Carbon loss after forest drainage of three peatlands in southern Sweden

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Preface

This thesis is carried out for a MSc degree in Soil Science and corresponds to 20 credits on D level (advanced level). It is an integrated part in the research programme LUSTRA - Land-use strategies for reducing net greenhouse-gas emissions -, supported by MISTRA. Land-use in Sweden is to a large extent forestry and considerable areas have site conditions characterized by high groundwater levels and organic layers forming peat. Hence, this thesis concerning the impact of peatland afforestation on CO_2 emissions is central for LUSTRA. The study was enabled through data from long-term field experiments at the Department of Forest Soils at SLU.

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Front page photograph: Björn Söderbergh

Sammanfattning

En ökad koldioxidhalt i atmosfären påverkar det globala klimatet. Det är därför intressant att undersöka hur åtgärder inom skogsbruket påverkar fördelningen av kol mellan mark, växter och atmosfär. I den föreliggande studien undersöktes nettoförändringar av kolförrådet i myrar efter skogsdikning. En sänkning av grundvattenytan ökar generellt nedbrytningen av torven i en myr och medför därför ett ökat flöde av koldioxid till atmosfären. Samtidigt blir förutsättningarna för skogstillväxt bättre efter dikning, vilket är själva syftet med åtgärden, och kol binds därför in i trädens biomassa och tillförs även torven genom en ökad produktion av förna.

Tre myrområden i södra Sverige ingick i undersökningen: Siksjöbäckenområdet, där två dikade kärr, Letjärn och Särkalampi, och ett odikat kärr, Hamptjärn, undersöktes; Torvbråtenområdet, som består av en odikad och en dikad mosse, Myggbotjärn och Torvbråten; samt Gillermossen, som är ett dikat kärr. Skillnaderna mellan områdena gjorde det möjligt att studera hur förändringar i kolförådet efter dikning beror av olika ståndortsfaktorer. De två kärrområdena (Siksjöbäckenområdet och Gillermossen), mosseplanet på den dikade mossen och randzonen på den dikade mossen betraktades i undersökningen som fyra olika ståndorter. Gillermossen dikades 1990, Torvbråten dikades 1982 och Letjärn och Särkalampi dikades 1981.

I samband med dikningen av de undersökta myrarna gjordes en hydrologisk studie, varvid grundvattenrör placerades ut vid några "stationer" på varje myr. Med hjälp av dessa rör kunde förändringar i torvytans läge bestämmas, mellan dikningstillfället och den tidpunkt år 2000 då rörhöjderna mättes för den föreliggande undersökningen. I anslutning till dikningarna bestämdes också torvens volymvikt, på samma stationer. Förändringen i torvytans läge, de äldre volymviktsvärdena samt volymviktsvärden från nya volymbestämda prover användes för att räkna ut det totala kolinnehållet i torven, ned till en bestämd nivå, vid dikningstillfället och år 2000, dvs. 10-20 år senare. Nettoförändringen i torvens kolförråd efter dikningen bestämdes genom en jämförelse av kolinnehållet i torven vid dessa två tillfällen. För Siksjöbäcksområdet kunde de äldre volymviktsvärdena inte användas och kolinnehållet år 2000 för de dikade myrarna, Letjärn och Särkalampi, jämfördes istället med kolinnehållet i motsvarande lager i den odikade myren, Hamptjärn.

Syftet med att undersöka både dikade och odikade myrar var framför allt att de odikade myrarna kunde användas som referensmyrar för de dikade myrarna inom samma område. Genom att dra bort ändringen i kolförrådet på de odikade myrarna från ändringen på de dikade myrarna erhölls värden för de dikade myrarna som antogs motsvara endast den förändring i kolförrådet som orsakats av själva dikningen. För Gillermossen kunde ingen korrigering göras, eftersom det inte fanns någon användbar referensmyr. För Letjärn och Särkalampi behövdes ingen separat korrigering göras i och med den särskilda metod som användes för att räkna ut kolförlusten. Några av myrarna gödslades efter dikningen. Detta är en standardåtgärd och eventuella effekter av gödslingen räknades därför in i effekterna av dikningen.

Torven analyserades med avseende på pH, C-halt och N-halt, både i samband med dikningen och år 2000. Humifieringsgraden bestämdes på vissa stationer i samband med dikningen och på alla stationer år 2000. De tidiga värdena på pH, C/N-kvot och humifieringsgrad användes för att analysera skillnaderna i förändringarna i kolförrådet mellan olika ståndorter. En ytterligare ståndortsegenskap som beaktades var beskogning. Om de olika stationerna kunde anses beskogade eller inte bestämdes år 2000. Förändringarna i kolförrådet efter dikning antogs också vara relaterade till hur starkt dikningen påverkat grundvattennivån. Medelvärden för grundvattennivån över den tjälfria delen av året, på de olika stationerna, jämfördes för två år med liknande nederbördsmängder, ett före dikningen och ett några år senare då grundvattenytan kunde antas ha stabiliserat sig. Skillnaden tolkades som den grundvattensänkning som dikningen orsakat. I genomsnitt sänktes grundvattenytan med 30.4 cm på Letjärn och Särkalampi, 12.9 cm på Torvbråtens randzon, 28.8 cm på Torvbråtens mosseplan och 50.9 cm på Gillermossen.

Torvytan sjönk på alla stationer under den undersökta perioden, vilket var oväntat för de odikade myrarna. Medelavsänkningen var 6.9 cm för Hamptjärn, 12.5 cm för Letjärn och Särkalampi, 3.7 cm för Myggbotjärn, 9.7 cm för randzonen på Torvbråten, 39.4 för mosseplanet på Torvbråten och 11.0 cm för Gillermossen. De preliminära värdena på förändringar i kolförrådet, före korrigeringen med hjälp av referensmyrarna, visade samtidigt på en förlust av kol från samtliga stationer, även från de som inte dikats. Detta skulle kunna vara en indikation på reella kolförluster från de odikade myrarna, pga. torra perioder eller eventuellt pga. tillförsel av näringsämnen från antropogena källor. Det skulle dock också kunna vara ett resultat av systematiska fel i mätningarna. För att förklara avsänkningen och de relativt höga kolförlustvärdena för de odikade myrarna skulle ytterligare underlag behövas. Eftersom den föreliggande studien behandlar kolförluster orsakade av dikning ligger kolförluster från odikade myrar utanför ämnet. Fenomenet kan dock vara värt att undersöka vidare.

Efter korrigeringen av kolförlustvärdena med hjälp av referensmyrarna var medelkolförlusten 76 g C $m^{-2}år^{-1}$ för Letjärn och Särkalampi, 813 g C $m^{-2}år^{-1}$ för Gillermossen, 8 g C $m^{-2}år^{-1}$ för randskogen på Torvbråten och 635 g C $m^{-2}år^{-1}$ för mosseplanet på Torvbråten. Detta kan jämföras med den genomsnittliga inbindningen av kol i en odikad nordlig myr som är c.a 21 g C $m^{-2}år^{-1}$ (Clymo et al., 1998).

Osäkerheten vid bestämningen av torvytans läge var på många stationer relativt stor i jämförelse med den förändring i torvytans läge som var en följd av dikningen. Detta bedömdes utgöra den största felkällan i undersökningen. För att reda ut hur stora felen i de slutliga kolförlustvärdena maximalt skulle kunna vara gjordes två separata uppskattningar. Dels uppskattades det sammanlagda fel som skulle kunna komma sig av osäkerheten vid bestämningen av torvytans läge vid olika steg i undersökningen. Dels uppskattades, för de dikade myrar där kolförlustvärdena korrigerats med hjälp av referensmyrarna, d.v.s. för Torvbråten respektive Letjärn och Särkalampi, det fel i de slutliga kolförlustvärdena som skulle kunna vara kvar efter korrigeringen. Osäkerheterna bedömdes vara relativt stora, men inte större än att vissa slutsatser ansågs kunna dras om förhållandet mellan kolförlust och ståndortsegenskaper.

Förändringen av grundvattennivån, andelen stationer som kunde anses vara beskogade samt eventuellt torvens ursprungliga humifieringsgrad verkade vara de faktorer som i första hand påverkat storleken på förändringarna i kolförrådet, medan C/N-kvoten och pH-värdet verkade vara mindre viktiga. Torvbråtens mosseplan uppvisade t.ex. stora kolförluster trots lågt pH och hög C/N-kvot. Eftersom grundvattensänkningen var i stort sett densamma för mosseplanet som för de dikade kärren i Siksjöbäcksområdet (Letjärn och Särkalampi), 28.8 respektive 30.4 cm, antogs den stora skillnaden i kolförlust mellan dessa två ståndorter bero på den större andelen beskogade stationer i kärrområdet och/eller kärrtorvens högre ursprungliga humifieringsgrad. Den stora skillnaden i kolförlust mellan de två kärrområdena, Gillermossen respektive Letjärn och Särkalampi, berodde troligen på en kombination av olika faktorer: skillnad i grundvattensänkning, skillnad i C/N-kvot, avsaknad av referensmyrskorrigering för Gillermossen samt en kortare mätperiod för Gillermossen.

Summary

Increased amounts of carbon dioxide in the atmosphere influence the global climate. It is therefore important to understand the effects of forestry measures on the distribution of carbon between soil, plants and atmosphere. In the present study, net changes in the peat carbon stores of mires, as a result of forestry drainage, were investigated. Drainage of a mire generally increases the decomposition of the peat, which leads to an increased flux of carbon dioxide to the atmosphere. On the other hand, drainage increases forest growth, which leads to an accumulation of carbon into the biomass of the trees and thereby also an addition of carbon to the peat by an increased production of litter.

Three mire areas in southern Sweden were included in the study: the Siksjöbäcken area, where two drained fens, Letjärn and Särkalampi, and one undrained fen, Hamptjärn, were investigated; the Torvbråten area, which consists of one undrained and one drained bog, Myggbotjärn and Torvbråten; and Gillermossen, which is a drained fen. The differences between the areas made it possible to study how changes in the carbon stores after drainage depend on site factors. The two fen areas (the Siksjöbäcken area and Gillermossen), the Torvbråten bog plane and the Torvbråten marginal slope were regarded as four different sites. Drainage was carried out at Gillermossen in 1990, at Torvbråten in 1982 and at Letjärn and Särkalampi in 1981.

In connection to the drainage of the mires, a hydrological study was carried out. Groundwater tubes were then installed at some stations at each mire. Using these tubes, the changes in the peat surface level after drainage could be measured for the present study. Volumetric peat samples were also collected in connection to the drainage, at the same stations. The change in the peat surface level, together with volume weights calculated for the early volumetric samples and for new volumetric samples, were used to calculate the total carbon content in the peat, down to a certain level, at a point in time close to the drainage and in the year 2000, i.e. 10-20 years later. The net change in the peat carbon store was determined by comparing the total carbon content of the peat at these two occasions, for each station. For the Siksjöbäcken area, the earlier values of volume weight could not be used and the carbon content calculated for the drained mires for the year 2000, in a certain layer, was instead

compared to the carbon content in the corresponding layer in the undrained reference mire, Hamptjärn, in the same year.

The main purpose of investigating both drained and undrained mires was that the undrained mires could serve as reference mires for the drained mires in the same area. The changes in the carbon stores of the undrained mires were subtracted from the changes at the drained mires and the resulting values were assumed to represent only the changes in the carbon stores that were actually caused by drainage. No correction could be made for Gillermossen, since there was no reference mire. For Letjärn and Särkalampi, no separate correction was needed, due to the different method used to calculate the carbon loss. The possible effects of the fertilization carried out on some of the mires, in connection to the drainage, were included in the "effects of drainage", since it is common practice to fertilize a mire after it has been drained.

The peat was analyzed with respect to pH, C-content and N-content, both in connection to the drainage and in the year 2000. The degree of decomposition was determined for some stations in connection to the drainage and for all stations in the year 2000. The early values of pH, C/N ratio and degree of decomposition were used to analyze why the changes in the carbon stores differed between sites. Another site factor considered was the tree cover. If the different stations could be regarded as having a tree cover or not was decided in the year 2000. The changes in the carbon stores after drainage were also assumed to be related to how much the groundwater level had been lowered. At each station, the average groundwater level, during the frost-free part of the year, was compared for two years with similar amounts of precipitation, one before drainage and one some years after drainage, when the water table was assumed to have stabilized. The difference was interpreted as the change in the groundwater table that was caused by drainage. The water-level drawdown was then 30.4 cm at Letjärn and Särkalampi, 12.9 cm at the Torvbråten marginal slope, 28.8 cm at the Torvbråten bog plane and 50.9 cm at Gillermossen.

The peat surface subsided at all stations during the period studied, which was unexpected for the undrained mires. The mean subsidence was 6.9 cm at Hamptjärn, 12.5 cm at Letjärn and Särkalampi, 3.7 cm at Myggbotjärn, 9.7 cm at the Torvbråten marginal slope, 39.4 cm at the Torvbråten bog plane and 11.0 cm at Gillermossen. The preliminary calculations of changes in the carbon stores, before the corrections using the reference mires, also showed a loss of carbon from all stations, even from those that were not drained. This could be an indication of real losses of carbon from the undrained mires, caused by dry periods or possibly by deposition of nutrients from anthropogenic sources. However, it could also be a result of systematic errors in the measurements. Explaining the subsidence and the relatively high values of carbon loss at the undrained mires requires additional information and is beyond the scope of the present study. However, it should be an interesting subject of further investigations.

After the correction of the carbon loss values, by the use of the reference mires, the mean loss of carbon was 76 g C $m^{-2}a^{-1}$ for Letjärn and Särkalampi, 813 g C $m^{-2}a^{-1}$ for Gillermossen, 8 g C $m^{-2}a^{-1}$ for the marginal slope at Torvbråten and 635 g C $m^{-2}a^{-1}$ for the bog plane at Torvbråten. These values can be compared to the average accumulation of carbon for an undrained northern peatland, which is 21 g C $m^{-2}a^{-1}$ (Clymo et al., 1998).

The uncertainties in the determinations of the peat surface level were at many stations relatively large compared to the change in the peat surface level that was caused by drainage. These uncertainties were considered to be the largest source of errors in the carbon loss values. The maximum errors in the carbon loss values were estimated, in two different ways. First, the errors that could arise from the uncertainties regarding the determinations of the peat surface level, at different stages in the investigation, were estimated and added together. Secondly, the errors in the final carbon loss values, that could still be left after the reference mire correction, were estimated by the calculation of confidence intervals, for the mires where the reference mires were used, i.e. for Torvbråten and for Letjärn and Särkalampi. The uncertainties were found to be quite large, but they were regarded to be small enough to allow some conclusions to be drawn about how the amounts of carbon lost may be related to site factors.

The drainage impact, the tree cover and perhaps the initial degree of decomposition seemed to be the most important factors influencing the changes in the carbon stores, while the C/N ratio and the pH seemed to be less important. As an example, the losses of carbon from the Torvbråten bog plane were large despite a low pH and a high C/N ratio. Since the change in the groundwater table was virtually the same for the bog plane as for the fens in the Siksjöbäcken area (Letjärn and Särkalampi), 28.8 cm and 30.4 cm respectively, the large difference in carbon loss between these sites was assumed to be caused either by the larger share of tree-covered stations in the fen area or by the initially higher degree of decomposition of the fen peat, or by both. The large difference in carbon loss between the two fen areas, Gillermossen on the one hand and Letjärn and Särkalampi on the other hand, was probably due to a combination of different factors: a difference in drainage impact, a difference in C/N ratio, the lack of a reference mire correction for Gillermossen and a shorter period of study for Gillermossen.

1. Introduction

1.1. Background

Due to an increasing concern about the possible influence of anthropogenic emissions of greenhouse gases on the global climate, attention has been directed towards mires as being sources or sinks for the greenhouse gases N_2O, CH_4 and CO_2.

