Effect of forestry drainage on the carbon balance and radiative forcing of peatlands in Finland

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Academic dissertation

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Natural peatlands are usually carbon (C) accumulating ecosystems. They affect the global climate by decreasing the quantity of carbon dioxide (CO_2) and increasing the quantity of methane (CH_4), both of which are so-called greenhouse gases, in the atmosphere. Forestry drainage may alter these fluxes and thus the radiative forcing (i.e. “greenhouse impact”) of peatlands as well. The changes in CO_2 and CH_4 fluxes from peatlands and consequent changes in radiative forcing were investigated for this thesis. Change in peat C balance was studied using geological methods, based on peat samples from drained and undrained peatlands whereas CH_4 fluxes were measured directly using static chambers. Sequestration of C into tree stands was simulated using MELA-stand simulator and biomass and C-density models. Finally, the effect of forestry drainage on the C balance and radiative forcing of Finnish peatlands for the period of 1900-2100, was calculated from the results from these studies and other subject-related literature. It was found that peat C stores and the rate of C sequestration may in the long-term increase or decrease after drainage for forestry, depending on the peat nutrient level (mire site type) and climatic conditions (temperature sum). C stores in vegetation increase after drainage, but do so markedly only in the tree stand. Areal CH_4 emissions decrease after drainage, although ditches continue to emit CH_4 at a rate similar to undrained peatland surfaces. Finnish peatlands as a whole were found to be an important factor in national greenhouse gas emissions. Forestry drainage has significantly decreased the greenhouse effect of peatlands and is predicted to continue to do so at least for the next century. This is caused by increases in peat and tree stand C sequestration, and especially by a decrease in net CH_4 emissions from peatlands after drainage. The calculations presented here include many uncertainties involved in the actual parameter values, in the models used and in the numerous assumptions. Despite all these uncertainties, the result can be considered reliable at least quantitatively: drainage of peatlands for forestry has decreased the greenhouse effect of these ecosystems. However, further drainage of natural mires is not recommended, since these ecosystems may contain values, which might be considered even more important than the mitigation of predicted changes for Finland in climatic variables.

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V Minkkinen, K., Laine, J., Nykänen, H. and Martikainen, PJ. 1997: Importance of drainage ditches in emissions of methane from mires drained for forestry. Canadian Journal of Forest Research 27: 949-952.

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Definitions

Carbon balance (*C balance*) is defined as the *net C exchange* (i.e. net change in the C store) between the system specified and the environment in the area and period specified (units: g C m^{-2} a^{-1} or Tg C a^{-1}). Positive *C balance* values mean *C sequestration* (i.e. *C accumulation* or increase in C store) into the system whereas negative C balance values mean *C loss* (decrease in C store) from the system.

Flux and ***emission*** are commonly used terms in gas exchange measurements. *Flux* is a two-directional flow of matter into or out of the system, which can have negative or positive values, while *emission* refers to the flow of gas out of the system, thus being one-directional flux. The *net flux* of a gas is equal to the *net exchange* of the gas (units e.g: g CO_2 m^{-2} a^{-1}) between the system and the atmosphere.

The greenhouse effect is the global atmospheric warming effect caused by the imbalance in the long-wave radiation energy budget between the Earth and space. The greenhouse effect is a natural phenomenon which keeps the Earth's surface c. 30°C warmer than it would be if all emitted radiation was transferred to space.

Radiative forcing is the perturbation in the Earth's radiation energy budget which forces the global temperature to move towards a new equilibrium (unit: W m^{-2} or mW m^{-2}). Positive values indicate a potential warming of the atmosphere (i.e. "enhanced greenhouse effect") and negative ones a cooling of the atmosphere.

Mire is a wetland ecosystem in which organic matter derived from mire plants is accumulated as peat because of the high water table level and consequent poor decomposition processes. Thus the definition includes only functionally undisturbed ecosystems in which the vegetation is formed by plants adapted to wet conditions.

Peatland is land on which the soil is formed of peat. In addition to mires, this definition includes lands drained for forestry or otherwise utilized, in which peat accumulation no longer occurs. In this thesis, the term *undrained peatland* (used as a counterpart to *forestry-drained peatland*) equals the definition of mire (above).

Forestry drainage is the drainage of peatlands for forestry purposes.

Subsidence is the drop in the elevation of the peat surface after drainage and water-level drawdown.

1 Introduction

1.1 Background

Mires are vast reservoirs of carbon. The amount of carbon (C) accumulated in northern (i.e. boreal and subarctic) peatlands is estimated at c. 455 Pg (10^{15} g) (Gorham 1991), which is c. 60% of the C pool in the atmosphere and one third of the total C store in soils (IPCC 1996c). As the accumulated carbon is derived from atmospheric carbon dioxide (CO_2), and partly converted to methane (CH_4) in the anaerobic conditions of water-saturated peat, mires reduce the amount of CO_2, but at the same time increase the amount of CH_4 in the atmosphere. Land use changes such as drainage for forestry, agriculture or peat harvesting, and possible global warming alter the fluxes of these greenhouse gases in peatlands in ways that are not well understood. The role of peatlands as global greenhouse gas sinks and sources has often been mentioned, but both positive (Armentano and Menges 1986, Gorham 1991, Oechel et al. 1993, Botch et al. 1995) and negative feedback (Hobbie 1996, Laine et al. 1996b, Myneni et al. 1997) of the greenhouse gas emissions following utilization and/or global warming have been suggested.

