Geological factors affecting on after-use of Finnish cut-over peatlands with implications on the carbon accumulation

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Academic dissertation
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Abstract

In Finland, peat harvesting sites are utilized down almost to the mineral soil. In this situation the properties of mineral subsoils are likely to have considerable influence on the suitability for the various after-use forms. The first aim of this study was to recognize the chemical and physical properties of mineral subsoils, which may limit after-use alternatives of cut-over peatlands. The second aim was to define a minimum practice for mineral subsoil studies, to enable safe after-use planning. Also the role of different geological areas was studied: chemical characteristics of the mineral subsoils were assumed to be related to the geological areas. The future percentages of the different after-use forms were predicted to help planning both economical and environmental management of the after-use. Predicting the future land-use split between different after-use forms made it possible to predict also carbon accumulation in this future situation. Carbon accumulation effectiveness before the intervention was evaluated on three sites (representing sites typically considered for peat production).

Mineral subsoils of 54 different peat production areas (9800 hectares) were studied. In field conditions all mineral subsoils were classified to either tills or various sorted sediments. Laboratory studies included sieving and areometer analysis. Other general items studied were pH, electrical conductivity, organic matter, water soluble nutrients (P, NO₃-N, NH₄-N, S and Fe) and exchangeable nutrients (Ca, Mg and K). In some cases also other elements were analysed.

In additional case studies 3 mires (927 hectares) in Oulu district were studied. These sites represented peatlands typically considered for peat production. Their carbon accumulation history was studied. Items analysed were bulk density, dry weight and ash content. Also a few pollen profiles were determined in laboratory. ¹⁴C dating was carried out on 5 sampling points.

Some after-use limiting properties in mineral subsoils were detected. Areas with relatively sulphur rich mineral subsoil and pool-forming areas with very fine and compact mineral subsoil together covered approximately 1/5 of all areas. These areas were unsuitable for commercial use. They were recommended for example for mire regeneration. Another approximate 1/5 of the areas included very coarse or very fine sediments. Commercial use of these areas would demand special techniques - like using the remaining peat layer for compensating properties missing from the mineral subsoil. In some till areas also presence of large boulders limited agricultural use.

One after-use form was seldom suitable for one whole released peat production area. Three typical distribution patterns (models) of different mineral subsoils within individual peatlands were found. 57 % of studied cut-over peatlands were well suited for forestry. In a conservative calculation 26% of the areas were clearly suitable for agriculture, horticulture or energy crop production. If tills without large boulders were included, the percentage of areas suitable to field crop production would be 42 %, 9-14 % of all areas were well suitable for mire regeneration or bird sanctuaries, but all areas were considered possible for mire regeneration with correct techniques. Also another 11 % was recommended for mire regeneration to avoid disturbing the mineral subsoil, so total 20-25 % of the areas would be used for different forms of rewetting.
There were differences between different geochemical provinces and geological areas. High sulphur concentrations and acidity were typical to the areas below the highest shoreline of the ancient Litorina Sea and Lake Ladoga – Bothnian Bay zone. Also differences related to nutrition were detected. In fine sediments these differences were not significant for after-use planning. In very coarse sediments natural nutrient concentration was clearly higher in Lake Ladoga – Bothnian Bay zone and in the areas of Svecokarelian schists and gneisses, than in Granitoid area of central Finland and in Archaean gneiss areas.

Based on this study the recommended minimum analysis for after-use planning was for pH, sulphur content and fine material (<0.06 mm) percentage. Nutrition capacity could be analysed using the natural concentrations of calcium, magnesium and potassium. “Nutrient number” (based on concentrations of Ca, Mg and K) was the suggested tool for classifying the mineral subsoils according to their suitability for forestry and agriculture.

Carbon accumulation scenarios were developed based on the land-use predictions. These scenarios were calculated for areas in peat production (59 300 ha) and the areas released from peat production (15 671 ha). Carbon accumulation of the scenarios varied between 0.074 and 0.152 million t C a⁻¹. Carbon accumulation rate 0.096 million t C a⁻¹ was reached in a scenario, where after-use was most tied to mineral subsoil suitability for different after-use forms. Carbon accumulation scenarios were based on relative short term carbon accumulation rates collected from the literature.

Three peatlands considered for peat production, were studied in Oulu area. In the two fens the long term carbon accumulation rates were 13 and 15 g C m⁻² a⁻¹, these rates were close to the mean of the Finnish fens. The only bog had the rates 22 and 24 g C m⁻² a⁻¹, close to the mean of the Finnish bogs. Anyhow, the natural annual carbon accumulation had been decreasing towards the time of possible intervention. If all the three sites were taken to production, the future annual carbon accumulation in the after-use would be 731 tonnes on the area of 927 hectares, according to the after-use scenario most probably suitable for these sites.

Keywords: After-use, carbon accumulation, cut-over peatlands, Lake Ladoga - Bothnian Bay zone, Litorina zone, mineral subsoils, sulphur
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Author’s contribution to the publications:
Author P. Picken (earlier P. Lötjönen) was responsible for planning the research behind all the articles with helping comments by V. Klemetti. The geographical study area was defined together with V. Klemetti. In paper I P. Picken was responsible for presenting the physical and chemical study and results. V. Klemetti was responsible for introducing the background and targets for the study and P. Selin was responsible for describing the socio-economical impacts related to the after-use. In papers II, III and IV P. Picken was responsible for the whole articles.

In addition the thesis includes previously unpublished data (additional case studies). Additional case study I: Peatland development before peat harvesting (3 case studies). Additional case study II: Two example cases of after-use recommendations based on mineral subsoils. In all additional case studies P. Picken was responsible for the whole content.
1 Introduction

1.1 Peatlands, their use and carbon content in Finland

1.1.1 Peatlands in Finland
Geological peatland is defined as an area larger than 20 hectares with a peat layer deeper than 0.3 m. The surface area of geological peatlands in Finland is 5.1 million hectares. The average size for geological peatlands is 153 ha and the number of individual peatland areas is 33 000. The area of peatlands possible for technical utilization is 1.2 million ha and peat volume 30 billion m$^3$ in situ (Virtanen et al. 2003).

Biological mire or peatland (classification used in forestry) is an area covered by a peat layer or an area where more than 75 % of vegetation is mire vegetation. So, this definition covers also sites of paludification. This definition also covers geological peatlands. The area covered by peatland according to this definition in Finland is 8.9 million hectares. On the top of these areas there are peatlands in agricultural use, under landfills and under water reservoirs. (Virtanen et al. 2003). The original biological mire area in Finland has been 10.4 million hectares (Mikola 1989; Lappalainen & Hänninen 1993).

54 % of Finnish peat resources are Sphagnum-dominated and 45 % Carex-dominated. One percent is composed of Bryales peat (Virtanen et al. 2003).

1.1.2 Current use of Peatlands in Finland
A large share of Finnish peatlands is in commercial use. They are used for forestry or they are hosting water reservoirs or covered by roads. 5.9 million hectares of Finnish peatlands are drained for forestry. Under roads there are 30 000 hectares of peatlands (Virtanen et al. 2003). Current status of mire utilization is presented in Table 1.

59 300 ha of Finnish peatland was in peat production in 2004 (Silpola 2004). 84 % of the production was milled fuel peat and 8 % was sod peat (fuel). The last 8 % covered all the non-fuel products including for example substrate raw materials, bedding peat and composting additive material.

1.1.3 Current after-use of cut-over peatlands in Finland
The proportion of peat production area released from production is growing. According to Selin (1999) there was approximately 10 000 ha of cut-over peatlands in total released from peat production around 1998. The total area released by the end of year 2004 was 15 671 ha (Silpola & Tuomanen 2005). The most important after-use forms were forestry (26 %), energy crop production (14 %) and other agricultural production (27 %). Other after-use forms cover regenerated wetlands (including also bird sanctuaries), temporary after-use forms (for example production supporting areas) and areas under preparation for after use.

In Finland mire regeneration is usually understood as reflooding the site and in this way creating suitable conditions for natural development of mire vegetation. Forestation is usually understood as adjusting the groundwater level with ditches, planting trees and fertilising. In some cases it also may include treating the soil surface, for example mixing the surface peat and mineral soil. In after-use statistics also strong natural forest development belongs to this category. Energy crop growing means Canary grass (Phalaris arundinacea) production. Bird sanctuaries are lakes with natural vegetation on closest surroundings.

| Table 1. Peatland exploitation in Finland (Virtanen et al. 2003). |
|-----------------|-----------------|
| Forestry        | 56 %            |
| Natural state   | 24 %            |
| Protection      | 11 %            |
| Agriculture     | 7 %             |
| Water reservoirs| 1 %             |
| Peat production | 0.6 %           |
1.2 Pristine mires and carbon accumulation

1.2.1 General information of carbon and mires
Carbon accumulation in mires is high because the decomposition rate is smaller than the biomass production. Boreal and subarctic mires have been estimated to include at least 1/5 of the total C-pool in world soils (Post et al. 1982).

Mire plants bind inorganic carbon from the air into an organic form. Plant biomass forms peat because of the low rate of decomposition. Part of the material is oxidised in acrotelm and leaves the mire as carbon dioxide and water. Part of the biomass breaks in the catotelm (deeper in anaerobic conditions) into methane. Part of the carbon dioxide released is taken back by vegetation immediately on the mire. For example in Lakkasuo mire hummocks 10% of carbon dioxide used by mire plants is derived from local carbon source (Jungner et al. 1995).

Peat is an important carbon storage, but also the mineral subsoil under a peat layer acts as a carbon sink. This carbon sink might account for approximately 5 % of the unaccounted carbon in the global carbon budget (Turunen et al. 1999). One studied case is Lakkasuo mire, where the carbon store in the mineral subsoil has increased at least within 4500 years (Turunen et al. 1996).

1.2.2 Paludification, overgrowing and mire development phases
New mire area is developing for example in coastal areas around Bothnian Bay where land is still emerging from the sea due to the glacioisostatic land uplift. Lakes and ponds can turn into mires by vegetation growth (overgrowing) and subsequent organic mass accumulation (filling in). Paludification can take place in forests in situations where mire vegetation takes over, usually in form of Sphagnum growth.

The share of peatlands is highest in some watercourse areas around Bothnian Bay. A large presence of peatlands derives from very little variation in topography, small amount of lakes and rapid land uplift. The share of peatlands is smallest in the southern coastline and upper Lapland areas, where land uplift rate is fairly slow (Virtanen et al. 2003).

*Sphagnum* growth in coniferous forest has been studied in Alaska and the results are interpreted as early phases of paludification. The surface of *Sphagnum* patches enlarge over time in surface area at about 2 % per year. *Sphagnum mendocinum* and *Sphagnum squarrosum* invade first the wet depressions and *Sphagnum girgensohnii* is the first peat colonising the moss floor of the forest (Noble et al. 1984).

Korhola (1994) divides the theories related to paludification and mire development into two different groups. In the first group of theories peat accumulation is started by changes in macroclimate towards more moist conditions. In this situation decay has slowed down and offered better circumstances for mire vegetation. The other group of theories relate to the local moisture conditions. It is important to notice that same circumstances can increase development towards mires in some ecosystems, but decrease in others.

Mire cover type changes during the development of the mire. All mires start in more or less minerotrophic conditions. Ombrotrophic conditions are the final stage in mire succession after the development phases. Reaching the ombrotrophic phase has not taken place simultaneously across Finland. In some areas ombrotrophic phase started already 8000 years ago, in central Finland approximately 3000 years ago and in Lapland this started 2000 years ago (Korhola & Tolonen 1998).

