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Development of Finnish peatland area and carbon storage 1950–2000

Jukka Turunen

Geological Survey of Finland, Kuopio Unit, P.O. Box 1237, FI-70211 Kuopio, Finland

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This study summarizes the present knowledge of Finnish peatland areas and carbon (C) storage in peat from 1950 to 2000. In 1950, approximately 8.8 million ha of the Finnish peatland area was still undisturbed and 1.4 million ha drained. In 2000, almost 55% (5.7 million ha) of the peatland area in Finland was drained for forestry, 38.4% (4.0 million ha) was undrained, 0.8% (85 000 ha) was in agriculture, 0.6% (60 000 ha) was under water reservoirs, 0.3% (35 000 ha) was under roads and 0.6% was in peat harvesting or had been removed from the harvesting business (63 000 ha). The change in mire area is considered relatively reliable, whereas the net changes in the actual C sequestration and the actual C storage change from 1950 to 2000 involves much more uncertainty. In 2000, the total C storage of Finnish peatland ecosystems was estimated at 5960 Tg, which includes 5304 Tg as peat. Since 1950, the C sequestration of undrained and drained peatlands (peat, plant biomass) basically compensated for the anthropogenic losses. The most important forms of anthropogenic C losses have occurred from agricultural peat soils, water reservoirs, harvested peat and DOC output from forestry drained peatlands. From 1950 to 2000, the total C storage of Finnish peatlands, which includes peat and living plant biomass, was estimated to increased by 52 Tg because the intensive peatland drainage significantly increased the total C storage of vegetation. However, the actual C storage in peat decreased by about 73 Tg. The well-defined changes include the decrease of mire diversity because of forestry drainage.

Introduction

Peatlands are a substantial reservoir of carbon (C) in the boreal and subarctic regions, constituting at least one-fifth of the total soil C pool in the world (Post *et al*. 1982), and approximately half the amount of CO_2-C in the atmosphere (Houghton *et al*. 1990). During the Holocene, boreal and subarctic mires (346 million ha) accumulated about 200 to 455 Pg C (Pg = 10^{15} g = Gt) as peat (Sjörs 1981, Gorham 1991, Lappalainen 1996) with an update of 270 to 370 Pg C (Turunen *et al*. 2002). The large range in the global C storage estimate mainly reflects uncertainty in the depth of peat deposits because detailed results on depths are available only for a few countries such as Finland.

The total land area of Finland is 30.5 million hectares, of which about 30% is classified as peatland (Tomppo and Henttonen 1996). The estimated C reservoir in peat (5500 Tg, Minkkinen *et al*. 2002) is about 900% larger as compared with the total reservoir of living trees in Finland (618 Tg, Kauppi *et al*. 1997). Overall, more than 2/3 of the C reservoir of ecosystems in Finland is in peat (Kauppi *et al*. 1997). Thus, knowledge of Finnish peatland C reservoirs and their changes throughout the last 50 years is essential to evaluate their possible sustainable use and role in the national C balance.

The use of peatlands for forestry drainage, agriculture, energy production, road building and peat harvesting has decreased the total mire area of Finland. Since 1950, forestry drainage has been the most extensive land use applied to Finnish mires. Forest drainage activity started slowly in the early 1950s and developed into a large-scale campaign in the 1960s–1970s. Today, approximately 5.7 million ha of the mire area in Finland has been drained for forestry (Finnish statistical yearbooks of Forestry 1979–2001). Also, an additional 700 000 ha of mires may have been used for agriculture (Heikurainen 1971, Virtanen *et al*. 2003).

This study will focus on the present knowledge of total C storages in Finnish peatlands and their possible changes because of land use from 1950 to 2000. Minkkinen *et al*. (2002) is the last extensive study of C storage changes in Finnish peatlands concentrating on the impact of forestry drainage on C storage changes (peat, tree stand) since 1900. In this study, all land use forms of peatlands are taken into account and their impact on peatland area and total C storages will be evaluated. Factors causing changes and uncertainties in the C storage estimates will be identified.

For clarity, both terms — mire and peatland — are used in this study. A mire is a peatland where peat is currently being formed. A peatland is an area with or without vegetation, with a naturally accumulated peat layer at the surface, including mires drained for forestry, agriculture, horticulture and energy production (Joosten and Clarke 2002). A precondition for mire/peatland C accumulation is that the net primary production exceeds decomposition. Atmospheric CO_2 is bound in the photosynthesis of the plants and deposited as litter on and in the peat. Part of the C photosynthesized by plants is returned to the atmosphere as CO_2 and CH_4 by microorganisms that break down the dead organic matter even during the winter (Alm *et al*. 2007). Also, CO_2 is released in the maintenance respiration of above- and belowground parts of plants and in the respiration of soil animals. Additional C losses occur by dissolved organic C and fires (e.g. Aitkenhead and McDowell 2000, Pitkänen *et al*. 1999). The remaining C is deposited on and in the peat as plant structures and dead plant matter.

Throughout the text, the terms RERCA and LORCA will be used. The recent apparent rate of C accumulation (RERCA, g C m^{-2} a^{-1}) is based on the column of known dry bulk density, C concentration and age of the peat between the surface and a given dated horizon. Similarly, the long-term apparent rate of C accumulation (LORCA, g C m^{-2} a^{-1}) is based on the column section between the surface and the basal peat. RERCA is always significantly lower as compared with LORCA because of the continuous plant decay in the upper oxic acrotelm and the thicker anoxic catotelm (Clymo 1984, Tolonen and Turunen 1996, Clymo *et al*. 1998).

Material and methods

Peatland area

Information on past and present peatland area, peatland types, average depth, dry bulk density, C concentrations, growth and output rates of peat deposits are needed to analyze the potential change in Finnish peatland area and C storage from 1950 to 2000. Calculations were made for ten peatland site types and five regions adopted from Minkkinen (1999) (Table 1 and Fig. 1). For undrained peatlands, the ten mire type groups were derived from the original eight groups (Turunen *et al*. 2002) to be compared with the drained site types that the undrained types developed into after drainage.

The area of forestry drained and undrained peatlands and the mire types distribution in 1950 were obtained from the Third National Forest Inventory of Finland 1951–1953 (Ilvessalo 1956, 1957a, 1957b). The changes in areas from 1950 to 1978 were obtained from Keltikangas *et al*. (1986). Area changes from 1978 to 2000 were calculated using the annual statistics of forestry drained areas (Finnish statistical yearbooks of Forestry 1979–2001). The estimates of mire areas drained for peat harvesting and agriculture are based on statistics from The Association of Finnish Peat Industry, Suomen turvetuottajat ry, SVT (1954), Erviö (1982) and Myllys and Sinkkonen (2004). The areal distribution of cultivated organic soils and peat harvesting areas are based on Myllys and Sinkkonen (2004) and the Vahti-database obtained from the Finnish Environment Institute, respectively. The results of Selin (1999) were used to estimate the peatland area under roads, water reservoirs and dumps.

C storage and accumulation

The mean mass of dry organic matter per unit area was taken from Turunen *et al.* (2002), where the mass values represent the mean depths of different mire type groups within the Finnish mire vegetation regions. The analysis was based on 1302 dated peat cores covering each mire vegetation region of Finland. For a more detailed description, *see* Turunen *et al.* (2002). The C storage values were calculated using an average C concentration of 50.3% (Virtanen *et al.* 2003)

Table 1. The peatland type groups. The classification is based on Minkkinen (1999) and Turunen *et al.* (2002). The drained peatland types following Laine (1989). The original, undrained site types are paired with drained site types, into which they develop following drainage. *See* Appendix for more detailed description of drained site types.