Drainage is one of the land use practices with the greatest impact on the fluxes of greenhouse gases to and from forest land. Its net effect on the climate is very difficult to determine since the emissions and accumulation of both CO_2, CH_4 and N_2O, three important greenhouse gases, are affected. Drainage of mires generally increases CO_2 emissions from the peat and decreases CH_4 emissions (Silvola and Alm 1992, Martikainen et al. 1994). N_2O emissions often increase from nutrient-rich sites (Martikainen et al. 1993). However, in most cases drainage also causes an increased production of biomass, especially when a previously treeless mire becomes forested. This means that large quantities of CO_2 are removed from the air and accumulated into the new vegetation (Laiho, 1997).

Attempts have been made to estimate the combined effect of the changes in the fluxes of greenhouse gases after water-level drawdown, e.g. by Finnish scientists (Laine et al. 1996). Such information is needed e.g. as a basis for political decisions. However, further research is needed on the separate processes, to obtain a clearer picture. As an example, long term studies on the changes in the peat carbon balance after drainage are rare (Minkkinen and Laine, 1998). This is where the present study wants to contribute.

1.2. Purpose of the study

The overall purpose of this study was to quantify the long-term loss of carbon from the peat at drained mires in southern Sweden. The study is a part of the LUSTRA (Land Use STRAtegies for reducing net greenhouse gas emissions) project, which has as its goal to deliver integrated strategies for how changes in land use and land management in Sweden can optimally contribute to reduce net emissions of greenhouse gases during the periods 2000-2030, 2000-2100 and 2000-2500.

The study focused on the peat carbon balance of three mire areas that were drained for forestry. The carbon content in the surface layer, down to 40, 50 or 100 cm depth, was determined after a period of 10-20 years after drainage. This value was related to the initial carbon content in the same layer and the difference was interpreted as the net loss of carbon from the peat during the post-drainage period.

The net peat carbon loss per year, during the period studied, was calculated and differences between sites were investigated. Attempts were made to relate the carbon loss values to the water-level drawdown and to site factors such as the density of the tree cover, nutrient status and pH.

2. Description of the areas

The investigations were carried out in three main areas: Torvbråten, Siksjöbäcken and Gillermossen. The Torvbråten area consisted of two raised bogs, Myggbotjärn and the actual Torvbråten bog, where Torvbråten was drained and Myggbotjärn was the reference area (Lundin and Bergquist, 1990). In the Siksjöbäcken area, the mire parts of three catchments were investigated: Hamptjärn, Letjärn and Särkalampi. These were mainly low sedge fens. Letjärn and Särkalampi were drained while Hamptjärn served as the control. The Gillermossen area consisted of only one catchment with two small low sedge fens, one of which was used in the investigation. The small fens were both drained.

2.1. The Siksjöbäcken area

The Siksjöbäcken catchment is located where the three counties of Värmland, Dalarna and Västmanland meet, about 30 km north of Hällefors, Sweden, E 14° 23'; N 66° 53'. The elevation is about 300 m above sea level and the annual precipitation amounts to 900 mm (Eriksson, 1980). The area shows a typical inland climate with warm summers and cold winters. The mean annual temperature is +4°C, with -6°C in January and +15°C in July (Raab and Vedin (eds), 1995).

The peat-covered part of the area (about 10 %) consists mainly of soligeneous low sedge fens, which were formed by paludification. The thickness of the peat layer is generally 2-3 m. The Letjärn and Särkalampi areas were drained in Mars-April 1981 and some parts were fertilized with P and K in May 1983. Samples were collected from thirteen stations, three on Hamptjärn, four on Letjärn and six on Särkalampi (Figures 1-4).

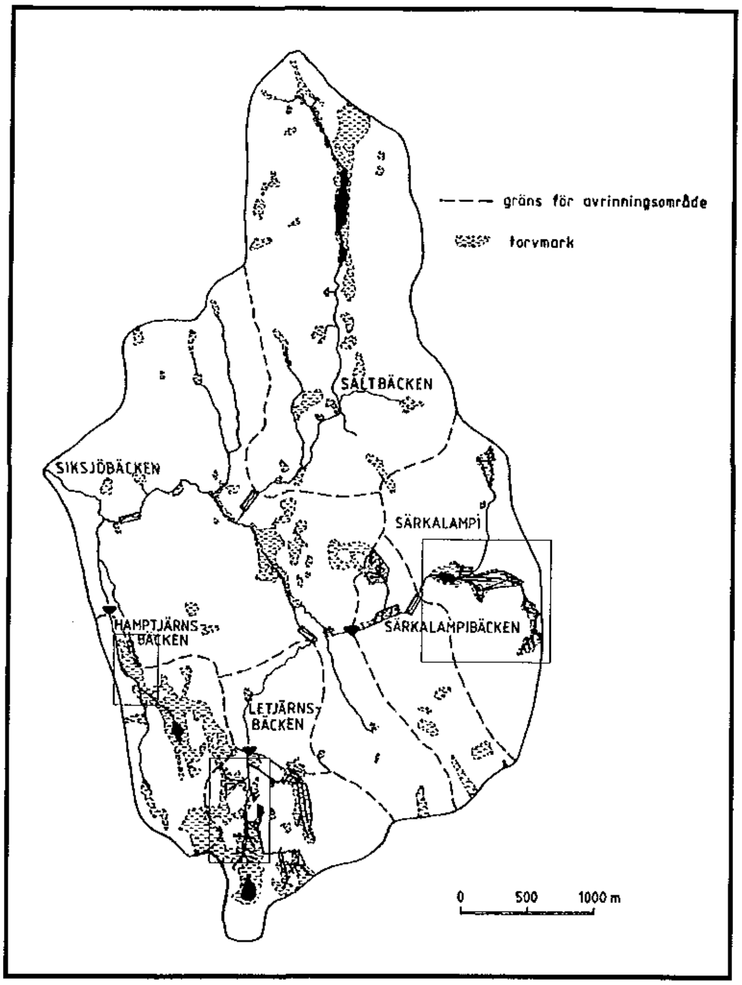

Figure 1. The Siksjöbäcken catchment. The marked areas were studied.

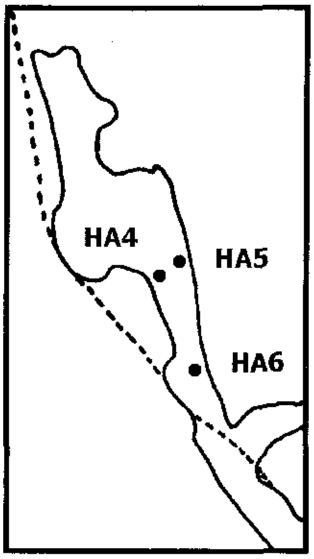

Figure 2. Hamptjärn, with the stations HA4, HA5 and HA6.

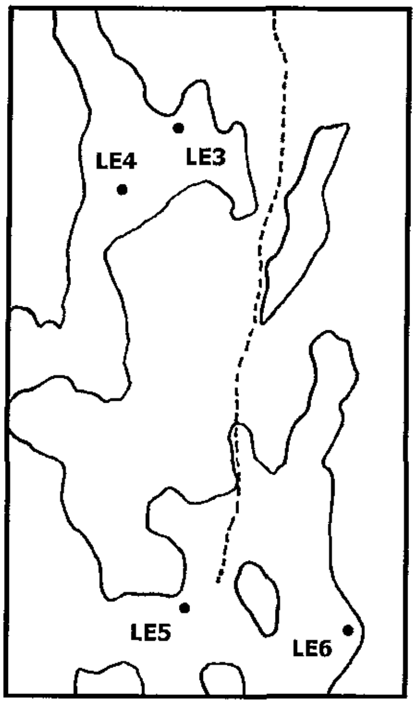

Figure 3. Letjärn, with the stations LE3, LE4, LE5 and LE6.

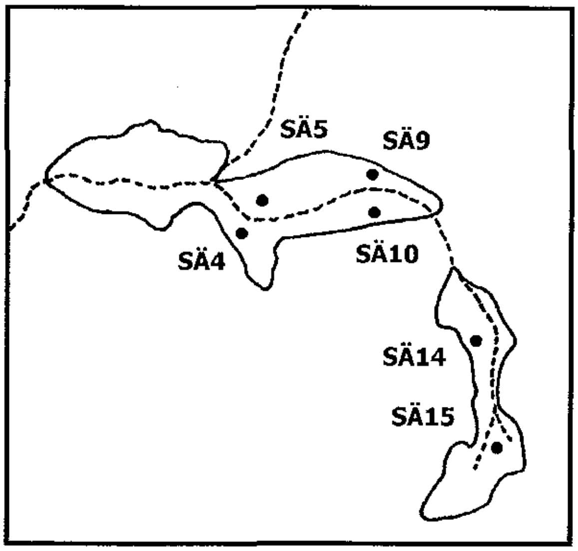

Figure 4. Särkalampi, with the stations SÄ4, SÄ5, SÄ9, SÄ10, SÄ14 and SÄ15.

2.2. The Torvbråten area

The Torvbråten watershed is located in Värmland, Sweden (E 13° 32'; N 59° 40'), at about 100 m above sea level. The annual mean precipitation is 750 mm (Eriksson, 1980), the annual mean temperature is +5°C and the mean temperatures of July and January are +17°C and –5.5°C, respectively.

The two bogs studied, Myggbotjärn and Torvbråten, are ombrotrophic. The peat is 3-6 m thick and is built up from Sphagnum in the upper layers (0-3 m) and Carex in the deeper layers. Torvbråten was drained between December 1981 and July 1982. The trees planted on the bog plane, at Torvbråten, were fertilized, with P and K, in 1984 and the marginal slope pine forest was fertilized, also with P and K, in 1985, except on the T15 station. Myggbotjärn was not fertilized. Samples were collected from three stations at Myggbotjärn and four stations at Torvbråten (Figure 5 and 6).

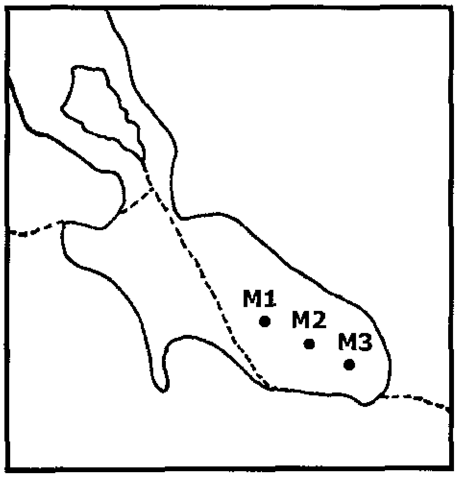

Figure 5. Myggbotjärn, with the stations M1, M2 and M3.

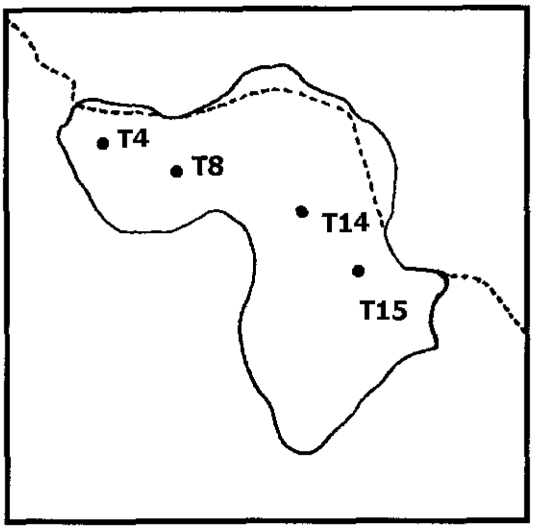

Figure 6. Torvbråten, with the stations T4, T8, T14 and T15.

2.3. The Gillermossen area

About 50 km east of Siksjöbäcken, at E 14° 23'; N 66° 53', the Gillermossen catchment is found. The area, at 270-275 m above sea level (Lundin, pers. comm., 2000), has a precipitation of about 860 mm (Lundin, 1982). The mean annual temperature is about +4.2°C, with -6°C in January and +15°C in July (Knutsson et al., 1995).

The two small peatlands in the Gillermossen catchment had a considerable tree cover (114 m^3 ha^{-1}, 60 % pine, 20% spruce) even before drainage (Lundin, 1994) and were about 0.5–2.0 m deep in the undrained state (Lundin, pers. comm., 2000). Drainage was carried out in 1990. Two stations, both in the larger southern fen, were investigated (Figure 7).

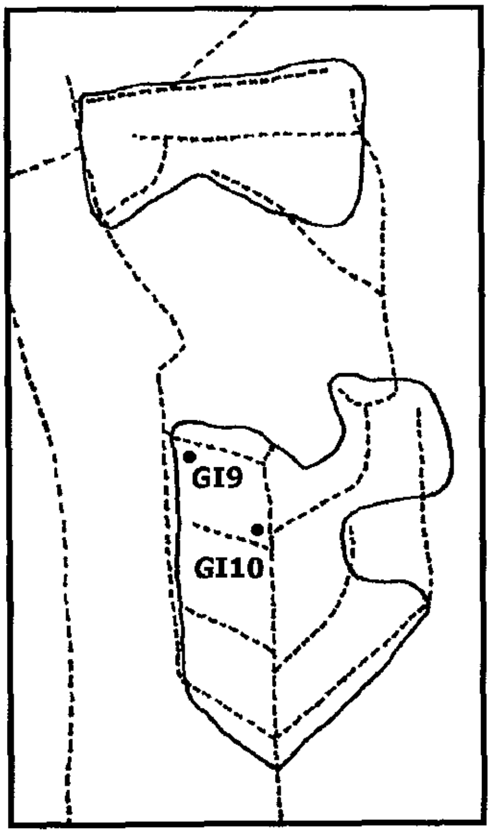

Figure 7. Gillermossen, with the stations GI9 and GI10.

3. Method

3.1. The method in general

3.1.1. The change in carbon stores after drainage

The change in carbon stores after drainage was calculated as the difference between the carbon content in the year 2000 and at a point in time close to the drainage, i.e. 10-20 years earlier, in a layer where all the decomposition after drainage was assumed to take place. The carbon content in the layer of interest was calculated from the weights of volumetric samples, their dry matter content and the carbon content in the dry matter. The carbon content was calculated separately for each station.

3.1.2. The layer studied

All peat above a certain level was included in the layer studied. The lower boundary of the layer was defined in relation to the peat surface as the conditions were on the day when the earlier samples were collected. For the earlier samples, the layer chosen was at 0-40 cm depth for the Siksjöbäcken stations, at 0-50 cm depth for Torvbråten and for Gillermossen at 0-50 cm depth for GI9 and at 0-100 cm depth for GI10.

It was assumed that almost all swelling, compaction and decomposition of the peat takes place in the upper 40 cm of the peat (considered from the original peat surface), i.e. in the layer studied. The peat at the lower boundary of the chosen layer could therefore be considered as stable. It was assumed that only negligible amounts of carbon moved across this limit, into or out of the layer studied, during the period studied. This assumption should be valid at least at the stations where the peat at this level was constantly waterlogged.

The peat surface level depends on the groundwater level in the peat (Johansson, 1974), and the peat also collapses after drainage, mainly because its structure is destroyed by decomposition (Eggelsmann, 1986). This means that the change in peat surface level between the two sampling occasions had to be known to be able to find the same peat layer a second time.

3.1.3. The change in peat surface level

The change in peat surface level after drainage was determined using groundwater tubes, which were installed to investigate the groundwater regime before and after drainage. These tubes were kept at the sites during the whole period studied. The tubes were levelled, i.e. their vertical positions were determined in relation to fixed points e.g. in the bedrock. Since the distances between the peat surface and the upper ends of the tubes were measured, the position of the peat surface in relation to the fixed points could be calculated. In the year 2000 the tubes were levelled again and their heights above the peat surface were measured. The level of the peat surface calculated from this new data was compared to the earlier surface level (Figure 8). On the stations where two groundwater tubes were available, the change in the peat surface level was calculated separarely for the two tubes and the mean value was used.

