution of lake sediment and peat in NE Uppland, Sweden. SKB R-01-12, Svensk Kärnbränslehantering AB.

Borren W, Bleuten W, Lapshina E D, 2004. Holocene peat and carbon accumulation rates in the southern taiga of western Siberia. Quaternary Research 61, 42–51.

Botch M S, Kobak, K I, Vinson T S, Kolchugina T P, 1995. Carbon pools and accumulation in peatlands of the former Soviet Union. Global Biogeochemical Cycles 9, 37–46.

Brydsten L, 2004. A mathematical model for lake ontogeny in terms of filling with sediments and macrophyte vegetation. SKB TR-04-09, Svensk Kärnbränslehantering AB.

Brydsten L, Strömgren M, 2010. A coupled regolith-lake development model applied to the Forsmark site. SKB TR-10-56, Svensk Kärnbränslehantering AB.

Busby J R, Bliss L C, Hamilton C D, 1978. Microclimate control of growth rates and habitats of the boreal forest mosses, *Tomenthypnum nitens* and *Hylocomium splendens*. Ecological Monographs 48, 95–110.

Børsheim K Y, Christensen B E, Painter T J, 2001. Preservation of fish embedment in *Sphagnum* moss, peat or holocellulose: experimental proof of the oxopolysaccharidic nature of the preservative substance and of its antimicrobial and tanning action. Innovative Food Science & Emerging Technologies 2, 63–74.

Campbell I D, Campbell C, Yu Z, Vitt D H, Apps M J, 2000. Millennial-scale rhytms in peatlands in the western interior of Canada and in the global carbon cycle. Quaternary Research 54, 155–158.

Charman D, 2002. Peatland and environmental change. Wiley.

Clymo R S, 1984. The limits to peat bog growth. Philosophical Transactions of the Royal Society of London B 303, 605−654.

Clymo R S, Hayward P M, 1982. The ecology of *Sphagnum*. In Smith A J E (ed). Bryophyte ecology. London: Chapman and Hall, 229–289.

Clymo R S, Turunen J, Tolonen K, 1998. Carbon accumulation in peatland. Oikos 81, 368−388.

Couwenberg J, 2009. Emission factors for managed peat soils (organic soils, histosols): an analysis of IPCC default values. Ede, The Netherlands: Wetlands International.

Damman A W H, 1986. Hydrology, development and biogeochemistry of ombrogeneous peat bogs with specialreference to nutrient relocation in a western Newfoundland bog. Canadian Journal of Botany 64, 384–394.

Davidson E A, Janssens I A, 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.

Davis A M, 1984. Ombrotrophic peatlands in Newfoundland, Canada: their origins, development and trans-Atlantic affinities. Chemical Geology 44, 287–309.

Eggelsmann R, 1976. Peat consumption under influence of climate, soil condition and utilization. In Proceedings of the 5th International Peat Congress, Poznán, Poland, 21–25 September 1976. International Peat Society, 233–247.

Eggelsmann R, 1990. Wasserregulung im Moor. In Göttlich K (ed). Moor- und Torfkunde. 3rd ed. Stuttgart: Schweizerbart, 321–348. (In German.)

Eggelsmann R, Bartels R, 1975. Oxidativer Torfverzehr im Niedermoor in Abhängigkeit von Entwässerung, Nutzung und Düngung. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 22, 215–221. (In German.)

Franzén L G, Lindberg F, Viklander V, Walther A, 2012. The potential peatland extent and carbon sink in Sweden, as related to the Peatland / Ice Age Hypothesis. Mires and Peat 10. Availbale at: http://pixelrauschen.de/wbmp/media/map10/map_10_08.pdf

Fredriksson D, 2004. Forsmark site investigation. Peatland investigation Forsmark. SKB P-04-127, Svensk Kärnbränslehantering AB.

Freibauer A, Droesler M, Partners, 2012. Preliminary synthesis of carbon balance and GHG fluxes in managed German peatlands. In Proceedings of the 14th International Peat Congress, Stockholm, 3–8 June 2012. Abstract 362.

Frolking S, Roulet N T, Moore T R, Richard P J H, Lavoie M, Muller S D, 2001. Modeling northern peatland decomposition and peat accumulation. Ecosystems 4, 479–498.

Glenn S, Heyes A, Moore T, 1993. Carbon dioxide and methane fluxes from drained peat soils, southern Quebec. Global Biogeochemical Cycles 7, 247–257.

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

Gorham E, Janssens J A, Glaser H P, 2003. Rates of peat accumulation during the postglacial period in 32 sites from Alaska to Newfoundland, with special emphasis on northern Minnesota. Canadian Journal of Botany 81, 429–438.

Granlund E, 1932. De svenska högmossarnas geologi: deras bildningsbetingelser, utvecklinghistoria och utbredning jämte sambandet mellan högmossebildning och försumpning [Geology of Swedish raised bogs]. (Sveriges geologiska undersökning C 373) (In Swedish.)

Grigal D F, Buttleman C G, Kernik L K, 1985. Biomass and productivity of the woody strata of forested bogs in northern Minnesota. Canadian Journal of Botany 63, 2416–2424.

Grønlund A, Hauge A, Hovde A, Rasse D P, 2008. Carbon loss estimates from cultivated peat soils in Norway: a comparison of three methods. Nutrient Cycling in Agroecosystems 81, 157–167.

Gunnarson U, 2005. Global patterns of *Sphagnum* productivity. Journal of Bryology 27, 269–279.

Gunnarson U, Rydin H, 2000. Nitrogen fertilization reduces *Sphagnum* production in bog communities. New Phytologist 147, 527–537.

Havas P, 1967. Zur Ökologie der Laubwälder, insbesondere der Grauerlenwälder an der Küste der Bottenwiek. Aquilo. Ser. Botanica 6, 314–346.

Hedenström A, Sohlenius G, 2008. Description of the regolith at Forsmark. Site descriptive modelling, SDM-Site Forsmark SKB R-08-04, Svensk Kärnbränslehantering AB.

Hendriks D M D, van Huissteden J, Dolman A J, van der Molen M K, 2007. The full greenhouse gas balance of an abandoned peat meadow. Biogeosciences Discussions 4, 277–316.

Hilbert D W, Roulet N, Moore T, 2000. Modelling and analysis of peatlands as dynamical systems. Journal of Ecology 88, 230–242.

Hillebrand K, 1993. The greenhouse effects of peat production and use compared with coal, oil, natural gas and wood. VTT Tiedotteita – Meddelanden – Research Notes 1494, Technical Research Centre of Finland, Espoo, Finland.

Hjertstedt H, 1946. De organogena odlingsjordarnas beskaffenhet i olika län med avseende på torvslag, förmultningsgrad och reaktion samt innehåll av kalk och kväve, kali och fosforsyra, organisk substans, seskvioxider och svavelsyra. Svenska Vall- och Mossekulturföreningens kvartalsskrift, 255–277. (In Swedish.)

Hoogland T, van den Akker J J H, Brus D J, 2012. Modeling the subsidence of peat soils in the Dutch coastal area. Geoderma 171–172, 92–97.

Hutchinson J N, 1980. The record of peat wastage in the East Anglian fenlands at Holme Post 1848–1978 A.D. Journal of Ecology 68, 229–249.

Huttunen A, Tolonen K, 2006. Mire development history in Finland. In Lindholm T, Heikkilä R (eds). Finland: land of mires. (Finnish environment 23), 79–88.

Hytönen J, Aro L, Maljanen M, Mäkiranta P, Potila H, Laine J, Lohila A, Martikainen P, Minkkinen K, Pihlatie M, Shurpali N, 2007. The effect of afforestation of organic croplands and cutaway peatlands on greenhouse gas balance. In Sarkkola S (ed). Greenhouse impacts of the use of peat and peatlands in Finland. Research programme final report. Ministry of Agriculture and Forestry, Finland, 31–37.