Forestry drainage has been the most extensive land use applied to peatlands, estimated at 15 million ha (Paavilainen and Päivänen 1995), which is c. 4% of the total area of northern peatlands (350 million ha, Kivinen and Pakarinen 1981, Gorham 1991). Over 90% of the area drained is situated in Nordic countries (i.e. Finland, Sweden and Norway) and Russia (Paavilainen and Päivänen 1995). For countries like Finland, where one-third of the land area is covered by peatlands, and over half of that has been drained for forestry purposes, peatlands and their use may form a significant component of national greenhouse gas balances.

Against this background, a research project called "Carbon Balance of Peatlands and Climate Change" (SUOSILMU) was started in 1990 as a part of the "Finnish Research Program on Climate Change" (SILMU), funded by the Academy of Finland. The research work described in this thesis concentrates on the carbon balance of forestry-drained peatlands, emphasizing the effect of forestry drainage on national greenhouse gas balances. It was started under SUOSILMU and finished under another research project "Northern Peatlands and Climatic Change", funded by the University of Helsinki in 1996-1998. This thesis is based on my own empirical studies and on other subject-related studies, many of which were also conducted under these research projects.

1.2 Carbon dynamics in peatland ecosystems

1.21 Undisturbed mire ecosystems

Mires are carbon accumulating ecosystems. Atmospheric C is bound in the photosynthesis of the plants and deposited as litter both on and in the soil. Because the water table (WT) in mires is permanently close to the mire surface, the soil is largely anoxic and decomposition processes remain slow. As the net primary production exceeds decomposition, C accumulates as peat. The past average long-term rate of C accumulation in Finnish mires is estimated at 15-30 g C m^{-2} a^{-1}, but the variation within and between mires is large (2-89 g C m^{-2} a^{-1}; Korhola et al. 1995, Tolonen and Turunen 1996). The accumulation rate has been related to the mire's geographical location (south>north), age (young>old) and type (bogs>fens) (Korhola et al. 1995).

The carbon cycle in mires is schematically presented in Fig. 1. Part of the C photosynthesized by plants is returned to the atmosphere as CO_2 in the maintenance and growth respiration of above- and below-ground parts of the plants. The remaining C is transformed into plant structures, and finally deposited as dead plant matter, i.e. litter, on (or in) the soil. In the aerobic surface parts of the peat (acrotelm; Ingram 1978) c. 80-95 % of the litter is decomposed by aerobic bacteria and released as CO_2, before it is sunk by the gradually rising water table (Reader and Stewart 1972, Pakarinen 1975, Clymo 1984, Reinikainen et al. 1984, Bartsch and Moore 1985). In the water saturated, anaerobic parts of the peat the decomposition processes are very slow (from less than 1% to a few percent (Clymo 1984)) and C is released and emitted to the atmosphere mainly as CH_4.

Methane is formed from organic or gaseous carbon by methanogenic bacteria living in the anaerobic, water-saturated peat layers. A major part of the methane thus formed originates, however, from new carbon (e.g. Whiting and Chanton 1993, Schimel 1995) brought to the anaerobic peat layers by deep-rooted plants, such as sedges (Saarinen 1997). In the upper, more oxic peat layers live methanotrophic bacteria, which in turn oxidize part of the CH_4 diffusing upwards to CO_2 (e.g. Sundh et al. 1994). Many wetland plants possess aerenchyma, required to provide the roots with oxygen. At sites where such plants dominate (sedge fens especially), most of the methane is transported into the atmosphere via these plants' aerenchyma (e.g. Schimel 1995, Shannon et al. 1996, Frenzel and Rudolph 1998, Rusch and Rennenberg 1998), thus avoiding the oxidative peat layers. Thus, the methane cycle may be relatively independent of the long-term C cycle: mires in their early fen stages may act as methane pumps, converting atmospheric CO_2 to CH_4 (Korhola et al. 1996).

The variation in the CO_2 and CH_4 emissions from boreal mires is very large. Soil respiration measurements, which include the C released by decomposition of organic matter as well as the respiration of plant roots and heterotrophic organisms, give average figures for annual CO_2 emissions between 50 and 400 g C m^{-2} a^{-1}, depending on climate and mire site type (Raich and Schlesinger 1992, Moore 1996, Silvola et al. 1996a). Microtopographical differences within sites (e.g. Moore 1989) and differing climatic conditions between years (Silvola et al. 1996a) further increase the variation in CO_2 fluxes from mires. Root respiration may account for 10-40% of soil respiration in peatlands, the major part of which is probably derived from decomposing root exudates, not from the maintenance respiration of roots (Silvola et al. 1996b). Annual CH_4 emissions from boreal peatlands have varied between 0 and 70 g CH_4 m^{-2} a^{-1} (Crill et al. 1992), mean fluxes for Finnish undisturbed bogs and fens being 8 and 19 g CH_4 m^{-2} a^{-1} respectively (Nykänen et al. 1998), usually comprising less than 10% of the annual net C flux from peat to the atmosphere (Alm et al. 1997). In Finnish conditions about 80% of the emissions of CO_2 and CH_4 occur during the growing season (Alm et al. 1999), but a considerable part (20%) of the C fixed in the ecosystem is lost during winter when no C fixing occurs.

Carbon also flows in and out of the mire dissolved (i.e. DOC) in the groundwater (Urban et al. 1989, Sallantaus 1992). As mires have very high C densities, the C output is usually higher than the input, i.e. there is a net loss of C from the mire by the throughflow of water. The C leaching rate is largely dependent on the quantity of throughflow and primary productivity of the ecosystem: quite small net losses of 5-9 g C m^{-2} a^{-1} have been measured at a mire in central Finland (Sallantaus 1992, Sallantaus and Kaipainen 1996), whereas considerably higher net losses (30-35 g C m^{-2} a^{-1}) have been reported from North American peatlands of warmer climates and higher throughflow (DeVito and LaZerte 1989, Dosskey and Bertsch 1994).