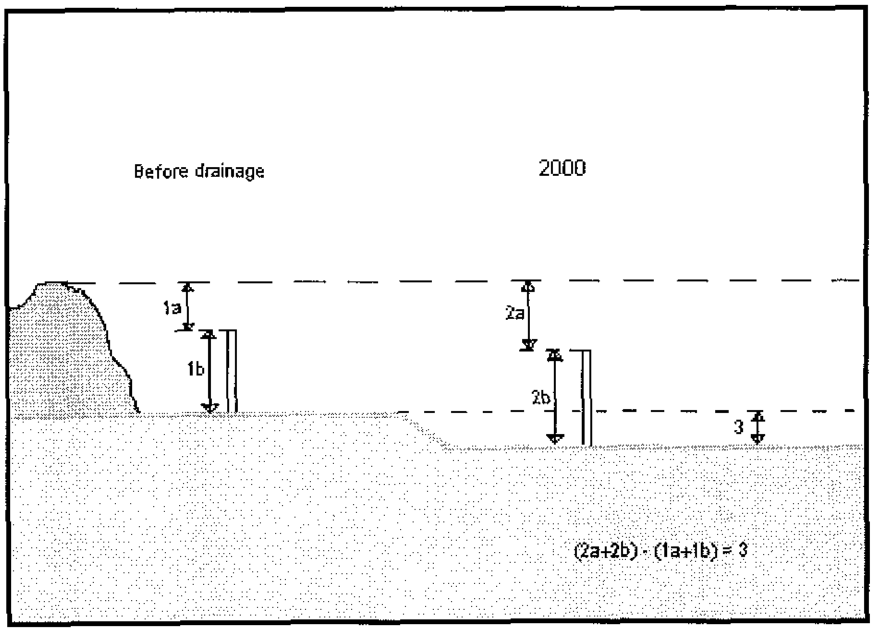

Figure 8. Determination of the change in peat surface level after drainage.

The values obtained showed the change in peat surface level between the two days, one in the year 2000 and one in an earlier year, when the tube heights were measured. The values of interest in the present investigation was, however, the changes in peat surface level, for the different stations, between the two sampling days. In the year 2000, the samplings and the tube height measurements were carried out on the same day, but this was not the case in the earlier years. To avoid errors, corrections had to be made to estimate the peat surface level on the actual sampling day for the years close to drainage.

On Gillermossen, the early samples were collected on 13/6-90, while the tube heights were measured on 29/6-90. The groundwater level rose considerably between these dates, but since it did not reach higher than 45 cm below the peat surface on the station GI 9 and not higher than 60 cm depth on the station GI10, it was assumed that the peat surface level was not affected.

On Torvbråten, the tube heights were not measured on a specific day, but on different occasions during May 1981. The volumetric samples were collected on 3/6-81. During some years before and after drainage, the peat surface level was measured continously at each station in the Torvbråten area. This was done with a special device with a reinforcement rod that was pushed down into the subsoil and a wooden frame that rested on the mire surface. The movements of the frame in relation to the rod were read on a scale on the rod. These measurements were used to calculate the difference in peat surface level between the days when the tube heights were measured and the day when the samples were collected. A mean value for the May levels was compared to the 3/6-81 level, at each station. The difference was used as a correction factor to calculate the peat surface level on the sampling day from the tube heights measured in May.

At Siksjöbäcken, the tube heights were measured during the first half of July 1979. Every tube was measured at installation. As will be discussed in the next section, the early samples were not used at all for the Siksjöbäcken stations. However, when calculating the peat subsidence, the day when the first groundwater measurements were made, 19/7-79, was used as a ”reference day”, equivalent to an ”early sampling day”. From measurements in the following years it could be concluded that the changes in peat surface levels in the beginning of July were usually quite small, about 0-3 centimetres. It was therefore assumed that the peat surface levels remained stable during the time when the tubes were installed and up until the first measurements of the groundwater level, on 19/7-79.

3.1.4. A different method for Siksjöbäcken

For the Siksjöbäcken area, there were no measurements of the peat surface level at the time when the early samples were collected. The peat surface level was determined only in July 1979, two years before drainage, when the tubes were installed. The first useful samples were collected on 23/9-1984, three years after the drainage of Letjärn and Särkalampi in 1981.

Earlier, in 1982 and 1983, samples had been collected only with a so called Hiller corer, which is not reliable for volumetric sampling.

Even when comparing two days with similar groundwater levels, the peat surface level could not be assumed to be the same in 1984 as in 1979, on Letjärn and Särkalampi, since the peat was drained in 1981. Drainage generally causes subsidence, since the water pressure is lowered and since the peat structure is destroyed by decomposition (Eggelsmann, 1986). The peat surface level on 23/9-1984 was therefore unknown, and the peat samples could not be used since it was not known which layer they were collected from.

Despite the disqualification of the early samples, it was possible to calculate an approximate mean value for the loss of carbon at the Letjärn and Särkalampi stations, using the reference mire, Hamptjärn. The three mires were assumed to be very similar before drainage. The mean carbon content for the Hamptjärn stations in the year 2000, in a certain layer, was compared to the mean carbon content for the corresponding layer at the Letjärn and Särkalampi stations, in the year 2000. Any differences in carbon content between the areas could be regarded as an effect of the drainage.

Before drainage, a layer measured from the peat surface and down to a certain depth could be compared for the three mires. After drainage, this was impossible, because of the subsidence of the peat. To find the same layer in the drained and the undrained mires in the year 2000, this had to be related to a layer defined in relation to the peat surface before drainage. The peat layer that was at 0-40 cm depth below the peat surface when the peat surface levels were measured in 1979, was chosen as a reference layer, for each station.

As was explained in the previous section, the hydrological conditions were assumed to be approximately the same for all stations during the first half of July, when the peat surface levels were measured. Direct comparisons between stations were therefore possible. Since the change in peat surface level was known between the early peat surface measurements and the sampling day in the year 2000, the reference layer could be found, for each station, in the year 2000.

3.1.5. The volumetric samples

Volumetric samples were collected from each station both in connection to the drainage and in the year 2000. A peat corer with a diameter of about 2.5 cm (cross-section area 4.38 cm^2) was used. Additional samples were collected in the year 2000 using a so called "humus corer", with a diameter of 10.2 cm. The humus corer samples were used to find out in which ways the volume weights of the samples were influenced by the sampling technique.

Subsamples from the volumetric samples were used to determine the dry matter content and the carbon content in the dry matter for each station. The samples collected in the year 2000 were also analysed for C-content, N-content and pH. Results from similar analyses, carried out in connection to the draining of the mires, were available for comparison.

3.1.6. Site factors

In the year 2000, it was determined which stations that could be considered as having a tree cover. The degree of decomposition, according to the von Post scale, was also determined, down to a depth of about one metre. Values from earlier measurements of the groundwater levels, from just before and some years after drainage, were available. This data, together with the laboratory values of C-content, N-content and pH, was used in an attempt to correlate the net change in carbon store to site factors.

3.2. Methods in the field

3.2.1. Levellings

The groundwater tubes were levelled, using a Wild-Heerbrug levelling device, which is an optical instrument on three legs. The instrument was placed out between two points to determine their vertical position in relation to one another. The points could be the top of a rock and the top of a groundwater tube. One person peeps through the instrument and determines the vertical position of a ruler-like pole, which is held on top of e.g. the rock by another person. The ruler is then held on top of e.g. the tube and its position is noted again. The difference in heights between the two points gives the vertical position of the tube in relation to the rock.

On most stations, there were initially two thin tubes, one for the peat groundwater level and one for the subsoil groundwater level. Both these tubes were levelled and used when calculating the peat surface level. At some stations the tubes had been damaged, but repaired or replaced. It was assumed that they were restored to the same height as before the damage.

3.2.2. Tube heights and the definition of the soil surface

When measuring the heights of the tubes, one has to know what can be defined as the soil surface. This is difficult in mires, since the plants themselves build up the soil in which they grow. In Sphagnum dominated mires the individual plant even grows on top of partly decomposed parts of itself.

The surface of interest was, in this case, the surface of the peat. The definition of what kinds of material that can be classified as true peat is a matter of debate (Ilomets, pers. comm., 2000). In this investigation, the distinction between what was regarded as peat and what was regarded as only ”dead organic matter” was made on the basis of how loose or compact the material was.

When the earlier samples were collected, the corer was pushed down through the living plants and the loose part of the sample was removed when the corer was opened. In the year 2000, the loose material was removed by scratching the soil gently with a gloved hand before sampling. It has been assumed here that though the peat surface level was determined by different people in the year 2000 and in the years just before and after drainage, using two different methods, the judgements were made in a similar way and the results are comparable. This assumption is supported by the observation in the year 2000 that the boundary between the loose and the more compact organic matter is often very clear.

Clymo (1992) defined four structural layers and four functional layers in peatlands (Bozkurt, 2000). The structural layers, as opposed to the functional layers, were not related to the water table. The structural layers were, from the surface of the mire:

**The euphotic layer*: the upper 2-5 cm, where the plants are alive and photosynthesising.

**The aerobic layer*: a 10–50 cm thick layer, where most of the material is dead, but still very porous.

**The collapse layer*: a 2-15 cm thick layer where the dead plant material has collapsed due to the weight of the higher layers and the dry bulk density is about 0.1 g cm^{-3}.

* *The lower peat layer*: a layer often over 100 cm thick, which consists of amorphous, highly humified peat.

It seems that by the "loose or compact" definition, the collapse layer and the lower peat layer were regarded as peat. In some cases, mainly on the tree-covered stations where cones and needles stabilize the material, the aerobic layer was also included in the peat layer.

The peat surface did not show an even level around the groundwater tubes. One reason for this is the natural mire pattern of hummocks and hollows or flarks and strings (Sjörs, 1948). However, on most stations it was also very noticeable that tussocks had formed around the tubes. Obviously, the mosses grow better in connection with a tube, maybe because they can cling to it or perhaps because tramping animals and people avoid the tube. When the tube heights were measured and the samples collected in connection to the drainage, this was done from what seemed to be a mean ground level around the tube. In the year 2000 the approximate mean level beside the tussock was used, avoiding hollows that seemed to be the result of tramping (Figure 9).

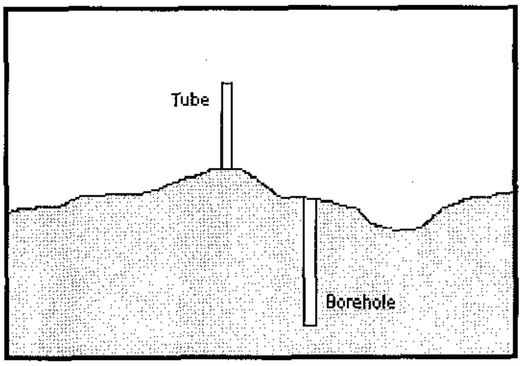

Figure 9. The placing of the samples.

3.2.3. Volumetric sampling

3.2.3.1. The peat corer

The same corer was used for both the old and the new samples – a “peat corer” with a cross-section area of 4.38 cm^2 and about 1.5 m long. The peat corer was open on one side when it was pushed into the ground. It was then closed by turning the handle, and pulled up. The corer opened by turning the handle again and it then contained a peat core that was up to about 1 m long. The peat core was cut into samples of appropriate lengths when it was still in the corer.

Five peat cores were collected at each station. The sample depths were the same in the year 2000 as for the early samples; at Siksjöbäcken 0-20 cm, 20-40 cm, and at some stations 40-60 cm; at Torvbråten 0-20 cm, 20-40 cm and 40-50 cm and at Gillermossen 0-20 cm, 20-50 cm and, at one station, 50-100 cm. The samples were collected in plastic bags and the air was pushed out to mitigate further decomposition. All samples were refrigerated within 5-6 days after sampling and stored for a maximum time of five months before the laboratory work was carried out.

3.2.3.2. Compaction or expansion in the corer

Some samples were compacted when the corer was pushed down into the soil and some expanded beyond their original upper limit when the corer was opened. In the year 2000 each sample was measured from where its upper end would have been without any compaction or expansion, i.e. from the level which corresponds to the peat surface in the mire. In the early years the sample length was measured from the upper end of the compacted or expanded sample, which means that the position of this level in relation to the peat surface of the mire is not known exactly.

3.2.3.3. The humus corer

In the year 2000, additional samples were collected with a so-called ”humus corer”, which has a diameter of 10.2 cm and reaches about 25 cm into the peat. Three samples were collected at each station. The lengths of these samples were measured both on the actual peat core and in the hole. Volume weights calculated using the sample lengths measured in the holes should be relatively accurate and not affected by compaction or expansion. The peat cores were measured when they had been pushed out of the corer. Most of them were compacted when they were in the corer, some expanded when they were released, some kept their shape and some may have been further compacted. The humus corer samples were collected in plastic bags with as little air as possible, and refridgerated, as the peat corer samples.

3.2.4. Properties of the sites

3.2.4.1. Degree of decomposition

The degree of decomposition was determined in 10 cm intervals, down to a depth of about one metre, according to the von Post scale (v. Post and Granlund, 1926). The classifications were carried out according to thorough instructions. Since this was done by an inexperienced person, however, the results should be seen as approximate.

3.2.4.2. Tree cover

The stations were crudely divided into two groups, on the basis of whether they had a tree cover or not. Generally, stations with at least 10 m high pines or 5 m high spruces were regrded as having a tree cover. When there was doubt, e.g. when there were trees on one side of the station and no trees on the other side (e.g. LE3), the station was classified as having a tree cover if the trees were large enough, many enough and close enough to the station to seem to be able to produce a considerable amount of above- and below-ground litter.

3.2.4.3. Groundwater levels

The groundwater levels were measured in the groundwater tubes, with a plummet.

3.3. Laboratory methods

3.3.1. Weights

The samples were weighed in the laboratory, in their plastic bags. The weights of the plastic bags were subtracted from the sample weights. The weights were recorded in grams, with two decimals for the peat corer samples and one for the humus corer samples.

3.3.2. Dry matter content

To determine the dry matter content, subsamples of about 10 g were dried in 105°C, for about 20 hours, and weighed before and after drying. The samples were left to cool down in an exsiccator for half an hour before the second weighing. One subsample was taken from each peat corer sample and three from each humus corer sample.

3.3.3. Ash content

For each sample depth, one of the dried peat corer subsamples was burnt in 500°C, overnight, to determine the loss on ignition or, inversely, the ash content. This was done to detect any inputs of mineral soil to the peat, which could affect the volume weights.

3.3.4. Carbon and nitrogen content

Three of the dried peat corer samples, for each sample depth, were ground and used for analyses of the carbon and nitrogen content. For Siksjöbäcken and Torvbråten the C and N contents were determined in different ways for the early samples and for the samples collected in the year 2000. The early samples were analysed with wet chemical methods and the later samples with a LECO CNS 100 elementar analyses device. For Gillermossen all samples were analyzed on the LECO apparatus.

3.3.5. pH

Fresh material from the peat corer samples was used for pH measurements. Two samples from each sample depth were used. Subsamples of about 10 ml were shaken with 25 ml of deionised water, left over night and shaken again. The pH was measured, with a pH meter, when the suspended material had sedimented.

4. Results

4.1. Changes in carbon store after drainage

4.1.1. The change in peat surface level

As was explained in the "Methods" section, a correction was made for the Torvbråten values, because the early tube heights were not measured on 3/6 in 1981, when the early samples were collected, but on different days during May 1981, and the peat surface level seemed to have changed between these occasions (Table 1).

Table 1. Subsidence at the Myggbotjärn and Torvbråten sites, 1981-2000.