Höper H, 2002. Carbon and nitrogen mineralization rates in German agriculturally used fenlands. In Broll G, Merbach W, Pfeiffer E-M (eds). Wetlands in Central Europe: soil organisms, soil ecological processes, and trace gas emissions. Berlin: Springer, 149–164.

Höper H, Blankenburg J, 2000. Emissionen klimarelevanter Gase aus niedersächsischen Mooren und Möglichkeiten der Reduzierung. NNA-Berichte 13, 110–117. (In German.)

Ilnicki P, 2002. Restoration of carbon sequestrating capacity and biodiversity in abandoned grassland on peatland in Poland. Poznán: August Cieszkowski Agricultural University.

Ilnicki P, Okruszko H, 2002. The moorsh horizons as quality indicators of reclaimed organic soils. In Parent L-E, Ilnicki P (eds). Organic soils and peat materials for sustainable agriculture. Boca Raton, FL: CRC Press, 1–14.

Ivitsky A I, 1975. Hydrological fundamentals of bog drainage. IAHS Publication 105, 97–108.

James A, 2010. Feasibility in using historical data to perceive changes in peatlands: changes in peatland's structure and vegetation over the past 91 years**.** Master's thesis. Physical Geography and Quaternary Geology, Stockholm University.

Johnson L C, Damman A W H, 1991. Species-controlled *Sphagnum* decay on a south Swedish raised bog. Oikos 61, 234–242.

Johnson L C, Damman A W H, 1993. Decay and its regulation in *Sphagnum* peatlands. Advances in Bryology 5, 249–296.

Joosten H, Clarke D, 2002. Wise use of mires and peatlands: background and principles including a framework for decision-making. Totnes: International Mire Conservation Group and International Peat Society.

Jurczuk S, 2000. Wpływ regulacji stosunków wodnych na osiadanie i mineralizację gleb organicznych [The influence of groundwater table management on subsidence and mineralization rate of organic soils]. Biblioteczka Wiadomości IMUZ 96. (In Polish.)

Kasimir-Klemedtsson Å, Klemedtsson L, Berglund K, Martikainen P, Silvola J, Oenema O, 1997. Greenhouse gas emission from farmed organic soils: a review. Soil Use and Management 13, 245–250.

Kasimir-Klemedtsson Å, Nilsson M, Sundh I, Svensson B, 2000. Växthusgasflöden från myrar och organogena jordar. Rapport 5132, Naturvårdsverket. (In Swedish.)

Kechavarzi C, Dawson Q, Leeds-Harrison P B, 2010. Physical properties of low-lying agricultural peat soils in England. Geoderma 154 196–202.

Klarqvist M, 2001. Peat growth and carbon accumulation rates during the Holocene in Boreal mires. PhD thesis. Swedish University of Agricultural Sciences, Umeå.

Kluge B, Wessolek G, Facklam M, Lorenz M, Schwärzel K, 2008. Long-term carbon loss and CO_2–C release of drained peatland soils in northeast Germany. European Journal of Soil Science 59, 1076–1086.

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. Initation of a sloping mire complex in southwestern Finland: autogenic *versus* allogenic controls. Ecoscience 3, 216–222.

Korhola A, Tolonen K, Turunen J, Jungner H, 1995. Estimating long-term carbon accumulation rates in boreal peatlands by radiocarbon dating. Radiocarbon 37, 575–584.

Korhola A, Tolonen K, 1996. The natural history of mires in Finland and the rate of peat accumulation. In Vasander H (ed). Peatlands in Finland. Helsinki: Finnish Peatland Society, 20–26.

Kremenetski K V, Velichko A A, Borisova O K, MacDonald G M, Smith L C, Frey K E, Orlova L A, 2003. Peatlands of the Western Siberian lowlands: current knowledge on zonation, carbon content and Late Quaternary history. Quaternary Science Reviews 22, 703–723.

Kuhry P, 1997. The palaeoecology of a treed bog in western boreal Canada: a study based on microfossils, macrofossils and physico-chemical properties. Review of Palaeobotany and Palynology 96, 183–224.

Kuhry P, Turunen J, 2006. The postglacial development of boreal and subarctic peatlands. In Wieder R K, Vitt D H (eds). Boreal peatland ecosystems. Berlin: Springer. (Ecological Studies 188), 25–46.

Kuhry P, Vitt D H, 1996. Fossil carbon/nitrogen ratios as a measure of peat decomposition. Ecology 77, 271–275.

Kuikman P J, de Groot W J M, Hendriks R F A, Verhagen J, de Vries F, 2003. Stocks of C in soils and emissions of CO_2 from agricultural soils in the Netherlands. Wageningen: Alterra – Research Institute for the Green World. (Alterra-rapport 561)

Kuntze H, 1992. Peat losses by liming and fertilization of peatlands used as grassland. In Fredriksson D (ed). Proceedings of the 9th International Peat Congress, Uppsala, Sweden, 22–26 June 1992, Vol 2, 306–314.

Kuzyakov Y, Friedel J K, Stahr K, 2000. Review of mechanisms and quantification of priming effects. Soil Biology and Biochemistry 32, 1485–1498.

Laiho R, 2006. Decomposition in peatlands: reconciling seemingly contrasting results on the impacts of lowered water levels. Soil Biology and Biochemistry 38, 2011–2024.

Laiho R, Laine J, Trettin C C, Finér L, 2004. Scots pine litter decomposition along drainage succession and soil nutrient gradients in peatland forests, and the effects of interannual weather variation. Soil Biology and Biochemistry 36, 1095–1109.

Lappalainen E (ed), 1996. Global peat resources. Jyskä, Finland: International peat society.

Lindborg T (ed), 2010. Landscape Forsmark – data, methodology and results for SR-Site. SKB TR-10-05, Svensk Kärnbränslehantering AB.

Lindborg T, Brydsten L, Sohlenius G, Strömgren M, Andersson E, Löfgren A, 2013. Landscape development during a glacial cycle: modeling ecosystems from the past into the future. Ambio 42, 402–413.

Loisel J, Garneau M, 2010. Late Holocene paleoecohydrology and carbon accumulation estimates from two boreal peat bogs in eastern Canada: potential and limits of multi-proxy archives. Paleogeography, Paleoclimatology, Paleoecology 291, 493–533.

Lundgren T, Modig E, 2013. Torvmarkernas utveckling i Östra Uppland. Självständigt arbete 65. Department of Earth Sciences, Uppsala University. (In Swedish.)

Löfgren A (ed), 2010. The terrestrial ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere. SKB TR-10-01, Svensk Kärnbränslehantering AB.

Löfgren A, 2011. Dissolved inorganic carbon and organic carbon in mires in the Forsmark area. A pilot study. SKB P-11-23, Svensk Kärnbränslehantering AB.

MacDonald G M, Beilman D W, Kremenetski K V, Sheng Y, Smith L C, Velichko A A, 2006. Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. Science 314, 285–288.

Mäkilä M, Saarnisto M, Kankainen T, 2001. Aapa mires as a carbon sink and source during the Holocene. Journal of Ecology 89, 589–599.

Maljanen M, 2003. Greenhouse gas dynamics of farmed or forested organic soils in Finland. PhD thesis. Department of Environmental Sciences, University of Kuopio, Finland.

Maljanen M, Komulainen V-M, Hytönen J, Martikainen P J, Laine J, 2004. Carbon dioxide, nitrous oxide and methane dynamics in boreal organic agricultural soils with different soil characteristics. Soil Biology and Biochemistry 36, 1801–1808.

Maljanen M, Hytönen J, Mäkiranta P, Alm J, Minkkinen K, Laine J, Martikainen P, 2007. Greenhouse gas emissions from cultivated and abandoned organic croplands. In Sarkkola S (ed). Greenhouse impacts of the use of peat and peatlands in Finland. Research programme final report. Ministry of Agriculture and Forestry, Finland, 27–30.