Carbon is also leached downwards in the peat profile (Charman et al. 1994, Domisch et al. 1998), all the way to the underlying mineral soil (Turunen et al. 1999a). Based on the differences in C stores between mineral subsoils under young mires (<500 years) and adjacent upland soils, the C input into the mineral subsoil has been estimated at 10-20 g C m^{-2} a^{-1} (Turunen et al. 1999a).

1.22 The effects of forestry drainage

Following drainage for forestry and the consequent drawdown of the water-level, plant structures collapse and the peat surface subsides rapidly (Lukkala 1949). The surface peat layers are consequently compacted into a smaller volume, and the peat density is increased. At the same time the aerobic surface peat layer increases in thickness.

In the changed conditions, the litter and peat decay rates increase, since decomposition in aerobic conditions is always much faster than in anaerobic ones (e.g. Clymo 1984). Higher decomposition rates in connection with peatland drainage and have been reported, especially measured as cellulose mass loss (Karsisto 1979, Lieffers 1988, Bridgham et al. 1991) or as a change in CO_2 emissions in laboratory conditions (Moore and Knowles 1989). However, the effect of in-

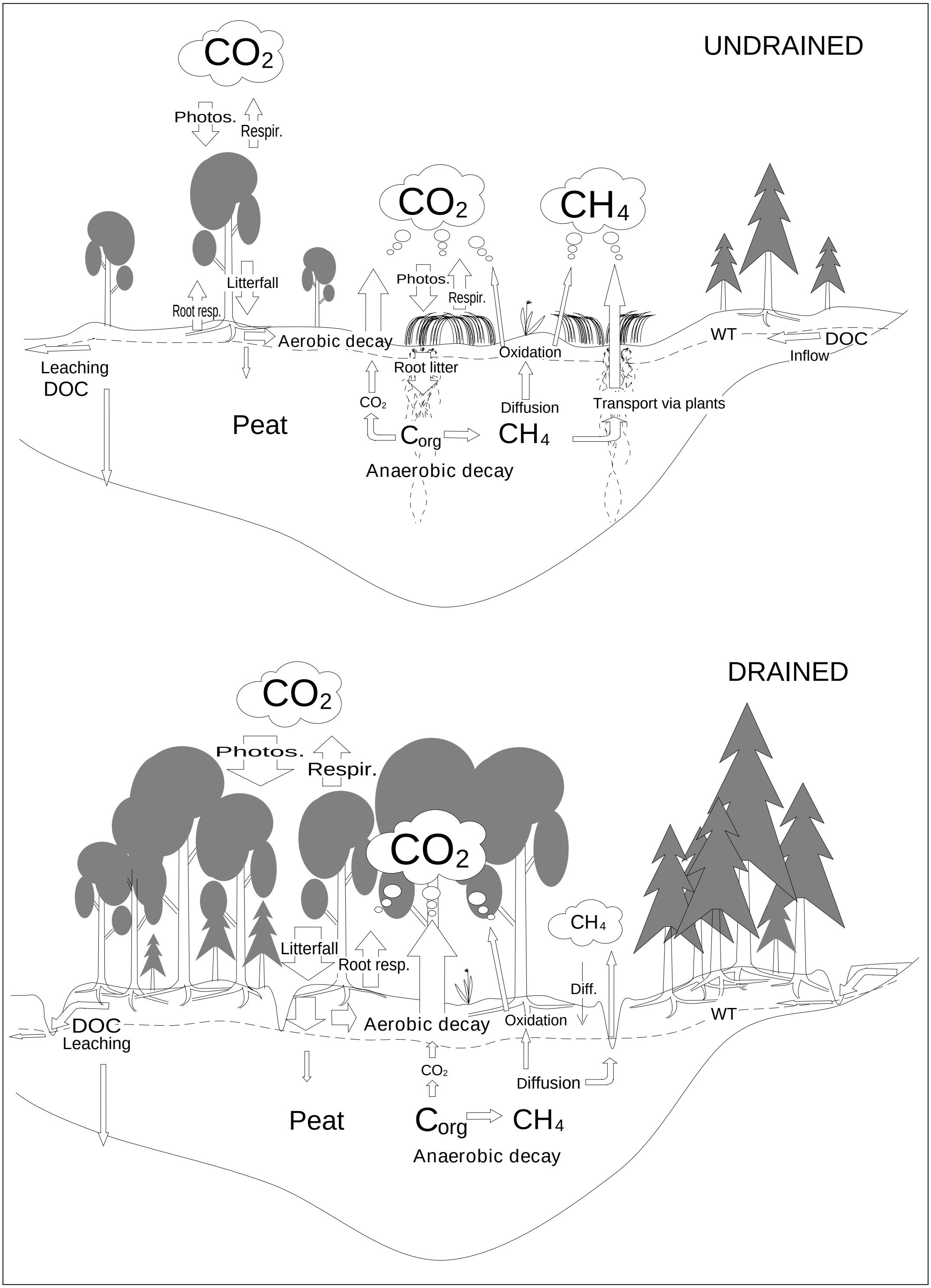

Figure 1. Schematic view of carbon flows in undisturbed (above) and forestry-drained peatlands (below).