Station	Subsidence May -81 -- 24-26/8-00	Subsidence May -81 -- 3/6-81	Subsidence 3/6-81 -- 24-26/8-00
M1	5,6	1,3	4,3
M2	3,9	2,0	1,9
M3	7,1	2,1	5,0
T4	16,5	5,2	11,3
T15	13,8	5,7	8,1
T8	41,4	1,9	39,5
T14	40,5	1,3	39,2

According to the final, corrected, values (Table 2), the peat surface subsided between the sampling occasions on all the stations studied, during the periods 1990-2000 (10 years), 1981-2000 (19 years) and 1979-2000 (21 years) for Gillermossen, Torvbråten and Siksjöbäcken, respectively. It is remarkable that the peat subsided even on the undrained sites, since the mean groundwater table was 0.7 cm higher on Hamptjärn and 4.0 cm higher on Myggbotjärn on the later sampling occasion. However, it is possible that dry periods or perhaps deposition of nutrients increased by anthropogenic sources (Franzén, pers. comm., 2000) have led to subsidence of the peat due to decomposition.

The mean subsidence was 6.9 cm at Hamptjärn (std 1.8), 12.5 cm at Letjärn and Särkalampi (std 7.4), 3.7 cm at Myggbotjärn (std 1.7), 9.7 cm at the Torvbråten marginal slope (std 2.3), 39.4 cm at the Torvbråten bog plane (std 0.2) and 11.0 cm at Gillermossen (std 2.6).

Table 2. The change in peat surface level between sampling occasions, for each station.

Station	HA4	HA5	HA6	LE3	LE4	LE5	LE6	SÄ4	SÄ5	SÄ9	SÄ10
Change in peat surface level between sampling occasions (cm)	-5,7	-9,0	-6,2	-13,8	-13,4	-10,6	-27,1	-5,4	-9,8	-6,6	-20,5
Station	SÄ14	SÄ15	GI9	GI10	M1	M2	M3	T4	T15	T8	T14
Change in peat surface level between sampling occasions (cm)	-16,0	-2,3	-9,1	-12,8	-4,3	-1,9	-5,0	-11,3	-8,1	-39,5	-39,2

4.1.2. Adjusting the samples for peat subsidence

In the year 2000, the samples were collected at the same depths as the early samples, e.g. 0-20 cm and 20-40 cm, but the starting-point was the subsided peat surface level. This means that parts of the deepest samples from the year 2000 reached below the sampling depth for the early samples. These parts were outside the layer of interest and their carbon content should not be included in the calculations (Figure 10).

The carbon content in the redundant part of a sample was calculated as the carbon content of the whole sample divided by the length of the sample and multiplied by the number of cm of subsidence. For most stations, only the lowest sample was partly redundant, but if the surface had subsided very much, two or even three of the samples from each peat core were involved.

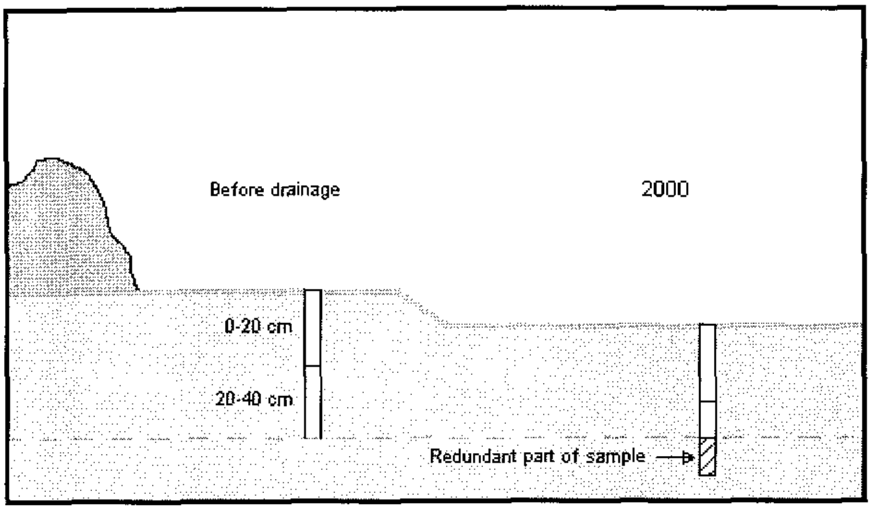

Figure 10. Cross-section of a corer-hole, showing how a part of each of the deepest samples in the year 2000 becomes redundant.

4.1.3. The carbon content in the dry matter

The wet chemical methods for the analyses of carbon content in the dry matter, which were used for the early Torvbråten and Siksjöbäcken samples, did not seem to give correct results. This has been recognized earlier, e.g. in the National Survey of Forest Soils and Vegetation. In the present study, the carbon content values for the early samples, based on wet chemical methods, were about 42 % of the dry matter and the values from the elemental analyses of the more recent samples were about 50 %. This difference could not be a result of decomposition after drainage only, but was probably caused by incorrect values from the wet chemical analyses. (Karltun, pers. comm., 2000). Therefore, for Torvbråten, the percentage values from the year 2000 were used for calculating the total carbon content for both the early and the late samples.

4.1.4. Compaction or expansion during sampling

Some of the early samples were compacted in the corer and measured from the compacted surface. This means that deeper layers were sampled than was originally intended. Others expanded before they were measured and cut, which means that they did not reach down to the intended depth (Figure 11). In this way, peat was added or removed at the lower end of the sample, where the density was comparably high. Hence, every cm of compaction or expansion caused a fairly large change in the total carbon content of the sample. The change in the final value of carbon loss, for every cm of compaction or expansion, was on average 23 g C m^{-2} yr^{-1} for the Torvbråten area and 62 g C m^{-2} yr^{-1} for Gillermossen. At Siksjöbäcken, corer compaction or expansion did not cause any problems since the early samples were never used.

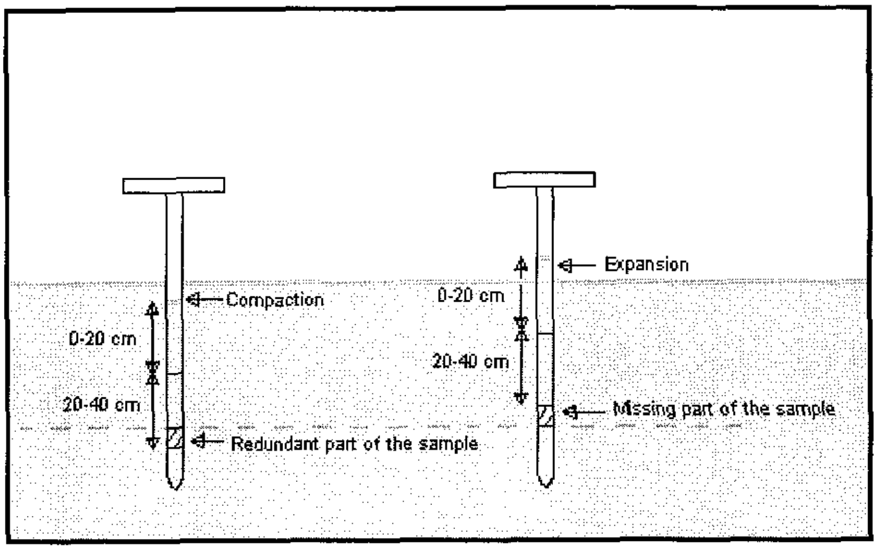

Figure 11. Compaction or expansion in the corer.

The only measurements available that could be used to estimate the compaction or expansion in the corer were the length measurements of the humus corer samples in the year 2000. The difference between the length of a humus corer sample measured in the hole and measured on the sample, was interpreted as the compaction or expansion in the humus corer. Assuming that the compaction or expansion in the corer depends more on the properties of the peat than on the type of corer, the mean value of compaction or expansion for the humus corer samples should be similar to the mean value for the peat corer samples, at the same station. In this way, values of the compaction or expansion of peat corer samples, collected by the method used for the early values but under the conditions that prevailed in the year 2000, could be estimated.

The mean compaction or expansion of the humus corer samples for each station were calculated, for the year 2000. Before the calculations, three values out of 61 were removed since they were regarded as "outlayers". The corer influence on the sample length, calculated as a mean value for each station, varied between 3 cm compaction and 0.5 cm expansion at Hamptjärn, 2.7 cm compaction and 1.5 cm expansion at Letjärn and Särkalampi, 2.5 and 1.0 cm compaction at Myggbotjärn, 2.3 and 0.3 cm compaction at Torvbråten, and 1.8 and 1.6 cm expansion at Gillermossen. Average values for each mire were calculated from the compaction or expansion values for the different stations. The mean corer compaction was then 1.3 cm for Hamptjärn (reference), 0.4 cm for Letjärn and Särkalampi (drained), 1.8 for Myggbotjärn (reference) and 1.6 for Torvbråten (drained). The Gillermossen samples (drained) had expanded 1.6 cm, on average.

It seems that samples collected at the reference mires were more compacted in the corer than those collected at the drained mires. There were also differences between the three mire areas, with the largest compaction at the Torvbråten area, less compaction at the Siksjöbäcken area and expansion at the Gillermossen area. A possible explaination of these differences was the correlation which was found between the compaction or expansion of the humus corer samples and their dry bulk density (dry weight/total volume) in their unchanged state. Generally, low-density peat was compacted more than high-density peat and low-density peat was more likely to have been compacted instead of expanded, compared to high-density peat. (Figure 12).

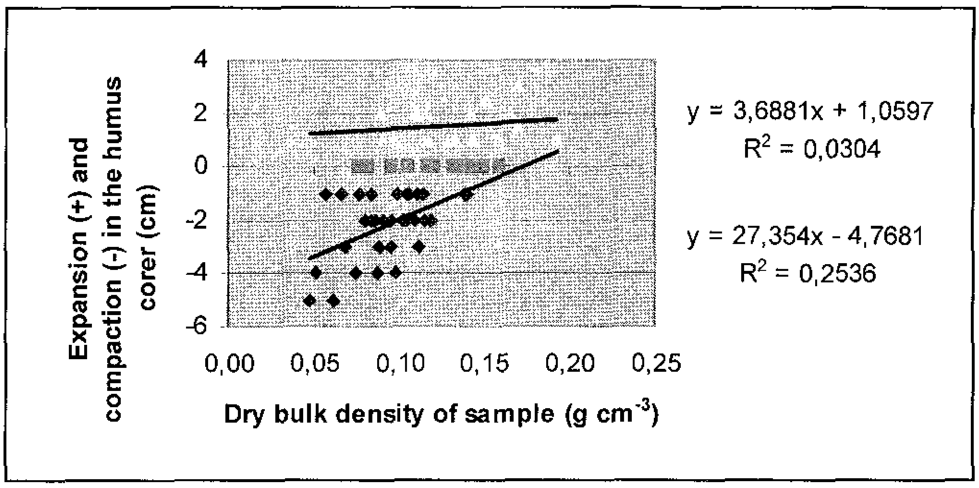

Figure 12. Relation between the dry bulk density of the peat layer and the compaction or expansion in the corer.

The mean dry bulk density, calculated from the humus corer samples measured in the hole, was 0.10 g cm^{-3} (std 0.02) at Hamptjärn, 0.11 g cm^{-3} (std 0.03) at Letjärn and Särkalampi, 0.08 g cm^{-3} (std 0.02) at Myggbotjärn, 0.09 g cm^{-3} (std 0.01) at Torvbråten and 0.15 g cm^{-3} (std 0.01) at Gillermossen. These values correspond very well to the values of corer compaction or expansion for the same mires.

Important to know for the present study was the corer compaction or expansion for the early samples at Torvbråten, Myggbotjärn and Gillermossen. Dry bulk density values calculated from the early samples were available, but the corer compaction or expansion could not be calculated from them, since they were themselves affected by corer compaction or expansion.

In the Torvbråten area, the early samples were collected before drainage and the average corer compaction should be similar to that of Myggbotjärn in the year 2000, as long as the groundwater levels were similar. The mean groundwater level in the peat at Myggbotjärn was, however, 7.8 cm lower on the first sampling occasion than on the second. This should have given a higher dry bulk density and the mean corer compaction at Torvbråten and Myggbotjärn in 1981 should therefore have been smaller than the mean value of 1.8 cm on Myggbotjärn in the year 2000. It was assumed to be zero.

For Gillermossen, there was no reference mire where groundwater levels could be compared. Most probably, however, the dry bulk density of the peat was lower for the early samples than for the ones collected in the year 2000. The mean expansion should then have been smaller than the 1.6 cm measured in the year 2000, since more samples would have been compacted instead of expanded. As for Torvbråten, the mean corer compaction or expansion for the mire was assumed to be zero.

Even though corer compaction or expansion was assumed not to influence the mean values of carbon loss for the mires, the values for single stations could be affected. For single stations in the year 2000, the maximum deviation from the true sample length was 2.5 cm compaction at Myggbotjärn, 2.3 cm compaction at Torvbråten and 1.8 cm expansion at Gillermossen. The maximum error caused by the corer technique in the Torvbråten area was assumed to be 3 cm, i.e. 69 g C m^{-2} yr^{-1}, or 22 % of the calculated final mean carbon loss for the mire. For Gillermossen, as mentioned above, a lower bulk density of the peat before drainage should have lead to smaller values of expansion for the early samples. However, the variation could be larger than the two available stations show. The maximum error caused by expansion during the sampling was therefore assumed to be 2 cm, i.e. 124 g C m^{-2} yr^{-1}, or 15 % of the calculated final mean carbon loss from the mire.

4.1.5. Carbon content in the layer studied

The carbon content per square metre, at each sample depth, was calculated from the mean carbon content of the five samples collected at that depth. The values of carbon content for the two or three sample depths were added together. For the year 2000, the carbon content calculated for the redundant parts of the lowest samples was subtracted from the total value. For Gillermossen and Torvbråten, values of the total carbon content in the layer studied, per square metre and for each station, were obtained in this way for the two different points in time. All stations showed lower values of carbon content in the year 2000 than in the years close to drainage (Table 3).

Table 3. The carbon content of the layer studied, in the years close to drainage and in the year 2000.

Station	Layer, measured from the original surface (cm)	C content, 1990 and 1981, respectively (g/m2)	C content, 2000 (g/m2)
GI9	0-50	31245	26381
GI10	0-100	64752	57562
M1	0-50	28477	16991
M2	0-50	20359	13326
M3	0-50	27534	20888
T4	0-50	26225	17713
T15	0-50	23502	14945
T8	0-50	21487	2429
T14	0-50	22175	1587

4.1.6. Special calculations for the Siksjöbäcken area

As mentioned in the "Methods" section above, it was not possible to use the early samples for the calculation of carbon loss at the Siksjöbäcken stations. However, a reasonable mean value of carbon loss could be calculated for Letjärn and Särkalampi, using data from the reference mire, Hamptjärn.

The carbon content in the year 2000, in a layer that was at 0-40 cm depth in 1979 (under certain hydrological conditions), was determined for all stations (Table 4). The mean carbon content for the undrained stations was 14900 g C m^{-2} (std 835) in the year 2000. For the undrained stations the mean carbon content was only 13500 g C m^{-2} (std 4200). Since the mean carbon content before drainage was assumed to be the same for the three mires in the Siksjöbäcken area, the difference between the drained and the undrained stations in the year 2000 should be a measure of the mean loss of carbon due to drainage.

Table 4. The carbon content in the year 2000, for the 1979 0-40 cm layer, at each station in the Siksjöbäcken area.

Station	Carbon content in the year 2000, for the 1979 0-40 cm layer (g/m2)
HA4	15853
HA5	14711
HA6	14227
LE3	15469
LE4	13290
LE5	9329
LE6	7200
SÄ4	19727
SÄ5	15448
SÄ9	10819
SÄ10	9375
SÄ14	15571
SÄ15	18638

4.1.7. The loss of carbon

The change in carbon content after drainage was calculated in terms of carbon loss, i.e. for Torvbråten and Gillermossen the early carbon content values were subtracted from the values in the year 2000. The loss of carbon per year after drainage was calculated (Table 5). It was assumed that carbon was lost only in the years after drainage, even when the measurements started out at a point in time before drainage, as on Torvbråten and Siksjöbäcken.