Growth rate on the mire surface can be relatively high. According to Lindholm (1979) *Polytrichum strictum* grows on average at 10.8 mm a\(^{-1}\), *Sphagnum fuscum*, 11.6 mm a\(^{-1}\) and *Sphagnum rubellum* 10.9 mm a\(^{-1}\). Variation between years is rather small in this study. Peat accumulation though is a combination of growth, compression and decomposition. In general vertical peat accumulation in Finnish mires varies between 0.2 and 4.0 mm a\(^{-1}\)and average is 0.5 mm a\(^{-1}\) (Korhola & Tolonen 1998).

Decomposition is related to the time peat spends in the acrotelm. The age of the lower part of acrotelm ranges between 50-200 years (Vasander 1998). Deeper in the catotelm,
decomposition proceeds more slowly. This is the true site of peat accumulation.

In a late phase of the development, the decay in all depths grows so large that organic mass fed from the top cannot increase the peat mass anymore. The mire is in a steady state (Clymo 1984, 1992). The thickness of boreal mires in Finland, Estonia and North America have been estimated to be on average approximately 1/3 away from their steady state thickness, the maximum thickness (Tolonen et al. 1994).

Vertical mire growth is not the only item to be measured. The lateral expansion of mires in different time periods should also be considered when long-term carbon accumulation rates are calculated (Tolonen et al. 1992; Korhola, 1994). Relevance of lateral growth has also been brought up in studies in North America by Harden et al. (1992). In Finnish ombrotrophic bogs the lateral expansion has mostly occurred when the mire has been in the minerotrophic stage (Korhola & Tolonen 1998).

1.2.3 Carbon accumulation
There are three common definitions for carbon accumulation. The long-term apparent rate of carbon accumulation (LORCA, g C m\(^{-2}\) a\(^{-1}\)) is measured from a peat column on a certain site. It is based on dry bulk density of the peat layer, carbon concentration in peat and the age of the basal peat. The recent apparent rate of carbon accumulation (RERCA, g C m\(^{-2}\) a\(^{-1}\)) is also based on dry bulk density and carbon concentration, but it is calculated from a part of the peat column between surface and a dated horizon. The actual net rate of carbon accumulation (ARCA) is based on peat accumulation models like Clymo’s (1984) model. Ages from several levels of the peat column and cumulative dry peat mass are used to calculate rate of organic matter addition and decay coefficient.

Different rates for LORCA are presented in Table 2. The mean for the average LORCA in boreal mires studied in Finland is 22.6 g C m\(^{-2}\) a\(^{-1}\) +/- 0.5 (Tolonen & Turunen 1996b; Tolonen et al. 1996). The range is 1.5 –102.8 g C m\(^{-2}\) a\(^{-1}\). The average LORCA is higher in bogs (25.5 +/-0.5, range 6.6-85.8) compared to fens (17.2 +/- 0.3, range 2.3 –102.8). LORCA is also higher in treeless and pine fens than in fens with spruce-birch-alder vegetation (Tolonen et al. 1994). Quite different early results have been presented from studies in England by Clymo (1970): the accumulation rate there was higher in pools

<table>
<thead>
<tr>
<th>Area</th>
<th>Range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finnish research, bogs</td>
<td>24 g C m(^{-2}) a(^{-1})</td>
<td>Tolonen &amp; Turunen (1996a)</td>
</tr>
<tr>
<td></td>
<td>16.7 –22.3 g C m(^{-2}) a(^{-1})</td>
<td>Mäkilä (1997)</td>
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<td></td>
<td>10.2 g C m(^{-2}) a(^{-1})</td>
<td>Pirkänen et al. (1999)</td>
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<tr>
<td></td>
<td>20.8 g C m(^{-2}) a(^{-1})</td>
<td>Turunen et al. (2002)</td>
</tr>
<tr>
<td>Finnish research, fens</td>
<td>15.1 g C m(^{-2}) a(^{-1})</td>
<td>Tolonen &amp; Turunen (1996 a;b)</td>
</tr>
<tr>
<td></td>
<td>5.6 g C m(^{-2}) a(^{-1})</td>
<td>Pirkänen et al. (1999)</td>
</tr>
<tr>
<td></td>
<td>16.9 g C m(^{-2}) a(^{-1})</td>
<td>Turunen et al. (2002)</td>
</tr>
<tr>
<td>Artic and subartic regions</td>
<td>1.2 to 16.5 g C m(^{-2}) a(^{-1})</td>
<td>Vardy et al. (2000)</td>
</tr>
<tr>
<td>Russian Karelia (whole holocene)</td>
<td>20 g C m(^{-2}) a(^{-1})</td>
<td>Elina et al. (1984)</td>
</tr>
<tr>
<td>Western Canada</td>
<td>19.4 g C m(^{-2}) a(^{-1})</td>
<td>Vitt et al. (2000)</td>
</tr>
</tbody>
</table>
compared to hummocks. In Finland there are differences between regions representing different mire combination types. LORCA is highest in the areas of eccentric bogs and lowest in northern aapa-mire areas (Turunen et al. 2002).

RERCA in general varies from 30 to 120 g C m\(^{-2}\) a\(^{-1}\) over the past 100 to 200 years (Turunen 2003). In Finnish mires it ranges from 40 to 81 g C m\(^{-2}\) a\(^{-1}\). (Tolonen & Turunen 1996a; Pitkänen et al. 1999). RERCA appears to be much higher on ombrotrophic bog sites than on virgin fen sites. Drainage seems to change the situation. On drained ombrotrophic sites RERCA is approximately the same as on virgin fen sites (Tolonen et al. 1996).

A carbon accumulation rate given for young mire carbon accumulation is 75 g C m\(^{-2}\) a\(^{-1}\) (Vasander & Roderfelt 1998).

ARCA presented for Finnish mires is 8.1-23.0 g C m\(^{-2}\) a\(^{-1}\). ARCA seems to be 29-85 % of LORCA, without actual trends related to location, age, or vegetation of the sites studied (Tolonen et al. 1994; Tolonen & Turunen 1996b; Tolonen et al. 1996).

3D dynamic modelling with a hydrological approach in Backhar Bog complex in Western Siberia has given the carbon accumulation rate for the past 6500 years. According to this study by Borren and Bleuten (2004) the accumulation declined from 17.2 g C m\(^{-2}\) a\(^{-1}\) to 7.4 g C m\(^{-2}\) a\(^{-1}\). This model was specially built by using the environmental modelling language PCRaster and groundwater model MODFLOW-2000.

According to Tolonen et al. (1994) carbon accumulation is most effective in mires younger than 4500 years. This can be due to changes in climate and more loss in decay or fires in older mires. The highest accumulation values are measured in very young mires along the eastern shore of the Gulf of Bothnia. In the same studies the lowest values come from a geologically older area in eastern Finland from 9500-5000 years old mires. These old mires are also in fairly continental conditions and have experienced several peatland fires.

1.2.4 Future scenarios of pristine mires and carbon

According to estimations climate warming shifts the existing mire regimes northwards. Northern aapa fens might change to Sphagnum bogs and develop higher carbon accumulation levels. Current Sphagnum bogs and their future is probably dependent on precipitation (Tolonen et al. 1994; 1996). In this future scenario, mires are more effective as carbon sinks. Sphagnum bogs also release less CH\(_4\) and N\(_2\)O (Crill et al. 1992).

1.3 Carbon content of peat and Finnish peatlands

The average dry matter contents in surface peat in Finnish peatlands in different provinces are 53-79 kg/ m\(^3\). In the base peat layers the same range is 72-107 kg/ m\(^3\) (Virtanen et al. 2003).

According to a review by Turunen (2003) in many Finnish calculations for carbon accumulation the carbon concentration in dry mass has been assumed to be 50 % and actual measurements have been relatively close to this value. One example from studies in Canada is 49.3 % (Turunen & Turunen 2003). Coefficient 0.5 for carbon in dry mass is used also by Tolonen et al. (1996). In studies by Geological Survey of Finland the average carbon content in peat is 50.3 % (Virtanen et al. 2003).

The carbon amount in Finnish geological peatlands is 3 193 Tg. This number does not include the carbon content in biological mires or paludification areas (Virtanen et al. 2003). Minkkinen (1999) has estimated the total carbon amount in Finnish peatlands to be 5 600 Tg. Another estimation is 6 300 Tg by Hillebrand (1993).

Minkkinen (1999) has estimated the annual peat accumulation in Finnish peatlands to be 15 million tonnes CO\(_2\). Selin (1999) has estimated the limit for sustainable use of energy peat to be 37 TWh a\(^{-1}\).
1.4 Carbon accumulation in different after-use forms

1.4.1 Mire regeneration and carbon accumulation

Mire regeneration and peatland restoration are terms used in same contexts, but increasingly peatland restoration seems to refer to very active (even complicated) procedure, leading to the site recolonisation by mire vegetation. In this study mire regeneration is a term mainly used and it covers different approaches, from reflooding to detailed and controlled restoration.

According to Charman (2002) peatland restoration requires at least 50-100 cm of compressed, humified peat. All sources of nutrient enrichment (air and water borne) should be excluded. There also should be a buffer zone between the site and agricultural land. There also should be a local source for plant colonization.

Many peatland remnants only have strongly humified peat and this does not favour redevelopment of Sphagnum carpets. On the other hand shallow inundation (<0.3 m) provides suitable growing conditions for most peat mosses. Compartmentalization of terrain is also helpful. Very important is the development of hydrologically self-regulating acrotelm (Smolders et al. 2003).

In two self-regenerated mire sites in Sweden and in Estonia the vegetation found has been mainly Sphagnum cuspidatum and Sphagnum magellanicum. On hummocks Sphagnum fuscum was the dominating species together with Eriophorum but these had grown on top of a slightly decomposed layer of Sphagnum magellanicum and Eriophorum. In depressions the new biomass was mainly coming from Sphagnum cuspidatum. Hydrology in self regenerated places represented almost saturated conditions in surface layers. pH was fairly low (under 4.5) and total nitrogen under 5 mg l⁻¹ and total phosphorus under 1 mg l⁻¹ (Lode et al. 2002). In Finland, studies on a cotton-grass dominated rewetted cut-over site have showed that raising water table level to or above the soil surface helps rapid succession towards closed mire vegetation (Tuittila et al. 2000b). In these sites Eriophorum vaginatum and Carex rostrata were favoured and bryophytes typical of disturbed peat surface became more common.

More detailed work practices have been introduced in Canada. According to Gorham & Rochefort (2003) peatland restoration requires provision of appropriate hydrological regime, manipulating surface topography, microclimate improvement, appropriate diaspores, manipulating base status where necessary, fertilizing in some cases, excluding inappropriate invaders, adaptively managing through at least one flood/drought cycle (ensuring sustainability) and long-term monitoring. General environmental monitoring is also important in regeneration processes. For example phosphorus leaching often increases (Vasander et al. 2003).

Getting growth started on peatland restoration sites without delay has been important for carbon balance. Sphagnum growth gets a better start for example when nursed by a pioneer plant like Polytrichum strictum. This is due to moisture and temperature regulation offered by the nurse plant (Groeneveld et al. 2002). Also high density presence of ericaceous shrubs has supported Sphagnum growth in beginning (Boudreau & Rochefort 1997).