Peatland type group	Mire type	Finnish drained peatland forest type	Ecological classification of peatlands
1	Eutrophic paludified hardwood-spruce forest, LhK Herb-rich hardwood-spruce swamp, RhK Eutrophic hardwood-spruce fen, VLK	Rhtkg (treed)	Eutrophic forested mires
2	Paludified *Vaccinium myrtillus* spruce forest, KgK *Vaccinium myrtillus* spruce swamp, MK *Vaccinium vitis-idaea* spruce swamp, PK	Mtkg I (treed)	Meso-oligotrophic forested mires
3	Herb-rich sedge fen, RhSN Eutrophic fen, VL Eutrophic flark fen, RiL Herb-rich flark fen, RhRiN	Mtkg II (treeless)	Meso-eutrophic treeless mires
4	Eutrophic birch fen, KoL Herb-rich sedge birch-pine fen, RhSR Eutrophic pine fen, LR Tall-sedge hardwood-spruce fen, VSK Herb-rich sedge hardwood-spruce fen, RhSK	Mtkg II (sparsely treed)	Meso-eutrophic sparsely treed mires
5	Spruce-pine swamp, KR Paludified pine forest, KgR *Carex globularis* pine swamp, PsR *Carex globularis* spruce swamp, PsK	Ptkg I (treed)	Oligotrophic forested mires
6	Tall-sedge fen, VSN Flark fen, VRiN	Ptkg II (treeless)	Oligotrophic open fens
7	Tall-sedge pine fen, VSR Cottongrass-sedge pine fen, TSR	Ptkg II (sparsely treed)	Oligotrophic fen-like sparsely treed mires
8	Low-sedge *Sphagnum papillosum* fen, LkKaN Low-sedge fen, LkN *Sphagnum fuscum* bog, RaN	Vatkg (treeless)	Ombro-oligotrophic open bogs
9	Dwarf-shrub pine bog, IR Cottongrass pine bog, TR	Vatkg (treed)	Ombro-oligotrophic pine bogs
10	*Sphagnum fuscum* pine bog, RaR Ridge-hollow pine bog, KeR Low-sedge *Sphagnum papillosum* pine fen, LkR	Jätkg (sparsely treed)	Ombrotrophic pine bogs

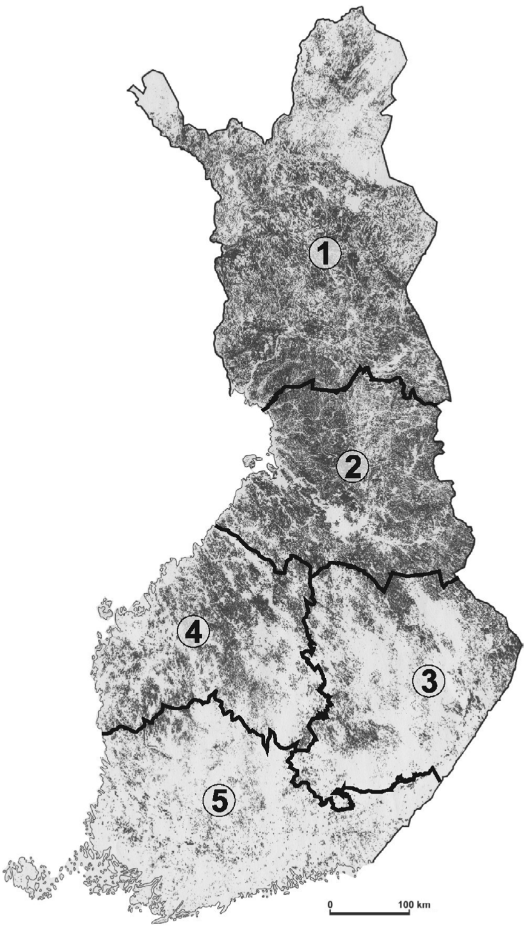

Fig. 1. Peatland distribution in Finland (grey) and the outlines of the 5 study regions used in this study. 1 = Lapland, 2 = northern Ostrobothnia, 3 = eastern Finland, 4 = western Finland, 5 = southern Finland.

based on 3670 samples analysed by the Geological Survey of Finland. However, an average C concentration of 54% was used for peatland type groups 3–4 and 6–7 (Table 1) based on the extensive material from Minkkinen and Laine (1998). The average long-term apparent rates of carbon accumulation (LORCA) obtained from Finnish mires (Turunen *et al*. 2002) and the recent C accumulation rates obtained from drained peatlands (Minkkinen 1999) were used to calculate the peat C accumulation of Finnish mires from 1950 to 2000. The average plant biomass of undrained and drained peatlands was estimated based on the results of Laiho (1997). The average total plant biomass values of 3119 and 8283 g m^{-2} were used for undrained and drained peatlands, respectively. The dry mass of vegetation was converted into carbon, based on 50% C in vegetation. The total amount of wood buried in Finnish peatlands was based on Virtanen *et al*. (2003). For the mineral subsoil beneath peat, the results of Turunen *et al*. (1999) were used.

A lack of agricultural peat soils inventories and their original peat depths make it difficult to estimate the original C storage of these cultivated peat soils. However, it is reasonable to assume that the agricultural peat soils originally had a relatively shallow peat layer, especially on the large cultivated areas of western Finland (Ilvessalo 1957b). The original C storage of agricultural peat soils was estimated using a mean dry bulk density of 91 g dm^{-3} (Mäkilä 1994, based on 49 953 samples of the Geological Survey of Finland), a mean C concentration of 50.3% (Virtanen *et al*. 2003) and area-weighted mean depth of 1.1 m (third National Forest Inventory of Finland; Ilvessalo 1956, 1957a, 1957b).

C losses

The results of Maljanen *et al*. (2007) were used to estimate the average CO_2 and CH_4 losses from agricultural peat soils (grass, cereals, fallow and abandoned field) of Finland. For peat harvesting areas, the average CO_2 and CH_4 losses were calculated based on the result in Alm *et al*. (2007).

The cumulative use of peat for peat production from 1970 to 2001 is based on The Association of Finnish Peat Industries (www.turveliitto.fi) and Hannu Haavikko of Suomen turvetuottajat ry. (pers. comm.). The Association of Finnish Peat Industries covers the major peat harvesting companies but there are also 104 minor peat producers who are not members of the Association of Finnish Peat Industries. A mean dry bulk density of 178 g dm^{-3} and the mean C concentration of 55% were used for harvested peat (Alakangas 2000).

Fluxes of dissolved organic carbon (DOC) were calculated for drained peatlands (forestry drainage, agriculture, peat harvesting). For undrained peatland areas, the LORCA values represent the net C accumulation in peat including C losses in the form of DOC and through possible forest fires. However, the C accumulation rates for drained peatlands are available only for ca. 60 years, and it is uncertain how these rates will develop in the future. Therefore, the C accumulation rates of Minkkinen *et al*. (2002) are considered as a recent apparent rate of C accumulation (RERCA) comparable to the corresponding results of Tolonen and Turunen (1996) and Turunen *et al*. (2004). The average DOC output rate of 15.3 g m^{-2} a^{-1} (Sallantaus 1992) was used for forestry drained peatlands, agricultural peat soils and peat harvesting areas.

Results

Peatland area 1950–2000

The total area of Finnish biological mires after he World War II is an estimated 10.4 million ha (Mikola 1989). In the third National Forest Inventory made in 1951–1953, the total peatland area was estimated to be 9.7 million ha (Ilvessalo 1956, 1957a, 1957b). According to the 8th National Forest Inventory (1986–1994), the total peatland area was estimated at only 8.9 million ha. However, these estimates do not include the cultivated area of peat soils. In 1950, the cultivated area of peat soils was estimated to be as large as 500 900 ha (SVT 1954). Altogether, about 700 000 ha of mires may have been used for agriculture throughout the land use history of Finland (Heikurainen 1971, Virtanen *et al*. 2003).

Since 1950, forestry drainage has been the most extensive land use applied to Finnish mires. The area annually drained increased steadily up to 1969, when 294 000 ha was drained (Finnish statistical yearbooks of Forestry 1979–2001) (Fig. 2A). In 1980, the area drained for forestry exceeded the natural mire area. Today, the total area of undrained mires is ca. 4.0 million ha. Drainage has been most intensive in southern and eastern Finland, where 88%–90% of the peatland area has been drained, in contrast to 23% in Lapland (Fig. 2A). However, most of the drained peatland area is situated in northern and western Finland, where peatlands represent a higher proportion of the land area. Similarly, the main proportion of large drained geological peatlands exceeding 20 ha and over 30 cm in depth are located in northern and western Finland (Virtanen *et al*. 2003). Today, the forestry drainage of mires is marginal and replaced by improvement ditching, which had an average area of 75 000 ha between 1990 and 2000 (Finnish statistical yearbooks of Forestry 1979–2001).