creased aeration on increased decomposition rates may be accompanied by decreases in peat pH (Lukkala 1929, Laine et al. 1995a), low peat temperature (Heikurainen and Seppälä 1963, Hytönen and Silfverberg 1991, Minkkinen et al. 1999) and reductions in litter quality (Laiho and Laine 1996), which are all important determinants of the rate of organic matter decomposition (Ivarson 1977, Coulson and Butterfield 1978, Berg et al. 1993). In undisturbed minerotrophic peatlands the groundwater flow brings base cations into the mire from surrounding upland mineral soils, neutralizing the organic acidity of the peat. After drainage this influx of water is largely prevented by ditches, and even more cations are taken by the increasing tree stand, causing thus the peat pH to decrease. The decrease in thermal conductivity in the drier surface peat and the increasing shading by trees usually cause the surface peat temperature to decrease in the long-term after drainage (Heikurainen and Seppälä 1963, Hytönen and Silfverberg 1991, Minkkinen et al. 1999), although increases in temperature shortly after drainage have also been reported (Lieffers 1988). The decomposition rate of litter is highly dependent on the litter quality, sugars and starches being the easiest organic compound to decompose and lignin being the most difficult (Meentemeyer 1984). After drainage the lignin content of litter may be expected to increase because of the great increase in woody vegetation, which would also partly counteract the effect of increased aeration on the litter decomposition rates.

Drainage initiates a vegetation succession in which typical mire plant species are gradually replaced by forest vegetation (Sarasto 1961, Laine and Vanha-Majamaa 1992, Laine et al. 1995a). The flark and lawn level species are the first to disappear, whereas hummock-species, being more resistant to the water-level drawdown, persist longer. The rate of change depends mainly on the nutrient level and the quantity of water-level drawdown (Laine et al. 1995a). On nutrient-poor, thick-peated bog sites, where efficient drainage is difficult to maintain, vegetation succession is slow and often even stops or reverts to original mire vegetation when ditches get choked with mosses and sedges. On minerotrophic sites with originally high WT (fens), a thin peat layer and high peat nutrient content, the change is much faster. Because of sufficient drainage and nutrients in the peat, the tree growth increases rapidly during the first five years after drainage, and tree stand soon constitutes the dominant vegetation layer. Later on, shading by the tree stand directs the succession of the ground vegetation towards shade-tolerant flora. Species diversity decreases in the long-term following drainage, along with the disappearance of microtopographical differences (Laine et al. 1995a).

The simultaneous changes in vegetation and decomposition processes after drainage alter the carbon dynamics of the mire. The CO_2 emissions usually increase (Silvola 1986, Moore and Dalva 1993, Silvola et al. 1996a), while the emissions of CH_4 decrease (Roulet et al. 1993, Martikainen et al. 1995, Nykänen et al. 1998). In Finnish peatlands, annual CO_2 emissions from peat have been reported to increase by 6-190% (mean 50%; increase from 135-340 on undrained sites to c. 160-460 g C m^{-2} a^{-1} on those drained; Silvola et al. 1996a), and CH_4 emissions to decrease by 30-100% (from 3-22 on the undrained sites to 0-6 g C m^{-2} a^{-1} on the drained; Nykänen et al. 1998), depending greatly on the drainage intensity (water-level drawdown) and mire site type.

The increased CO_2 emissions have been interpreted to indicate a decrease in the soil C storage (e.g. Silvola 1986, Gorham 1991). However, the incoming C fluxes also change after drainage. The net primary production and biomass of the vegetation usually increase overall, the greatest increase occurring in the tree stand with some decrease in the moss layer (Reinikainen 1981, Reinikainen et al. 1984, Laiho 1996, Laiho and Laine 1997).

The importance of the tree stand on the total above ground biomass and primary production of the mire was stressed in the study by Reinikainen et al. (1984), where the lowest biomasses (c. 100 g C m^{-2}, 50% C content assumed) were found in treeless fens and the highest (c. 10 000 g C m^{-2}) in old drained peatland forests. Primary production varied more (70 to 700 g C m^{-2} a^{-1}), low production values being given for both drained and undrained sites but higher productions (over 250 g C m^{-2} a^{-1}) always being found on the drained sites, where the tree stand constituted 84-96% of the primary production. A decrease after drainage in primary production and biomass has been measured only in the most nutrient-poor sites (Vasander 1982).

The deposition of litter increases (Laiho and Laine 1996, Finér and Laine 1998) simultaneously with increased tree stand growth. Tree litter, enriched with lignin, is resistant to decay (e.g. Melillo et al. 1982, Meentemeyer 1984). Increases in above ground litter production up to five fold (from 30 to 150 g C m^{-2} a^{-1}; Laiho and Laine 1996), and two fold increases in litter production below ground (from 72 to 138 g C m^{-2} a^{-1}; Vasander 1982) have been estimated. These changes in the quantity and quality of the above- and below-ground litter, which form the organic C flow into the soil, may significantly contribute to the post-drainage C balance of a mire, and thus the increase in CO_2 emissions does not necessarily indicate a decrease in peat C balance.

The leaching of organic C increases during and immediately after digging the drainage network (Bergquist et al. 1984, Ahtiainen 1988), but because the groundwater flow through the peatland is decreased by ditches trapping the inflowing water, the long-term increase in organic C leaching is small (c. 10%; Ahtiainen 1988, Sallantaus 1994) or may even decrease (Heikurainen et al. 1978, Lundin and Bergquist 1990). Leaching of C downwards in the peat profile may be expected to increase because of the increased fluctuation in the water table after rainfall events. This would form a further outflow of C from the mire as well as more rapid relocation of C downwards in the peat deposit. However, no comparative studies on this issue on undrained and drained peatlands are known to the author.