Even if Sphagnum bogs seem to be the most effective carbon sink, fen vegetation has a value as its own as fens can be very rich in species. For example Brackagh Bog in Northern Ireland is a cut-over site and has one of the most species-rich fen vegetation in its district (Wheeler 1997). In Finland fen vegetation development on mire regeneration sites is expected because of high nutrient levels on the sites with almost all the peat removed. On the other hand bogs have originated within a fen habitat (Weber 1908) and this is likely to be development in future as well. Roderfelt et al. (1994) have measured carbon accumulation rate 64 g C m⁻² a⁻¹ on a mire regeneration site. According to Tuittila et al. (1999) in the early stage carbon accumulation in mire regeneration is 64.5 g CO₂-C m⁻² a⁻¹. These rates are also in line with the recent apparent rate of carbon accumulation (RERCA) in Finnish mires. Tolonen et al. (1985) have studied a regrowth layer in a North-American peatland and measured dry mass accumulation range 120 – 430 g m⁻² a⁻¹.
Joosten (1995) has collected peat accumulation range 100 – 490 g m\(^{-2}\) a\(^{-1}\) from a variety of studies. Approximately half of this peat accumulation can be estimated to be carbon.

### 1.4.2 Forestation and carbon accumulation

Information from forestation experiments on previous peat production sites exists already spanning several decades. A critical work phase also in forestation is the correct adjustment of the water table. In principle forestation can be carried out both by planting trees or from seed (natural seeding or artificial seeding). Adjusting the correct nutrient level is also relevant especially in the early phases. Also other work phases and adjustments may be needed in different cases.

One calculated example rate for carbon accumulation in forested after-use sites is 90 g C m\(^{-2}\) a\(^{-1}\). This is determined by Selin (1999) and based on forest growth values by Kaunisto and Aro (1998). Based on the same sources 188 g C m\(^{-2}\) a\(^{-1}\) is a rate for young birch forests and 266 g C m\(^{-2}\) a\(^{-1}\) is a rate for maximum wood production. These rates are based on stem and branch wood production only and the used carbon content coefficient is 0.5. In another study Laiho (1997) has used carbon coefficient 0.52 for carbon in tree stands. According to Aro and Kaunisto (1998) stem wood production in naturally established birch stands varies from 119 m\(^{3}\) ha\(^{-1}\) to 211 m\(^{3}\) ha\(^{-1}\) in 31 years. In pine stands the stem wood production varies from 36 m\(^{3}\) ha\(^{-1}\) to 219 m\(^{3}\) ha\(^{-1}\) in 35 years (Aro and Kaunisto, 1998). Lohila et al. (2004) have calculated carbon accumulation to be 90-210 g C m\(^{-2}\) a\(^{-1}\), in pine stands on a cut-away peatlands based on the information from the study by Aro and Kaunisto (1998).

### 1.4.3 Energy crop growing and carbon accumulation

Growing energy plants is an increasing after-use form. One suggested carbon accumulation value for Phalaris arundinacea is 250 – 360 g C m\(^{-2}\) a\(^{-1}\) (Puuronen et al. 1998; Selin 1999). In a study by Huttunen et al. (2004) the estimated uptake of carbon is 300-600 g C m\(^{-2}\) a\(^{-1}\). In the same study the estimated total carbon gain was over 600 g C m\(^{-2}\) a\(^{-1}\) in an optimal case and carbon loss over 100 g C m\(^{-2}\) a\(^{-1}\) in “a high respiration – low production” case. When the carbon balance of energy crop production is studied, the carbon use for energy must be taken to consideration. A large proportion of the plant mass above the ground gets harvested annually for energy use.

### 1.5 Peatlands and greenhouse gas emissions

Peatlands both absorb and release greenhouse gases in their biological functions. Most important of these are H\(_2\)O, CO\(_2\), CH\(_4\), and N\(_2\)O.

N\(_2\)O emissions in natural peatland are not significant. Emissions measured are 9.3 and 7.8 kg N\(_2\)O-N ha\(^{-1}\) a\(^{-1}\) in two different years. CO\(_2\) emission has been measured as 1.5 x 10\(^4\) kg CO\(_2\) ha\(^{-1}\) a\(^{-1}\) from a site with vegetation. A similar result on a peatland site without vegetation is 2.2 x 10\(^4\) kg CO\(_2\) ha\(^{-1}\) a\(^{-1}\). Methane emissions in pristine mire (measured as CH\(_4\)-C) are 149 and 259 kg ha\(^{-1}\) a\(^{-1}\). Cultivated peatlands have higher N\(_2\)O – fluxes than pristine mires. This is thought to indicate higher availability of mineral nitrogen (Nykänen et al. 1995). Fluxes from cultivated peatland have been higher than fluxes from drained and forested peatlands (Martikainen et al. 1993). Efficiency of CH\(_4\) as a greenhouse gas is 24.5 times the efficiency of CO\(_2\) and efficiency of N\(_2\)O 320 times the efficiency of CO\(_2\) (IPPC 1994).

Peatlands also release a lot of water vapour (H\(_2\)O). Water vapour is the largest by quantity greenhouse gas, but it is difficult to estimate its effect.

According to Laine et al. (1996) in Finland the impact on the greenhouse effect of CH\(_4\) emissions of natural state peatlands are roughly compensated by the carbon accumulation in peat. Drainage seems to decrease CH\(_4\) emissions.

In Finland, in a cotton-grass dominated rewetted cut-over site, CH\(_4\) exchange has been measured to be clearly higher after the rewetting compared to situation before that but still lower than emissions from pristine mires in the same area (Tuittila et al. 2000a). Tuittila et al. (2000c) have documented methane fluxes between -0.1 and 0.3
mg C m⁻² h⁻¹ on Sphagnum surfaces and bare peat. In Lakkasuo mire complex methane emissions have been over 30 g CH₄ m⁻² a⁻¹ in Carex-rich fen parts (Nykänen et al. 1998) and 2–5 g CH₄ m⁻² a⁻¹ in more Sphagnum-rich parts (Laine et al. 2002).

1.6 Sediments underlying the peat
Sediment types underlying the peat in Finland have been generally identified during the general peat surveys by Geological Survey of Finland. According to Lappalainen & Hänninen (1993) 37% of the mineral subsoils under peatland in Finland are tills, 8% are clays and 18% are silt and fine sand. 36% are gravel and sand. The share of tills is highest in Lapland and smallest close to southern coastline and South-Western Finland. In these areas there is more clay than elsewhere in Finland. This information covers all peatlands studied during years 1975 – 1991, including also peatlands not suitable for industrial peat harvesting.

However the peat core samplers used in field studies may not always penetrate well into basal sediment. Identification is often made from a relatively small amount of sample taken from the bottom of the peat core (Riley & Michaud 1994). Detailed planning of after-use benefits from studies carried out, when the majority of the peat layer has already been removed and mineral subsoil is more accessible.

1.7 Cut-over site suitability to different after-use forms
1.7.1 Sulphur and Litorina sediments
Litorina zone is the area once covered by the ancient Litorina Sea and it has been known for a long time as the area of acid sulphate clays. The coverage of the ancient Litorina Sea can be found from descriptions by Eronen & Haila (1990). Sulphate soils of this area were brought to science publications for example by Purokoski (1959). According to estimations the amount of sulphate soils in Finland is 336 000 ha. This estimation includes sulphate soils under 2 m depth from the surface (Puustinen et al. 1994). According to estimations (Yli-Halla et al. 1999), there are 50 000 ha of agricultural fields in Finland with a pH<3.5 between the surface and 125 cm depth. 16% of cultivated fields in Finland are estimated to be acidic (Bärlund et al. 2004). Not draining acidic sulphate soils can prevent further oxidation of sulphides and prevent acidity (Yli-Halla 2003). In Litorina zone stream water sulphate concentrations are also high (Lahermo et al. 1996).

The origin of sulphur in Litorina clays is from the seawater sulphates of the ancient sea. Microbes (especially Desulfovibrio desulfuricans) used the oxygen of the sulphates while oxygenizing organic material and sulphide produced this way settled down in reduced conditions with iron (II) as iron sulphide. Later land uplift has brought these sea bottom sediments above the sea level. Drying soils create oxygenating conditions. In these conditions sulphides oxidise forming sulphuric acid, iron oxides and forms hydroxides (Yli-Halla 2003). The pH is likely to settle between 3.5 and 4.0 according to research by Hartikainen & Yli-Halla (1986).

Equation 1

\[
\text{FeS} + \frac{9}{4} \text{O}_2 + \frac{5}{2} \text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + \text{H}_2\text{SO}_4
\]

The oxidation of these sediments also affects on the mobility of the other elements. The extent of the release of a metal on oxidation is controlled by the pH-level reached in the oxidation for example in case of aluminium and copper (Åström, 1998). Cadmium, cobalt, nickel, yttrium and zinc are highly mobile in acid sulphate soils and likely to get enriched in the recipient streams (Åström & Deng 2002).

Acidity of sulphur-rich soils can be a limiting factor also in peat production area after-use planning. The presence of sulphur must be studied when artificial lakes, ponds or ditches reaching the mineral subsoil are being built to the peatland site. The two ponds in Hirvineva and Rastunsuo artificial lakes are good example cases. In Hirvineva pH of the smaller pond was followed for some years after developing the pond. The pH development was downwards: 1993 4.99, 1994 4.52 and 1995 4.17 (Siira 1996). In the long run
the accumulation in the bottom of the pond started to insulate the sensitive bottom sediment from the water and situation improved. A peat layer was successfully used as insulating material from the beginning when Hirvineva bigger pond was built. In Rastunsuo (far from the Litorina zone) no problems occurred with the artificial lake (Selin 1999).

1.7.2 Sulphur in Lake Ladoga - Bothnian Bay Zone

Lake Ladoga – Bothnian Bay Zone is located on the margin of Archaean continent and it divides the bedrock in Finland to two different domains. Many of the rocks of this zone are formed in an island arc environment: they have originated through collision of the continental plate and an oceanic plate. These rocks include many famous Finnish ores, for example Vihanti and Pyhäsalmi (Saltikoff et al. 2006).

In a large part of the area the direction of the long belt in bedrock is approximately the same as the last main direction of the glacial flow during the latest glaciation. This contributes to the existence of the geochemical province with the same name, Lake Ladoga – Bothnian Bay Zone, defined by Geological Survey of Finland. According to Koljonen (1992) till in Lake Ladoga – Bothnian Bay Zone is enriched in Ag, Ba, Co, Cu, Mg, Mn, P, Sr and Zn. Especially well present are elements typical to low-temperature sulphide deposits.

Approximately the same area is also known as the main sulphide ore belt of Finland. For example Vihanti-Pyhäsalmi metallogenic zone includes deposits belonging to volcanogenic massive sulphide type (Saltikoff et al. 2006). Outokumpu metallogenic zone is also located inside the geochemical province Lake Ladoga – Bothnian Bay Zone. According to Lahermo et al. (1996) the sulphide in the rocks in Outokumpu area is also an important reason for the sulphate concentration in stream waters of the area. The rocks of the area include for example black schists, calcium-silicate rocks, serpentinites and a non-clastic quartz rock (Saltikoff et al. 2006). Black schists in general can have very high sulphur concentrations.

Sulphate concentrations (with any origin) in soil are often reflected for example in the acidity. The reflection of the presence of non-organic sulphate and its affect on pH has been described among others by Kortelainen et al. (1989) in case of small lakes in southern Finland.

1.7.3 Grain size, nutrients and suitability for forestry and agriculture

Mineral subsoil has an effect on tree growth rates. Forest growth is weaker when the amount of fine particles (<0.06 mm) is less than 15-20 % compared to finer grained sediments (Aro et al. 1997; Aro & Kaunisto 1998).