The mire types most commonly drained were the treed oligotrophic sites (Table 1, types 5 and 7), consisting mostly of pine mires. Their combined area is 2.3 million ha, which is about 40% of the total peatland area under drainage and about 80% of their original area before drainage (Minkkinen *et al*. 2002). Drainage occurred least on the originally treeless mires (types 3, 6 and 8), of which about 80% are in their natural state (Fig. 2B).

Since 1950, the total area classified as cultivated peat soils (500 900 ha) has significantly decreased. According to Erviö (1982), the cultivated area estimate in 1982 varied from 240 000 to 420 000 ha. In 2000, the estimate of arable land on peat was only 85 000 ha (Myllys and Sinkkonen (2004).

Peat harvesting companies have at their disposal approximately 120 000 ha of peatlands. Total area of peatlands in peat harvesting or removed from the harvesting is about 63 000 ha (Selin 1999) or 0.6% of the original mire area. In 2005, about 52 000 ha was in peat harvesting (Electrowatt-Ekono 2005). The biggest peat production companies in Finland are Vapo Oy (40 000 ha) and Turveruukki Oy (5500 ha). Also, minor peat producers (104 members) have approximately 6400 ha of peatlands under production (H. Haavikko, Suomen Turvetuottajat ry., pers. comm.).

In Finland, some of the mire areas are protected. There are a total of 173 established mire reserves with the total area of 453 000 ha in the National Mire Protection Programme (www.miljo.fi/default.asp?contentid=168589&lan=fi&clan=en). In addition, approximately the same area of mires is included in other types of conservation areas (e.g. national parks, strict nature reserves, wilderness areas, etc.). Thus, about 950 000 ha of mires is protected (www.miljo.fi/default.asp?contentid=168589&lan=fi&clan=en). Also, about 164 000 ha of mires are reserved for the National Mire Protection Programme, but

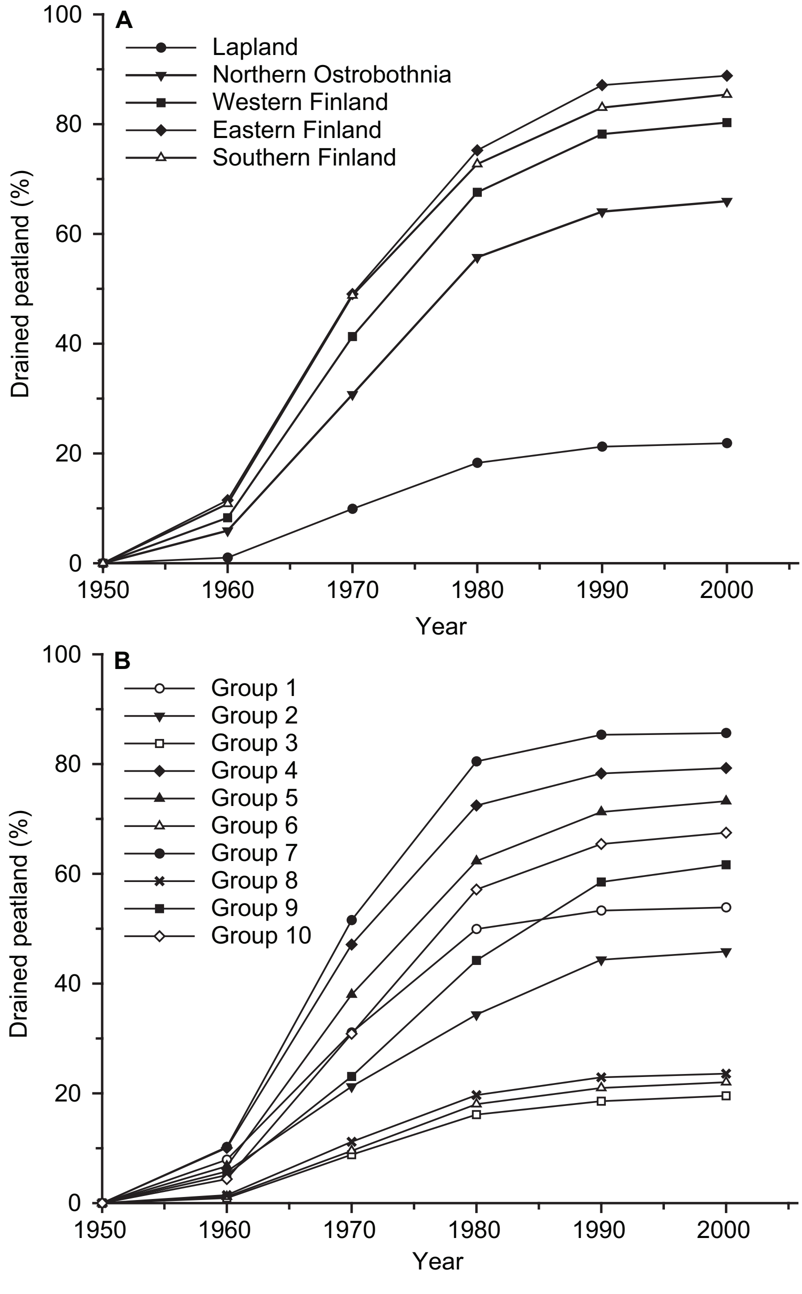

Fig. 2. (**A**) Percentage of drained peatland area in Finland by area and (**B**) by peatland type groups from 1950 to 2000 (*see* Table 1 for the peatland type groups).

these areas have not been established yet. These protection area estimates may be a slight overestimation since for example the upland forest sites within the protected mire area were included into the estimates. However, according to Virkkala *et al*. (2000), the protected mire area estimate of Finland is 1 101 400 ha of the peatland area based on the 8th National Forest Inventory (possible error 5% or 160 000 ha). Nevertheless, regionally the situation is unbalanced, since over 90% of all protected mires are situated in the northern part of the country, where 13% of the original mire area has been protected. In the southern Finland, less than 2% of the mires are protected (Aapala *et al*. 1998). The distribution of mire exploitation in Finland in 1950 and 2000 is shown in Fig. 3.

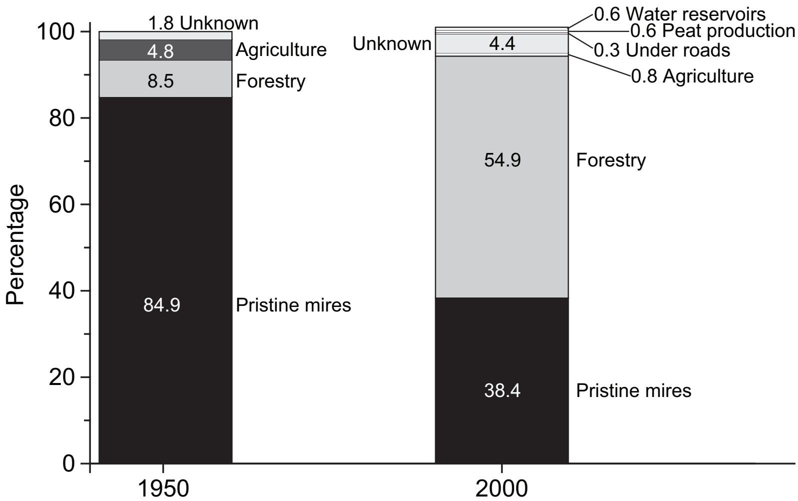

Fig. 3. Mire exploitation in Finland (%). The percentage values are based on the original biological mire area of Finland after World War II (10.4 million ha, *see* Mikola (1989)).