Maljanen M, Sigurdsson B D, Guðmundsson J, Óskarsson H, Huttunen J T, Martikainen P J, 2010. Greenhouse gas balances of managed peatlands in the Nordic countries – present knowledge and gaps. Biogeosciences 7, 2711–2738.

Maljanen M, Hytönen J, Mäkiranta P, Minkkinen, K, Laine J, Martikainen P J, 2012. Atmospheric impact of abandoned boreal organic agricultural soils depends on hydrology of peat. In Proceedings of the 14th International Peat Congress, Stockholm, 3–8 June 2012. Extended abstract 97.

Malmer N, Wallen B, 2004. Input rates, decay losses and accumulation rates of carbon in bogs during the last millennium: internal processes and environmental changes. The Holocene 14, 111–117.

Mc Afee M, 1984. Drainage of peat soils: a literature review. Report 143, Swedish University of Agricultural Sciences, Department of Soil Sciences.

Mc Afee M, 1985. The rise and fall of Bälinge mossar. Report 147, Swedish University of Agricultural Sciences, Department of Soil Sciences.

Meyer K, Höper H, Blankenburg J, 2001. Spurengashaushalt und Klimabilanz von Niedermooren unter dem Einfluß des Vernässungsmanagements. In Kratz R, Pfadenhauer J (eds). Ökosystemmanagement für Niedermoore: Strategien und Verfahren zur Renaturierung. Stuttgart: Ulmer, 104–111. (In German.)

Minkkinen K, Laine J, Penttilä T, 2007. Greenhouse gas emissions from forestry-drained peatlands and contributing environmental factors. In Sarkkola S (ed). Greenhouse impacts of the use of peat and peatlands in Finland. Research programme final report. Ministry of Agriculture and Forestry, Finland, 20–26.

Minkkinen K, Byrne K A, Trettin C, 2008. Climate impacts of peatland forestry. In Strack M (ed). Peatlands and climate change. Jyväskylä: International Peat Society, 98–122.

Moore T R, Basiliko N, 2006. Decomposition in Boreal peatlands. In Wieder R K, Vitt D H (eds). Boreal peatland ecosystems. Berlin: Springer. (Ecological Studies 188), 125–144.

Moore T R, Trofymow J A, Taylor B, Prescott C, Camiré C, Duschene L, Fyles J, Kozak L, Kranabetter M, Morrison I, Siltanen M, Smith S, Titus B, Visser S, Wein R, Zoltai S, 1999. Litter decomposition rates in Canadian forests. Global Change Biology 5, 75–82.

Moore T R, Dalva M, 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. Journal of Soil Science 44, 651–664

Mundel G, 1976. Untersuchungen zur Torfmineralisation in Niedermooren. Archiv fur Acker und Pflanzenbau und Bodenkunde 20, 669–679.

Mäkilä M, 1997. Holocene lateral expansion, peat growth and carbon accumulation on Haukkasuo, a raised bog in southeastern Finland. Boreas 26, 1–14.

Mäkilä M, Goslar T, 2008. The carbon dynamics of surface peat layers in southern and central boreal mires of Finland and Russian Karelia. Suo 59, 49–69.

Nieuwenhuis H S, Schokking F, 1997. Land subsidence in drained peat areas of the Province of Friesland, the Netherlands. Quarterly Journal of Engineering Geology and Hydrogeology 30, 37–48.

Norberg L, Berglund Ö, Berglund K, 2012. Migrating greenhouse gas emissions from cultivated organic soils, carrots, pastures, barely or potatoes? Which crop to choose? In Proceedings of the 14th International Peat Congress, Stockholm, 3–8 June 2012. Extended abstract 148.

Nykänen H, 2003. Sensitivity of CH_4 and N_2O dynamics in boreal peatlands to" anthropogenic and global change. Department of Environmental Sciences, University of Kuopio.

Nykänen H, Alm J, Lång K, Silvola J, Martikainen P J, 1995. Emissions of CH_4, N_2O and CO_2 from a virgin fen and a fen drained for grassland in Finland. Journal of Biogeography 22, 351–357.

Oldfield F, Thompson R, Crooks P R J, Gedye S J, Hall, Valerie A, Harkness D D, Housley R A, McCormac F G, Newton A J, Pilcher J R, Renberg I, Richardson N, 1997. Radiocarbon dating of a recent high latitude peat profile: Stor Amyran, northern Sweden. Holocene, 7, 283–290.

Oleszczuk R, Regina K, Szajdak L Höper H, Maryganova V, 2008. Impacts of agricultural utilization of peat soils on the Greenhouse gas balance. In Strack M (ed). Peatlands and climate change. Jyväskylä: International Peat Society, 70–97.

Osvald H, 1937. Myrar och myrodling. Stockholm: Kooperativa förbundets bokförlag. (In Swedish.)

Okruszko H, 1989. Wirkung der Bodennutzung auf die Niedermoorentwicklung. Ergebnisse eineslangjährigen Feldversuches. Zeitschrift für Kulturtechnik und Landentwicklung 30, 167–176.

Okruszko H, 1993. Transformation of fen-peat soils under the impact of draining. Zeszyty Problemowe Postepów Nauk Rolniczych 406, 3–73.

Ovenden L, 1990. Peat accumulation in northern wetlands. Quaternary Research 33, 377–386.

Painter T J, 1991. Lindow man, Tollund man and other peat-bog bodies: the preservative and antimicrobial action of sphagnan, a reactive glycoronoglycan with tanning and sequestering properties. Carbohydrate Polymers 15, 123–142.

Persson C, 1985. Jordartskarta 121 Östhammar NO med beskrivning. Geological survey of Sweden Ae 73. (In Swedish with English summary.)

Persson C, 1986. Jordartskarta 131 Österlövsta SO/13J Grundkallen SV med beskrivning. Geological survey of Sweden Ae 76. (In Swedish with English summary.)

Peteet D, Andreev A, Bardeen W, Mistretta F, 1998. Long-term Arctic peatland dynamics, vegetation and climate history of the Pur-Taz region, Western Siberia. Boreas 27, 115–126.

Prasad M, Verhagen J B G M, Aendekerk T G L, 2000. Effect of peat type and pH on breakdown of peat using Fourier Transform Infrared Spectroscopy. Communications in Soil Science and Plant Analysis 31, 2881–2889.

Påsse T, Andersson L, 2005. Shore-level displacement in Fennoscandia calculated from empirical data. GFF 127, 253–268.

Regina K, Myllys M, 2009. Mitigation of greenhouse gas fluxes from cultivated organic soils by raising water table. IOP Conference Series: Earth and Environmental Science 6, 242034. doi:10.1088/1755-1307/6/24/242034

Reicosky D C, Archer D W, 2007. Moldboard plow tillage depth and short-term carbon dioxide release. Soil and Tillage Research 94, 109–121.

Renger M, Wessolek G, Schwärzel K, Sauerbrey R, Siewert C, 2002. Aspects of peat conservation and water management. Journal of Plant Nutrition and Soil Science 165, 487–493.

Rundgren M, 2008. Stratigraphy of peatlands in central and northern Sweden: evidence of Holocene climatic change and peat accumulation. GFF 130, 95–107.

Runefelt L (ed), 2008. Svensk mosskultur: odling, torvanvändning och landskapets förändring 1750–2000. Stockholm: Kungliga skogs- och lantbruksakademien. (Skogs- och lantbrukshistoriska meddelanden 41) (In Swedish.)

Rydin H, Jeglum J, 2006. The biology of peatlands. Oxford: Oxford University Press.

Saarinen T, 1996. Biomass and production of two vascular plants in a boreal mesotrophic fen. Canadian Journal of Botany 74, 934–938.