Sorted gravel (2-20 mm) and coarser sands (0.2 –2 mm) are difficult substrates in agriculture (Heinonen et al. 1992). These coarse sediments have poor water holding capacity and cation exchange capacity. In clay soils water retention is high, but water absorption is slow. Clays can also be hard and they split when they dry. In some cases though splitting can improve water penetration into the clay. Soils rich in fine silts (0.002 – 0.02 mm) and clay (<0.002 mm) can in some circumstances be difficult soils in agriculture. These soils commonly turn hard after rain. Tills can be suitable to agricultural use, if there is enough fine material and the proportion of stones is not too large. The proportion of boulders in till is relevant for land-use: for example working with machinery on boulder-rich areas is difficult.

1.7.4 Different zones within individual peatlands

Different parts of individual peatlands are not necessary suitable for the same after-use. Choosing different after-use forms for different areas within the same peatland is needed. After-use can also mean repeating the earlier ecological succession of the peatland. Where a lake once turned to mire due to overgrowing, rewetting is a natural choice. Rewetting includes mire regeneration and building artificial ponds and bird sanctuaries. Topography of these sites is also usually suitable for rewetting. If mire development originally started because of paludification of forestland, the same areas are often suitable for forestation after peat production.
This principle has been applied for example in after-use plans by Korhonen (1998).

1.8 Aims of the study

This study is based on following hypotheses:

- In mineral subsoils of cut-over peatlands there are properties, which affect the suitability for different after-use forms after peat production.
- There are differences in mineral subsoils of peatlands between different geochemical provinces and geological areas. These differences are large enough to be taken to consideration in after-use management of cut-over peatlands.
- Different mineral subsoil zones are commonly found also inside individual peatlands. Typical patterns of the distribution of subsoil types can be found in peatlands.

In Finland, peat harvesting sites are exploited down almost to the mineral soil and the properties of mineral subsoil are likely to have considerable influence on the suitability for the various after-use forms. The purpose of this study was to recognize the chemical and physical properties of mineral subsoils, which may limit after-use alternatives of cut-over peatlands. Limitations in suitability had already been detected in some case studies and the hypothesis was, they do exist also on a larger scale. Also a minimum analysis practice was needed to be defined for safe after-use planning.

Another hypothesis was that differences between different geological areas are large enough to be taken into consideration in after-use planning. This hypothesis needed to be tested.

The future percentages of the different after-use forms needed to be predicted. This was relevant for planning both economical and environmental management of the after-use. Future carbon accumulation capacity of the cut-over peatlands was an interesting subject in after-use discussion. Another question was the carbon accumulation effectiveness on the latest development stages on sites typically considered for peat production: how effective carbon sinks were the sites before the intervention.
2 Overview of the papers

2.1 Paper I

2.1.1 Material and methods

Mineral subsoils of 54 different peat production areas (9800 hectares) were studied in this study. These sites are presented in Figure 1. Study sites were areas operated by Vapo Oy. In choosing the study sites peatlands were prioritized according to proportion of the area owned by the producer. In these cases the producer was more able to choose the after-use form. Mostly research line orientations were chosen to cross the previously known glacial flow directions (Koljonen 1992), but close to the ice marginal formations the latest glacial flow direction was used as research line orientation. This way research line orientations were likely to cross most of the different mineral subsoil zones lying under the peat. For 100 hectares of peatland 3 – 5 research lines were used, with 50 - 200 m sampling interval. All the samples were studied under field conditions and part of the samples were also studied in the laboratory. In field conditions all mineral subsoil samples were classified to either tills or various sorted sediments. Laboratory studies included the grain size distribution analysis and chemical analysis. Grain size distribution was analysed by dry sieving and areometer analysis. pH analysis was done according to EN 13037:1999 and electrical conductivity according to EN 13038:1999 (methods accepted by European committee for standardization), from water solution. Organic matter was analysed according to EN 13039:1999. P, NO₃-N, NH₄-N, S and Fe was analysed from water solution (EN 13652:2001). Ca, Mg and K (exchangeable elements) were determined by modified EN 13651. Extraction with 0.5 M ammonium acetate (pH 4.65) was used instead of extraction with calcium chloride/DTPA (CAT). Nutrient analysis was carried out with atomic absorption spectrophotometer.

In some cases also water soluble Fe and Al and total concentrations of some heavy metals were analysed. Samples for heavy metal analysis were extracted using microwave wet digestion (HNO₃:H₂O:HF; 5:4:5:0,5) and measured with graphite furnace (GFAAS) or flame atomic absorption spectrophotometer (FAAS). Water soluble Al and Fe and the heavy metal total concentrations were analysed mainly from the samples coming from the Lake Ladoga – Bothnian Bay zone, Litorina zone and of samples with especially rusty colouring. These analysis results (36 times water soluble iron concentration, 27 times total iron) were naturally less representative than those representing the whole research area and they were mainly supposed to serve local planning purposes.

Aro & Kaunisto (1998) have presented the level 15-20% of fine particles in the sediment to be reasonable for forest growth, so 15% fine particles was chosen to be the lower limit value for fine material (<0.06 mm) percentage. Very coarse sediments are also known to be difficult in agriculture (Heinonen et al. 1992) and for simplicity the same limit value was used for agriculture. Upper limit value for agriculture and forestry was 90 % of fine material (<0.06 mm). It was chosen in the first pre-study phases (Lötjönen 1999), because it ruled out grain size class 0.002 –0.02 mm, which is known to be difficult in cultivation (Heinonen et al. 1992). This way classification was kept simple and all grain-size related limit values were based on the percentage of 0.06 mm grains. This approach included a risk of ruling out also good clay soils, but clay soils can also be problematic in cultivation in some circumstancess (Heinonen et al. 1992). Mentioned pre-study also showed that clays were commonly found in the deepest parts of the peatlands, these areas can be difficult to drain.

An early definition for sulphur rich mineral soils (Equation 1) was used in this study. The weight was on sediments already giving low pH.

Equation 1

[pH = (4.5 or less)] and

[(sulphur, mg/l, water soluble) > (average + standard deviation)]

Nutrient number (Equation 2) was another tool developed in the early phases of this study, for analysing the suitability for forestry or agriculture. The nutrient number was based on the
exchangeable amounts of potassium, magnesium and calcium because of the common appearance of these nutrients in mineral subsoils. For example nitrogen and phosphorus were present in too small amounts to be relevant. K, Mg and Ca were made equal items by using coefficients 1, 3 and 8. These coefficients were based on their relations in the study results.

Equation 2

\[
\frac{\text{Ca mg/kg} + 3 \times \text{Mg mg/kg} + 8 \times \text{K mg/kg}}{100}
\]

Differences between areas were studied and area classification used was based on Geochemical provinces, areas defined by the Geological Survey of Finland. These areas are based on chemical studies of fine material in till. Chemical differences in till are closely related to differences in the bedrock (Koljonen 1992). The extent of the ancient Litorina sea was defined by Eronen & Haila (1990).

2.1.2 Results

Paper I provided an overview of issues related to mineral subsoils of cut-over peatlands and the after-use planning. Distribution of mineral subsoil types was described. Also the typical distribution models of different mineral subsoil types within individual peatlands were described. A suggestion for after-use planning approach was presented (repeating the original succession). Preliminary proofs of differences in mineral subsoils of cut-over peatlands, between different larger geological areas, were presented. A classification tool related to nutrient capacity was presented.

Till and till covered with thin layer of sand, silt or clay covered 29 % of all areas studied and sorted sediments covered the rest of the area. In most common case there was varying layers of sand and silt – giving very poor distribution curve for different grain sizes. The percentages of different soil types are presented in Table 3. Very fine sediments (> 90 % of particles smaller than 0.06 mm) covered 24 % of the area studied. Coarse sediments (< 15 % of particles smaller than 0.06 mm) covered 15 % of the area studied.

Table 3. Mineral subsoil distribution under cut-over peatlands.

<table>
<thead>
<tr>
<th>Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>till</td>
<td>27 %</td>
</tr>
<tr>
<td>till covered with thin layer of sand, silt or clay</td>
<td>16 %</td>
</tr>
<tr>
<td>clay</td>
<td>13 %</td>
</tr>
<tr>
<td>fine silt</td>
<td>13 %</td>
</tr>
<tr>
<td>coarse silt and fine sand</td>
<td>7 %</td>
</tr>
<tr>
<td>coarse sand and gravel</td>
<td>4 %</td>
</tr>
<tr>
<td>various layers of sand and silt</td>
<td>20 %</td>
</tr>
</tbody>
</table>

Figure 1. Study sites of the mineral subsoil study, with the approximate extent of the ancient Litorina sea and the approximate area of the Lake Ladoga – Bothnian Bay zone.
Soil types with different water permeability and chemical features were found in a variable order depending on the geological environment. Three typical patterns of mineral subsoil distribution were found: the central-lake model, central-stream model and end-moraine model. Especially one of these patterns (the central-lake model) was well adapted for mire regeneration. In the central-lake model the centre part of the area was usually clay and surrounded by coarser sediments and finally till in the outer circle. This mineral subsoil combination was relatively common among all studied areas, but it was most common in areas where the latest direction of movement of the continental ice shield was less dominating in topography. The central stream model was especially typical close to eskers and in so-called base till areas, where the direction of movement of the ice shield moving is very dominant in topography. In these cases an esker and spread esker sands were commonly found on one side and till ridge on the other side of the peatland. Between these two there were sorted sediments in a river-like depression with flood sediments on the sides. In the end-moraine model (commonly found around Salpausselkä area) there was a gradation of particle size which decreased in line with the distance from the moraine. The distribution of different mineral subsoil models is presented in Figure 2.

In all three cases described above the same after-use form would not be well suitable for the whole released peat production area. Suggested way for reuse was repeating the earlier succession. Those parts of the mire that were originally lake could be relooded in different ways - as also topography usually favours this. Areas, where paludification had started in a forest, could be used for forestation. Different parts of cut-over peatlands could be turned back to what they used to be before they became parts of the peatland.

Mineral subsoils were poor in phosphorus and nitrogen. EC could not be used for describing nutrition level as it was controlled heavily by sulphur concentration. The nutrient number (based on natural calcium, magnesium and potassium concentrations) was suggested as a tool to describe the nutrient capacity of mineral subsoils (and suitability for agriculture and forestry). The preliminary classification presented in Paper I was only poorly calibrated to real-life tree growth and was almost purely statistical. Nutrient numbers smaller than 2 represented a low nutrient capacity and nutrient numbers larger than 12 represented high nutrient capacity. Normal range was divided to two: lower normal level was between 2 and 7.
and higher normal level between 7 and 12.

Preliminary evidence was presented to prove, that the chemical features typical to the geochemical provinces (defined by Geological Survey of Finland) were also reflected in mineral subsoils of the peatlands. The most interesting geochemical province was the Lake Ladoga - Bothnian Bay zone. Mineral subsoils rich in sulphur or heavy metals were in many cases found in this area. For example the sulphur content in soil was 17 mg/kg in this area. In the Granitoid area of central Finland the average sulphur content was only 5 mg/kg. Differences in nutrient number were also seen between geochemical provinces. Mineral subsoils with same coarseness had different average nutrient numbers in different geochemical provinces. Lake Ladoga - Bothnian Bay zone had higher nutrient numbers than for example granitoid and gneiss areas.

Another interesting geological area was the area below the highest shoreline of the ancient Litorina sea. The average pH of all mineral subsoils under the highest shoreline of Litorina sea was 5.5 and 6.1 above the highest shoreline. The average sulphur concentration was 106 mg/kg below and 15 mg/kg above the highest shoreline of the Litorina sea. Below the highest shoreline of the Litorina sea 13 % of mineral subsoils were classified as sulphide-rich soils (according to the first, preliminary classification equation used).