Carbon storage in 1950

Carbon storage in peat

In 1950, the C storage in Finnish undrained and forestry-drained peatlands (peat only) was estimated as 5125 Tg. The aapa mire region (study areas 1 and 2) and the raised bog region (study areas 3–5) included 3298 Tg (64%) and 1827 Tg (36%), respectively. The C storage of undrained mires of the aapa mire region and the raised bog region were 3173 and 1533 Tg, respectively. The corresponding C storages of forestry-drained peatlands were 125 and 294 Tg, respectively.

The original C storage of the cultivated area of peat soils (500 900 ha) in 1950 was estimated at 252 Tg. Most of the C storage was found in western Finland (90 Tg), where peatlands constitute a higher proportion of the land area (Table 2). Thus, the undrained mires contained 88% of the total peat C storage (Table 2).

There is also wood material buried in the peat deposits. The decomposition degree of the wood varies from a highly decomposed mass to hard and undecomposed stem and stump material. Relatively large amounts of wood occur in the peat deposits of southern and eastern Finland, and the amount of wood material in peat decreases from south to north (Virtanen *et al*. 2003). The total amount of wood buried in Finnish peatlands was estimated at 163 million m^3 (Virtanen *et al*. 2003). Based on the average C content of the wood, 350.4 kg C m^{-3} (www.mmm.fi/luonnonvarat_ vesivarat_maanmittaus/luonnonvarapolitiikka/natura2000/ilmastomets%C3%A4.PDF), the total amount of C buried as a wood material in Finnish peatlands was estimated at 57 Tg.

Table 2. The C storage (Tg) of undrainedrow numbers mires, forestry-drained peatlands and cultivated peat soils in five study regions of Finland in 1950 and 2000. The values include peat C only.

Study region	1950				2000			
	Undrained	Drained	Cultivated	Total	Undrained	Drained	Cultivated	Total
1. Lapland	2060	37	11	2109	1677	392	7	2076
2. Northern Ostrobothnia	1112	88	51	1252	414	795	33	1242
3. Eastern Finland	452	81	29	563	65	476	19	560
4. Western Finland	659	116	90	864	123	664	58	845
5. Southern Finland	422	97	70	589	57	478	46	581
Total	4705	419	252	5377	2336	2805	163	5304

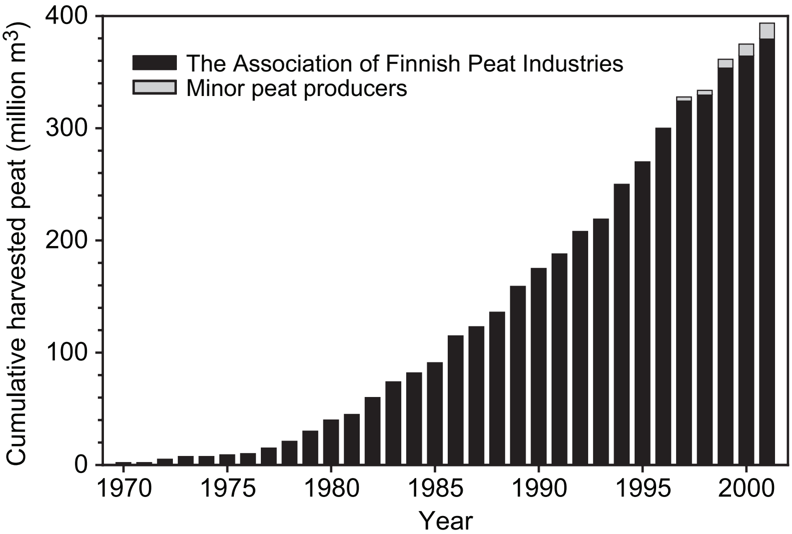

Fig. 4. The cumulative amount of harvested peat in Finland from 1970 to 2001 (www.turveliitto.fi, H. Haavikko, Suomen Turvetuottajat ry., pers. comm.).

Carbon storage in vegetation

In peatland ecosystems, additional C storage is also found in the live vegetation. In this study, the average plant biomass (tree stand, tree seedlings, ground vegetation, detritus, below-ground roots) estimates were based on the results of Laiho (1997), which were obtained from undrained and drained tall-sedge pine fens representing the sites most commonly drained for forestry in Finland and the "nutrient-level median" of the forest drainage areas. In 1950, the undrained and drained Finnish peatlands had about 138 and 36 Tg C in live vegetation, respectively.

Carbon storage in mineral subsoil

The mineral subsoil under peatlands is an additional C sink that has been overlooked and could account for some 5% of the unaccounted C in the global C budget (Turunen *et al*. 1999, Turunen and Moore 2003). The results of Turunen *et al*. (1999) indicated that the average total C density in the mineral subsoil of mire areas to a depth of 70 cm from the bottom of the A-horizon (podzolic texture), would correspond to a peat depth of about 18 cm. Turunen *et al*. (1999) estimated the C storage of Finnish subsoils as 300 Tg. However, this is a conservative estimate of the total C storage of subsoils since only the paludified soils are included in the calculations. For a more detailed description, *see* Turunen *et al*. (1999).

Total carbon storage

In 1950, the estimated total C storage of Finnish peatlands (undrained and forestry-drained peatlands + cultivated peat soil + buried wood + vegetation + subsoil) was approximately 5125 + 252 + 57 + 174 + 300 Tg = 5908 Tg.

Mire exploitation

Harvested peat

Before 1970, the amount of annually harvested peat was marginal. Since then the cumulative use of peat for peat production has steadliy been growing (Fig. 4). Between 1990 and 2000, the total amount of annually harvested peat varied between 7 and 31 million m^3, the amount of peat harvested by minor peat producers being 869 000–3 640 000 m^{-3} a^{-1} (1997–2001, H. Haavikko, Suomen turvetuottajat ry., pers. comm.). In the 1990s, the average annually harvested C from Finnish peatlands was about 2.0 Tg. The total amount of peat harvested between 1950 and 2000 was about 395 million m^3. The total amount of C harvested from Finnish peatlands between 1950 and 2000 was about 38.5 Tg, which is about 0.7% of the total C storage of Finnish peatlands. The net change of total C buried as a wood material from 1950 to 2000 was considered marginal and was ignored in the calculations.

Gas emissions

Annual C losses from harvesting areas also occur through CO_2 emissions (Ahlholm and Silvola 1990, Nykänen *et al*. 1995, Alm *et al*. 2007). The average CO_2 and CH_4 losses from milled peat harvesting areas in Finland were 263 g CO_2-C m^{-2} a^{-1} and 4.5 g CH_4-C m^{-2} a^{-1}, respectively (Alm *et al*. 2007). During the active peat-harvesting period between 1970 and 2000 (Fig. 4), the total C loss by gas emissions from past and present peat harvesting areas (63 000 ha) was estimated at 5.2 Tg (Table 3).

It is likely that the net C loss from agricultural peat soils through CO_2 from 1950 to 2000 was significant (e.g. Nykänen *et al*. 1995). CH_4 losses from agricultural drained peatlands were found to be marginal and even the net uptake was measured (Nykänen *et al*. 1995, Maljanen *et al*. 2003). Integrated estimates of C losses from agricultural peat soils via gas emissions were calculated based on the area estimates of 500 900 (year 1950), 400 000 (1956), 340 000 (1982), 127 000 (1987) and 85 000 ha (2004) (SVT 1954, Erviö 1982, Myllys and Sinkkonen 2004). The average CO_2 and CH_4 losses from agricultural peat soils (grass, cereals, fallow and abandoned field) in Finland were 566 g CO_2-C m^{-2} a^{-1} and 0.31 g CH_4-C m^{-2} a^{-1}, respectively (Maljanen *et al*. 2007). Assuming a linear decrease of agricultural peat soils between the existing inventory years, the total C loss by gas emissions from agricultural drained peatlands was estimated at 86.3 Tg (Table 3).

Leaching of organic carbon

The average DOC output rate of 15.3 g m^{-2} a^{-1} (Sallantaus 1992) was used for forestry-drained peatlands, agricultural peat soils and peat harvesting areas. The output rates of DOC were calculated for the total peatland area based on the annual development of undrained and drained peatland areas in Finland between 1950 and 2000. The total fluxes of DOC from forestry drained, agricultural and peat harvested peatlands between 1950 and 2000 were 24.5, 2.3 and 0.3 Tg, respectively (Table 3).