Saetre P, Valentin J, Lagerås P, Avila R, Kautsky U, 2013. Land-use and food intake of future inhabitants: outlining a representative individual of the most exposed group for dose assessment. Ambio 42, 488–496.

Sarkkola S (ed), 2007. Greenhouse impacts of the use of peat and peatlands in Finland. Research programme final report. Ministry of Agriculture and Forestry, Finland.

Schoning K, 2014. Torvtillväxt och kolackumulation hos unga torvmarker i Uppland. SGU-rapport 2014:35, Sveriges geologiska undersökning, Uppsala. (In Swedish.)

Schoning K, James A, Sohlenius G, 2012. Recent changes in peat properties and vegetation in Swedish mires. In Proceedings of the 14th International Peat Congress, Stockholm, 3–8 June 2012.

Schothorst C J, 1977. Subsidence of low moor peat soils in the western Netherlands. Geoderma 17, 265–291.

Schuch M, 1977. Das Donaumoos und einige seiner gegenwärtigen Hauptprobleme. Telma 7, 167–173.

Segers R, 1998. Methane production and methane consumption: a review of processes underlying wetland methane fluxes. Biogeochemistry 41, 23–51.

Sheppard S, Long J, Sanipelli B, Sohlenius G, 2009. Solid/liquid partition coefficients (K_d) for selected soils and sediments at Forsmark and Laxemar-Simpevarp. SKB R-09-27, Svensk Kärnbränslehantering AB.

Sheppard S, Sohlenius G, Omberg L-G, Borgiel M, Grolander S, Nordén S, 2011. Solid/liquid partition coefficients (K_d) and plant/soil concentration ratios (CR) for selected soils, tills and sediments at Forsmark. SKB R-11-24, Svensk Kärnbränslehantering AB.

SKB, 2010. Biosphere analyses for the safety assessment SR-Site – synthesis and summary of results. SKB TR-10-09, Svensk Kärnbränslehantering AB.

SKB, 2011, Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB.

SKB 2014. Safety analysis for SFR. Long-term safety. Main report for the safety assessment SR-PSU. SKB TR-14-01, Svensk Kärnbränslehantering AB.

Stenberg M, 1936. ”Gissleåsmyrens sättning under tioårsperioden 1922–1932. Föredrag vid Svenska Mosskulturföreningens sammanträde den 20 mars 1935”. Utdrag ur Lantbruksveckans handlingar 1935, 173–191. (In Swedish.)

Sternbeck J, Land M, Nilsson Ö, 2006. Oskarshamn and Forsmark site investigations. ^{210}Pb and ^{14}C dating of sediments and peat. Accumulation rates of carbon, nitrogen and phosphorus. SKB P-06-301, Svensk Kärnbränslehantering AB.

Strack M (ed), 2008. Peatlands and climate change. Jyväskylä, Finland: International Peat Society..

Swanson D K, 2007. Interaction of mire microtopography, water supply, and peat accumulation in boreal mires. Suo 58, 37–47.

Svensson G, 1988. Bog development and environmental conditions as shown by the stratigraphy of Store Mosse mire in southern Sweden. Boreas 17, 89–111.

Szanser M, 1991. CO_2 diffusion from peat-muck soils. I. Dependence of diffusion on temperature, moisture content and origin of soil. Polish Ecological Studies 17, 85–99.

Szumigalski A R, Bayley S E, 1996. Net above-ground primary production along a bog-rich fen gradient in central Alberta, Canada. Wetlands 16, 467–476.

Thormann M N, Bayley S E, 1997. Aboveground net primary production along a bog-fen-marsh gradient in southern Boreal Alberta, Canada. Ecoscience 4, 374–384.

Thormann M N, Szumigalski A R, Bayley S E, 1999. Aboveground peat and carbon accumulation potentials along a bog-fen-marsh wetland gradient in Southern boreal Alberta Canada. Wetlands 19, 305–317.

Tolonen K, Turunen J, 1996. Accumulation rates of carbon in mires in Finland and implications for climate change. The Holocene 6, 171–178.

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

Turunen J, 2003. Past and present carbon accumulation in undisturbed boreal and subarctic mires: a review. Suo 54, 15–28.

Turunen J, Tahvanainen T, Tolonen K, Pitkänen A, 2001. Carbon accumulation in West Siberian mires, Russia *Sphagnum* peatland distribution in North America and Eurasia during the past 21,000 years. Global Biogeochemical Cycles 15, 285–296.

Turunen J, Tomppo E, Tolonen K, Reinikainen A, 2002. Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions. The Holocene 12, 69–80.

Valmari A, 1977. Torrläggningsfrågor på myrjordar. Nordisk Jordbrugsforskning 59, 640–641.

van Bellen S, Garneau M, Booth R K, 2011. Holocene carbon accumulation rates from three ombrotrophic peatlands in boreal Quebec, Canada: impact of climate-driven ecohydrological change. The Holocene 21, 1217–1231.

van den Akker J J H, Kuikman P J, de Vries F, Hoving I, Pleijter M, Hendriks R F A, Wolleswinkel R J, Simões R T L, Kwakernaak C, 2008. Emission of CO_2 from agricultural peat soils in the Netherlands and ways to limit this emission. In Farrell C, Feehan J (eds). After wise use: the future of peatlands: proceedings of the 13th International Peat Congress, Tullamore, Ireland, 8–13 June 2008. Jyväskylä: International Peat Society, 645–648.

van den Akker J J H, Jansen P C, Hendriks R F A, Hoving I, Pleijter M, 2012. Submerged infiltration to halve the subsidence and GHG emissions of agricultural peat soils. In Proceedings of the 14th International Peat Congress, Stockholm, 3–8 June 2012. Extended abstract 383.

van den Bos R M, 2003. Restoration of former wetlands in the Netherlands; effect on the balance between CO_2 sink and CH_4 source. Geologie en Mijnbouw 82, 10 325–10331.

van den Bos R M, van de Plassche O, 2003. Incubation experiments with undisturbed cores from coastal peatlands (western Netherlands): carbon dioxide fluxes in response to temperature and water-table changes. In van den Bos R M. Human influence on carbon fluxes in coastal peatlands; process analysis, quantification and prediction. PhD thesis. Vrije Universiteit, Amsterdam, 11–34.

van Huissteden J, van den Bos R, Alvarez M I, 2006. Modelling the effect of water-table management on CO_2 and CH_4 fluxes from peat soils. Geologie en Mijnbouw 85, 3–18.

Verhoeven J T A, Liefveld W M, 1997. The ecological significance organochemical compounds in *Sphagnum*. Acta Botanica Neerlandica 46, 117–130.

Verhoeven J T A, Toth E, 1995. Decomposition of *Carex* and *Sphagnum* litter in fens : effect of litter quality and inhibition by living tissue homogenates. Soil Biology and Biochemistry 27, 271–275.

Vitt D H, 1990. Growth and production dynamics of boreal mosses over climatic, chemical and topographic gradients. Botanical Journal of the Linnean Society 104, 35–59.

Vitt D H, Halsey L A, Bauer I E, Campbell C, 2000. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Canadian Journal of earth Sciences 37, 683–693.

von Post L, Granlund E, 1926. Södra Sveriges torvtillgångar 1. Stockholm. (Sveriges geologiska undersökning C 335)

Wanner H, Beer J, Bütikofer J, Crowley T J, Cubasch U, Flückiger J, Goosse H, Grosjean M, Joos F, Kaplan J O, Küttel M, Müller S A, Prentice I C, Solomina O, Stocker T F, Tarasov P, Wagner M, Widmann M, 2008. Mid- to Late Holocene climate change: an overview. Quaternary Science Reviews 27, 1791–1828.