1.3 Greenhouse gases, radiative forcing and carbon balance

Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), all emitted from peatlands, are so-called *greenhouse gases*. Together with other greenhouse gases (water vapour, ozone and chlorofluorocarbons), they absorb infrared radiation emitted from the Earth, emit a part of the radiation energy back to the Earth's surface and thus decrease the Earth's radiation energy transfer to space. In short, they cause the well-known *greenhouse effect*, a natural phenomenon that keeps the Earth's surface c. 30 °C warmer than it would be, if all emitted radiation was transferred to space (IPCC 1990).

Climate is never in a steady state, but keeps changing constantly. If, for example, the concentration of greenhouse gases in the atmosphere changes, the radiation balance between the Earth and space alters as well. This change in the Earth's radiation energy balance, which forces the global temperature to seek a new equilibrium, is called *radiative forcing* (expressed as W m^{-2}) and any factor that can alter this equilibrium (greenhouse gas, solar radiation, aerosols, albedo) is called a *radiative forcing agent* (IPCC 1990). Positive radiative forcing values indicate a warming effect and negative ones a cooling effect.

The properties of the greenhouse gases affecting radiative forcing vary widely between gases. For example CH_4 absorbs infrared radiation 21 times more efficiently than CO_2, expressed on a molecule/molecule ratio, and 58 times as efficiently expressed on mass/mass ratio, whereas N_2O is 206 times more efficient than CO_2, calculated in both ways (IPCC 1990). However, the gases also have different lifetimes and they interact in different ways with the environment, which makes such comparisons between them more complicated. Gases have *direct* radiative forcing impacts, which result directly from the change in the atmospheric concentrations of the gases themselves. Some gases also have *indirect* impacts through the alterations they cause in atmospheric chemistry. For example increased CH_4 concentrations enhance the formation of tropospheric ozone, and the decay of CH_4 produces water vapour in the stratosphere; these changes together increase the radiative forcing of methane by 20-30% (IPCC 1994).

Because of natural alterations in the radiative forcing agents, radiative forcing never equals zero. However, it is the anthropogenic changes in the climate, such as the *enhanced* greenhouse effect, that we are interested in. As is well-known, the atmospheric concentrations of greenhouse gases have greatly increased since pre-industrial times (i.e. since c. A.D. 1750). For example, the concentration of CO_2 has increased from 280 to 360 ppm during the last century because of the destruction of large areas of forest and the increased use of fossil fuels (IPCC 1996b). The concentrations of CH_4 and N_2O have also risen as a result of human activities such as agriculture, waste disposal and fossil fuel production and use. It has been estimated that these changes in the greenhouse gas concentrations (CO_2, CH_4, N_2O) have already increased the radiative forcing by 2.2 W m^{-2} (IPCC 1996b). Various scenarios show that the radiative forcing caused by all radiative forcing agents, would increase 4 to 8 W m^{-2} by the year 2100, which would lead to an increase of 0.9-3.5 °C in mean global temperature (IPCC 1996a).

The atmospheric CO_2 concentrations have not risen as much as has been expected from calculations based on fossil fuel emissions and the known C sinks. This has led to a search for other sinks of C in the biosphere, at first in oceans and recently in terrestrial ecosystems. Since a high proportion (1/3) of terrestrial C is sequestered into peatlands, their role in the global CO_2 fluxes has often been discussed. Increased CO_2 levels and higher temperatures might increase the primary productivity of these ecosystems leading to increased C sequestration and negative feedback on the greenhouse effect (Makulec 1991, Laine et al. 1996b, Myneni et al. 1997). Usually, however, the predicted global warming and the utilization of peatlands have been hypothesized to turn peatlands from C sinks to C sources to the atmosphere because of the dominance of water-level drawdown over possible increases in temperature (Armentano and Menges 1986, Gorham 1991, Oechel et al. 1993, Botch et al. 1995). On the other hand, the forms of utilization (peat harvesting, agriculture, forestry) may have very different effects on greenhouse gas fluxes, and thus these estimates of the utilization of peatlands on global warming remain quite imprecise.

The relative effect of greenhouse gas emissions on atmospheric warming is often estimated by calculating global warming potential (GWP), which is the time-integrated warming effect of the gas relative to that of CO_2 (mass/mass basis) (Houghton 1996). However, in this approach the time scale naturally affects the results, as lifetimes of gases vary widely, and the dynamic aspects of the phenomena (greenhouse gas emission history or scenario) are lost. Radiative forcing models (Korhonen et al. 1993, Sinisalo 1998), offer a useful tool in assessing greenhouse impacts caused by dynamic phenomena, such as drainage of peatlands for forestry. The data needed for such calculations would be the changes in greenhouse gas flux rates per unit area and the change in areas. The collection of such data, however, is not easy. The CH_4 emissions can be measured using chamber techniques (e.g. Crill et al. 1988), but the CO_2 balance is difficult to quantify since it includes C fluxes both in gaseous and organic forms. Short-term net CO_2 exchange can be measured in treeless peatlands using dynamic or static chambers (Silvola et al. 1985, Alm et al. 1997). On tree-covered peatlands micrometeorological methods using towers are the only direct ways of measuring the net CO_2 exchange (e.g. Fowler et al. 1995) of the whole peatland ecosystem. High costs, the need for a long monitoring period and large homogenous peatland areas, however, restrict the usability of this method.