Other forms of mire exploitation

Relatively large peatland areas have been lost under roads, water regulation projects and reservoirs. Altogether, 220 water level regulation projects were carried out in Finland, affecting water levels in 310 lakes, with a combined area of 1.01 million ha (www.miljo.fi/default.asp?contentid=168589&lan =fi&clan=en). Additionally, there are 22 artificial water reservoirs in Finland, with a total area of 61 000 ha (www.miljo.fi/default.asp?contentid=168589&lan=fi&clan=en). The largest reservoirs are situated in northern Finland including Lokka (completed in 1967) and Porttipahta (completed in 1981). These two reservoirs alone have a combined area of 44 100 ha under water (data from Karesniemi 1975, Ruuhijärvi and Kukko-oja 1975, Virtanen *et al*. 1993). According to Selin (1999), a total of 97 000 ha of peatlands are under roads (35 000 ha), water reservoirs (60 000 ha) and dumps. Using a mean dry bulk density of 91 g dm^{-3} (Mäkilä 1994, based on 49 953 samples

Table 3. Estimated carbon losses and accumulation of Finnish peatlands from 1950 to 2000.

Element	Carbon (Tg)
Carbon losses	
Harvested peat C mass	–38.5
CO_2 and CH_4 losses from harvesting areas	–5.2
CO_2 and CH_4 losses from agricultural peat soils	–86.3
DOC output from peat harvesting areas	–0.3
DOC output from agricultural peat soils	–2.3
DOC output from forestry drained peatlands	–24.5
Other forms of mire exploitation (roads, water reservoirs, dumps)	–62.6
Carbon accumulation	
Into peat (undrained mires)	+66.7
Into peat (drained peatlands)	+80.4
In vegetation	+124.2
In mineral subsoil	+0.05
Total change	+51.7

of the Geological Survey of Finland), a mean C concentration of 50.3% and mean depth of 1.41 m (Virtanen *et al*. 2003) in calculations, the C losses caused by this type of peatland exploitation was estimated at 62.6 Tg (Table 3).

Carbon storage in 2000

Carbon accumulation of peat

The average long-term apparent rates of carbon accumulation (LORCA) obtained from different mire regions and site-type groups (Turunen *et al*. 2002) were used to calculate the net C accumulation of Finnish undrained mires from 1950 to 2000. For forestry-drained peatlands, the corresponding results of Minkkinen (1999) were used. By applying these rates to both undrained and drained peatlands, the rate of C sequestration into peat from 1950 to 2000 was estimated at 2.9 Tg a^{-1} and the total C accumulation into peat at 147 Tg (Table 3); the peat C storage in 2000 is shown in Table 2.

Carbon accumulation of vegetation

The intensive peatland drainage increased the total C storage of vegetation significantly. The average total plant biomass values of 3119 and 8283 g m^{-2} (Laiho 1997) were used for undrained and drained peatlands, respectively. In 2000, the undrained and drained Finnish peatlands had about 62.4 and 236.1 Tg C in live vegetation, respectively (Table 3). Thus, the increase of total C storage of vegetation from 1950 to 2000 was about 124 Tg.

Carbon accumulation in mineral subsoil

The average long-term apparent rate of carbon accumulation (LORCA) in the mineral subsoil beneath old peat deposits was found to be marginal (Turunen *et al*. 1999). An average LORCA of 0.5 g m^{-2} a^{-1} was used for the net C accumulation in the mineral subsoil. For a more detailed description, *see* Turunen *et al*. (1999). The total C accumulation into the mineral subsoil between 1950 and 2000 was estimated as 0.05 Tg (Table 3).

Total carbon storage

The estimated total C storage of Finnish peatlands from 1950 to 2000 increased by 52 Tg (Table 3). However, the total plant biomass development (tree stand, tree seedlings, ground vegetation, detritus, below-ground roots) seemed to play an important role in the post-drainage C balance of peatlands and the actual C storage of peat decreased about 73 Tg. In 2000, the total C pool of Finnish peatlands was estimated as 5960 Tg.

Discussion

Peatland area

The total land area of Finland is 30.5 million hectares, of which about 30% is classified as peatland. It is notable that the total mire area (9.7 million ha) derived from the third National Forest Inventory (1951–1953) differs from the estimate (10.4 million ha) presented by Mikola (1989). This is natural because agricultural land is not included in the National Forest Inventories. By adding the cultivated area estimate of 0.5 million ha (SVT 1954) to the peatland area estimate of the third National Forest Inventory, the total peatland area is close to the biological mire area estimate of Mikola (1989).

According to the 8th National Forest Inventory (1986–1994), the total peatland area was estimated at only 8.9 million ha. The use of peatlands for forestry drainage, agriculture, energy production, road building and peat harvesting had obviously decreased the total mire area of Finland. However, most of the differences in National Forest Inventories may originate from mire/peatland classification problems in the field; part of the shallow mires used earlier for agriculture have been afforested and are classified as forestry land. The results of Reinikainen *et al*. (2000) showed that the distribution and abundance of peatland vegetation changed over the last 50 years and this may be reflected in the results of field inventories as well. The changes due to peatland drainage for forestry purposes have decreased the diversity of vegetation by making the communities more similar to those of mineral soil forests (Reinikainen *et al*. 2000). Some differences may originate from the general estimation characteristics used in National Forest Inventories as indicated in Virkkala *et al*. (2000).

In 2000, 55% (5.7 million ha) of the original peatland area in Finland was drained for forestry, while only 38.5% (4.0 million ha) was undrained, 0.8% (85 000 ha) was in agriculture, 0.6% (60 000 ha) was under water reservoirs, 0.6% was in peat harvesting or removed from the harvesting business (63 000 ha) and 0.3% (35 000 ha) was under roads. Particularly, the area used for agriculture decreased dramatically from 500 900 ha in the early 1950s (SVT 1954) to 85 000 in 2000. In this study, the original C storage of the cultivated area of peat soils decreased from 252 Tg in 1950 to 163 Tg in 2000. Based on cultivated peatland area estimates of 2001, over 400 000 ha of previous peatlands were missing. However, some of the cultivated peat soils may have mistakenly been classified as organic mull soils (Myllys and Sinkkonen 2004), and the total cultivated peat soil area was underestimated in recent inventories. Selin (1999) estimated that 650 000 ha of shallow peatlands may have been lost or the remaining organic material is mixed with the mineral soil. Due to the originally large area, an updated inventory of agricultural peat soils is needed.

The well-defined changes also include a decrease in the diversity of mires, especially due to forestry drainage. Drainage was most intensive in southern and eastern Finland, where ca. 90% of the peatland area was drained, in contrast to 23% in the north. However, less than 2% of the mires are protected in the southern part of the country (Aapala *et al*. 1998). Also, the existing nature reserves or mires in a natural state include mainly pine bogs and poor fens whereas the rich mire types such as spruce mires or rich fens are rare, fragmented and small in size. In northernmost Lapland, the drainage was less intensive and large mire complexes with rich diversity still exist.

Carbon storage

As a whole, the net change of total peat or C storage from 1950 to 2000 is a complicated issue. The change in peatland area is considered relatively reliable, whereas the changes in the actual C storage involve much more uncertainty. A lack of updated inventories of agricultural peat soils (500 000–700 000 ha) and their present peat depths or afforested state, for example, make C storage comparisons in different decades difficult. However, it is reasonable to assume that the agricultural peat soils originally had a relatively shallow peat layer. In this study, the area-weighted mean depth of mire type groups was 1.1 m, varying from 43 cm to 225 cm. In comparison, in over 5.1 million ha of Finnish geological peatlands the mean depth is 1.4 m (Virtanen *et al*. 2003), indicating that Finnish peatlands are relatively shallow. Although large areas of cultivated peat soils have lost part of their original peat layer, many of them have been used for forestry and their C storage in tree stand has increased significantly. Therefore, the total changes in C storages of ex-agricultural peat soils (peat, tree stand) are probably marginal, although the ecosystem type has changed.