Weinzierl W, 1997. Niedermoore in Baden-Würtemberg – Bilanzierung der CO2-Emission am Beispiel des Donaurieds, Mitteilungen der Deutschen Bodenkundlichen Gesellschaft, 85, 1059–1062.

Wessolek G, Schwärzel K, Renger M, Sauerbrey R, Siewert C, 2002. Soil hydrology and CO_2 release of peat soils. Journal of Plant Nutrition and Soil Science 165, 494–500.

Wieder R K, 2006. Primary production in boreal peatlands. In Wieder R K, Vitt D H (eds). Boreal peatland ecosystems. Berlin: Springer. (Ecological Studies 188), 145–164.

Yu Z C, 2006. Holocene carbon accumulation of fen peatlands in boreal western Canada: a complex ecosystem response to climate variation and disturbance. Ecosystems 9, 1278–1288.

Yu Z C, Vitt D H, Campbell I D, Apps M J, 2003. Understanding Holocene peat accumulation pattern of continental fens in western Canada. Canadian Journal of Botany 81, 267–282.

Yu Z C, Beilman D W, Jones M C, 2009. Sensitivity of northern peatland carbon dynamics to Holocene climate change. In Baird A J, Comas X, Slater L D, Belyea L R, Reeve A S (eds). Carbon cycling in northern peatlands. Washington, DC: American Geophysical Union. (Geophysical monograph 184), 55–69.

Zeitz J, Velty S, 2002. Soil properties of drained and rewetted fen soils. Journal of Plant Nutrition and Soil Science 165, 618–626.

Zoltai S C, Vitt D H, 1990. Holocene climatic change and the distribution of peatlands in western interior Canada. Quaternary Research 33, 231–240.

Zoltai S C, 1991. Estimating the age of peat samples from their weight: a study from west-central Canada. The Holocene 1, 68–73.

Zoltai S C, 1995. Permafrost distribution in peatladns of west-central Canda during the Holocene warm period 6000 years BP. Geographie physique et Quaternaire 49, 45–54.

Appendix 1

Table A1-1. The subsidence of peat at "Bälinge mosse" close to Uppsala in Sweden. The peatland was initial drained 1908 (from Mc Afee 1985).

	1908–1938		1938–1964		1964–1984		Totals	
Studied point	loss (cm)	cm/year	loss (cm)	cm/year	loss (cm)	cm/year	loss (cm)	cm/year
1	67	2.2	38	1.4	45	2.2	150	1.97
2	77	2.6	52	2.0	40	2.0	169	2.22
3	71	2.4	52	2.0	38	1.9	161	2.10
4	73	2.4	43	1.6	42	2.1	158	2.08
5	60	2.0	57	2.2	40	2.0	157	2.06
6	75	2.5	48	1.8	31	1.6	154	2.02
7	70	2.3	47	1.8	36	1.8	153	2.01
8	54	1.8	52	2.0	27	1.4	133	1.75

Table A1-2. Summary of the physical properties of the drained fen peat in "Bälinge mossar" (from Mc Afee 1985). It is clear that porosity increases and dry bulk density decreases with depth below the ground surface.

Area	Level (cm)	Bulk density, saturated (g/cm^3)	Bulk density, dry (g/cm^3)	Density of solids (g/cm^3)	Loss on ignition (%)	pH	Porosity (vol. %)
A	0–50	1.07	0.24	1.66	80.3	5.7	85.5
	50–100	1.18	0.21	1.58	87.0	5.4	86.1
B	0–50	1.08	0.24	1.56	83.6	5.5	83.3
	50–100	1.14	0.18	1.50	88.4	5.4	87.8
	100–150	1.12	0.14	1.49	86.3	5.4	90.7
	150–200	1.09	0.13	1.48	79.9	5.8	91.0
C	0–50	1.08	0.25	1.62	81.7	5.7	84.8

Table A1-3. Physical properties of cultivated peat in England (from Kechavarzi et al. 2010). The highest densities were found in the uppermost samples and can be explained by compaction and a high ash content. The restively high ash content in the uppermost samples is an effect of the ongoing oxidation of organic matter, which mainly take place in the uppermost soil horizon.

Study area	Sampling depth (m)	Soil type	Degree of humification	Organic content (%)	Organic content g/cm^3	Ash content g/cm^3	Dry bulk density g/cm^3	Porosity (cm^3/cm^3)
1	0–15	Peaty loam	–	39.0	17.1	26.8	0.44	0.72
1	35–50	Humified peat	H8	60.1	10.2	5.9	0.17	0.87
1	85–100	Semi-fibrous peat	H6	69.3	6.2	2.5	0.09	0.92
2	0–15	Amorphous peat	H10	67.3	23.6	11.4	0.35	0.80
2	35–50	Semi-fibrous peat	H5	80.1	12.0	3.0	0.15	0.87
2	85–100	Fibrous peat	H 2.5	80.5	9.6	2.3	0.12	0.86

Table A1-4. Physical properties of cultivated organic soils in Finland (from Maljanen et al. 2007). At many of these sites the deposits have dry bulk densities higher than the cultivated peat shown in other studies (e.g. Table A1-2, A1-3).

Site	C/N	Bulk density (g/cm^3)	pH (H_2O)	Peat depth (m)	Drainage (years ago)
1	21	0.49–0.51	5.8	Nd	100
2	16	0.33	6.0	0.2	40
3	19	nd	5.3	1.4	60
4	18	0.24–0.29	5.6	Nd	50
5a	31–32	0.32–0.50	4.8	0.3–0.7	Nd
5b	16–19	0.33–0.47	4.3–5.9	0.2–> 1.0	50–100

Table A1-5. A) Dry densities and B) porosity of undrained fen peat from the surroundings of the Forsmark site (Sheppard et al. 2009, Sternbeck et al. 2006, Löfgren 2011, unpublished data from a SGU-project). Data from *Sphagnum* peat was excluded since that peat type is not commonly cultivated. C) Porosity and dry density of peat used for cultivation in the surroundings of the Forsmark site (data from Sheppard et al. 2011).

A)

	Dry bulk density (kg/m^3)					
	N	**Average**	**Std**	**Min**	**Max**	**m.a.s.l.**
Rönningarna	7	102	26	70	152	11.5
Backbotten	4	119	25	94	148	29
L Hjortronmossen	1	136				13
Stenrösmossen	12	97	31	40	154	8.5
Labboträsk II	4	65	35	34	111	3–5
Labboträsk I	4	82	33	54	120	2.7
Average of the studied mires	6	100	25	65	136	

B)

	Porosity (m^3/m^3)				
	N	**Average**	**Std**	**Min**	**Max**
Rönningarna	4	0.92	0.02	0.90	0.94
Backbotten	4	0.90	0.02	0.88	0.93
L Hjortronmossen	1	0.90			
Stenrösmossen	4	0.90	0.01	0.88	0.90
Average of the studied mires	4	0.90	0.01	0.89	0.92

C)

Porosity (m^3/m^3)				
N	**Average**	**Std**	**Max**	**Min**
5	0.75	0.03	0.80	0.71
Dry bulk density (kg/m^3)				
N	**Average**	**Std**	**Max**	**Min**
5	274	39	320	220

Appendix 2

Table A-2. Data used in Section 4 for constructing the succession of wetlands in Uppland. All peat and sediment types are shown in the stratigraphy column. The column "Depth to" shows the depth to the lowest extension (below ground surface) of each deposit. The peat types were used to reconstruct the successions of the wetlands. "Age of isolation" shows when, in years before present (BP), each basin was isolated from the Baltic Sea. "Altitude of threshold" is the level of each basins threshold above the present sea level. Each basin was isolated from the Baltic Sea when the sea level was situated at that altitude. All coordinates (east and north) are in Sweref 99 TM.