Since direct measurements of CO_2 balance are difficult, time-consuming and expensive, other methods have been tried. If the C fluxes in the form of CH_4 and DOC in the ecosystem are known, the net CO_2 exchange can be estimated indirectly by measuring changes in the C stores of the ecosystem. The effect of drainage on the CO_2 balance of the mire could be studied by comparing drained and undrained sites or by measuring the same site before and after drainage. This kind of measurement gives a time-integrated net change in the C stores, thus avoiding the problems involved in the variation of CO_2 emissions over time. On the other hand, all dynamic aspects are lost, and quite a long period (decades) is needed to get accurate results. If the C stores had been accurately measured before drainage, the methods would be easy to apply. Usually this is not the case, which means that the pre-drainage values must be estimated using specific techniques, which introduce new problems and error terms into the results. However, if the changes in the C stores can be quantitatively estimated, the CO_2 and CH_4 emissions and consequent radiative forcing of the peatland could be calculated, as has been done in this thesis.

1.4 Aims and approaches

The aims of this thesis were 1) to examine the changes in peatland C stores (peat and vegetation) and CH_4 emissions caused by forestry drainage and 2) to calculate the effect of forestry drainage on the C balance and radiative forcing of Finnish peatlands in total.

The calculations were based on the substudies and other subject-related literature. The post-drainage changes in the physical structure and C stores in peat were determined by two different methods, utilizing an extensive (I and II) and intensive (III, VI) approach. Changes in vegetation C stores (tree stand and ground vegetation) were investigated by measuring biomasses (III) and by simulating tree growth in drained peatlands (IV). The importance of drainage ditches in areal methane emissions was assessed (V) in order to correct the areal CH_4 emission estimates of peatlands derived from the literature. The greenhouse impact of a mire after drainage for forestry (VI) was calculated to determine the relative importance of C fluxes in different forms (C stores in peat, tree stand and wood products together with CH_4 emissions) for C balance and radiative forcing. The methods and results of the substudies are summarized briefly, and finally, the effect of forestry drainage on the C balance and radiative forcing of Finnish peatlands from 1900 to 2100 is calculated.

2 Summary of substudies

2.1 Material and methods

2.1.1 Carbon stores (I-IV)

2.1.1.1 Extensive study material; peat (I, II)

Post-drainage changes in peat structure, bulk density (D_b), C density (D_C) and C store were investigated using extensive sample material collected from numerous undrained and 50-60 year old drained peatlands throughout Finland in 1990-1993 (I and II). Five regions from the south to the north were selected to cover the macroclimatic gradient and the main zones of mire vegetation in the country. Three nutrient levels, represented by the following pine fen site types, were chosen: 1) Herb-rich sedge birch pine fen (RhSR), 2) Tall sedge pine fen (VSR) and 3) Cottongrass sedge pine fen (TSR) or its northern counterpart Low-sedge *Sphagnum papillosum* pine fen (LkR) (site type names by Laine and Vasander (1990)).

The drained sites had been drained mainly in the 1930s. At the time of drainage detailed information was gathered from the field during the planning of the drainage networks (including peat thickness, ditch directions and lengths) which made it possible for us to locate the old measurement points (called ‘pole-points’ in II). At every point, peat thickness was measured again and volumetric peat samples from the peat surface down to a depth of 80 cm were collected for the determination of peat D_b, C concentration and D_C. As pre-drainage D_C values for the drained sites were not available, sample material from undrained mires of the same regions and site types was collected. This was used to compare peat D_b values between drained and undrained sites (I) and to construct a regression model for estimating D_C before drainage (II). The C stores before and after drainage were calculated as the product of D_C and peat thickness and the changes in these quantities were calculated as the difference between the drained and undrained values (II). The effects of categorical (site type, region) and continuous variables (temperature, nutrients, stand volume, peat thickness) on the response variables (peat subsidence and changes in peat D_b, D_C and C stores) were determined by the t-test, ANOVA and ordinary least squares (Systat 1996) and hierarchical variance component regression models (Woodhouse 1995).

2.1.1.2 Intensive study material; peat and vegetation (III)

The changes in the C stores and C balance of a peatland soil and vegetation after drainage for forestry (1961) was studied in Lakkasuo mire, Central Finland (61° 48’N, 24° 19’E, ca. 150 m. a.s.l) by comparing undrained and drained parts of the mire (III). Measurements were carried out in 1991 at four sites with different peat nutrient status: site 1 - Tall sedge fen (VSN), site 2 - Tall sedge pine fen (VSR), site 3 - Dwarf shrub pine bog (IR) and site 4 - Cottongrass pine bog with *Sphagnum fuscum* hummocks (RaTR). It was assumed that the vegetation and pre-drainage development of the peat deposits had been similar on both sides of the border ditch and any differences between undrained and drained parts were caused by drainage (and post-drainage silvicultural treatments) only.

The ground vegetation was harvested at the time of maximum annual biomass from areas of 0.1 m^2, after which the samples were dried and weighed. The C store was calculated assuming a C concentration of 50% of dry biomass. The trees (diameters and heights) were measured on 100 m^2 circular plots and the volume of the tree stand was computed. The volumes were transformed to total above ground tree stand C stores using the equation given in Laiho and Laine (1997).

The peat surface was levelled and volumetric peat cores from the peat surface down to the bottom of the peat deposit were collected. The cores were analysed for D_b and C concentration in 20 cm slices. Tree-specific pollen ratio diagrams were prepared in 1-2 cm slices in order to synchronize the peat cores with each other and to calculate the post-drainage subsidence of the peat surface. The peat C stores in undrained and drained parts of the mire were then calculated to the depth at which no further increase (caused by drainage) in C density was observed. The changes in C balances (peat, tree stand, ground vegetation) after drainage were calculated as the differences between these drained and undrained C stores.