In C storage calculations, peat reservoirs under roads, dumps, water regulation projects and water reservoirs (97 000 ha) were deemed lost because these infrastructures are considered permanent. However, it is likely that only a part of the peat storage under the water reservoirs, for example, is lost since these structures were completed. The results of Huttunen *et al*. (2002) indicate that more than 20 years after flooding, these reservoirs were still largely supersaturated with dissolved CH_4 and CO_2. During open water conditions (May–September), the mean C emissions derived from the CH_4 and CO_2 data of Huttunen *et al*. (2002) were in the magnitude of 65 g C m^{-2}. It is notable that the winter emissions were not included and will increase the total emission values. The results of Huttunen *et al*. (2002) suggest that the intensive internal C cycle associated with the primary production may maintain high CH_4 and CO_2 production for decades.

Estimates of the CO_2 sink of undrained mires used in this study were based on the long-term rates of C accumulation (LORCA) during the entire Holocene (Turunen *et al*. 2002). The LORCA is naturally significantly lower compared to the recent apparent rate of carbon accumulation (RERCA) because of the ongoing processes of C loss from the peat (e.g. process of aerobic and anaerobic decay, leaching, peat fires, etc.). Also, severe C losses (order of 100 g C m^{-2} a^{-1}) can occur even in years with an average temperature close to and precipitation well above the long-term means (Alm *et al*. 1999). As a long-term average, only ca. 2%–16% of the biomass produced annually forms peat (Tolonen 1979, Gorham 1991, Warner *et al*. 1993, Gorham and Janssens 1992). The recent studies indicated that the present Finnish mires are still strong C sinks: the RERCA over the past 150 years was 40–81 g C m^{-2} a^{-1} (Tolonen and Turunen 1996, Pitkänen *et al*. 1999). The average net accumulation rate of C decreases with time and the long-term rates of C accumulation can be considered as true C sinks. In comparison, Roulet *et al*. (2007) also found that the mean contemporary 6-year (1998–2004) C exchange balance from a northern ombrotrophic bog was comparable to the LORCA values obtained from peat cores from the same bog for the last 3000 years (14–22 g C m^{-2} a^{-1}).

The drainage of mires has changed the net uptake of C in Finnish peatlands. In this study, the rate of C sequestration into peat between 1950 and 2000 was estimated at 2.9 Tg a^{-1} as compared with 1.8 Tg a^{-1} when all peatlands were undrained. However, estimates of the CO_2 sink of drained peatlands used in this study were based on the development of C storage after water level drawdown during the last 60 years (Minkkinen 1999). Some estimated C balance values of Minkkinen (1999) are extremely high, especially values for originally treeless mires (types 3, 6 and 8 in Table 1). In site type 8, for example, the C balance values ranged from 39 g C m^{-2} a^{-1} in the northern aapa mire region to 349 g C m^{-2} a^{-1} in the southern raised bog region (Minkkinen 1999, Minkkinen *et al*. 2002). However, any extensive C accumulation studies of these drained and nutrient poor peatlands were not available to verify the possible error. The extensive material collected by Minkkinen (1999) and Minkkinen *et al*. (2002) represents the sites most commonly drained for forestry in Finland (types 4 and 7, Table 1). Thus, it is possible that the C accumulation of nutrient poor drained peatlands was overestimated in this study. Also, it is uncertain how the C accumulation rates of drained peatlands will develop in the future. The C accumulation rates of drained peatlands may be considered as RERCA, comparable to the corresponding results of Tolonen and Turunen (1996), Pitkänen *et al*. (1999), Turunen *et al*. (2004) and Roulet *et al*. (2007) for undrained mires.

The extensive study of Minkkinen and Laine (1998) showed that the C stores of drained peatlands, especially in originally forested meso- and oligotrophic mires, at least temporarily increased after drainage, and the tree stand development seemed to play an important role in the post-drainage C balance of peat soils. Minkkinen *et al*. (2002) estimated that the rate of C sequestration into peat increased up to 3.6 Tg a^{-1}. Reasons for the increased C sequestration may be the relatively minor water level drawdown at drained sites in Finland (less than 40 cm, Minkkinen *et al*. 2002). The effect of increased aerobic conditions may be reduced by decreased peat pH, temperature and litter quality. Also CH_4 emissions from peat deposits into the atmosphere greatly decrease because of forestry drainage (Nykänen *et al*. 1998).

Generally, the sequestration of C into peatland plant biomass (tree stand, tree seedlings, ground vegetation, detritus, below-ground roots) increased significantly after drainage. Here, the average total plant biomass values of 1560 and 4141 g C m^{-2} were used for undrained and drained peatlands (Laiho 1997), and the total plant biomass of Finnish peatlands was estimated at 174 and 298 Tg C in 1950 and 2000, respectively. In comparison, Minkkinen *et al*. (2002) estimated the C storage in the tree stand at 75 and 170 Tg in 1950 and 2000, respectively. Thus, 3.1% and 5.3% of the total peatland C (peat and plant biomass) occurred in the form of plant biomass in 1950 and 2000, respectively. These estimates are comparable to those of Gorham (1991), who estimated that about 1.5% (2000 g C m^{-2}) of the total C is found as biomass in the live vegetation, while 98.5% occurs in the form of peat. However, one possible error in the total plant biomass calculations for drained peatlands may be that the plant biomass results of Laiho (1997) were applied to all of the drained peatlands in Finland. The effects of drainage on tree stand growth have also been poor on many peatlands. Mikola (1989) indicated that at least 10%–15% of the total drainage area was waste drainage where the recovery of the tree stand had been ineffective. Therefore, a cautious estimate of waste drainage area, where lower estimates of total plant biomass should probably be used, would be approximately 550 000–850 000 ha. Overall, the possible error in total plant biomass may be marginal. For example, if a conservative lower plant biomass value of 1560 g C m^{-2} was applied to drained but originally treeless or sparsely treed ombro-oligotrophic bogs of total 766 000 ha (types 4 and 7, Table 1), the total plant biomass was 7% (20 Tg) lower than the estimated 298 Tg in 2000.

Export of dissolved organic carbon (DOC) is an important form of C output from forested and peatland catchments and agricultural land. DOC export from temperate and boreal terrestrial catchments generally range from 1 to 50 g m^{-2} a^{-1}, with the largest export from catchments with high runoff or a high proportion of wetlands within the catchment (e.g. Aitkenhead and McDowell 2000, Roulet *et al.* 2007). In forested catchments in Finland, the average leaching of total organic C is approximately 5–6 g m^{-2} a^{-1} (Kortelainen and Saukkonen 1998). The results of Rekolainen (1989) suggest that leaching from agricultural land is comparable to the total leaching from forested areas, even though leaching from forested land is much lower per unit surface area (Kortelainen and Saukkonen 1998). Also, the forestry drainage of mires significantly increased the output rates of DOC from peatland catchments (8.0 *vs.* 14.1 g m^{-2} a^{-1} for undrained and drained fen catchments and 12.4 *vs.* 16.6 g m^{-2} a^{-1} for undrained and drained bog catchments, Sallantaus 1992). In this study, the average DOC output rate of 15.3 g m^{-2} a^{-1} (Sallantaus 1992) was used for forestry-drained peatlands, agricultural peat soils and peat harvesting areas. This DOC export estimate was consistent with values observed in other peatland catchments (e.g. Aitkenhead and McDowell 2000, Waddington and Roulet 1997, Worrall *et al.* 2003, Billett *et al.* 2004, Roulet *et al.* 2007).

The total annual C sink of Finnish mires (2.9–3.6 Tg a^{-1}) is assumed to remain at the current level (Minkkinen *et al.* 2002). However, it is important to keep in mind that the past peat accumulation rates cannot be taken for granted even in the near future. Increased temperature and CO_2 concentration together with any changes in precipitation, irradiation and evapotranspiration could affect the hydrology of the peatlands and accelerate the C turnover rate in peatlands both in the aerobic and anaerobic layers. Rising atmospheric CO_2 concentration and temperature conditions could nullify the peat C sink and release more gases in peatlands. It is possible, at least in some drained sites, that increased primary production and C input into the deeper peat layers exceeds the increased DOC export and the decomposition of older peat deposits and keeps the C balance positive or in a steady-state. It is clear that more knowledge is needed to deal with the responses of biogeochemical processes for the predicted atmospheric changes.