2.2 Paper II

2.2.1 Material and methods
Research material, field and laboratory methods were as in Paper I. Limit values used for sediment fine material percentage (for areas well suitable for agriculture and forestry) were same as in Paper I.

A new definition was used for sulphur-related acidity in mineral subsoils. “Relatively sulphur rich” sediments in this study were defined in a statistical way (Equation 3). This was a category for mineral subsoils that are acidic or have potential to produce acidity.

Equation 3

\[ \text{[pH} < \text{(average pH - standard deviation)}] \text{ and [sulphur, mg/l, water soluble} > \text{ average]} \]

Carbon accumulation in different land-use scenarios was calculated. Coefficients for carbon accumulation were collected from literature. The rate used for forested after-use sites was 90 g C m\(^2\) a\(^{-1}\), defined by Selin (1999) based on Kaunisto and Aro (1998). In one calculation a rate 266 g C m\(^2\) a\(^{-1}\) was used in one calculation for optimised wood production. This rate was defined as by Selin (1999) and based on Kaunisto and Aro (1998). The carbon accumulation rate (short term) for mire regeneration was 64 g C m\(^2\) a\(^{-1}\). This value was an average of studies by Roderfelt et al. (1994) and Tuittila et al. (1999). The carbon accumulation value considered for energy crop growing was 300 g C m\(^2\) a\(^{-1}\) and based on range 250 –360 g C m\(^2\) a\(^{-1}\) (Puuronen et al. 1998; Selin 1999).

2.2.2 Results
Preliminary land-use possibilities and land-use and carbon fixation scenarios were presented in Paper II.

57 % of mineral subsoils were classified suitable for forestry based on mineral subsoil physical and chemical features. 39 % were not recommended for forestry because of being too coarse or too fine. In some cases the same sediments were also relatively sulphur rich. 4 % of the cut-over peatlands were not recommended for forestry because of sulphur and acidity (relatively sulphur rich).

26 % of mineral subsoils were well suitable for agriculture. 39 % were not recommended for agriculture because of being too coarse or too fine. In some cases the same sediments were also relatively sulphur rich. 31 % of the areas were not recommended for agriculture because of possible boulder-problem. In this classification all boulder-including (till) areas were ruled out. 4 % of the cut-over peatlands were not recommended for agriculture because of sulphur and acidity (relatively sulphur rich).

Three preliminary after-use scenarios were created for 47 000 hectares of peat production area (Finnish peat production area 2003). Large percentages of forestry use were partly based on earlier strong interest for forestry, based on Selin´s survey (1999). In a minimum scenario 60 % was forested and 10 used for mire regeneration. The rest of the areas were assumed to be used for
purposes with non-significant carbon accumulation. In the second scenario 70% of the area was forested and 20% used for mire regeneration. In the third scenario 60% of the areas were used for optimised wood production and 10% for mire regeneration. In the first scenario the annual carbon fixation was 0.03 million tonnes C a⁻¹, in the second scenario 0.4 million tonnes C a⁻¹ and in the third scenario 0.8 million tonnes C a⁻¹.

2.3 Paper III

2.3.1 Material and methods

In Paper III nutrition level, sulphur concentration and acidity differences between mineral subsoils under cut-over peatlands located in different geochemical provinces were analysed. Also comparison between areas above and below the highest shoreline of the ancient Litorina Sea was carried out.

Research material, field and laboratory methods were as in Paper I and Paper II. Limit values used for sediment fine material percentage (for areas well suitable for agriculture and forestry) were same as in Paper I and Paper II. Equation 2 from Paper I and Equation 3 from Paper II were used for calculating Nutrient number and defining “relatively sulphur rich” areas.

Differences between areas were studied and area classification used was based on geochemical provinces, areas defined by the Geological Survey of Finland. These areas are based on chemical studies of fine material in till. Chemical differences in till are mostly related to differences in the bedrock (Koljonen 1992). The extent of the ancient Litorina Sea was delineated according to Eronen & Haila (1990).

Factor analysis with Principal Components extraction was used to identify underlying patterns in mineral subsoil features. Rotation Method Varimax was used with Kaiser Normalization. Statistical work was done using SPSS version 12.

2.3.2 Results

In Paper III considerable differences between mineral subsoils located in different geological areas were presented. Large differences were detected in sulphur concentrations and acidity. Also significant differences in coarse sediments nutrition levels between different areas were detected. In finer sediments differences were less significant considering the after-use of the cut-over peatlands.

A large proportion of all relatively sulphur rich mineral subsoils were located below the highest shoreline of the Litorina Sea. In this area 25% of studied areas turned out to be relatively sulphur rich. In this area the average concentration of water soluble sulphur in mineral subsoils was 106 mg/kg and average pH 5.5. Above the highest shoreline the average water soluble sulphur concentration was 15 mg/kg and average pH 6.1. In uncertain “border areas” the average water soluble sulphur concentration was 28 mg/kg.

Another area with a large proportion of relatively sulphur rich mineral subsoils was located in the Lake Ladoga – Bothnian Bay zone. In the Lake Ladoga – Bothnian Bay zone also nutrition level was relatively high. In this area very coarse sediments (less than 15% <0.06 mm grains) were rich in calcium, magnesium and potassium, compared to the granite areas and Archaean gneiss areas. In general the differences between geochemical provinces were most significant in the coarse materials and seemed to diminish slightly towards the finer range of sediments.

Relatively sulphur rich sediments were mainly sorted sediments. In all samples from all areas only two samples of relative sulphur rich sediments represented tills. Both samples came from the same peatland site in the Areas of Svecokarelian schists and gneisses.

The average nutrient number was 2.5 for sediments with 15% of fine material (<0.06 mm) in Finland. This average was calculated actually from all samples with fine material content 13-17%. There were though differences between geochemical provinces. In the Areas of Svecokarelian schists and gneisses 2.5 was the exact nutrient number for sediments with fine material percentage 15. In Lake Ladoga – Bothnian Bay zone nutrient number 2.5 was reached, when fine material content was only 12%. In Granitoid area of Central Finland 22% of
fine material was needed to reach nutrient number 2.5. In Archaean gneiss areas even 25% of fine material was needed. Areas with granitoids and gneisses were in general poorer in nutrients than other areas.

Five new statistical principal components were extracted from the research data. These components were named nutrient feature, sulphur compound feature, iron component, bulk density feature and nitrate. The Granitoid area of central Finland was especially weak in nutrient feature, but Lake Ladoga – Bothnian Bay zone and the Areas of Svecokarelian schists and gneisses gave more positive results. The sulphur compound feature was strongest in the Areas of Svecokarelian schists and gneisses, probably due to mires of this area being often located inside the Litorina zone. In Litorina-comparison inside the Litorina zone sulphur compound feature was clearly positive and outside of it clearly negative. The sulphur compound feature got the lowest values in Granitoid area of central Finland. Iron component got highest values in Lake Ladoga – Bothnian Bay zone.

### 2.4 Paper IV

#### 2.4.1 Material and methods

In paper IV the focus was on the actual quantity of land area possible for different after-use forms on cut-over peatlands. Land-use scenarios were updated according to the recent after-use trends, current production area statistics and after-use statistics were used. Carbon accumulation scenarios were calculated for all after-use scenarios. The general physical and chemical properties of the mineral subsoils were analysed and a recommendation for minimum analysis before after-use was presented based on the results. Also the suitability of the limit values used was re-evaluated.

Research material, field and laboratory methods were as in papers I-III. Limit values used for sediment fines percentage (for areas well suitable for agriculture and forestry) were same as in papers I-II. Equation 3 from Paper II was used for defining “relatively sulphur rich” areas. The field data related to the amounts and common sizes of boulders was also used in this study. Also the probability of flooding after production on the sites was taken to consideration.

Correlations between different features were analysed (Pearson’s correlation coefficient, two-tailed significance). Statistical work was done using SPSS versions 12 and 13.

Different land-use scenarios were based on different assumptions. In one scenario the percentages of the final land-use forms in after-use stayed the same as they are. In other scenarios the possibilities for forestry, agriculture and energy crop production were in focus.

Carbon accumulation in different land-use scenarios was calculated. Coefficients for carbon accumulation were collected from literature. The rate used for forested after-use sites was 90 g C m\(^{-2}\) a\(^{-1}\), defined by Selin (1999) based on Kaunisto and Aro (1998). The carbon accumulation value used for Phalaris (energy crop) was 300 g C m\(^{-2}\) a\(^{-1}\) and based on range 250–360 g C m\(^{-2}\) a\(^{-1}\) (Puuronen et al. 1998; Selin 1999). The carbon accumulation rate (short term) for mire regeneration was 64 g C m\(^{-2}\) a\(^{-1}\). This value was an average of studies by Roderfelt et al. (1994) and Tuittila et al. (1999).

#### 2.4.2 Results

In Paper IV general characteristics of the mineral subsoils and features suitable to be used as tools in after-use planning were presented. After-use and carbon accumulation scenarios were presented for cut-over peatlands.

Concentrations of phosphorus and nitrogen were low, mostly close to the detection limits. The presence of organic matter in the mineral subsoil did not clearly control the concentrations of phosphorus, nitrogen and sulphur. The presence of organic matter was relatively small due to the sampling depth. Sulphur (mg/l) and EC had a significant correlation and EC and pH had a negative correlation.

Concentrations of calcium, magnesium and potassium followed the fine material (<0.06 mm) percentage. When fine material percentage was 20 or larger, Ca- Mg- and K- concentrations were clearly larger than in coarser sediments. In sediments with fine material percentage 15 - 20
the medians of Ca, Mg and K were very similar to the sediments with less than 15% of fine material. Standard deviation was though smaller than in coarser sediments. This result supports the choice of 15% of fine material as the lower limit value.

Approximately 15% of mire bottoms had less than 15% of fine material (grains < 0.06 mm) in their mineral subsoil. 24% of the area studied represented very fine sediments with > 90% of fines (grains < 0.06 mm). In 43% of the area studied the mineral subsoil was till or till covered with thin layer of sorted sediments. In some cases tills may be unsuitable for agriculture if large boulders are present or if surface is very uneven. 52% of the till areas were relatively boulder-poor and 47% of till covered by a thin layer of sorted sediments was relatively boulder-poor. In other till areas boulders with over 60 cm diameter were largely present and in many cases even 1-2 meter boulders were present.

Approximately half of all clays were located on probable former lake-forming depressions. These were areas likely to be flooded in the end of peat production. 30% of fine silts were located on similar sites. In total 9% of all areas were very fine sediments (with > 90% of grains smaller than 0.06 mm) located in pool-forming depressions, in the middle of central-lake model sites. Total 14% of all areas were clay or fine silt (or till covered by fine sediments) located on these pool-forming locations.

Part of the fine or coarse mineral subsoils were also relatively sulphur rich, these cases covered 7% of all the areas. There was also a 4% share of the total area with relatively sulphur rich sediments without physical land-use limitations. Together 11% of all studied areas were relatively sulphur rich.

61% of studied areas were well suited for forestry based on physical features of the mineral subsoil. They were not too coarse or not too fine, but 4% of these areas were relatively sulphur rich. In a conservative calculation 26% of the areas studied were clearly suitable for agriculture, horticulture or energy crop production. If tills without large boulders were included, the percentage of areas suitable to field crop production would be 42%. If the compensation possibilities based on remaining peat layer are taken to consideration, the percentage of areas suitable to both field crop production and forestry would be still higher.