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
727460	6631169	12.7	2190	50	*Bryales* peat	8
				100	*Bryales* peat	6
727519	6630925	12.7	2190	50	*Bryales* peat	8
				60	*Sphagnum* peat	3
				100	Unknown deposit	3
				150	*Carex* peat	6
				200	Gyttja	
727449	6630542	12.7	2190	50	*Sphagnum* peat	3
				100	*Carex* peat	4
				150	Sedge peat	7
				200	Gyttja	1
				230	Sand	
727472	6630007	12.4	2144	160	*Sphagnum* peat	4
				200	Gyttja	
727571	6629197	12.4	2144	100	*Sphagnum* peat	4
				150	*Carex* peat	4
				200	Gyttja	
				220	Clay gyttja	
727900	6631108	14.5	2459	50	*Sphagnum* peat	6
				100	*Sphagnum* peat	4
				150	Gyttja	
726060	6629548	10.1	1784	50	*Sphagnum* peat	6
				100	*Sphagnum* peat	4
				170	*Carex* peat	4
				210	Gyttja	
723186	6634773	8.5	1524	100	*Carex* peat	4
				150	Gyttja	
				200	Clay	
				50	*Sphagnum* peat	4
721415	6635236	7.5	1357	100	*Carex* peat	6
				120	Gyttja	
				150	Clay	
722091	6637605	16.5	2747	50	*Sphagnum* peat	4
				200	*Sphagnum* peat	3
				210	*Carex* peat	4
				250	Gyttja	
				300	Clay gyttja	
723119	6640480	15.5	2604	50	*Bryales* peat	7
				100	Woody sedge peat	8
				150	Clay gyttja	
722939	6640541	16.5	2747	50	*Bryales* peat	7

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
				150	Woody sedge peat	8
				160	Clay gyttja	
692679	6625445	11.2	1958	70	Decomposed peat	
				80	Sand	
				100	Clay gyttja	
				150	Clay	
691025	6626852	11.5	2005	50	Decomposed peat	
				175	Clay gyttja	
				180	Unknown deposit	
693660	6624470	12.5	2159	50	*Carex* peat	5
				150	Gyttja	
				200	Clay gyttja	
693029	6624894	11.2	1958	50	Decomposed peat	
				112	Gyttja	
				122	Clay gyttja	
				130	Clay	
703061	6625163	33	4655	50	*Bryales* peat	7
				85	*Bryales* peat	
				95	Woody sedge peat	9
				110	Clay	
704139	6623818	11	1927	50	Sedge peat	
				110	Clay gyttja	
				120	Clay	
701406	6624942	22	3474	50	*Sphagnum* peat	8
				100	*Sphagnum* peat	
				175	*Sphagnum* peat	9
				180	*Sphagnum* peat	8
				200	*Sphagnum* peat	6
				262	*Equisetum* peat	8
				268	Clay gyttja	
690693	6626603	11.5	2005	70	Decomposed peat	
				80	Clay	
				100	Gyttja	
				205	Clay gyttja	
				215	Sand	
690763	6625080	34	4744	50	*Sphagnum* peat	4
				100	*Carex* peat	5
				160	Woody sedge peat	8
				180	Clay	
690780	6625205	34	4744	50	Decomposed peat	
				120	Sedge peat	7
				130	Clay	
691478	6625703	24.5	3775	50	Decomposed peat	
				100	Woody sedge peat	9
				150	Woody sedge peat	8
				200	Clay	
692026	6624972	21	3349	100	Sedge peat	7
				150	Woody sedge peat	8
				207	Woody sedge peat	
				230	Gyttja clay	

X (East)	**Y (North)**	**Altitude of threshold (m.a.s.l.)**	**Age of isolation (years BP)**	**Depth to (cm)**	**Stratigraphy**	**Degree of humification**
691526	6623915	25.5	3890	50	*Sphagnum* peat	5
				170	*Carex* peat	4
				200	Gyttja	
				230	Marl	
				298	Clay	
				300	Sand	
692597	6623655	11.2	1958	70	Decomposed peat	
				80	Sedge peat	
				225	Clay gyttja	
				230	Clay	
692031	6622895	11.2	1958	50	Decomposed peat	
				210	Gyttja	
				215	Clay gyttja	
				220	Clay	
692929	6620661	36	4913	50	Decomposed peat	
				118	Gyttja	
				155	Clay gyttja	
				180	Clay	
693860	6620958	36	4913	50	Decomposed peat	
				160	Clay gyttja	
				180	Clay	
689197	6621829	14.5	2459	65	Decomposed peat	
				80	Sand	
				100	Clay	
689491	6621729	14.5	2459	66	Decomposed peat	
				80	Sand	
				114	Clay gyttja	
				130	Sandy clay	
693467	6618535	44	5468	50	*Sphagnum* peat	5
				150	*Sphagnum* peat	4
				200	*Sphagnum* peat	5
				250	*Carex* peat	6
				418	Gyttja	
				465	Clay gyttja	
				475	Clay	
				480	Sand	
692892	6618114	44.2	5479	70	*Carex* peat	7
				80	Woody sedge peat	7
				162	Gyttja	
				180	Clay gyttja	
				200	Sand	
691026	6617906	57	5954	50	Woody sedge peat	7
				100	Clay	
690454	6617456	57	5954	50	*Carex* peat	7
				100	Woody sedge peat	8
				150	Clay	
689211	6617935	30	4369	50	Decomposed peat	
				122	Woody sedge peat	9
				130	Clay	
689184	6616858	36	4913	50	*Sphagnum* peat	8

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
				100	*Carex* peat	8
				150	Woody sedge peat	8
				200	Clay	
688270	6616783	14.5	2459	70	Decomposed peat	
				80	Clay	
688466	6616138	15	2532	50	Decomposed peat	
				100	*Magnicaricetum* peat	5
				150	Gyttja	
				255	Clay gyttja	
				275	Clay	
689227	6623238	17.5	2886	70	Decomposed peat	
				80	Clay	
690454	6629177	14	2385	50	Decomposed peat	
				110	Gyttja	
				122	Clay gyttja	
				130	Sand	
691065	6629142	14	2385	70	Decomposed peat	
				80	Sedge peat	9
692217	6628635	28	4164	50	*Bryales* peat	7
				100	*Sphagnum* peat	4
				150	*Sphagnum* peat	
				200	Woody sedge peat	8
				270	Woody sedge peat	
				280	Clay	
693079	6628525	24	3716	50	Decomposed peat	
				120	Sedge peat	8
				130	Marl	
				175	Clay gyttja	
				180	Sand	
692314	6627636	18.5	3022	15	Decomposed peat	
				20	Clay	
691543	6627389	27	4057	125	Sedge peat	6
				130	Gyttja	
				176	Marl	
				180	Gyttja	
				200	Clay gyttja	
695188	6628884	17	2816	70	Decomposed peat	
				80	*Bryales* peat	3
				100	*Bryales* peat	4
				150	Clay gyttja	
				250	Clay	
694936	6629518	17	2816	50	Decomposed peat	
				125	Sedge peat	7
				180	Gyttja	
				200	Clay gyttja	
696293	6628539	17	2816	50	Decomposed peat	
697124	6628105	17.5	2886	50	Sedge peat	6
				120	Sedge peat	
				130	Clayey sand	
696119	6628079	17	2816	70	Decomposed peat	