Table 5. The loss of carbon after drainage.

Station	Loss of carbon (g/m2/year)
M1	638
M2	391
M3	369
T4	473
T15	475
T8	1059
T14	1144
GI9	486
GI10	719
LE+SÄ	74

4.1.8. Correction using the reference mires

Before drainage, the drained mires were assumed to be similar to their corresponding reference mires. The differences between the mires after drainage were therefore assumed to be a result of the drainage. To determine the carbon loss caused only by drainage, the average carbon loss from the corresponding reference mire was subtracted from the carbon loss value for each drained station. In this way, all factors other than drainage, which could have influenced the carbon loss, were eliminated. The effects of fertilization in connection to the drainage were also regarded as "drainage effects" in this sense, and the absence of the usual accumulation was included in the carbon loss values.

By definition, mires are peat-forming wetlands (Löfroth, 1991). Therefore, net losses of carbon, like the values presented for Myggbotjärn in table 5, are not normal for undrained mires. This indicates that the losses of carbon from the drained stations were partly caused by factors other than drainage. Possible influences could have been a lower precipitation or a higher evaporation than usual, or perhaps deposition of nutrients from anthropogenic sources (Franzén, pers. comm., 2000). Most likely, however, the strongest irrelevant influences on the values of carbon loss were systematic errors during the sampling or while measuring the groundwater tubes. The difficulties in defining the peat surface should have been an important source of such errors. To obtain correct values of the carbon loss due to drainage, corrections using the reference mires were therefore essential.

For Gillermossen, no reference samples were available. However, if systematic errors were disregarded and if an imagined reference mire was accumulating carbon at a rate of $21 \text{ g C m}^{-2} \text{ a}^{-1}$ (the average for undrained northern peatlands, according to Clymo et al. 1998), the loss of carbon, caused by drainage only, could be calculated for Gillermossen as well as for the other mires. The absence of the accumulation assumed for the reference mire is regarded as a loss of carbon in such a calculation. The annual accumulation value was therefore multiplied by the number of years between the drainage and the year 2000 and this value was added to the carbon loss values calculated for each station.

For Siksjöbäcken, all values of carbon content were derived from the samples collected in the year 2000. Systematic errors from the samplings and from the tube height measurements were therefore eliminated when the mean carbon content for the undrained stations was subtracted from the mean carbon content for the drained stations. The absence of accumulation was also included in the total carbon loss. No further correction was needed.

4.1.9. Final carbon loss values

After the reference mire correction of the carbon loss values calculated for Torvbråten and Gillermossen in one way and for Siksjöbäcken in another way, the results could be considered as final. The average values of carbon loss for the different sites were 8 g C m^{-2} a^{-1} (std 2) for the marginal slope at Torvbråten, 635 g C m^{-2} a^{-1} (std 60) for the bog plane at Torvbråten, 813 g C m^{-2} a^{-1} (std 165) for Gillermossen and 76 g C m^{-2} a^{-1} (std unknown) for Siksjöbäcken (Table 6).

Table 6. The final values of carbon loss after drainage.

Station	T4	T15	T8	T14	Gl9	Gl10	LE+SÄ
Carbon loss (g/m2/year)	7	9	593	678	696	929	74
Average carbon loss for the site (g/m2/year)	(marginal slope) 8		(bog plane) 635		813		74

4.1.10. Degree of decomposition

The degree of decomposition was determined in 10 cm layers, down to a depth of about one metre, at all stations in the year 2000 (Table 7). For some stations there were earlier notes on the degree of decomposition. However, it was not possible to see any clear trends in the change over time by comparing these to the new samples. At some stations, like M3 and LE6, the earlier samples were classified as more decomposed than the later ones. This seems unreasonable, but it is possible that the early samples were stored in plastic bags for some time before classification. This often causes a slightly too high degree of decomposition.
The degrees of decomposition at drained and undrained stations were compared. At Siksjöbäcken, it was clear that the upper layer that consists of weakly decomposed peat was

thinner for the drained stations. The depth down to which the degree of decomposition was less than H6 was 66.7 cm (std 25.2) on Hamptjärn and 27.0 cm (std 9.5) on Letjärn and Särkalampi. This difference was statistically significant on the 1% level and could not be explained only by the subsidence of 12.5 cm (std 7.4) at Letjärn and Särkalampi, especially not since the peat surface subsided at Hamptjärn as well, by 6.9 cm (std 1.8). The higher degrees of decomposition at the drained stations confirm that the drainage has caused secondary decomposition of the peat.

In the Torvbråten area, there was a clear difference between the bog plane stations and the marginal slope stations, especially for the drained stations. The peat on the bog plane was less decomposed. No obvious difference could be seen between the drained and the undrained marginal slope stations. At the two drained bog plane stations, T8 and T14, the degree of decomposition was very low (H2-H3) and did not increase with depth. At the only undrained bog plane station, M2, the degree of decomposition varied between H2 and H5 in the upper 100 cm. The higher degree of decomposition at Myggbotjärn is probably a result of a more intense primary decomposition. M2 is closer to the marginal slope than T8 and T14 and the site was probably richer in nutrients from the beginning. Even if the early C content values were not entirely reliable the early C/N ratios could give a hint on the initial nutrient status. The C/N ratio was 59.3 for M2, 97.2 for T8 and 69.3 for T14.

Table 7. The degree of humification for each 10 cm layer, down to 100 cm depth, in a year close to drainage and in the year 2000, at each station.

Mire	**Hamptjärn (undrained fen)**									
Station	**HA4**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H3	H4	H4	H4	H4	H5	H5	H5	H5	H6
1982	H4	H4	H4	H4	H4	H5	H5	H5	H5	H5
Station	**HA5**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H4	H5	H5	H5	H6	H4	H5	H6	H6	H6
1982	-	-	-	-	-	-	-	-	-	-
Station	**HA6**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H4	H5	H5	H4	H4	H5	H5	H7	H7	H7
1982	H5	H5	H5	H5	H5	H8	H8	H8	H8	H8
Mire	**Letjärn (drained fen)**									
Station	**LE3**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H3	H5	H5	H6	H6	H7	H8	H8	H8	H8
1982	-	-	-	-	-	-	-	-	-	-
Station	**LE4**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H3	H5	H5	H6	H6	H7	H8	H8	H8	H8
1982	-	-	-	-	-	-	-	-	-	-
Station	**LE5**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H3	H4	H4	H5	H8	-	-	-	-	-
1982	H5	H5	H5	H5	H5	H7	H7	H7	H7	H7
Station	**LE6**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H4	H4	H5	H5	H6	H6	-	-	-	-
1982	H7	H7	H7	H7	H7	H8	H8	H8	H8	H8
Mire	**Särkalampi (drained fen)**									
Station	**SÄ4**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H2	H5	H5	H7	H8	H8	H8	H8	H6	H6
1982	-	-	-	-	-	-	-	-	-	-
Station	**SÄ5**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H2	H3	H7	H6	H6	H7	H7	H7	H6	H6
1982	H6	H6	H6	H6	H6	H8	H8	H8	H8	H8
Station	**SÄ9**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H3	H5	H7	H6	H8	-	-	-	-	-
1982	-	-	-	-	-	-	-	-	-	-

Station	**SÄ10**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H4	H4	H6	H8	H8	H8	-	-	-	-
1982	-	-	-	-	-	-	-	-	-	-
Station	**SÄ14**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H3	H8	H8	H8	H8	-	-	-	-	-
1982	H4	H4	H4	H4	H4	H9	H9	H9	H9	H9
Station	**SÄ15**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H3	H4	H4	H8	H8	-	-	-	-	-
1982	-	-	-	-	-	-	-	-	-	-
Mire	**Gillermossen (drained fen)**									
Station	**Gl9**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H5	H6	H8	H8	H8	H8	H8	H8	H8	H9
1990	H4	H4	H7	H7	H7	H8	H8	H8	H8	H8
Station	**Gl10**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H4	H6	H7	H8	H8	H8	H8	H8	H8	H8
1990	H5	H5	H7	H7	H7	H7	H7	H7	H7	H7
Mire	**Myggbotjärn (undrained bog)**									
Station	**M1**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H2	H4	H5	H3	H5	H4	H5	H5	H5	H5
1983	-	-	-	-	-	-	-	-	-	-
Station	**M2**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H2	H3	H4	H3	H4	H4	H4	H4	H4	H5
1983	H3	H3	H3	H3	H3	-	-	-	-	-
Station	**M3**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H2	H3	H5	H5	H3	H3	H5	H5	H5	H3
1983	H7	H7	H7	H7	H7	-	-	-	-	-
Mire	**Torvbråten (drained bog)**									
Station	**T4**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H2	H4	H5	H5	H5	H7	H7	H6	H6	H3
1983	-	-	-	-	-	-	-	-	-	-
Station	**T15**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H5	H4	H3	H4	H5	H5	H5	H5	H5	H3
1983	H4	H4	H4	H4	H4	-	-	-	-	-
Station	**T8**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H3	H3	H3	H3	H3	H3	H3	H3	H3	H3
1983	-	-	-	-	-	-	-	-	-	-
Station	**T14**									
Depth (cm)	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
2000	H2	H3	H3	H3	H3	H3	H3	H3	H3	H3
1983	H2	H2	H2	H2	H2	-	-	-	-	-

4.2. The change in groundwater table after drainage

The change in the groundwater table after drainage was calculated as the difference between the mean groundwater level, during the frost-free part of the year, for one year before drainage and one year after drainage. The frost-free season was generally assumed to last from May to October, but in some cases only June to October or May to September values were available.

Years with about the same amount of precipitation were chosen for the comparison. For the Torvbråten and Siksjöbäcken areas, the years 1980 and 1984 were the most suitable. The drainage was carried out December 1981 to July 1982 for Torvbråten and Mars to April 1981 for Siksjöbäcken. For Gillermossen, 1989 and 1996 were similar with regard to precipitation, and the mire was drained in January to Mars 1990. In 1984 and 1996, respectively, the new groundwater levels should have been well established, as long as they were not affected by an increased or decreased water uptake by trees (Lundin, pers. comm., 2000).

Generally, the groundwater levels were measured in the peat layer, but there were some exceptions. At GI10, a tube perforated below the peat layer, at 1.2-1.4 m depth, was used. At GI9 a peat layer tube, perforated at 25-75 cm depth, was used before drainage and a subsoil tube, perforated at 90-110 cm depth, was used after drainage. The difference between the subsoil water table and the peat water table was probably small at these stations (Lundin, pers. comm., 2000). For the calculations it was assumed that the water-table was the same in the peat and in the subsoil.

For Siksjöbäcken and Torvbråten the observed groundwater levels were related to the top of the groundwater tube. The tubes were levelled, and the values could be corrected for any vertical movements of the tubes. The early and the late measurements were therefore directly comparable. For Gillermossen, the groundwater levels were measured as in relation to the soil surface, but both the early and the late measurements were related to the peat surface on the same occasion, the day when the tube heights were measured in 1990, and the values could therefore be compared.

The change in groundwater level was recorded for the undrained as well as for the drained stations. All stations showed a drawdown of the groundwater level (Table 8). The mean water-level drawdown was 5.9 cm (std 2.1) and 4.8 cm (std 3.4) on the reference mires Hamptjärn and Myggbotjärn, respectively. On the drained mires the values were 36.3 cm (std 18.4) at Letjärn and Särkalampi, 17.7 (std 9.2) at the Torvbråten marginal slope, 33.6 (std 2.7) at the Torvbråten bog plane and 50.9 cm (std 2.9) at Gillermossen. The water-level drawdown on the undrained stations indicates that the values for the drained stations were exaggerated, at least at Letjärn, Särkalampi and Torvbråten. This was corrected for by subtracting the mean water-level drawdown for each reference mire from the values for the corresponding drained stations. No correction could be made on Gillermossen, since there was no reference mire. It had to be assumed that the Gillermossen values were correct from the beginning.

The final mean values of water-level drawdown after drainage were 30.4 cm (std 18.4) at Letjärn and Särkalampi, 12.9 cm (std 9.2) at the Torvbråten marginal slope, 28.8 cm (std 2.7) at the Torvbråten bog plane and 50.9 cm (std 4.1) at Gillermossen (Table 9).

The two Torvbråten values were both significantly different from the Gillermossen value, on the 5 % level. The value for Letjärn and Särkalampi was also significantly different from the Gillermossen value, but on the 10 % level. The differences between the Torvbråten values and the Letjärn and Särkalampi value were not significant on any level. The water-level drawdown differed significantly between the bog plane and the marginal slope, at Torvbråten, at the 10 % level.

Table 8. The water-level drawdown after drainage, preliminary values.

Station	Water-level drawdown after drainage (cm)	Mean	Std
HA4	4,8	5,9	2,1
HA5	4,5		
HA6	8,3		
LE3	20,7	36,3	18,4
LE4	21,3		
LE5	23,2		
LE6	43,3		
SÄ4	29,6		
SÄ5	41,1		
SÄ9	26,8		
SÄ10	72,7		
SÄ14	62,0		
SÄ15	22,1		
M1	0,9	4,8	3,4
M2	6,3		
M3	7,3		
T4	11,2	17,7	9,2
T15	24,2		
T8	31,7	33,6	2,7
T14	35,5		
GI9	53,8	50,9	2,9
GI10	48,0		

Table 9. The water-level drawdown after drainage, final (corrected) values for the drained stations.

Station	Water-level drawdown after drainage, final values for the drained stations (cm)	Mean	Std
LE3	14,8	30,4	18,4
LE4	15,4		
LE5	17,4		
LE6	37,5		
SÄ4	23,7		
SÄ5	35,2		
SÄ9	20,9		
SÄ10	66,9		
SÄ14	56,1		
SÄ15	16,2		
T4	6,3	12,9	9,2
T15	19,4		
T8	26,8	28,8	2,7
T14	30,7		
GI9	53,8	50,9	4,1
GI10	48,0		

4.3. Site factors

The site factors investigated in this study that could influence the carbon emissions or accumulation were the nutrient status, the tree cover and the pH.

4.3.1. The nutrient status

The nutrient status of the peat was investigated by analysing the content of carbon and nitrogen in the peat samples and calculating the C/N ratio (Table 10). Higher nitrogen concentrations have been shown, by Coulson and Butterfield (1978), to increase the decomposition for at least some plant species. The effects of the phosphorus concentration on decomposition were investigated in the same study and did not show any positive correlations. On the contrary, higher concentrations of phosphorus decreased the rate of decomposition for Sphagnum by 32 %. The phosphorous content was not measured in the present study, but the areas that were fertilized with phosphorus and potassium, as described in the "Description of the areas" section, should have an increased concentration of phosphorus.

As has already been mentioned, the carbon content analyses from the years immediately after drainage were not reliable for Torvbråten and Siksjöbäcken. On the other hand, for these areas, the mean C/N ratios for the reference mires could be assumed to be equal to the initial mean C/N ratios on the corresponding drained areas. The mean C/N ratios before drainage were then 22.5 for Gillermossen, 28.6 for the Siksjöbäcken area and 58.5 for the Torvbråten area. These values fall into the normal ranges of about 15-35 for fen peat, 20-70 for highly decomposed bog peat and 50-100 for weakly decomposed bog peat (Naucke et al., 1993). Since the values of the C/N ratios were obtained from the reference mires, no differences in C/N ratio within the Torvbråten or Siksjöbäcken areas could be determined.

The mean initial C/N ratio for the fen stations was 26.2, which was significantly different from the mean initial C/N ratio for the bog stations (58.5), on the 1 % level. The difference in the initial C/N ratio between the two fen areas, Siksjöbäcken and Gillermossen, was significant on the 10 % level. The C/N ratio before and after drainage was significantly different on the 10 % level for Torvbråten, but not significant on any level for Gillermossen or for Letjärn and Särkalampi.

Table 10. The C/N ratio in the 0-40 or 0-50 cm layer.