Best after-use for the sulphur rich areas (11% of all areas) would be probably mire regeneration; demanding minimum amount of disturbing the mineral subsoil. 9-14% of all areas (depending on the way of calculation) were fine sediments on probable former lake-forming depressions. These were areas especially easy to flood and difficult to drain in the end of peat production. These were all different areas from the sulphur-rich areas that would be best suitable for bird sanctuaries or mire regeneration. This means that minimum 20% (-25%) of cut-over peatlands include clear economical after-use limitations.

Economical interests and mineral subsoil soil suitability may lead to a reasonably large quantity of forestry on Finnish cut-over peatlands. Currently energy crop production has a strong position in cut-over sites after-use. 26% of areas could be easily converted to field crop production (same areas were also suitable for forestry), but total 42% were suitable, when tills with small boulders were accepted. Possibly up to 80% of the areas are possible areas for forestry and up to 65% for field crop production, if for example remaining peat layer was used to compensate very fine or very coarse mineral subsoil. Areas poorly suited for forestry, agriculture, horticulture and energy crop production could be recommended for mire regeneration and bird sanctuaries. Also most areas with sensitive mineral subsoils (relatively sulphur rich) could be recommended for mire regeneration as this often means no need to disturb the subsoil. Also much larger areas would be very likely to be possible for mire regeneration as this land use form does not demand very deep pools, just possibilities for water level adjustment.

Different carbon accumulation scenarios were created for the area covering both areas in peat production (59 300 ha, 2004) and the areas released from peat production (15 671 ha, before 2005). In all scenarios the areas already in final after-use form were naturally calculated to be in the after-use type they actually already are in. In different scenarios the carbon fixation values varied between 0.074 and 0.152 million t C a⁻¹. The most optimistic
one of the scenarios was an energy crop production oriented scenario, with 65% of the areas in energy crop production and 15% in forestry. Though it is important to realise, that energy crops would be harvested and used annually. The annual carbon accumulation value would be 0.074 million t C a⁻¹, if the percentages of land-use forms would remain the same as now in the future. This scenario is not though realistic in the long run considering the quality of the mineral subsoils. A carbon accumulation rate 0.096 million t C a⁻¹ was reached in a scenario tied to mineral subsoil types: energy crop production covered 26% of the best area with sorted sediments, the best till areas (31%) were used for forestry. The last 43% was used for mire regeneration. The scenario was also called “mire regeneration basis”.
3 Additional case studies

3.1 Additional case studies I: Peatland development before peat harvesting

Predicted carbon accumulation on after-use sites needed to be compared to information of the past carbon accumulation. The general past carbon accumulation information on mires was collected from literature (and is also included in Introduction). Unpublished earlier case studies from Oulu district were collected here to represent past carbon accumulation on sites typically considered for peat production.

3.1.1 Material and methods

Three different peatlands in Oulu district, Northern Finland were studied during 1995-1997. Peatlands studied were Järvineva in Ruukki municipality, Huhanneva in Rantsila municipality and Kaupinsuo in Kuivaniemi municipality. Location of these sites is presented in Figure 3. The total area studied was 927 hectares. Areas with deeper peat layer than 1.5 m covered together 444 hectares. The lowest spot was 50 m and highest 108 m above the sea level. The field study was carried out on a total 96 points, surface sampling on 57 points and drilling (including disturbed and undisturbed samples) on 35 points.

Peatlands studied are defined in Table 4. These sites were under planning or consideration for taking to industrial peat production. They were chosen to represent different typical “good peat resources”. Good resource in the study case was defined as suitable peat material (horticultural and energy peat), thick enough peat layer and reasonable traffic connections. The study was carried out mainly on the pristine mire parts of the areas, but there was also small amount of area drained for forestry. Parts of these areas studied have been prepared for peat production afterwards.

Peat layers were drilled and sampled from the surface to the mineral subsoil. Field research was planned according to earlier research lines, these lines were set by Geological Survey of Finland (Virtanen & Herranen 1987, Virtanen & Ristaniemi 1983). Current mire cover types, botanical composition of peat and humification were determined. Growth rates of the living top layer were measured using the annual growth markings of *Sphagnum fuscum* and *Polytrichum strictum*, to calculate the age of the bottom of the studied column. 3-5 plants were used in each determination and an undisturbed surface sample was taken from the same site for dry weight analysis. Regular 20 cm sampling depth was used for this test, representing only very recent growth without any relevant quantity of decomposition.

Earlier published peat resource mapping information of Järvineva and Kaupinsuo was used in this study. This information included average total bulk density in Järvineva, 71.4 g/l and industrially usable peat amount, 1.2 million m$^3$ *in situ*, spread on 60 hectares area (Virtanen & Herranen 1987). In Kaupinsuo the used information was average bulk density, 82 g/l and industrially usable peat amount, 0.5 million m$^3$ *in situ*.
Table 4. Basic details of three peatlands studied.

<table>
<thead>
<tr>
<th>Peatland &amp; location</th>
<th>X</th>
<th>Y</th>
<th>Finnish national basic map code</th>
<th>Area, ha</th>
<th>Height above sea level, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Järvineva, Ruukki</td>
<td>71716</td>
<td>25610</td>
<td>2443 08</td>
<td>265</td>
<td>50-52</td>
</tr>
<tr>
<td>Huhanneva, Rantsila</td>
<td>71395</td>
<td>25610</td>
<td>3412 04</td>
<td>362</td>
<td>87-93</td>
</tr>
<tr>
<td>Kaupinsuo, Kuivaniemi</td>
<td>72730</td>
<td>34590</td>
<td>3521 10</td>
<td>300</td>
<td>101-108</td>
</tr>
</tbody>
</table>

...situ, spread on 35 hectares area (Virtanen & Ristaniemi 1983).

Bulk density, dry weight, ash content and a few pollen profiles were determined in laboratory. Also 14C dating was carried out on 5 sampling points. Bulk density was measured from undisturbed samples. Dry weight was analysed by drying the samples in an oven at 105 °C. For bulk density measurements different humification levels in different layers were analysed separately by cutting and dividing the sample. Ash content (in 550 °C) was also used to measure the amount of minerals in basal peat layers. Large quantity of mineral elements could have been misleading in peat carbon content calculations. Pollen analysis was carried out according to Hyvärinen (1986). Radiocarbon dating (AMS) was produced by the Helsinki University Radiocarbon Laboratory. All columns used for carbon accumulation calculation were from natural state parts of the peatlands.

In carbon calculations the used coefficient for carbon (in dry mass) was 0.503. This was based on a known Finnish average (Virtanen et al. 2003). The resulting surface carbon accumulation rates were rounded to the nearest 10 C m⁻² a⁻¹. The rates measured for the actual peat columns were not rounded.

Correlations between different features were analysed (Pearson’s correlation coefficient), using SPSS version 12.

3.1.2 Results

Järvineva peatland

Mire cover types in Järvineva varied from sedge fen to ombrotrophic bog. 71 % of the study points represented bog cover type, 19 % fen cover type and 10 % were spruce mires with only a shallow peat layer. The oldest peat layers in Järvineva were combination of Carex, Sphagnum and wood-reminis. Latest development phases represented Sphagnum-dominated vegetation with small amounts of Eriophorum and Carex. In deepest parts of the peatland under the peat layer there was mixed clay and gyttja. Silt and fine sand were the other main mineral subsoils.

In Järvineva the age of the bottom peat layer (Point A800) was 4130 +/- 80 14C a BP. The depth of the peat layer was in this point 220 cm. In another mineral subsoil depression (Point A200) the age for the bottom layer was 3490 +/- 100 14C a BP. Depth of the bottom layer in this point was 210 cm. The age of a later horizon (Point A800) on the level 140 cm under the surface was 3270 +/- 90 14C a BP. This level was just under the line, where the presence of Sphagnum started clearly increasing (in this part of the mire). Sphagnum actually became dominant later, at the depth of 95 cm under the surface. Also the amounts of Betula and Alnus pollen decreased slightly between the depths 130 and 150 cm, while conifers were in small increase, indicating slight general environmental change in the area.

Calculated one-column result for long term carbon accumulation during the peatland existence in Järvineva centre (Point A800) was 22 g C m⁻² a⁻¹. Carbon accumulation since 3270 +/- 90 14C a BP (the recent carbon accumulation) was relatively small, 15 g C m⁻² a⁻¹. Carbon accumulation during the starting phase, first (~) 860 years, was 45 g C m⁻² a⁻¹. In another point (A200) long term carbon accumulation during the whole mire existence in Järvineva was 24 g C m⁻² a⁻¹.
If the industrially usable peat amount in the suitable 60 hectares area was calculated as carbon (using the average bulk density), this 60 hectares would have been accumulating 10.4 tonnes carbon in a year, which is same as 17 g carbon m\(^{-2}\) a\(^{-1}\). This result might include a small error: the industrially usable quantity does not include the deepest depressions of peatland, but the dating is done from the very bottom of the peat layer.

In Järvineva the change from mineral subsoil to organic sediment and finally to actual peat was gradual. The used starting level for mire generation was the level where ash content changes suddenly from 26 % to 3 %.

The growth rate of the living surface was measured at six points. Average carbon fixation of all these hummock points was ~300 g C m\(^{-2}\) a\(^{-1}\). The role of decomposition was very small in these surface samples. Results from different points are presented in Table 5.

Huhanneva peatland

In Huhanneva peatland in Rantsila 42 % of the study points represented fen cover type and 32 % represented bog cover type. 26 % represented spruce mires. Huhanneva vegetation was Carex-dominated through the development. In early phases there also was a lot of Equisetum. Shrubs and Eriophorum were relatively common in mid-phases. Towards the present time the presence of Sphagnum had increased. Peat column and pollen flora (describing the area vegetation changes) are presented in Figure 4. Mineral subsoil consisted mainly of sand and silt, small amounts of till was located in the side areas.

In Huhanneva the age of the bottom peat layer (Point A400) was 5820 +/− 90 \(^{14}\)C a BP. The depth of the peat layer in this spot was 350 cm. A later horizon (Point A400) on the level 180 cm under the surface was 4420 +/− 90 years \(^{14}\)C a BP. This upper dating horizon was chosen based on the presence / absence of Picea pollen (Figure 4) to keep the study expandable. Long term carbon accumulation during the mire existence in Huhanneva centre (Point A400) was 15 g C m\(^{-2}\) a\(^{-1}\). Carbon accumulation since 4420 +/− 90 years \(^{14}\)C a BP was only 8 g C m\(^{-2}\) a\(^{-1}\). Carbon accumulation before 4420 +/− 90 years \(^{14}\)C a BP was 32 g C m\(^{-2}\) a\(^{-1}\).

<table>
<thead>
<tr>
<th>peatland</th>
<th>point</th>
<th>carbon accumulation rate, g C m(^{-2}) a(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Järvineva</td>
<td>A800</td>
<td>~430</td>
</tr>
<tr>
<td>Järvineva</td>
<td>A600-400</td>
<td>~300</td>
</tr>
<tr>
<td>Järvineva</td>
<td>A1000</td>
<td>~340</td>
</tr>
<tr>
<td>Järvineva</td>
<td>A200-600</td>
<td>~430</td>
</tr>
<tr>
<td>Järvineva</td>
<td>A200</td>
<td>~170</td>
</tr>
<tr>
<td>Järvineva</td>
<td>A100+200</td>
<td>~250</td>
</tr>
<tr>
<td>Huhanneva</td>
<td>A400</td>
<td>~240</td>
</tr>
<tr>
<td>Huhanneva</td>
<td>A0</td>
<td>~240</td>
</tr>
<tr>
<td>Kaupinsuo</td>
<td>A600+400</td>
<td>~240</td>
</tr>
<tr>
<td>Kaupinsuo</td>
<td>A500</td>
<td>~290</td>
</tr>
<tr>
<td>Kaupinsuo</td>
<td>B1000+100</td>
<td>~190</td>
</tr>
<tr>
<td>Kaupinsuo</td>
<td>A500-200</td>
<td>~190</td>
</tr>
<tr>
<td>Kaupinsuo</td>
<td>A400</td>
<td>~250</td>
</tr>
<tr>
<td>Järvineva</td>
<td>average</td>
<td>~300</td>
</tr>
<tr>
<td>Huhanneva</td>
<td>average</td>
<td>~240</td>
</tr>
<tr>
<td>Kaupinsuo</td>
<td>average</td>
<td>~230</td>
</tr>
</tbody>
</table>

Figure 4. Relative pollen presence for selected taxa, Huhanneva, site HA400. Peat type column on the left.
The accumulation rate related to the living surface growth in both measured points was ~240 g C m\(^{-2}\) a\(^{-1}\). The role of decomposition was not studied in these cases. Huhanneva results can be compared to the results from the two other peatlands in Table 5.