In 2000, the total C storage of Finnish peatland ecosystems was estimated at 5960 Tg, which includes 5304 Tg as peat (Table 2). This estimate was of the same magnitude as compared with the estimates reported in previous studies (Lappalainen and Hänninen 1993, Kauppi *et al.* 1997, Minkkinen *et al.* 2002, Virtanen *et al.* 2003). The amount is eight fold larger than the C storage of tree stands and five fold larger than the forest soil C of Finland. Generally, more than 2/3 of the Finnish C reservoir is in peat. The total C storage of Finnish peatlands from 1950 to 2000 was estimated to have increased by 52 Tg, whereas the actual C storage in peat decreased about 73 Tg. Despite the uncertainties in the C storage estimates, this exercise gives the magnitude of possible C storage change in peatland ecosystems; the C sequestration of undrained and drained peatlands (peat, vegetation) basically compensated or even exceeded the anthropogenic C losses even though the peat C storage actually decreased in Finnish peatlands.

References

Aapala K., Heikkilä R. & Lindholm T. 1998. Suoluonnon monimuotoisuuden turvaaminen. In: Vasander H. (ed.), *Suomen suot*, Suoseura, Helsinki, pp. 45–57.

Ahlholm U. & Silvola J. 1990. Turvetuotannon ja turpeen käytön osuus maapallon ja Suomen hiilitaseessa. *Ministry of Trade and Industry, Ser. D* 183: 1–57.

Aitkenhead J.A. & McDowell W.H. 2000. Soil C:N ratio as a predictor of annual riverine DOC flux at local and global scales. *Global Biogeochem. Cy.* 14: 127–138.

Alakangas E. 2000. *Suomessa käytettävien polttoaineiden ominaisuuksia*. Tiedotteita 2045, VTT Energia, VTT, Espoo.

Alm J., Schulman L., Walden J., Nykänen H., Martikainen P.J. & Silvola J. 1999. Carbon balance of a boreal bog during a year with an exceptionally dry summer. *Ecology* 80: 161–174.

Alm J., Shurpali N.J., Minkkinen K., Aro L., Hytönen J., Laurila T., Lohila A., Maljanen M., Mäkiranta P., Penttilä T., Saarnio S., Silvan N., Tuittila E. & Laine J. 2007. Emission factors and their uncertainty for the exchange of CO_2, CH_4 and N_2O in Finnish managed peatlands. *Boreal Env. Res.* 12: 191–209.

Billett M.F., Palmer S.M., Hope D., Deacon C., Storeton-West R., Hargreaves K.J., Flechard C. & Fowler D. 2004. Linking landatmosphere-stream carbon fluxes in a lowland peatland system. *Global Biogeochem. Cy.* 18: GB1084, doi: 10.1029/2003GB002058.

Clymo R.S. 1984. The limits to peat growth. *Philos. Trans. R. Soc. London B* 303: 605–654.

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

Lahtinen P., Jokinen M. & Leino P. 2005. Role of the energy use of peat in the Finnish energy system. *KTM Julkaisuja* 14: 1–97. Ministry of Trade and Industry. [In Finnish with English summary].

Erviö R. 1982. The cultivated peatland area of Finland. *Suo* 33: 93–95. [In Finnish with English summary].

Finnish statistical yearbooks of Forestry 1979–2001. Finnish Forest Research Institute, Helsinki.

Gorham E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecol. Appl.* 1: 182–195.

Gorham E. & Janssens J.A. 1992. The paleorecord of geochemistry and hydrology in northern peatlands and its relation to global change. *Suo* 43: 117–126.

Heikurainen L. 1971. Virgin peatland forests in Finland. *Acta Agr. Fenn.* 123: 11–26.

Houghton J.T., Jenkins G.J. & Ephraums J.J. (eds.) 1990. *Climate change*. The IPCC Scientific Assessment. Cambridge University Press, Cambridge.

Huttunen J.T., Väisänen T.S., Hellsten S.K., Heikkinen M., Nykänen H., Jungner H., Niskanen A., Virtanen M.O., Lindqvist O.V., Nenonen O.S. & Martikainen P.J. 2002. Fluxes of CH_4, CO_2, and N_2O in hydroelectric reservoirs Lokka and Porttipahta in the northern boreal zone in Finland. *Global Biogeochem. Cy.* 16(1), 1003, doi:10.1029/2000GB001316.

Ilvessalo Y. 1956. The forests of Finland from 1921–24 to 1951–53. *Commun. Inst. For. Fenn.* 47(1): 1–227. [In Finnish with English summary].

Ilvessalo Y. 1957a. *The forests of Finland by forestry board districts. Results of the national forest inventory*. MTJ 47.3. Valtioneuvoston kirjapaino. Helsinki. [In Finnish with English summary].

Ilvessalo Y. 1957b. Suomen suot, valtakunnan metsien inventointiin perustuva kuvaus. *Suo* 8: 51–61.

Joosten H. & Clarke D. 2002. *Wise use of mires and peatlands*. Background and principles including a framework for decision-making. International Mire Conservation Group & International Peat Society.

Karesniemi K. 1975. *Kemihaaran altaan suo- ja turvetutkimus*. Tiedotus 86, Vesihallitus, Helsinki.

Kauppi P.E., Posch M., Hänninen P., Henttonen H.M., Ihalainen A., Lappalainen E., Starr M. & Tamminen P. 1997. Carbon reservoirs in peatlands and forests in the boreal regions of Finland. *Silva Fenn.* 31: 13–25.

Keltikangas M., Laine J., Puttonen P. & Seppälä K. 1986. Peatlands drained for forestry during 1930–78: results from field surveys of drained areas. *Acta For. Fenn.* 193: 1–94. [In Finnish with English summary].

Kortelainen P. & Saukkonen S. 1998. Leaching of nutrients, organic carbon and iron from Finnish forestry land. *Water Air Soil Pollut.* 105: 239–250.

Laiho R. 1997. *Plant biomass dynamics in drained pine mires in southern Finland. Implications for carbon and nutrient balance*. Metsäntutkimuslaitoksen tiedonantoja 631, The Finnish Forest Research Institute.

Laine J. 1989. Classification of peatlands drained for forestry. *Suo* 40: 37–51. [In Finnish with English summary].

Laine J. & Vasander H. 1990. *Suotyypit*. Kirjayhtymä Oy, Helsinki.

Lappalainen E. & Hänninen P. 1993. *The peat reserves of Finland*. Report of Investigation 117, Geological Survey of Finland. [In Finnish with English summary].

Lappalainen E. 1996. *Global peat resources*. International Peat Society and Geological Survey of Finland.

Maljanen M., Hytönen J., Mäkiranta P., Alm J., Minkkinen K., Laine J. & Martikainen P.J. 2007. Greenhouse gas emissions from cultivated and abandoned organic croplands in Finland. *Boreal Env. Res.* 12: 133–140.

Maljanen M., Liikanen A. Silvola J. & Martikainen P.J. 2003. Methane fluxes on agricultural and forested boreal organic soils. *Soil Use Manage.* 19: 73–79.

Mikola P. 1989. Suot Suomen metsätaloudessa. *Suo* 40: 71–78.

Minkkinen K. 1999. *Effect of forestry drainage on the carbon balance and radiative forcing of peatlands in Finland*. Ph.D. thesis, Department of Forest Ecology, University of Helsinki.

Minkkinen K., Korhonen R., Savolainen I. & Laine J. 2002. Carbon balance and radiative forcing of Finnish peatlands 1900–2100 — the impact of forestry drainage. *Glob. Change Biol.* 8: 785–799.

Minkkinen K. & Laine J. 1998. Long-term effect of forest drainage on peat carbon storages of pine mires in Finland. *Can. J. Forest Res.* 28: 1267–1275.