Station	C/N 0-40(50) cm Early samples	C/N 0-40(50) cm Year 2000 samples	Mire	C/N 0-40(50) cm Early samples Mean values	C/N 0-40(50) cm Year 2000 samples Mean values
HA4	28,1	33,1	Hamptjärn	25,1	28,6
HA5	25,8	26,9	(undrained)	(std 3,4)	(std 3,9)
HA6	21,5	25,8			
LE3	24,5	26,0	Letjärn and	25,6	32,0
LE4	27,8	26,6	Särkalampi	(std 4,2)	(std 8,4)
LE5	26,0	34,3	(drained)		
LE6	19,7	24,9			
SÄ4	21,1	25,4			
SÄ5	24,6	36,8			
SÄ9	35,0	46,2			
SÄ10	25,5	26,7			
SÄ14	24,2	45,8			
SÄ15	27,8	27,5			
GI9	21,1	19,6	Gillermossen	22,5	21,8
GI10	24,0	23,9	(drained)	(std 2,0)	(std 3,0)
M1	51,3	61,5	Myggbotjärn	54,6	58,5
M2	59,3	64,1	(undrained)	(std 4,2)	(std 7,6)
M3	53,1	49,9			
T4	45,1	43,6	Torvbråten	65,1	50,2
T15	49,0	51,7	(drained)	(std 23,9)	(std 4,5)
T8	97,2	52,9			
T14	69,3	52,7			

4.3.2. Tree cover

The trees continuously add carbon to the soil in the form of litter. According to earlier studies, the tree cover can influence the peat carbon store strongly through these inputs (Laiho, 1997). Litter from woody vegetation is also relatively resistant to decomposition due to its high content of lignin (Minkkinen, 1999). Tree litter consists of needles, leaves and cones, but also to a large extent of roots (Vogt et al., 1986). Fine roots play an important role in the production of below-ground litter in peatlands (Laiho and Finér, 1996). If the trees grow better after drainage, the input of litter increases. (Laiho and Laine, 1996; Finér and Laine, 1998).

All stations were classified as having or not having a tree cover (Table 11). 57 % of the stations in the Torvbråten area, 77 % in the Siksjöbäcken area and 100 % in the Gillermossen area were tree-covered. On both the reference mires, Hamptjärn and Myggbotjärn, two out of three stations had a tree cover. 80 % of the Letjärn and Särkalampi stations had a tree-cover and, at Torvbråten, the two marginal slope stations had a tree-cover (100 %) and the two bog plane stations were not tree-covered (0 %).

P and K are usually the nutrients limiting tree growth on peatlands (e.g. Paarlahti et al. 1971). Hence, fertilization with these elements generally increases tree growth and thereby also the input of litter. At Torvbråten, P and K fertilization was carried out around the planted trees on the bog plane in 1984 and on the marginal slope in 1985. Parts of the Letjärn and Särkalampi areas were fertilized in 1983. Gillermossen was not fertilized during the period studied.

Table 11. The presence or absence of a tree cover.

Station	HA4	HA5	HA6	LE3	LE4	LE5	LE6	SÄ4	SÄ5	SÄ9	SÄ10
Tree cover	x	x			x		x	x	x	x	x
No tree cover			x	x		x					
Station	SÄ14	SÄ15	GI9	GI10	M1	M2	M3	T4	T15	T8	T14
Tree cover	x	x	x	x	x		x	x	x		
No tree cover						x				x	x

4.3.3. pH

The average bog peat (Sphagnum) has a pH of about 3.5-4.0 (Franzén, 1987) and the pH for fen peat normally varies between 4.0 and 7.5 (Löfroth, 1991). The higher values for fens are due to the inflow of base cations from the surrounding soil (Minkkinen, 1999). In this investigation, the early pH mean values, measured in the upper 40-50 cm, were significantly different for the fen stations and the bog stations, on the 1 % level. The mean pH was 3.7 (std 0.2) for the bog stations and 4.6 (std 0.4) for the fen stations. The mean pH values were also different for the two fen areas, Siksjöbäcken and Gillermossen, but the difference was not significant. The mean pH was 4.9 (std 0.3) at Gillermossen and 4.6 (std 0.3) for the Siksjöbäcken stations. There was no significant difference in pH between the bog plane and the marginal slope at Torvbråten. (Table 12)

In minerotrophic mires the pH of the peat often decreases after drainage, because the inflow of base cations from the surroundings is cut off by the ditches and because more base cations are taken up by the tree stand (Minkkinen, 1999). In the present study, no significant differences in peat pH could be seen between drained and undrained mires in the year 2000 (Table 12). At Siksjöbäcken and Gillermossen, the pH did not change significantly between the two sampling occasions. At Torvbråten, there was a significant increase in pH, on the 1 % level, between the early and the late samples (3.7 (std 0.2) and 4.2 (std 0.2), respectively), but this was the case also for the reference mire Myggbotjärn (3.7 (std 0.1) for the early samples and 4.1 (std 0.2) for the late samples), though on the 5 % level. No effects of drainage on the pH could be established. At Siksjöbäcken, the early pH values were measured in 1984, three years after drainage, and may therefore not correspond to the pH in the totally undrained state.

Table 12. Values of pH for stations and mires.

Station	pH 0-40(50)cm Early samples	pH 0-40(50) cm Year 2000 samples	Mire	pH 0-40(50)cm Early samples Mean values		pH 0-40(50)cm Year 2000 samples Mean values	
HA4	4,3	4,2	Hamptjärn	4,5		4,4	
HA5	4,3	4,3	(undrained)	(std 0,3)		(std 0,3)	
HA6	4,8	4,7					
LE3	4,6	4,5	Letjärn and	4,6		4,5	
LE4	4,1	4,5	Särkalampi	(std 0,4)		(std 0,3)	
LE5	4,3	4,0	(drained)				
LE6	4,8	4,7					
SÄ4	4,9	4,5					
SÄ5	4,6	4,2					
SÄ9	3,8	4,1					
SÄ10	4,7	4,5					
SÄ14	4,8	4,9					
SÄ15	5,0	4,9					
GI9	5,1	4,8	Gillermossen	4,9		4,4	
GI10	4,7	4,0	(drained)	(std 0,3)		(std 0,6)	
M1	3,8	4,3	Myggbotjärn	3,7		4,1	
M2	3,8	4,0	(undrained)	(std 0,1)		(std 0,2)	
M3	3,6	4,0					
T4	3,5	4,0	Torvbråten	3,7	Marg. 3,6	4,2	Marg. 4,0
T15	3,7	4,0	(drained)	(std 0,2)	slope (std 0,2)	(std 0,2)	slope (std 0,0)
T8	4,0	4,3			Bog 3,8		Bog 4,3
T14	3,6	4,4			plane (std 0,2)		plane (std 0,1)

Ivarsson (1977) limed peat samples to different pH levels and measured the decomposition in terms of the production of CO_2. The decomposition increased with pH. In the present study, the pH on the different areas was correlated (negatively) to the C/N ratio (Figure 13), and the effects of these two factors on the change in carbon stores could therefore not be distinguished.

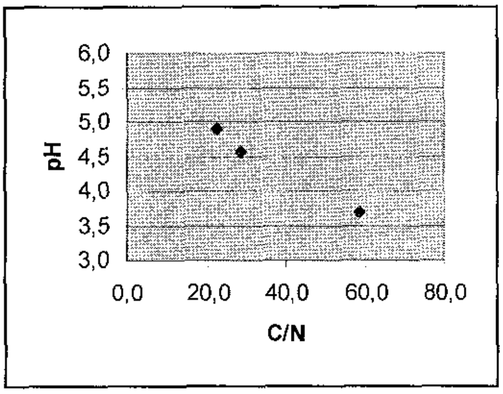

Figure 13. The correlation between the pH and the C/N ratio for the three mire areas (Gillermossen, Siksjöbäcken and Torvbråten), at a point in time close to drainage.

5. Discussion

5.1. Uncertainties in the calculations of carbon loss

During the course of determining the carbon loss for the different stations, uncertainties could have been introduced mainly in the following ways:

1. Through incorrect determinations of the peat surface level
2. Through mineral soil contamination of the peat samples, which would have disturbed the values of volume weight and C/N ratio
3. Through errors in the laboratory work
4. Through the use of the dry matter carbon contents for the samples collected in the year 2000, for the calculations of the total carbon content in the early samples (at Torvbråten)
5. Through the transfer of carbon across the lower limit of the layer studied.
6. Through the use of mean values with large standard deviations

5.1.1. The peat surface level

Errors concerning the peat surface level could occur when the heights of the groundwater tubes were measured, when the samples were collected, through the compaction or expansion of the samples during the sampling and due to differences in the peat surface level between the day when the samples were collected and the day when the peat surface level was measured. The possibilities to make corrections for these errors were investigated and elaborated in the following section.

The determinations of the peat surface level when the tube heights were measured and when the samples were collected, had to be assumed to be accurate, since there was no way to make a correction. For the corer compaction, the information derived from the humus corer samples allowed a correction of the mean values for the mires, but it was concluded that such a correction was not needed. The errors arising from the fact that the sampling days and the days when the tube heights were measured did not coincide, could be corrected using measurements of the peat surface level (Torvbråten), groundwater level measurements (Gillermossen) or groundwater level measurements from other years but during the same period (Siksjöbäcken). However, it was decided that a correction was needed only for Torvbråten.

Corrections reduce systematic errors but not random errors and some uncertainty remains also for the corrected values. An attempt was made to estimate the maximum errors, in the final mean carbon loss values for the drained mires, that could have been caused by errors concerning the peat surface level. Both the sources of errors where corrections could be made and those where corrections could not be made were considered. The errors were estimated, in the following section, in terms of centimeters of peat added or removed at the lower end of the deepest sample. The effects of the reference mire corrections were not included in the values. For Torvbråten, the maximum errors were assumed to be the same for the marginal slope and for the bog plane, since there was not enough data available to make a distinction between the sites.

5.1.1.1. The peat surface and the tube height measurements

Every time a groundwater tube was measured, a decision had to be made on which level and which spot around the tube that was to be regarded as the peat surface. These subjective judgements undoubtedly caused uncertainties in the values of the change in the peat surface level after drainage. At most stations there were two groundwater tubes and one calculation of the peat subsidence was made for each of them. The two values obtained in this way should have been very similar if the peat surface level had been determined in an objective way. In reality, they differed considerably on many stations.

The mean difference between the values for the two tubes were 3.3 cm (std 3.3) and on two of the stations, HA6 and SÄ4, the difference was more than 10 cm. On M3, T14 and on the two Gillermossen stations, there was only one tube available and no comparison could be made. If one of the values for each station was assumed to be accurate, the maximum error for the mean of the two values would be the difference between them divided by two (Table 13).

Table 13. Uncertainties in the subsidence values. S = subsoil groundwater tube. P = peat layer groundwater tube.

Station	HA4		HA5		HA6		LE3		LE4		LE5	
Tube	S	P	S	P	S	P	S	P	S	P	S	P
Change in peat surface level between sampling occasions (cm)	-5,8	-5,6	-7,4	-10,5	-1,0	-11,3	-13,5	-14,1	-10,1	-16,6	-9,3	-11,8
Mean	-5,7		-9,0		-6,2		-13,8		-13,4		-10,6	
Difference (cm)	0,2		3,1		10,3		0,6		6,5		2,5	
"Maximum error" (cm)	0,1		1,6		5,2		0,3		3,3		1,3	
Station	LE6		SÄ4		SÄ5		SÄ9		SÄ10		SÄ14	
Tube	S	P	S	P	S	P	S	P	S	P	S	P
Change in peat surface level between sampling occasions (cm)	-28,3	-25,9	-0,1	-10,7	-9,8	-9,8	-7,6	-5,6	-20,8	-20,1	-13,4	-18,6
Mean	-27,1		-5,4		-9,8		-6,6		-20,5		-16,0	
Difference (cm)	2,4		10,6		0,0		2,0		0,7		5,2	
"Maximum error" (cm)	1,2		5,3		0,0		1,0		0,3		2,6	
Station	SÄ15		GI9		GI10		M1		M2		M3	
Tube	S	P	S	P	S	P	S	P	S	P	S	P
Change in peat surface level between sampling occasions (cm)	-5,4	0,8	-9,1	-	-12,8	-	-4,5	-4,2	-0,1	-3,6	-5,0	-
Mean	-2,3		-9,1		-12,8		-4,3		-1,9		-5,0	
Difference (cm)	6,2		-		-		0,3		3,5		-	
"Maximum error" (cm)	3,1		-		-		0,2		1,8		-	
Station	T4		T15		T8		T14					
Tube	S	P	S	P	S	P	S	P				
Change in peat surface level between sampling occasions (cm)	-12,3	-10,3	-7,1	-9,1	-39,8	-39,3	-39,2	-				
Mean	-11,3		-8,1		-39,5		-39,2					
Difference (cm)	2,0		2,0		0,5		-					
"Maximum error" (cm)	1,0		1		0,3		-					

The mean value of the maximum errors for the stations was regarded as the maximum errror for the mean value of subsidence. For the Siksjöbäcken area, where there were two tubes at every station, the mean of the maximum errors for the stations was 1.9 cm (std 1.8). The mean value was smaller at the Torvbråten area (0.8 cm (std 0.7)) than at Siksjöbäcken. On the other hand, there were two stations in the Torvbråten area where there was only one useful tube and the errors were unknown. The maximum error of the mean subsidence could therefore have been larger than the calculated value. At Gillermossen, none of the two stations had two tubes that could be used for calculations. The peat at Gillermossen was more compact than at Siksjöbäcken or Torvbråten, at least in the year 2000, and it was therefore less doubt about which level that could be regarded as the peat surface. On the other hand, there were only two stations and the maximum error should not decrease very much by the calculation of a mean value for the mire. It was assumed that the maximum error of the mean value of subsidence was the same for the three mire areas. The Siksjöbäcken value was used as a guideline and the maximum error was considered to be 2 cm.

5.1.1.2. The peat surface and the sampling

Variations in the subjective determinations of what was to be regarded as the peat surface would have caused errors during the sampling. The samples around a groundwater tube should have been collected from a surface which corresponded to the surface from which the tube height was measured. If this was not the case, a too deep or too shallow layer was sampled.

Since the deeper layers of the peat generally were much more compact than the uppermost layers, deviations in the determinations of the peat surface level would have caused errors in the carbon content of the samples. Interpreted as an addition or subtraction of peat at the lower end of the deepest sample, the error for a single sample could probably be several centimetres. The mean error for the five samples at each station would, however, be smaller than the errors for single samples. The maximum mean error for a station was assumed to be 2.5 cm, at each sampling occasion.

When estimating the maximum error for each mire area, the properties of the mires should be considered. As for the errors for the subsidence values, it was considered that the peat at Gillermossen was more compact, but also that the mean value was calculated for only two stations. It was again assumed that the maximum mean error was the same for all the three mire areas. The maximum mean error for a whole mire should be smaller than the 2.5 cm estimated for a single station. A reasonable value would be 1.5 cm, at each sampling occasion. Since there were two sampling occasions, the total maximum mean error would be 3 cm.

5.1.1.3. Compaction or expansion in the corer

After considering both the compaction or expansion of the humus corer samples, the groundwater levels on the sampling occasions and the expected compaction of the peat after the drainage of a mire, it was concluded that the mean corer compaction or expansion was zero for the Torvbråten area and for Gillermossen. The maximum error for the zero values was assumed to be 1.5 cm. The effect of the corer technique on the mean carbon loss values for the Siksjöbäcken area was also zero, but in this case the reason was that the early samples, where the corer technique was a problem, were not used. This was 100 % certain and there were no errors.