In Huhanneva bulk density measured in depth 0 - 50 cm varied and the average was 73 g/l. In the dated column A400 bulk density in depth 0 - 50 cm was 27 g/l. Between the depths 50 and 100 cm the average bulk density of the whole peatland was 88 g/l and in column A400 65 g/l. In the lower peat layer the average bulk density was 71 g/l and in the dated column A400 it was 120 g/l. The same depth does not mean same age, but this leaves an impression that the dated column was not necessarily well representative.

**Kaupinsuo peatland**

In Kaupinsuo peatland in Kuivaniemi 48 % of the study points represented fen cover type and 46 % bog cover type. Bog cover types represented only first stages of bog development. Sedge fen and *Sphagnum papillosum* fen were common mire types in the middle. Some parts of the peatland were drained. Kaupinsuo peat was *Carex* dominated. In deeper layers also *Equisetum* and later *Eriophorum* remains were found. *Sphagnum* was slightly present in peat and at the surface there was a thin layer of *Sphagnum*-dominated peat. Wood remains were present almost all the way through the profile. Mineral subsoil in the area studied was mostly till.

In Kaupinsuo peatland the age of the deepest measured peat layer was 7340 +/- 100 14C a BP. The other measurements are presented in Table 6. The upper used horizon was close to a change from humification degree H5 to H3 (Von Post scale) and in beginning of a *Carex*-dominated period (in that part of the peatland).

Long term carbon accumulation rates of Kaupinsuo are presented in Table 7. For unknown reason the vertical growth of this peatland clearly slowed down very soon after beginning. One of the measured points was located in a mainly undisturbed pool (~300 m from the closest ditch). The other point was in another pool, within 100 m distance from the closest ditch.

If the industrially usable peat amount in the suitable 35 hectares area was calculated as carbon (using the average bulk density), this 35 hectares would have been accumulating 2.8 tonnes carbon in a year, which is same as 8 g carbon m\(^{-2}\) a\(^{-1}\). The possible difference of the bottom of the industrially usable peat layer and the bottom of the whole peat layer has not been taken to consideration.

The average carbon accumulation rate related to the living surface growth in Kaupinsuo peatland

**Table 6. Ages of the peat layers in Kaupinsuo peatland.**

<table>
<thead>
<tr>
<th>point</th>
<th>depth of the layer</th>
<th>age</th>
<th>additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>B500</td>
<td>210 cm</td>
<td>7340 +/- 100 14C a BP</td>
<td>bottom peat layer</td>
</tr>
<tr>
<td>A300</td>
<td>180 cm</td>
<td>6780 +/- 140 14C a BP</td>
<td>bottom peat layer</td>
</tr>
<tr>
<td>B500</td>
<td>95 cm</td>
<td>4090 +/- 90 14C a BP</td>
<td>vegetation change</td>
</tr>
</tbody>
</table>

**Table 7. Long term carbon accumulation in Kaupinsuo peatland.**

<table>
<thead>
<tr>
<th>point</th>
<th>period</th>
<th>carbon accumulation rate, g C m(^{-2}) a(^{-1})</th>
<th>additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>B500</td>
<td>from beginning to present</td>
<td>13</td>
<td>mainly undisturbed pool</td>
</tr>
<tr>
<td>B500</td>
<td>first 560 (~) years</td>
<td>90</td>
<td>mainly undisturbed pool</td>
</tr>
<tr>
<td>A300</td>
<td>from beginning to present</td>
<td>3</td>
<td>mainly drained pool</td>
</tr>
</tbody>
</table>
was ~230 g C m\(^{-2}\) a\(^{-1}\). The role of decomposition was not studied, samples were almost completely unhumified. Results from different study points are presented in Table 5.

In points studied average bulk densities in Kaupinsuo (in depths 0 - 100 cm) were 55 g/l in A-area and 60 g/l in B-area. In dated column B500 the average bulk density in depth 0 - 100 cm was 73 g/l. In lower peat layers the average bulk densities were 138 g/l in A-area and 109 g/l in B-area. In dated column B500 the average bulk density in deeper layers was 88 g/l. The same depth does not mean same age, but this slightly helps to estimate how representative the dated column was. In the upper parts of the dated column there was slightly more dry mass than in the upper layers of the surrounding area, but the basal peat of the chosen column had relatively low density compared to the surrounding areas.

**General statistical features in material**

Humification, depth, bulk density and botanical composition were tested statistically to find out how uniform different mires and different parts of the mires were in this study. Correlation coefficient between depth and humification was 0.57. Correlation coefficient between humification and bulk density was 0.55. Presence of *Sphagnum* (scale 0-4/4) resulted a negative correlation coefficient –0.61 with depth and presence of *Carex* correlation coefficient 0.58 with depth. Humification median was 4.5.

### 3.2 Additional case studies II: Two example cases of after-use recommendations based on mineral subsoils

Two example cases of individual peatlands from the mineral subsoil study are presented here with relevant details. These cases represent the practical application of using mineral subsoil information in recommending after-use forms for existing peat production areas.

#### 3.2.1 Material and methods

Research material was part of the same material as the total material in papers I-IV. Field and laboratory methods were as in papers I-IV. Limit values used for sediment fine material percentage (for areas well suitable for agriculture and forestry) were same as in papers I, II and IV.

#### 3.2.2 Ihkajansuo peatland

Ihkajansuo is located in central Finland in Vittasaari municipality and in the Granitoid area of central Finland. The surrounding area is mainly till with strong northwest-southeast-orientation. The location of the site is presented in Figure 3. The different areas within the peatland are presented in Figure 5.

The most southern part of Ihkajansuo is currently pump drained and is likely to become flooded after peat production has ended. The sediments under peat layer in the pump-drained area were mainly clay and gyttja. Largely in the southern field of Ihkajansuo, a gyttja layer covered the clay as a 50-100 cm layer. In the side areas there was till – except on the side closest to pond Sammalinen. Till in this area included 35 % of fine material (<0.06 mm grains). Calcium, magnesium and potassium concentrations were higher than the average concentration in tills in this study (all 54 peatlands). Natural pH was 6.1 and EC 2.8 mS/m. Nitrogen and phosphorus concentrations were very small, under detection limits. The sorted sediments in the southern field were coarse clay (30% of clay fraction) with total fine material percentage 82. The sulphur concentration was under detection limit, pH 6.7 and EC 2.7 mS/m.

The actual mineral sediments were suitable for several different after-use forms, but the topography of the southern field demanded after-use form that included flooding. Both mire regeneration and bird sanctuary were possible. If bird sanctuary (artificial lake) though was planned, some complementary studies of the gyttja covering the clay should be carried out. The chemistry of the clay does not indicate to harmful elements in the gyttja.

The till of the area 1 continued in the area 3, but also on the edges of the area 2. The till areas were well drained, so till-rich area 3 was well
suitable for forestry. In the area 2 a clay and gyttja layer similar to area 1 was found, surrounded by the till. This area with sorted sediments would be though alone quite small for field crop production, so mire regeneration and forestry were the best alternatives. The suitability for forestry can be though affected by the thickness of the remaining peat layer in this part of the field. In the deepest part the remaining peat layer might end up being too thick for forestry.

None of the features and sediments studied indicated to chemical limitations in after-use. The distribution of the mineral subsoil types of southern Ihkajansuo represented central-lake model.

3.2.3 Heinäsuon peatland
Heinäsuon peatland is also located in central Finland in Viitasaari municipality and in the Granitoid area of central Finland. Western side of the northern Heinäsuon peatland represented relatively coarse sorted sediments. Eastern side and southern parts represented till formations. The location of the site is presented in Figure 3. The different areas within the peatland are presented in Figure 6.

Coarsest sediments of the northern field (areas 4, 5 and 6) were sand with only 2% of fine material (<0.06 mm). There was 14 mg/l calcium and even less magnesium and potassium. Sulphur content was under determination limit. pH was 6.6 and EC 2.8. Silt in the middle of the same field included 70% of fine material, 210 mg/l calcium, 70 mg/l magnesium, 15 mg/l potassium and 4 mg/l sulphur. pH was 6.4 and EC 2.4 mS/m. Coarsest sediments covered just part of the field and relative large amount of the area was silt. Heinäsuon northern field (areas 4, 5 and 6) was largely suitable for field crop production and forestry. Sediments were also suitable for even bird sanctuary, but topography was not strongly pool-forming and did not naturally demand flooding. The current
The orientation of field ditches was east-west, crossing the different sediment layers. If the advantage of these existing ditch structures was taken, all sediments with different coarseness types could not serve different after-use forms. General decision based on average suitability was recommended. The clay and gyttja – rich part in the middle of the field (area 5) could be treated with special attention – as a slightly thicker peat layer is likely to be left to this part. Special attention is needed also to the very coarse sandy part.

In the central field of Heinäsuo peatland the sandy part was wider than in the northern field. So in average the mineral subsoil was coarser in this part of the peatland. Topography would be well suitable for field crop production, if the remaining peat layer could be used for compensating the poor presence of fine material. Forestry could be recommended with well chosen species and techniques (including nutrient poor soil fertilization demands). If these mineral subsoil properties were not compensated, rewetting (for example mire regeneration) would be the recommended after-use form.

Towards south till became more common. There was 21% of fine material in Heinäsuo till. In average case this should be approximately enough for successful forestation. On the other hand in this part of Finland 21 might be quite low fine material percentage considering the suitability for forestation: in this geochemical province the nutrient concentrations were low compared to sediments with same coarseness in other areas.

None of the features and sediments studied indicated to chemical limitations in after-use. Heinäsuo mineral subsoil distribution had features of the central-stream model.
4 Discussion

The shares of mineral subsoil types under the peat production areas seemed to be slightly different from the subsoil type distribution in the general Finnish peat resources mapping results (Lappalainen & Hänninen, 1993). This is likely to be due to the less representative geographical distribution of the peatlands in this study. For example the share of till in this study was smaller than the share of till under all peatlands in Finland. Many peatlands with till base are located in Lapland, which was not represented in the study area. Peatlands chosen for peat production are also generally relatively deep peat deposits.

Characteristic chemical features of the mineral subsoils of the Finnish cut-over peatlands included only small amounts of phosphorus and nitrogen (\(\text{NH}_4\)-N and \(\text{NO}_3\)-N). These elements were not especially well present in any coarseness level either. This was probably due to the low decomposition of organic mass in peatland environment. In this situation phosphorus and nitrogen concentrations were not suitable tools to estimate mineral subsoil suitability for any after-use forms. Concentrations of calcium, magnesium and potassium were strongly dependent on the fine material percentage of the sediments. Also Sepponen (1981; 1982) has pointed out, that fine particles of the sediments are the ones “releasing” nutrients. Both fine material percentage and Ca-, Mg- and K- concentrations seemed to be suitable tools for estimating suitability for agriculture and forestry. Also the earlier presented minimum limit 15-20 % for fine particles (Aro et al. 1997; Aro & Kaunisto 1998) could be seen as a limit for presence of small scale natural nutrition: above this level the concentrations (Ca, Mg and K) start to increase.