Myllys M. & Sinkkonen M. 2004. Viljeltyjen turve- ja multamaiden pinta-ala ja alueellinen jakauma Suomessa. *Suo* 55: 53–60.

Mäkilä M. 1994. *Calculation of the energy content of mires on the basis of peat properties*. Report of Investigation 121, Geological Survey of Finland. [In Finnish with

English summary].

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

Nykänen H., Alm J., Silvola J., Tolonen K. & Martikainen P.J. 1998. Methane fluxes on boreal peatlands of different fertility and the effect of long-term experimental lowering of the water table on flux rates. *Global Biogeochem. Cy.* 12: 53–69.

Pitkänen A., Turunen J. & Tolonen K. 1999. The role of fire in the carbon dynamics of a mire, eastern Finland. *Holocene* 9: 453–462.

Post W.M., Emanuel W.R., Zinke P.J. & Stangenberger A.G. 1982. Soil carbon pools and world life zones. *Nature* 298: 156–159.

Reinikainen A., Mäkipää R., Vanha-Majamaa I. & Hotanen J.-P. (eds.) 2000. *Kasvit muuttuvassa metsäluonnossa*. Tammi, Helsinki.

Rekolainen S. 1989. Phosphorus and nitrogen load from forest and agricultural areas in Finland. *Aqua Fenn.* 19: 95–107.

Roulet N.T., Lafleur P.M., Richard P.J.H., Moore T.R., Humphreys E.R. & Bubier J. 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Glob. Change Biol.* 13: 397–411.

Ruuhijärvi R. & Kukko-oja K. 1975. *Kemihaaran allasalueen luonto*. Tiedotus 87, Vesihallitus, Helsinki.

Sallantaus T. 1992. Leaching in the material balance of peatlands — preliminary results. *Suo* 43: 253–258.

Selin P. 1999. Turvevarojen teollinen käyttö ja suopohjien hyödyntäminen Suomessa. *Jyväskylä Studies in Biological and Environmental Science* 79: 1–239.

Sjörs H. 1981. The zonation of northern peatlands and their importance for the carbon balance of the atmosphere. *Int. J. Ecol. Environ. Sc.* 7: 11–14.

SVT 1954. *Suomen virallinen tilasto. Yleinen maatalouslaskenta v. 1950, osa 1: Yleinen osa*. Maatalous 45:1, Helsinki.

Tolonen K. 1979. Peat as a renewable resource: long-term accumulation rates in northeuropean mires. In: *Proceedings of the International Symposium on Classification of Peat and Peatlands Hyytiälä, Finland, September 17–21, 1979*, International Peat Society, pp. 282–296.

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

Tomppo E. & Henttonen H. 1996. *Finnish forest resources in 1989–1994 and their changes from 1951*. Metsätilastotiedote 354, Stat. Bull. 354, Finnish Forest Research Institute. [In Finnish with English summary].

Turunen J. & Moore T.R. 2003. Controls on carbon accumulation and storage in the mineral subsoil beneath peat in Lakkasuo mire, central Finland. *Eur. J. Soil Sci.* 52: 279–286.

Turunen J., Roulet N.T., Moore T.R. & Richard P.J.H. 2004. Nitrogen deposition and increased carbon accumulation in ombrotrophic peatlands in eastern Canada. *Global Biogeochem. Cy.* 18, GB300210.1029/2003GB002154.

Turunen J., Tolonen K., Tolvanen S., Remes M., Ronkainen J. & Jungner H. 1999. Carbon accumulation in the mineral subsoil of boreal mires. *Global Biogeochem. Cy.* 13: 71–79.

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

Virkkala R., Korhonen K.T., Haapanen R. & Aapala K. 2000. *Metsien ja soiden suojelutilanne metsä- ja suokasvillisuusvyöhykkeittäin valtakunnan metsien 8. inventoinnin perusteella*. Suomen ympäristö 395, Suomen ympäristökeskus and Metsäntutkimuslaitos.

Virtanen K., Hänninen P., Kallinen R.-L., Vartiainen S., Herranen T. & Jokisaari R. 2003. *Suomen turvevarat 2000*. Report of Investigation 156, Geological Survey of Finland.

Virtanen M., Hellsten S., Koponen J., Riihimäki J. & Nenonen O. 1993. *Pohjoisten tekojärvien veden laadun laskenta mittauksin varmistettuna*. Tiedotteita 1525, VTT Espoo.

Waddington J. & Roulet N.T. 1997. The hydrological movement of DOC, dissolved CO_2 and CH_4 in a northern Scandinavian peatland. *J. Hydrol.* 191: 122–138.

Warner B.G., Clymo R.S. & Tolonen K. 1993. Implications of peat accumulation at Point Escuminac, New Brunswick. *Quaternary Res.* 39: 245–248.

Worrall F., Reed M., Warburton J. & Burt T. 2003. Carbon budget for a British upland peat catchment. *Sci. Total Environ.* 312: 133–146.

Appendix

In the Finnish classification of drained peatlands in practical forestry, the post-drainage successional plant communities of recently drained areas have been traditionally classified based on their original mire type. However, the older drainage areas have been classified into so called "drained peatland forest types". The drained peatland types follow Laine (1989). A short description of "drained peatland forest types" used in this study is given below. See also Laine and Vasander (1990) for more detailed description.

Rhtkg drained peatland forest herb-rich type. Tree stand mainly composed of spruce (*Picea abies*) with a mixture of birch (*Betula pubescens*) and alder (*Alnus glutinosa*). Typical species include *Rubus idaeus, Sorbus aucuparia, Rhamnus frangula, Athyrium filix-femina, Dryopteris expansa, Matteuccia struthiopteris, Thelypteris connectilis, Filipendula ulmaria, Viola sp., Pyrola sp., Calamagrostis purpurea, Rhizomnium sp., Plagiomnium sp., Sphagnum. squarrosum, S. warnstorfii, S. centrale*. Peat typically highly decomposed sedge-wood peat.

Mtkg I drained peatland forest *Vaccinium myrtillus* type. Tree stand dominated by spruce (*Picea abies*) with a mixture of birch (*Betula pubescens*). Typical species include *Dryopteris carthusiana, Trientalis europaea, Equisetum sylvaticum, Linnea borealis, Maianthemum bifolium, Orthilia secunda, Hylocomium splendens, Polytrichum commune*. Peat typically highly decomposed *Sphagnum*-wood- peat.

Mtkg II drained peatland forest *Vaccinium myrtillus* type. Species similar to Mtkg I type. However, tree stand a mixture of spruce (*Picea abies*) and birch (*Betula pubescens*). Peat typically moderately decomposed *Sphagnum*-sedge- peat.

Ptkg I drained peatland forest *Vaccinium vitis-idaea* type. Tree stand varies from spruce (*Picea abies*) to pine forest (*Pinus sylvestris*) with a mixture of birch (*Betula pubescens, B. pendula*). Typical species include *V. vitis-ideae, V. myrtillus, V. uliginosum, Ledum palustre*. Peat typically moderately decomposed *Sphagnum*-wood- peat.

Ptkg II drained peatland forest *Vaccinium vitis-idaea* type mainly with pine (*Pinus sylvestris*) with a mixture of birch (*Betula pubescens*). Species similar to Ptkg I type. Peat typically *Sphagnum*-sedge or sedge-*Sphagnum*- peat.

Vatkg drained peatland forest dwarf-shrub type mainly with pine (*Pinus sylvestris*). Typical species include *Ledum palustre, Betula nana, Chamaedaphe calyculata, Vaccinium uliginosum, Vaccinium vitis-ideae, V. myrtillus, Pleurozium schreberi, Dicranum polysetum*. Peat typically weakly decomposed cotton grass (*Eriophorum*)–*Sphagnum* peat.

Jätkg drained peatland forest lichen type with pine (*Pinus sylvestris*). Typical species include *Cladonia arbuscula, Cladonia rangiferina, Calluna vulgaris*. Peat typically weakly decomposed *Sphagnum*-peat.