5.1.1.4. The difference in peat surface level between the samplings and the tube height measurements

It was assumed for the Siksjöbäcken and Gillermossen stations that the peat surface level did not change between the early tube height measurements and the early samplings. For Siksjöbäcken, the assumption was based on the stable groundwater table, which was not known through direct measurements but was assumed to be similar to that of the years immediately after the sampling year, in the same period. On Gillermossen, the peat surface level was assumed to be stable because the groundwater levels were fairly low. Since changes in the peat surface levels were not measured and therefore could only be estimated indirectly from the groundwater levels, there were uncertainties in the assumption that the peat surface did not move. The maximum mean error, for each mire, could not be zero but should not have been very large either. It was assumed to be 1.5 cm.

At Torvbråten, a correction was made using direct measurements of the peat surface level. However, the tube height measurements were carried out during the whole month of May in 1981, a period when the groundwater level was not considered to be stable. A mean value of the peat surface level for May, which varied with between 1.8 and 4.2 cm for different stations during this period, had to be used for the correction. In this way, uncertainties were introduced. The maximum mean error was then assumed to be the same as for Siksjöbäcken and Gillermossen: 1.5 cm.

5.1.1.5. Sum of the errors

In the extreme case when the maximum errors presented above were added, the sum would have been 6.5 cm for Siksjöbäcken and 8 cm for Torvbråten and Gillermossen. In every cm of the deepest sample, which was the one that would have been affected, the carbon content corresponded to 23 g C m^{-2} yr^{-1} for the Torvbråten area, 26 g C m^{-2} yr^{-1} for Siksjöbäcken and 62 g C m^{-2} yr^{-1} for Gillermossen, on average. The 6.5 or 8 cm would then correspond to a loss or an addition of about 169 g C m^{-2} yr^{-1} at Siksjöbäcken, 184 g C m^{-2} yr^{-1} at Torvbråten, and 496 g C m^{-2} yr^{-1} at Gillermossen.

5.1.2. Mineral soil in the samples

The content of ash in the peat was measured, to detect any inputs of mineral soil to the peat samples. Mineral particles are heavy compared to the organics of peat and their presence could cause unwanted effects on the volume weights and on the values of carbon and nitrogen content.

The ash content commonly ranges between 5 and 15 % of the dry matter for fen peat (Naucke et al., 1993) and between 1 and 6 % of the dry matter for bog peat (Grumpelt, 1991). In the peat samples collected for the present study, in the year 2000, the ash content varied between 1.7 and 15.6 % of the dry matter for the fen peat and between 0.5 and 4.1 % for the bog peat. Though some of the values were slightly outside the normal range, the deviations were not so large that they could not be explained by errors during the analyses. Hence, the ash content did not reveal any inputs of mineral soil to the peat.

5.1.3. Errors in the laboratory work

The laborations were carried out very carefully and the final values of dry matter content, carbon content, nitrogen content and pH, for each station, were mean values based on

2 to 9 subsamples. The laboratory results were therefore considered as reliable and errors in the final carbon loss values, caused by errors during the laborations, were regarded as negligible.

5.1.4. Carbon content in the dry matter at Torvbråten

For the early Torvbråten samples, the carbon content in the dry matter was determined by chemical methods that did not give satisfactory results. The values for the samples collected in the year 2000 were therefore used when calculating the values of total carbon content for the early as well as for the late samples.

For Gillermossen, where the values should be accurate, the carbon content in the dry matter increased with 1.0 %-units in the 0-20 cm layer and decreased with 0.6 %-units in the 20-50 cm layer, in the 10 years immediately after drainage. In Finnish mires, an increase in the dry matter carbon content by 1.6 % have been noted, over about 60 years after drainage (Minkkinen, 1999). A decrease in the dry matter carbon content by 1 %-unit, in the early Torvbråten samples, causes an increase of only about 2 g C m^{-2} yr^{-1} in the mean carbon loss from the mire. The error caused by using the dry matter carbon content for the year 2000, for the early samples as well, can be regarded as negligible.

5.1.5. Carbon fluxes across the lower limit of the layer studied

For the calculations of the loss of carbon from the soil after drainage, a layer was chosen where all decomposition, swelling and compaction was assumed to take place. It was assumed that no carbon was transferred across the lower boundary of this layer during the period studied. These assumptions may not be valid at all stations.

5.1.5.1. Decomposition below the layer studied

In the years immediately after drainage, the groundwater levels were measured regularly. It was found that on some of the stations (Table 14) the groundwater levels were well below the maximum sample depth during a large part of the season (Figure 14). At some stations the groundwater table remained low during the whole season (Figure 15). This could be expected to cause increased decomposition below the layer studied. If decomposition has been going on in the deeper layers, the loss of carbon may be underestimated for the stations with a low post-drainage groundwater table.

Table 14. The stations where the groundwater levels were well below the maximum sample depth during a large part of the season, in 1983 and 1984, respectively.

Station	HA4	HA5	HA6	LE3	LE4	LE5	LE6	SÄ4	SÄ5	SÄ9	SÄ10	SÄ14	SÄ15	GI9	GI10	M1	M2	M3	T4	T15	T8	T14
Stations with low groundwater levels in 1983				x	x		x	x	x	x	x	x		-	-							
Stations with low groundwater levels in 1984							x		x		x	x		-	-							

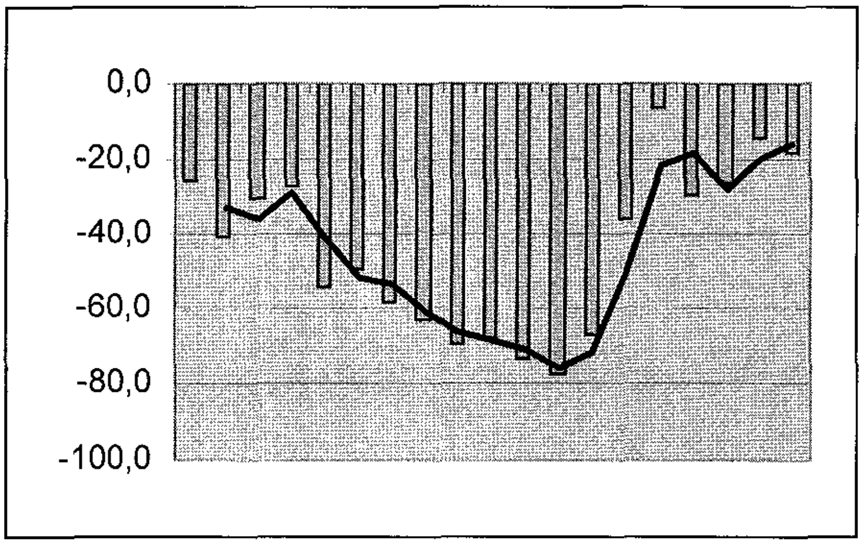

Figure 14. Groundwater levels over the 1983 season (15/6-27/10) for the station SÄ4, below the peat surface as it was on 25/7-80.

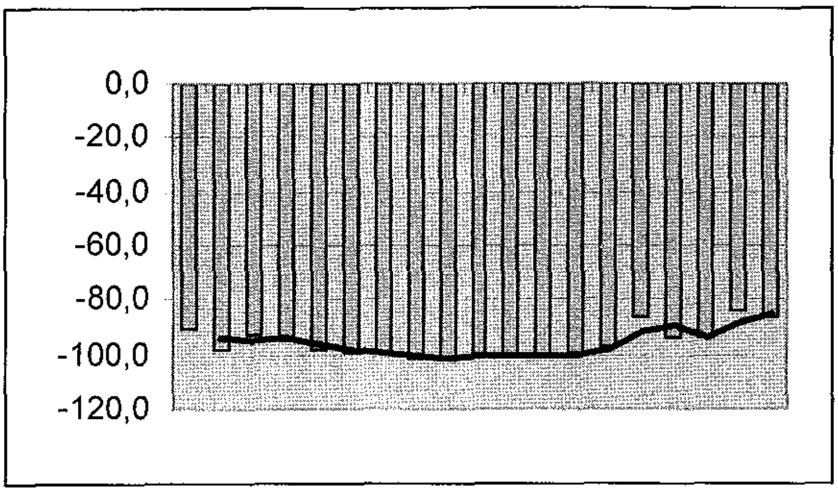

Figure 15. Groundwater levels over the 1983 season (15/6-27/10) for the station SÄ10, below the peat surface as it was on 25/7-80.

It has been suggested, on the other hand, that peat already strongly decomposed is more resistant to further decomposition than weakly decomposed peat, even when exposed to aerobic conditions (Hogg, 1992). In the present investigation, the very low groundwater tables were found only on the fen stations, and the exposed material which was below the sampled layer was indeed strongly humified. This may mean that the carbon losses from the deeper peat layers have been limited even when the groundwater levels have been low. In a study on Finnish mires (Silvola et al., 1996), an increase in CO2 flux with water-level drawdown was observed only down to a depth of the water table of about 30-40 cm. This supports the conclusion that the underestimation of the total carbon loss, due to decomposition below the layer studied, was small. The mean errors for the mires should be even smaller, since very low water tables did not occur at all stations.

5.1.5.2. Transfer of carbon past the lower limit of the layer studied

Decomposition in deeper layers, due to low groundwater levels, may not only cause losses of carbon but also subsidence, due to the carbon loss or due to the destruction of the peat structure. This means that carbon may have been transferred downwards, past the lower limit of the layer studied. If this has been the case, some of the carbon lost from the layer studied was not lost from the soil, but was only relocated within the soil. If the carbon loss from the layer studied was interpreted as the total carbon loss from the soil, the value would be exaggerated.

Subsidence in the deeper layers should be more pronounced for weakly decomposed peat, where the structure has not already collapsed. Since only fen stations, with strongly decomposed peat in the deeper layers, were subjected to the excessively low water tables, the subsidence effect should be small. If some subsidence has occurred due to loss of carbon, the exaggeration of the carbon loss value may compensate for the underestimation of the carbon loss value caused by any carbon lost below the layer studied.

In a study on Finnish fens, the bulk density of the peat increased significantly after forest drainage, down to a depth of 60 cm in all the regions studied and below 80 cm in southern Finland (Minkkinen and Laine, 1998). However, the groundwater levels were not assumed to be very low in this case and the subsidence was attributed to the increasing weight of the tree stand after drainage. A similar effect could have occurred on the tree-covered stations in the present study, though only to a small extent since the increase in tree growth after drainage was generally small.

5.1.6. Mean values

Mean values were used at three important stages in the calculations. The mean carbon content at Hamptjärn was subtracted from the mean carbon content at Letjärn and Särkalampi, to obtain a value of the carbon loss at Letjärn and Särkalampi. The carbon loss values at the Torvbråten stations were corrected using the mean value of carbon loss for Myggbotjärn. The carbon loss values for the separate stations were used to calculate mean values of carbon loss for the Gillermossen site, the Torvbråten marginal slope site and the Torvbråten bog plane site, respectively.

The coefficient of variation for the mean carbon content was 6 % for Hamptjärn (14900 g C m^{-2} (std 835)) and 31 % for Letjärn and Särkalampi (13500 g C m^{-2} (std 4200)). The mean carbon loss at Myggbotjärn, used for the reference mire correction on Torvbråten, had a coefficient of variation of 32 % (466 g C m^{-2} a^{-1} (std 149)). 6 % is fairly low and 31 % and 32 % can be regarded as acceptable.

The coefficient of variation was 10 % (635 g C m^{-2} a^{-1} (std 60)) for the mean value of carbon loss for the two bog plane stations and 22 % (8 g C m^{-2} a^{-1}(std 2)) for the two marginal slope stations, at Torvbråten. The coefficient of variation for the mean value of carbon loss for the two Gillermossen stations was 20 % (813 g C m^{-2} a^{-1} (std 165)). These values are not very high, but it should be considered that a standard deviation based on only two values does not contain very much information and a coefficient of variation calculated from it does therefore not say much about the reliability of the mean value.

5.1.7. Combined uncertainties

Inputs of mineral soil to the peat samples, errors during the laborations and errors caused by using the dry matter carbon content for the year 2000 for the early samples at Torvbråten, were regarded as negligible. Errors caused by the transfer of carbon across the lower limit of the layer studied were also assumed to be negligible, though the assumption was not very well supported, due to a limited knowledge on the behaviour of mires. The remaining sources of errors were those concerning the peat surface level and the use of mean values.

For the Torvbråten marginal slope, the Torvbråten bog plane and for Letjärn and Särkalampi, the errors in the mean carbon loss arising from incorrect determinations of the peat surface level were corrected by the use of the reference mires. If the drained mires and the corresponding reference mires were identical from the beginning and if the mean values of carbon content (Siksjöbäcken) or carbon loss (Torvbråten), calculated from the data for the available stations, were the true mean values for the mires, all errors would be eliminated. The errors in the final mean carbon loss values for the Torvbråten sites could therefore be regarded as results of incomplete reference mire corrections. Similarly, for Letjärn and Särkalampi, errors in the final mean carbon loss value should only occur if the subtraction of the mean carbon content at Hamptjärn, from the mean carbon content at Letjärn and Särkalampi, did not eliminate all errors.

It was not possible to find out if the drained mires and their reference mires were initially identical. The errors caused by any differences could not be quantified and had to be regarded as negligible. The relation between the calculated mean values and the true mean values, on the other hand, could be investigated through the calculation of confidence intervals. If the errors caused by the uncertainties in the mean values were regarded as the only errors, the confidence intervals could be used to find reasonable maximum and minimum values for each of the final mean carbon loss values, for the Torvbråten sites and for Letjärn and Särkalampi. 90 % confidence intervals were used.

For Gillermossen, no reference mire data was available and no correction was made for the errors concerning the peat surface level. Mean values were not used, except that a final mean value of carbon loss, with a coefficient of variation of 20 %, was calculated for the two Gillermossen stations. All other errors were regarded as negligible. Under these circumstances, the estimations of the errors concerning the peat surface level were assumed to give reasonable maximum and minimum values for the final carbon loss.

5.1.7.1. The Torvbråten sites

The 90 % confidence interval of the mean carbon loss, before the reference mire correction, was 466 ± 89 g C m^{-2} a^{-1} for Myggbotjärn, 474 ± 6 g C m^{-2} a^{-1} for the Torvbråten marginal slope and 1102 ± 268 g C m^{-2} a^{-1} for the Torvbråten bog plane, i. e. there was a 90 % chance that the true mean values would be found within these ranges. For the differences between the reference mire mean value and the mean value for each of the drained sites, confidence intervals could only have been calculated if the standard deviations for the mean values would have been similar. Since the standard deviation for the mean carbon loss at Myggbotjärn (mean 466, std 149) differed very much from the standard deviations for the mean carbon loss values at the Torvbråten marginal slope (mean 474, std 1.4) and the Torvbråten bog plane (mean 1102, std 60), respectively, this was not possible. However, by adding the confidence interval for Myggbotjärn to the confidence interval for each of the drained sites, intervals between the maximum and minimum values of the final mean carbon loss, which at least would not decrease the confidence level, could be obtained. The estimated mean carbon loss for the Torvbråten marginal slope, after the reference mire correction, was then 8 ± 95 g C m^{-2} a^{-1} (a possible variation beween an accumulation of carbon of 87 g C m^{-2} a^{-1} and a loss of carbon of 103 g C m^{-2} a^{-1}). For the Torvbråten bog plane, the estimated final mean carbon loss was 636 ± 357 g C m^{-2} a^{-1} (minimum and maximum values of 279 g C m^{-2} a^{-1} and 993 g C m^{-2} a^{-1}). The mean values of carbon loss for the single stations were more uncertain, since they could be influenced by random errors to a larger extent.

5.1.7.2. Letjärn and Särkalampi

At Siksjöbäcken, the 90 % confidence interval of the mean carbon content was 14900 ± 1408 g C m^{-2} for Hamptjärn and 13500 ± 2435 g C m^{-2} for Letjärn and Särkalampi. By the same reasoning as for Torvbråten, the true value of the change in the carbon stores after drainage could be somewhere between a loss of carbon of 2443 g C m^{-2} and an accumulation of carbon of 5243 g C m^{-2}, or between a loss of carbon of 276 g C m^{-2} a^{-1} and an accumulation of carbon of 128 g C m^{-2} a^{-1}.