2.1.1.3 Tree stand simulations (IV)

Tree stand dynamics and C sequestration into tree stands in four different drained peatland site types and two macroclimatic regions in Finland were simulated, using tree-level growth models by Hökkä (1997) and Hökkä et al. (1997) applied in the MELA stand simulator system (Siitonen et al. 1996), combined with biomass models developed by Marklund (1988) and Finér (1989) (V).

The stand development was simulated for managed and unmanaged stands. Diameter and height distributions for unmanaged stands, required for the baseline of the simulation, were obtained from data on undrained mires (Heikurainen 1971, Gustavsen and Päivänen 1986). Data on 15-25 year old drained mires (Hökkä and Laine 1988) were used for managed stands. The thinnings were planned to follow the thinning procedure used in practical peatland forestry, where the thinning interval is usually longer than in upland forests attributable to higher management costs caused by ditch network maintenance. The final felling (and stand regeneration) was done when the stands could not reasonably be thinned further (too few trees left, decreasing growth). The stands were regenerated by planting 2000 seedlings of spruce (RhK, MK) and pine (VSR, IR), per hectare. The new stands were treated with similar thinning procedures to the first post-drainage rotation.

Biomasses were calculated for different parts of the trees (stem, crown, stump and roots) using the modified tree-level models of Marklund (1988) and Finér (1989) and added to produce stand-level C stores.

2.1.2 Methane emissions (V)

Methane emissions in undrained and drained peatlands in Finland have already been studied, e.g. by Martikainen et al. (1995) and Nykänen et al. (1998), and the qualitative effect of drainage as reducing the CH_4 emissions from the peatland surface is fairly well known. However, as it was reported that CH_4 emissions from drainage ditches of a peatland in northern Ontario exceeded the reduction in emissions from the peatland surface between ditches (Roulet and Moore 1995), a study was conducted in Lakkasuo mire, to estimate the importance of ditches in CH_4 emissions in Finnish conditions (V).

Methane fluxes from drainage ditches (ditch bottoms and sides) and adjoining strips between the ditches were measured seven times at one week intervals in fall 1995. The fluxes were measured at six different mire sites using static chambers (diffusion and plant-mediated transport) and inverted funnels (ebullition). Three gas samples were taken from chambers with plastic syringes during a measuring period of 25 minutes, and were analysed for CH_4 within 24 hours by a gas chromatograph equipped with an FI detector. The CH_4 flux was calculated by linear regression of the concentration change in three samples, using at least two replicate injections from each sample. The release of bubbles from the ditch bottoms was measured by floating inverted funnels using a collecting period of one week. Because the CH_4 collected becomes diluted during the week, some fresh bubble samples, collected immediately after the ebullition event, were also analysed for CH_4 concentration. The bubble flux was calculated using the volume of gas collected in the funnels and the CH_4 concentration of the fresh samples. The integrated emissions from ditches were compared to those of undrained surfaces, and the proportion of ditch emissions relative to the total areal emissions was calculated.

2.1.3 Radiative forcing (VI)

Post-drainage changes in the C balance and radiative forcing of a pine mire in central Finland was investigated by utilizing data on changes in C stores in peat, tree stand and wood products (transformed to CO_2 fluxes) and CH_4 fluxes. The effect of N_2O emissions from drained pine mires on the radiative forcing is minor compared to that of CH_4 and CO_2 (Martikainen et al. 1993, Laine et al. 1996b), and was thus omitted from calculations.

The peat C store and CH_4 data was collected from an originally wet, minerotrophic mire site at Lakkasuo mire, central Finland. The change in the peat C store was estimated using method similar to that already described (intensive material, III): the pre-drainage C accumulation value was the same as long-term accumulation rate (LORCA, sensu Tolonen and Turunen (1996)) and the change in the rate was determined by comparing drained and undrained peat C stores above a synchronous baseline in the peat. CH_4 fluxes for undrained and drained conditions were determined by a static chamber method (Martikainen et al. 1992, 1995). Changes in tree stand C stores were calculated for two scenarios: 1) without and 2) with cuttings. Growth and yield tables for corresponding site types in upland forests (Ilvessalo and Ilvessalo 1975, Vuokila and Väliaho 1980) and tree growth data for peatlands (Keltikangas et al. 1986) were used to simulate the tree stand stem volume development after drainage. The standing stem volumes were converted to total biomass values using Finér's (1989) equation, and the stems removed in thinnings were converted to biomass using dry matter content 409 kg m^{-3}. The biomasses were converted to C using dry matter C content of 0.519 (Seppälä and Siekkinen 1993).

For simplifying the calculations, it was assumed that all the wood obtained from cuttings was used for pulp and paper, which are the major end products in the Finnish forest industry (Seppälä and Siekkinen 1993). Logging residues were left out of the calculations as their biomass will finally become part of the soil organic matter (peat). The lifetimes of the wood products were calculated according to Seppälä and Siekkinen (1993).

Radiative forcing caused by the changes in CO_2 and CH_4 emissions were calculated using the REFUGE model (Korhonen et al. 1993, Sinisalo 1998) for a period of 50 years before and 300 years after drainage. Only the direct radiative forcing effects of CH_4 and CO_2 were included. Since the change in the organic matter leaching was small (Sallantaus 1992), the annual net change in peat carbon store after drainage was assumed to be released directly to the atmosphere as CO_2, and the release was assumed to be linear during the whole 300 year period.

2.2 Results and discussion

2.2.1 Peat subsidence

The surface of peat subsides after forestry drainage. Subsidence in pine mires is, however, rather small and of short duration. Subsidence is mostly caused by physical compaction rather than oxidation of organic matter.