57 % of the areas studied were well suitable for forestry. Mineral subsoils well suitable for field crop production covered 26 % of the total area and another 31 % was till with suitable fine material percentage. Boulders though could be a problem in till areas. On the other hand approximately half of the tills of this study did not include large boulders, so even 42 % of the areas could be estimated to be well suitable for field crop production. Thinking of the chemical features 89 % were well suitable for bird sanctuaries based on the mineral subsoil quality, but topography was not necessarily favouring these after use forms in all of these cases. In principle mire regeneration was considered to be suitable after-use form in all of the areas – keeping open the possibility of different technical solutions for reflooding. 9 % of all areas were very fine sediments located in clearly pool-forming depressions. The rate was 14 %, if also relatively fine sediments in pool-forming depressions were included. These “pool areas” were also classified to the category of very fine sediments (difficult for commercial use) – leaving only the mire regeneration or other rewetting possible as an alternative.

In this study mire regeneration was considered as the most recommended solution for both areas difficult to drain and for areas with high sulphur concentrations. Mire regeneration was the after-use form recommended when other after-use forms became too difficult. A different approach has been developed by Gorham & Rochefort (2003): there should be prioritizing peatlands for restoration. Prioritizing should be based on the probability of the succession, the original ecological value, site’s possibilities to host rare species, functional linkages to other peatlands and ecosystems. So, approach used in this study was somehow opposite, but not leading to an opposite final result. For example areas with draining difficulties can be beneficial for mire regeneration. In Ireland the correct adjustment of the water table and control of water flow in the area has been enough for natural re-introduction of \(\text{Sphagnum cuspidatum}\) (Farrell & Doyle 2003). Also in Finnish studies water table has been critical factor for plant establishment in mire regeneration (Tuittila et al. 2000 b). There usually is also thicker peat layer left in depressions difficult to drain compared to the surroundings. Thick peat layer insulating the surface from the nutrient rich mineral subsoil is likely to be beneficial for mire vegetation reintroduction (Charman 2002). Also the local source for plant colonization is an important factor in mire regeneration. In Finland the amount of mires and peatlands is large and their distribution is wide. Problems related to the local vegetation source should be unlikely to occur.
Sulphur content (water-soluble) varied strongly, but was not directly dependent on fine material percentage. 11% off all mineral subsoils were relatively sulphur rich and this way likely to produce acidity when exposed to disturbances. Knowing sulphur concentration and pH were necessary for recognising mineral subsoils with strongest land-use limitations. In the 90’s sulphate soils were seen as a risk for after-use mainly in Litorina zone (Selin 1999). This study shows that the acidity risk should be taken into consideration also in other areas, especially in Lake Ladoga – Bothnian Bay zone.

Differences in the concentrations of calcium, magnesium and potassium were found between geochemical provinces. These differences were most significant in the coarsest mineral subsoils. In the Lake Ladoga – Bothnian Bay zone very coarse sediments had highest nutrient concentrations and granitoid areas and Archaean gneiss areas had the lowest concentrations. The areas of Svecokarelian schists and gneisses were between the extremes but closer to the nutrient rich end. This result could be possibly applied in practice: low fine material percentages could be seen less critical inside the Lake Ladoga – Bothnian Bay zone. Similar thinking could be applied in the areas of Svecokarelian schists and gneisses – and possibly other geochemical provinces known to have slightly similar features.

In a scenario tied to mineral subsoil types, with a relatively large percentage of mire regeneration, the current peat production area together with released areas and areas already in after-use, the carbon accumulation rate was 0.096 million t C a⁻¹. In an energy production oriented scenario the same rate was 0.152 million t C a⁻¹. The energy production oriented scenario was built to respect only the most critical after-use limitations related to the mineral subsoil. It is though relevant to question, would the same energy crop harvests be achieved in all non-optimal areas.

In the additional studies the three example cases presented peatlands typically chosen for peat production and their carbon accumulation history was studied. In these cases long term carbon accumulation in peat columns varied between 11 and 24 g C m⁻² a⁻¹. They represent both low and average levels among Finnish mires, as the known mean in Finland is 22.6 g C m⁻² a⁻¹ +/- 0.5 (Tolonen & Turunen 1996b; Tolonen et al. 1996) and range is 1.5 – 102.8 g C m⁻² a⁻¹. Starting phase carbon accumulation in the three mires studied varied between 32 and 89 g C m⁻² a⁻¹. In the later phases the rate had been between 3 and 15 g C m⁻² a⁻¹. It is though important to notice, that the length of starting phase in different cases varied between 560 and 1400 years, dependent on horizons suitable for age definition in upper peat layers. In all 3 cases the carbon accumulation rate in peat columns studied had been decreasing since starting phase.

Järvineva was the only site that had properly transferred to bog phase from the fen phase. The long term carbon accumulation rates in Järvineva, 22 and 24 g C m⁻² a⁻¹, were very close to the Finnish mean for bogs, 25.5 +/-0.5 (Tolonen & Turunen 1996a). In Järvineva also the freshest surface layers seemed to have higher recent carbon accumulation rates than Huhanneva and Kaupinsuo surfaces. Long term carbon accumulation in Huhanneva mire was 15 g C m⁻² a⁻¹, which is very close to the mean of Finnish fens, 17.2 +/- 0.3 (Tolonen & Turunen 1996a). Kaupinsuo, the other fen-dominated mire of the study, had the long term carbon accumulation rate 13 g C m⁻² a⁻¹. Carbon accumulation is commonly most effective in mires younger than 4500 years (Tolonen et al. 1994). Also in this study the youngest mire (Järvineva) had the highest long term carbon accumulation rates. The oldest mire had the weakest carbon accumulation rate. The age of Järvineva basal peat was 4130 +/- 80 ¹⁴C a BP. In Huhanneva the same age was 5820 +/- 90 ¹⁴C a BP and in Kaupinsuo the age was 7340 +/- 100 ¹⁴C a BP.

In Järvineva’s deepest parts mineral subsoil type (clay, gyttja) and topography would probably demand rewetting after peat production (in the deepest parts). In Huhanneva the mineral subsoil in many places was relatively coarse sorted sediment and in Kaupinsuo till. Topography, coarseness and boulders indicate, that mixed after-use scenario with reasonable quantity of mire regeneration and forestry might be realistic for these areas. Also at least one of the sites is clearly in Litorina zone and two on the edges. In the case of mire regeneration the conditions could be
adjusted for *Sphagnum* and effective carbon fixation. If recreated peat accumulation conditions stayed good, in theory the lost carbon in the case of peat production could be collected back much faster than the original accumulation happened in these three cases. Calculated according to the mire regeneration rich (43%) after-use scenario, the annual carbon accumulation of these three peatlands (927 hectares) would be after peat production 731 tonnes. According to multiple use scenario it would be 1110 tonnes carbon a⁻¹, including partly annually harvested crops. The original accumulation on these three sites in their natural state was 102 - 222 tonnes carbon (range 11 and 24 g C m⁻² a⁻¹). It is though important to notice, that lateral mire extension was not taken to consideration in these total carbon calculations: only the situation in limited surface area was studied.

In all carbon calculations related to after-use, the after-use rates represent RERCA and original carbon accumulation rates represent LORCA. It is relevant to notice, that RERCA usually refers to some hundreds of years old layers (Joosten & Clarke 2002), but in this case (related to after-use) even used RERCA represents unusually short time period.

In some cases benefiting from the existing structures (for example drainage) can be difficult to combine with applying the mineral subsoil information. In the case of Heinäsuon peatland the direction of current ditches was crossing all the mineral subsoil zones. In cases like this only the most critical limiting mineral subsoil features are likely to be taken to consideration. Compromises are likely to be made where it is possible. For example large boulders or acidity are critical limiting features for agriculture. In this study several different land-use scenarios were presented for the Finnish cut-over peatlands to leave space for necessary compromises. Also socio-economical reasons (Selin 1999) can be reason for compromising less critical mineral subsoil features.

Anyhow, studying the relevant features of the mineral subsoil of each peat production site is essential in decision making – especially when the remaining peat layer is very thin. Based on this mineral subsoil mapping the minimum analysis recommended are pH, sulphur content and fine material (<0.06 mm) percentage. Other relevant elements are calcium, magnesium and potassium. In good after-use planning practice it is also important to consider the differences in mineral subsoil between the different parts of the same production site. In most cases one after-use form is not the best alternative for the whole peat production site.
5 Conclusions

- There were properties in mineral subsoils that limit the after-use of the cut-over peatlands. Areas with relatively sulphur rich mineral subsoil and pool-forming sites with very fine and compact mineral subsoil covered total 20% of all areas. These areas were not suitable for commercial use and they were recommended for example for mire regeneration. Another 23% of areas were very coarse or very fine and their commercial use would demand special techniques - like using the remaining peat layer for compensating properties missing from the mineral subsoil. In some till areas (15% of all areas) also presence of large boulders limited possible field crop production.

- There were differences in mineral subsoils of peatlands, between different geochemical provinces and geological areas. High sulphur concentrations and acidity were typical to the areas below the highest shoreline of the ancient Litorina Sea and Lake Ladoga - Bothnian Bay zone. In very coarse sediments natural nutrient concentration was clearly higher in Lake Ladoga - Bothnian Bay zone and in the Areas of Sveokarelian schists and gneisses than in Granitoid area of central Finland and in Archaean gneiss areas. In finer sediments differences were not significant for after-use planning.

- There usually were several different mineral subsoil types under each individual peatland and same after-use form was seldom suitable for one whole released peat production area. Three typical distribution patterns (models) of different mineral subsoils within individual peatlands were found. These patterns were named the central-lake model, the central-stream model and the end-moraine model.

- Based on this study the recommended minimum analysis for after-use planning was for pH, sulphur content and fine material (<0.06 mm) percentage. Other relevant elements were calcium, magnesium and potassium. Suggested Nutrient number (based on concentrations of Ca, Mg and K) could be a tool for classifying the mineral subsoils according to their suitability for forestry and agriculture. Further calibrating with practical forestation experiments would though be needed for successful use of Nutrient number.

- Carbon accumulation scenarios for areas in peat production (59 300 ha) and the areas released from peat production (15 671 ha) varied between 0.074 and 0.152 million t C a⁻¹. The most optimistic scenario was the one, where all areas suitable for agriculture with any reasonable techniques were taken to energy crop production. Carbon accumulation rate 0.096 million t C a⁻¹ was reached in a scenario, where after-use followed most detailed way the mineral subsoil suitability for different after-use forms.

- In three typical peatlands suitable for peat production in coastal Northern Ostrobothnia, the long term carbon accumulation rates had been close to the mean rates of Finnish bogs and fens. The mire dominated by bog cover type had the rates 22 and 24 g C m⁻² a⁻¹ and the mires dominated by fen cover type had the rates 13 and 15 g C m⁻² a⁻¹. The youngest mire seemed to be the most effective carbon sink. These rates covered the whole existence of these mires. Anyhow, the natural annual carbon accumulation had been decreasing towards the time of possible intervention. Annual carbon accumulation in the after-use (according to the mire regeneration rich after-use scenario) would be 731 tonnes on the area of 927 hectares.
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