5.1.7.3. Gillermossen

For Gillermossen, since there was no reference mire, the maximum errors concerning the determination of the peat surface level were used to calculate maximum and minimum values of the final mean carbon loss. The mean value was then 813 ± 496 g C m^{-2} a^{-1}. The maximum value of carbon loss was 1309 g C m^{-2} yr^{-1} and the minimum value was 317 g C m^{-2} yr^{-1}. This method for calculating maximum-minimum intervals was not directly comparable to the method using confidence intervals. The method used for Gillermossen seemed to give lower values. Therefore, in reality, the uncertainty in the mean carbon loss value was probably larger for Gillermossen than for Torvbråten and for Letjärn and Särkalampi. A reference mire correction would probably have improved the accuracy.

5.1.7.4. The intervals

For Letjärn and Särkalampi and for the Torvbråten bog plane, the maximum-minimum intervals calculated from the confidence intervals, for the final carbon loss values, were larger than those calculated from the errors connected to the uncertainties in the determinations of the peat surface. This should, however, not mean that the certainty of the mean value decreased when the correction was made. It should be emphasized that the maximum and minimum values were not absolute, and should only be regarded as guidelines. They were based on assumptions and particularly on assumptions of which probabilities that could be regarded as negligible. For an estimated range, there is always a small probability that there will be values outside the range. The limit at which this probability was regarded as negligible was chosen arbitrarily and was probably different for the two calculation methods. The results generated from the use of the two different methods were therefore not fully comparable.

Even if, in some case, the uncertainty for the corrected mean value was indeed larger than for the value calculated from the peat surface level errors, the reference mire correction should still have improved the mean value, in the sense that the calculated mean value should be closer to the true mean value after the correction. The reference mire correction also should have reduced not only the errors connected to the determinations of the soil surface, but also errors that may have been caused by the transfer of carbon across the lower limit of the layer studied and perhaps other errors that have not been considered.

5.2. Differences in post-drainage carbon loss between sites

Regardless of the uncertainties investigated in the previous section, the most probable values of carbon loss for the mires were, naturally, the mean values. The correlations of these values to site factors were investigated. The factors influencing the rate of decay of organic matter are, generally, temperature, soil moisture content, nutrient supply, pH and the quality of the decomposing material. (Sylvia et al., 1998). The peat carbon stores are, in addition to these factors, influenced by inputs of carbon in the form of litter.

To cover as many as possible of the factors influencing the change in carbon stores after drainage, the C/N ratio, the pH, the tree cover and the post-drainage water-level drawdown were measured or estimated, at each station. The soil temperature was not measured, but the mean annual air temperatures and the mean January and July air temperatures are similar for the three mires (see the section "Description of the areas"). Over the relatively long periods studied, the mires were assumed to be similar with regard to temperature. The information gathered for the stations was used in an attempt to explain the differences in carbon loss between sites.

5.2.1. The fen areas

The two fen areas, Gillermossen and Siksjöbäcken, showed very different mean values of carbon loss for the drained stations: 813 g C $m^{-2} a^{-1}$ and 74 g C $m^{-2} a^{-1}$, respectively. When analysing the prerequisites of carbon loss, it was found that the water-level drawdown after drainage and the initial C/N ratio were both significantly different for the two areas, on the 10 % level. The initial pH values for the areas did not differ significantly. There was a tree cover at 80 % of the stations at Letjärn and Särkalampi and at 100 % of the Gillermossen stations. The carbon loss at Gillermossen was calculated over a 10 year period compared to a 19 year period for Letjärn and Särkalampi. The shorter period studied should have given a relatively higher value of carbon loss per year at Gillermossen, if the loss of carbon was larger in the years immediately after drainage and then declined. This is the normal process when weakly humified organic matter is decomposed under aerobic conditions (Sylvia et al., 1998). The water-level drawdown after drainage was 30.4 cm for Letjärn and Särkalampi and 50.9 cm for Gillermossen. The difference, 20.5 cm, was large and could be a main explaination of the differences in carbon loss. The C/N ratio was 25.5 for Letjärn and Särkalampi and 22.5 for Gillermossen. This difference was not very large, especially when compared to the Torvbråten value of 58.5. The denser tree cover at Gillermossen should probably have decreased the carbon loss by the input of litter and increased the differences between the mires. The shorter period of study at Gillermossen could very well have had a large influence on the difference in carbon loss between the two areas.

The uncertainty of the Gillermossen value, partly due to the lack of a reference mire correction, was considered. If the errors at Gillermossen were similar to the errors on Letjärn and Särkalampi and on Torvbråten, a reference mire correction would have decreased the mean value. The difference between the Gillermossen and the Letjärn and Särkalampi values of carbon loss would then have been smaller. This, together with the differences in water-level drawdown, C/N ratio and the number of years studied, could give a reasonable explaination of the difference in carbon loss between the two fen areas.

5.2.2. Differences between fen and bog site types

It seemed reasonable to investigate the bog plane and the marginal slope at Torvbråten as different sites, since they differed both with regard to the tree cover and the post-drainage water-level drawdown and since their values of carbon loss were very different. The study therefore covered two bog sites and two fen sites. A general comparison between fen and bog site types, with regard to carbon loss after drainage, could be made only if the sites studied were similar with regard to factors not particular to the site type. To begin with, the impact of drainage should be similar.

The mean water-level drawdown after drainage was 12.9 cm at the marginal slope, 28.8 cm at the bog plane, 30.4 cm at Letjärn and Särkalampi and 50.9 cm at Gillermossen. The Letjärn and Särkalampi value was not significantly different from any of the bog values. Gillermossen, on the other hand, differed significantly from both the bog sites, on the 5 % level. The Letjärn and Särkalampi site was therefore more suitable than the Gillermossen site to use for a comparison between fen and bog site types.

Other reasons for chosing Letjärn and Särkalampi to represent the fen site type were that the Gillermossen carbon loss values were more uncertain, that Siksjöbäcken and Torvbråten were studied during approximately the same period of time (19 and 20 years, respectively) and that the drained parts were fertilized on both Siksjöbäcken and Torvbråten. The tree cover, with 0 % tree covered stations on the Torvbråten bog plane, 100 % on the marginal slope, 80 % on Letjärn and Särkalampi and 100 % on Gillermossen, differed mainly between the bog plane and the other sites. The closer similarity to the marginal slope for Gillermossen compared to Letjärn and Särkalampi, with regard to the tree cover, was not regarded as an important reason to use Gillermossen in the comparisons.

5.2.2.1. The fen site and the bog plane site

The mean carbon loss was 635 g C m^{-2} a^{-1} (std 60) for the Torvbråten bog plane and 74 g C m^{-2} a^{-1} (std unknown) for the drained parts of Siksjöbäcken, i.e. Letjärn and Särkalampi. It seems that drainage caused a greater loss of carbon from the bog plane stations than from the fen stations. However, since the standard deviation of the Siksjöbäcken value was not known, it could not be decided if the mean carbon loss values were significantly different. Since the mean water-level drawdown was very similar for the bog plane and for Letjärn and Särkalampi (28.8 cm (std 2.7) and 30.4 cm (std 18.4), respectively), other factors than differences in the impact of drainage should have caused the difference in carbon loss.

The initial C/N ratio at Torvbråten was high (58.5), compared to the value for Letjärn and Särkalampi (28.6). The C/N ratio was not known for the separate stations, since it was derived from the mean value for the reference mire in the year 2000, but the more unreliable early values of the C/N ratio indicate that the mean C/N ratio was initially even higher for the bog plane than for the bog as a whole. The initial pH was 3.8 for the bog plane and 4.6 for Letjärn and Särkalampi. These factors indicate that the environment was not as favourable for decomposition at the Torvbråten bog plane as at Letjärn and Särkalampi.

The remaining investigated site factor that could explain the higher carbon loss from the bog plane site compared to the fen site, despite a lower pH and a higher C/N ratio, was the tree cover. The bog plane was treeless and 50 % of the Letjärn and Särkalampi stations were regarded as tree-covered. A tree cover can influence the carbon loss in several ways. As was mentioned in the "Results" section, the addition of litter, especially lignin-rich litter such as needles, could contribute considerably to the carbon store. On a tree covered bog site in Central Finland, a total annual input of above-ground and below-ground litter of 420 g C m^{-2} was measured (Laiho and Laine, 1996; Finér and Laine, 1998). A tree cover can also cause a lower soil temperatur, by shading the ground, which can decrease the rate of decomposition. Furthermore, a developing treestand can lower the groundwater table through increased evapotranspiration. If the groundwater table was lowered at the tree-covered stations in the present study, after the measurements of the water-level drawdown, this could be an additional factor influencing the final values of carbon loss.

Apart from the measured or estimated site factors, the quality of the decaying material should be considered. The fen peat was initially more decomposed than the bog plane peat and peat that is already strongly decomposed has been shown to be more resistant to further decomposition than weakly decomposed peat, even when exposed to aerobic conditions (Hogg, 1992). The mean initial degree of decomposition on Letjärn and Särkalampi, in the aerated layer, should have been about H4-H5, assuming that it was approximately equal to the present value at the reference mire Hamptjärn. The degree of decomposition was still only about H3 at Torvbråten, in the year 2000. This could be one explaination to the relatively high values of carbon loss for the bog plane stations in the Torvbråten area. High values of carbon loss from weakly decomposed bog peat, which was exposed to oxygen, were found by Hogg (1993), even in deep layers.

5.2.2.2. The fen site and the marginal slope site

The loss of carbon from the marginal slope was small, 8 g C m^{-2} a^{-1} (std 2), compared to the 74 g C m^{-2} a^{-1} (std unknown) lost from the Letjärn and Särkalampi fen site. The difference was not surprising, however, since all the considered prerequisits for carbon loss, at the marginal slope, were either similar to those at the fen site or less favourable. The post-drainage water-level drawdown on the marginal slope was 12.9 cm, which is relatively small. The C/N ratio was high, though possibly slightly lower than for the bog plane, and the pH was low (3.6). Both stations on the marginal slope had a tree cover, which was a larger share than at Letjärn and Särkalampi.

The degree of decomposition was about H4-H5 on the marginal slope, in the upper 50 cm, in the year 2000. The early value of H4 for the upper 50 cm of the peat at T15 suggests that the degree of decomposition did not change very much in the marginal zone after drainage. The initial degree of decomposition was therefore probably similar to that at Letjärn and Särkalampi (H4-H5).

5.2.3. The bog plane and the marginal slope

The difference in carbon loss between the bog plane and the marginal slope at Torvbråten was significant on the 1 % level. As mentioned in the previous section, the carbon loss was 635 g C m^{-2} a^{-1} (std 60) for the bog plane and 8 g C m^{-2} a^{-1} (std 2) for the marginal slope. The waterlevel drawdown after drainage was 28.8 cm at the bog plane and 12.9 cm at the marginal slope. The difference was significant on the 10 % level. The larger drainage impact for the bog plane was probably one, but not the only, reason for the difference in carbon loss between the two sites.

The general differences between the bog plane and the marginal slope of a bog arise from differences in the groundwater conditions. The groundwater table is lower at the marginal slope, which leads to better conditions for tree growth. A tree cover is one of the characteristic features of a marginal slope. When the groundwater table is low the dead organic material is also exposed to aerobic conditions for a longer time before entering the anaerobic layer, and it thereby reaches a higher degree of primary decomposition. A fairly high variability in the groundwater table at the marginal slope can also lead to secondary decomposition. The mean groundwater level for the summer of 1981, i.e. before drainage, below the peat surface as it was on 3/6-81, was about 24 cm for the marginal slope and about 10 cm for the bog plane. The initial degree of decomposition was estimated as about H4-H5 for the marginal slope and less than H3 for the bog plane.

The main reasons for the smaller carbon loss at the marginal slope compared to at the bog plane, at Torvbråten, were probably the smaller drainage impact, the tree cover (which should have added carbon in the form of litter) and the initially higher degree of decomposition (which could have meant that the peat was more resistant to further decomposition). The pH was not significantly different for the two sites and the C/N ratio was high for both sites but possibly higher for the bog plane, which, if anything, would have restricted the losses of carbon from the bog plane.

6. Conclusions

The four sites studied all showed losses of carbon from the peat after drainage. The mean carbon loss, caused by drainage, was 74 g C $m^{-2}a^{-1}$ over a period of 19 years for Letjärn and Särkalampi, 8 g C $m^{-2} a^{-1}$ over 18 years for the Torvbråten marginal slope, 635 g C $m^{-2} a^{-1}$ over 18 years for the Torvbråten bog plane and 813 g C $m^{-2}a^{-1}$ over 10 years for Gillermossen (Table 15). In the undrained state, the average northern peatland accumulates carbon at a rate of 21 g C $m^{-2}a^{-1}$ (Clymo et al., 1998).

The post-drainage water-level drawdown, the tree cover and perhaps the initial degree of decomposition of the peat seemed to be important factors determining the changes in the peat carbon stores. The C/N ratio and the pH seemed to be less important.

The results of the study indicate that the net carbon loss from the peat, after the drainage of a mire, may be greater for an open bog plane (Torvbråten) than for a partly tree-covered fen with a similar drainage impact (Letjärn and Särkalampi). The difference may be explained by the tree cover or by the initially higher degree of decomposition of the fen peat.

All stations at the drained mires showed a drawdown of the water-table, due to the drainage. The water-level drawdown varied considerably between stations. The peat subsided at all stations during the period studied, including the stations in the undrained areas. The subsidence at the undrained stations could not be explained in the present study. To give a picture of the reliability of the mean value of carbon loss for each site, maximum and minimum values were calculated. The maximum and minimum values were based either on a confidence interval calculated for the mean value of carbon loss after a correction of the value by the use of the corresponding reference mire, or on estimations of the errors that could arise from difficulties in determining the peat surface level. (Table 15)

Table 15. The water-level drawdown caused by drainage, the peat subsidence during the period studied and the change in the peat carbon stores caused by drainage, during the period studied. The change in the peat carbon stores is presented both for the single stations and as mean values for the sites, with maximum and minimum values.

Station	Water-level drawdown caused by drainag (cm)	Peat subsidence after drainage, (cm)	Change in the peat carbon stores caused by drainage (g/m2/a) Single stations	Change in the peat carbon stores caused by drainage (g/m2/a) Mean (max -- min)
HA4 (undrained)	(assumption) 0	5,7	(assumption) 0	(assumption) 0
HA5 (undrained)	(assumption) 0	9,0	(assumption) 0	(assumption) 0
HA6 (undrained)	(assumption) 0	6,2	(assumption) 0	(assumption) 0
LE3 (drained	14,8	13,8	(no values for single stations)	-74 (+128 -- -276)
LE4 (drained	15,4	13,4		
LE5 (drained	17,4	10,6		
LE6 (drained	37,5	27,1		
SÄ4 (drained)	23,7	5,4		
SÄ5 (drained)	35,2	9,8		
SÄ9 (drained)	20,9	6,6		
SÄ10 (drained)	66,9	20,5		
SÄ14 (drained)	56,1	16,0		
SÄ15 (drained)	16,2	2,3		
M1 (undrained)	(assumption) 0	4,3	(assumption) 0	(assumption) 0
M2 (undrained)	(assumption) 0	1,9	(assumption) 0	(assumption) 0
M3 (undrained)	(assumption) 0	5,0	(assumption) 0	(assumption) 0
T4 (drained	6,3	11,3	-7	-8 (+87 -- -103)
T15 (drained	19,4	8,1	-9	
T8 (drained	26,8	39,5	-593	-636 (-279 -- -993)
T14 (drained	30,7	39,2	-678	
GI9 (drained	53,8	9,1	-696	-813 (-317 -- -1309)
GI10 (drained	48,0	12,8	-929	

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