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
				80	Clay	
697045	6628814	17.5	2886	71	Decomposed peat	
				80	Clay	
698802	6628676	20	3220	70	*Bryales* peat	6
				80	*Sphagnum* peat	4
				100	*Magnicaricetum* peat	5
				160	*Magnicaricetum* peat	6
				180	*Bryales* peat	3
				225	Gyttja	
				268	Marl	
				280	Clay gyttja	
				300	Clay	
700534	6626290	8.7	1557	50	Decomposed peat	
				120	Peat	
				150	Gyttja	
				200	Clay	
703418	6625976	31.5	4515	50	Decomposed peat	
				100	Woody sedge peat	8
				160	Gyttja	
				210	Clay gyttja	
				220	Clay	
704066	6626338	31.5	4515	76	Decomposed peat	
				80	Clay	
710332	6632645	6	1102	67	*Sphagnum* peat	4
				77	*Carex* peat	4
				117	Gyttja	
				127	Clay	
707650	6633220	11.5	2005	50	*Bryales* peat	8
				60	*Sphagnum* peat	4
				100	Sedge peat	8
				150	Gyttja	
				170	Sand	
705348	6632672	7.5	1357	20	*Magnicaricetum* peat	5
				30	*Carex* peat	4
				35	Gyttja	
705169	6633442	7.5	1357	50	Decomposed peat	
				100	Gyttja	
				150	Clay	
704515	6634172	7.5	1357	72	Decomposed peat	
				79	Gyttja	
				100	Silt	
707144	6634834	9.9	1752	50	*Carex* peat	4
				100	*Carex* peat	6
				150	*Carex* peat	4
				200	Gyttja	
				250	Clay	
706217	6635845	15.5	2604	50	*Carex* peat	4
				100	*Carex* peat	
				150	Marl	
				200	Gyttja	

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
				250	Clay	
705164	6636270	12.5	2159	77	Decomposed peat	
				87	Sedge peat	8
				100	Marl	
				150	Clay	
705196	6636544	12.5	2159	57	Decomposed peat	
				67	*Sphagnum* peat	4
				100	Sedge peat	8
				152	Gyttja	
				155	Clay	
705365	6636972	12.5	2159	50	Sedge peat	6
				122	Sedge peat	7
				157	Gyttja	
				177	Clay	
706211	6636679	12.5	2159	72	*Carex* peat	4
				77	Clay	
707610	6636432	12.9	2220	50	*Carex* peat	3
				100	*Carex* peat	6
				130	Gyttja	
709468	6636786	4.5	839	72	Decomposed peat	
				77	Gyttja	
				100	Clay gyttja	
712582	6634287	27.5	4111	67	*Bryales* peat	8
				77	Woody sedge peat	9
				100	Woody sedge peat	7
				130	Woody sedge peat	8
				200	Woody sedge peat	
				300	Gyttja	
				350	Clay	
714799	6633599	20	3220	50	*Carex* peat	3
				100	*Carex* peat	
				200	Unknown deposit	
				300	Gyttja	
				350	Clay gyttja	
714791	6634747	17.9	2941	50	*Sphagnum* peat	4
				100	*Sphagnum* peat	3
				150	*Carex* peat	4
				200	Gyttja	
				250	Clay gyttja	
714473	6635311	18.2	2981	50	*Carex* peat	3
				100	Gyttja	
				250	Clay gyttja	
				300	Clay	
715329	6635239	17.9	2941	50	*Carex* peat	5
				100	*Carex* peat	
				150	Clay gyttja	
715543	6635567	17.9	2941	50	*Carex* peat	4
				200	Gyttja	
				250	Clay	
716209	6635737	12.5	2159	50	*Carex* peat	6

X (East)	**Y (North)**	**Altitude of threshold (m.a.s.l.)**	**Age of isolation (years BP)**	**Depth to (cm)**	**Stratigraphy**	**Degree of humification**
				100	*Carex* peat	?
				150	Gyttja	
				200	Clay gyttja	
716776	6636735	12.5	2159	50	*Carex* peat	3
				100	*Carex* peat	5
				150	Gyttja	
				200	Clay gyttja	
717780	6636226	10.7	1879	50	*Magnicaricetum* peat	6
				100	*Magnicaricetum* peat	7
				150	Gyttja	
				200	Clay gyttja	
715451	6640945	15	2532	50	Decomposed peat	
				107	Sedge peat	8
				210	Gyttja	
715058	6645037	15.5	2604	50	*Carex* peat	4
				100	*Carex* peat	5
				150	*Carex* peat	
				200	Clay gyttja	
713708	6647098	23	3597	67	Decomposed peat	
				77	Woody sedge peat	9
				117	Woody sedge peat	
				127	Gyttja	
				150	Clay gyttja	
714224	6647230	23	3597	50	Woody sedge peat	9
				100	Woody sedge peat	
				150	Gyttja	
				200	Clay gyttja	
714745	6647357	23	3597	50	Woody sedge peat	8
				112	Woody sedge peat	
				150	Gyttja	
				200	Clay gyttja	
711963	6645987	23	3597	50	*Carex* peat	4
				250	Gyttja	
				300	Clay gyttja	
711915	6645451	23	3597	50	Woody sedge peat	8
				157	Woody sedge peat	
				163	Peat	
				173	Gyttja	
				250	Marl	
712046	6645451	23	3597	50	Woody sedge peat	8
				100	Woody sedge peat	
				150	Marl	
				200	Clay gyttja	
712096	6645102	23	3597	62	Peat	
				150	Gyttja	
				200	Clay gyttja	
712114	6643585	22.5	3536	50	Decomposed peat	
				100	Sedge peat	8
				150	Marl	
				200	Gyttja	

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
				250	Clay gyttja	
713231	6644119	23.5	3657	50	Woody sedge peat	8
				100	Woody sedge peat	7
				167	Peat	?
				222	Gyttja	
				227	Clay gyttja	
713284	6644633	23.8	3693	50	Woody sedge peat	8
				100	Woody sedge peat	9
				150	Clay gyttja	
713268	6645215	24.7	3798	67	*Bryales* peat	8
				77	*Sphagnum* peat	4
				100	*Sphagnum* peat	3
				217	*Sphagnum* peat	
				227	*Sphagnum* peat	5
				250	Gyttja	
				300	Clay gyttja	
711427	6644101	22.5	3536	50	Decomposed peat	
				100	Sedge peat.	8
				150	Marl	
				200	Gyttja	
				250	Clay gyttja	
713423	6645223	24.7	3798	50	Woody sedge peat	9
				100	Woody sedge peat	
				150	Clay gyttja	
693069	6647248	20	3220	50	Sedge peat	6
				157	Sedge peat	
				207	Gyttja	
				217	Clay gyttja	
659738	6648282	26	3946	50	Sedge peat	
				90	Moss peat	7
				140	Clay gyttja	
					Gravel	
665155	6650418	30	4369	50	*Sphagnum* peat	8
				238	*Sphagnum* peat	5
				246	Gyttja	
				250	Clay	
671944	6653546	17	2816	50	Peat	3
				100	Peat	2
				179	Peat	4
				230	Gyttja	
				240	Sand	
				250	Clay.	
684149	6658848	20	3220	32	*Sphagnum* peat	3
				90	*Sphagnum* peat	7
				130	Decomposed peat	
				228	Gyttja	
				230	Clay.	
687048	6659954	19	3089	50	*Bryales* peat	8
				82	*Sphagnum* peat	6
				134	*Carex* peat	7

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
				192	Woody sedge peat	6
				280	Gyttja	
688002	6660603	15	2532	50	*Carex* peat	8
				100	*Carex* peat	6
				150	*Phragmites* peat	
				200	Gyttja	
				250	Clay	
691448	6673768	12.4	2144	20	*Sphagnum* peat	3
				91	*Sphagnum* peat	7
				100	Clay	
638916	6714463	29	4268	42	*Sphagnum* peat	4
				67	*Carex* peat	7
				90	Woody sedge peat	8
				112	Sedge peat	7
				140	*Bryales* peat	3
				160	*Carex* peat	4
				173	Gyttja	
				190	Gyttja clay	
670272	6704640	2	387	20	Sedge peat	4
				50	Gyttja	
				55	Sand	
				100	Clay	
640692	6714825	14	2385	48	*Sphagnum* peat	6
				167	*Sphagnum* peat	3
				175	*Phragmites* peat	4
				195	Gyttja clay	
701582	6670236	9	1606	55	*Sphagnum* peat	5
				90	Woody sedge peat	6
				110	*Phragmites* peat	3
				125	Gyttja clay	
				140	Clay	
				140	Till	
678094	6692007	4	750	10	Woody sedge peat	6
				30	*Carex* peat	4
				43	Gyttja	
				55	Clay gyttja	
				60	Gyttja clay	
641226	6715435	13	2235	67	*Sphagnum* peat	3
				88	*Sphagnum* peat	5
				122	*Carex* peat	5
				125	*Phragmites* peat	4
				135	Gyttja clay	
				135	Till	
671096	6702557	9.5	1687	5	Decomposed peat	10
				25	Sedge peat	6
				50	*Phragmites* peat	
				70	Gyttja	
				85	Gyttja clay	
				90	Sand	
667184	6707123	3.9	733	50	Sedge peat	

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
				80	Gyttja clay	
687112	6681373	17	2816	40	*Sphagnum* peat	
				95	Sedge peat	
				100	*Phragmites* peat	
				100	Till	
640577	6716988	10.2	1800	83	Sedge peat	
				93	Gyttja clay	
				100	Clay	
687303	6683180	11	1927	10	*Sphagnum* peat	6
				60	*Sphagnum* peat	3
				105	*Sphagnum* peat	4
				115	*Bryales* peat	3
				180	*Carex* peat	
				185	Sand	
675377	6697248	8.5	1524	12	*Carex* peat	6
				71	*Carex* peat	4
				90	*Phragmites* peat	3
				125	Clay gyttja	
				125	Till	
686879	6681052	13	2235	70	Sedge peat	5
				97	Woody sedge peat	7
				100	Gyttja clay	
640427	6715461	14.9	2518	5	Decomposed peat	10
				37	*Sphagnum* peat	4
				160	*Sphagnum* peat	3
				187	Sedge peat	4
				197	*Phragmites* peat	4
				220	Gyttja	
				270	Gyttja clay	
667386	6706249	5	928	30	Sedge peat	5
				55	Sedge peat	3
				60	*Phragmites* peat	
				80	Gyttja	
				90	Gyttja clay	
668584	6704550	7.2	1307	5	*Sphagnum* peat	7
				75	*Sphagnum* peat	2
				85	*Bryales* peat	5
				115	*Phragmites* peat	3
				120	Gyttja	
				135	Gyttja clay	
703061	6625163	33.5	4700	50	Woody sedge peat	7
				89	Woody sedge peat	8
				144	Clay gyttja	
				150	Clay	
677391	6639272	30.6	4429	50	*Sphagnum* peat	6
				100	Sedge peat	9
				167	Sedge peat	
				220	*Carex* peat	3
				280	Gyttja	
676932	6642655	26.5	4002	60	*Sphagnum* peat	3

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
				77	*Sphagnum* peat	6
				100	*Sphagnum* peat	3
				200	*Sphagnum* peat	
				270	*Carex* peat	3
				370	Gyttja	
				377	Clay gyttja	
697136	6625108	8	1273	73	Decomposed peat	
				80	Clay	
693491	6620877	36.5	4953	70	*Sphagnum* peat	5
				80	*Carex* peat	7
				168	Gyttja	
				204	Clay gyttja	
				227	Clay	
690996	6617743	57	5954	50	*Carex* peat	
				100	Woody sedge peat	
				150	Clay	
687788	6600742	18.7	3049	30	Highly decomposed peat	
				81	*Carex* peat	
				100	Gyttja	
				150	Clay gyttja	
				200	Clay	
689976	6601330	42.5	5378	50	*Sphagnum* peat	8
				100	Woody sedge peat	8
				140	Clay	
				145	Sand	
				150	Clay	
689495	6601959	38	5070	50	*Bryales* peat	7
				90	*Sphagnum* peat	3
				100	*Sphagnum* peat	8
				150	*Sphagnum* peat	3
				200	*Sphagnum* peat	7
				230	*Sphagnum* peat	6
				300	*Carex* peat	6
				350	Clay gyttja	
690252	6601991	43.2	5421	50	Woody sedge peat	8
				62	Woody sedge peat	
				80	Clay	
690728	6601927	44	5468	30	*Bryales* peat	8
				90	Woody sedge peat	8
				100	Clay	
691940	6602070	20.5	3285	50	Woody sedge peat	8
				90	Clay gyttja	
				100	Clay	
691998	6601255	28	4164	34	Woody sedge peat	9
				50	Clay	
691802	6602732	22	3474	50	Sedge peat	8
				130	Woody sedge Peat	7
				150	Clay gyttja	
				200	Clay	
690225	6602843	54	5888	50	Woody sedge peat	7

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
				89	Woody sedge peat	8
				140	Gyttja	
				150	Clay gyttja	
				200	Clay	
689976	6602684	32.9	4646	100	*Carex* peat	3
				150	*Carex* peat	
				250	Gyttja	
				255	Clay gyttja	
693984	6605255	39	5144	50	*Carex* peat	3
				100	*Carex* peat	2
				450	Gyttja	
				500	Clay gyttja	
694317	6605993	39	5144	50	*Carex* peat	5
				138	*Magnicaricetum* peat	4
				150	*Equisetum* peat	
				287	Gyttja	
				300	Clay gyttja	
				308	Clay gyttja	
693222	6605731	32.5	4609	45	Decomposed peat	
				50	Clay	
692904	6604913	34	4744	150	*Sphagnum* peat	6
				200	*Sphagnum* peat	8
				250	*Magnicaricetum* peat	5
				245	Gyttja	
				250	Clay gyttja	
				382	Clay gyttja	
				400	Clay	
687911	6603509	47.5	5649	50	*Carex* peat	4
				100	*Carex* peat	3
				150	*Magnicaricetum* peat	4
				300	Gyttja	
				450	Clay gyttja	
689031	6603810	37	4993	20	Decomposed peat	
				50	Clay	
				100	Gyttja	
				147	Clay gyttja	
				150	Clay	
689586	6603604	40	5215	50	Woody sedge peat	6
				100	Sedge peat	
				166	Clay gyttja	
				185	Clay	
689197	6604517	42	5347	50	Peat	
				100	*Phragmites* peat	
				150	Clay gyttja	
				200	Clay	
688515	6604469	47	5625	40	Sedge peat	
				55	Clay	
688269	6603953	38.9	5136	40	Decomposed peat	
				90	Sedge peat	7
				100	Clay	

X (East)	Y (North)	Altitude of threshold (m.a.s.l.)	Age of isolation (years BP)	Depth to (cm)	Stratigraphy	Degree of humification
694738	6605128	38	5070	42	*Sphagnum* peat	7
				50	*Sphagnum* peat	4
				82	*Sphagnum* peat	7
				150	*Carex* peat	6
				178	*Carex* peat	5
				200	*Carex* peat	
				250	Sedge peat	
				340	Gyttja	
				350	Clay gyttja	
				370	Clay	
				380	Sand	
690118	6603461	46.5	5601	50	*Sphagnum* peat	7
				100	*Sphagnum* peat	8
				150	*Sphagnum* peat	6
				250	*Sphagnum* peat	3
				300	*Carex* peat	5
				350	Gyttja	
				395	Clay gyttja	
				400	Sand	
689427	6605080	57	5954	35	*Sphagnum* peat	3
				50	*Sphagnum* peat	7
				150	*Carex* peat	8
				200	Woody sedge peat	7
				241	*Carex* peat	8
				250	Gyttja	
				296	Clay gyttja	
				300	Clay	
688900	6607993	53.5	5874	50	*Sphagnum* peat	8
				100	*Sphagnum* peat	7
				150	*Sphagnum* peat	4
				300	Woody sedge peat	8
				350	Woody sedge peat	7
				446	Clay gyttja	
				450	Clay	