The average subsidence values in our study (II) for different region-site type combinations varied between 10 and 30 cm, and in study (III) between 0 and 25 cm, depending on the site type and pre-drainage peat thickness. The values were similar to those reported by Lukkala (1949), for similar pine mires drained 5-13 years previously, 14 - 43 cm, which indicates that most of the subsidence has taken place soon after ditching, as concluded by Lukkala (1949), Eggelsman (1976) and Nesterenko (1976). Later on, the accelerated rate of organic matter decomposition and weight of the growing tree stand may have caused some further subsidence. However, subsidence was not significantly correlated with temperature (temp. sum, Table 4 in II), which is known to be an important factor in organic matter decomposition (Nilsson and Berg 1986, Berg et al. 1993). The correlation was not significant even when the effects of site type and tree stand volume, which may interact with temperature, were removed from the model. Tree stand volume, however, was highly significant, when site type effects were removed. Wetter and more nutrient-rich site types had significantly higher subsidence values than drier and poorer types.

These results support the view that oxidation may not be of great importance in the subsidence of the peat surface in boreal conditions (Glenn et al. 1993) even in the long-term, it mainly being caused by physical changes in peat structure, i.e. the immediate collapse of plant structures after removal of water and the pressure of the growing tree stand. Much higher subsidence values (of up to 4 metres in 130 years) from warmer climates after drainage of peatlands for agriculture have been reported by Schothorst (1976, 1977) and Hutchinson (1980), and even numerous formulae for calculating subsidence in the period after drainage have been developed (e.g. Eggelsman 1976, Nesterenko 1976). It is obvious that in these cases the peat soil has deteriorated by recurrent soil preparation and peat oxidation under efficient drainage, a situation which is very different to that in forestry drainage areas in Finland.

The subsidence of the original peat surface may have been greater than the difference between the measured peat thickness values in our study (II). In the post-drainage vegetation succession *Sphagna* are gradually replaced by forest mosses like *Pleurozium schreberi* (Laine et al. 1995b). Because of enhanced tree-growth after drainage increased amounts of litter are deposited on the moss layer, and a raw humus layer of 0-20 cm, with a mean of 8 cm, (Minkkinen, unpublished data, Kaunisto and Paavilainen 1988) may be formed upon the original peat surface. Since we included this layer in the post-drainage thickness measurements, the subsidence of the original peat surface has been actually somewhat greater (on average 8 cm) than the measured values which show the net change in peat thickness. However, even if the subsidences had been calculated without this layer, the average would still have remained similar to Lukkala's (1949) values, corroborating the conclusion that subsidence of peat surface in forestry drainage areas has mostly been caused by the physical compaction of peat after water removal.

2.2.2 Peat bulk density and carbon density

Peat bulk density (D_b) and carbon density (D_C) increase after drainage. The increase is concentrated on the surface layers of peat but may reach down to deeper, almost permanently anaerobic peat layers.

The D_b and D_C of the surface peat (0-80 cm) had significantly increased after drainage in all regions and site types (I, II); D_b values were 30-75 kg m^{-3} higher on the drained sites than on the undrained (I) and D_C values had increased by 10-42 kg m^{-3} (II), depending on the site type and region.

The increase in D_b and D_C may have several causes. Peat subsidence results in more compacted structure, thus increasing peat D_b (Laiho and Laine 1994, Rothwell et al. 1996, Silins 1997). Peat compaction by the increasing weight of the tree stand, the accelerated input of tree roots (Laiho and Finér 1996), and enhanced oxidation processes in the deepened aerobic peat layer after drainage further increase the peat D_b and D_C (II).

The C stores in peat C studies have usually been calculated using D_b values and a C concentration of 50%. However, the change in D_C can not be directly calculated from the change in D_b, since the C concentration in peat also normally varies between 50 and 60% (I), and also seems to increase after drainage. During oxidative microbial metabolism, the elemental composition of the organic matter changes continually (Naucke et al. 1993) so that while the oxygen concentration decreases the concentration of carbon increases. In our material (I, II) the C concentration was slightly but significantly higher in drained peats than in the undrained (+1.6%-units), and within both undrained and drained material C concentration correlated positively with D_b (I). Even though the difference in C concentration between drained and undrained conditions may be small, it is significant when comparisons between the peat profiles of these sites are made.

The increases in D_b and D_C were highest in southern Finland and in the surface layers of peat; in southern Finland a significant increase was still observed at a depth of 60-80 cm (I). Since the water-table in drained peatlands only seldom drops below this level (Laine 1986), decay processes remain slow in these deep anaerobic layers. As the fluctuation of the water table increases after drainage, the increases in D_b and D_C may thus be partly caused by relocation of soluble C from the upper peat layers (Charman et al. 1994, Domisch et al. 1998) and by recurrent compaction during dry seasons under the increasing weight of the tree stand.

The temperature sum and the volume of the tree stand correlated positively with the change in D_C (II). The temperature sum may affect peat D_C through enhanced decomposition of organic matter in a warmer climate. However, it is obvious that temperature sum and tree growth are positively correlated (Heikurainen 1973), and a higher growth rate raises both the weight of the tree stand and the productivity (of the fine roots) in a warmer climate, thus increasing peat D_C. In contrast with peat subsidence, there was no clear trend with D_C and nutrient level (site types), and the correlation with pre-drainage peat thickness was negative. Whereas peat subsidence is governed by the physical change in the peat structure when the water is removed, the change in D_C seems to follow the dynamics of C fixed by the growing tree stand and the temperature-dependent processes in organic matter transformations more closely.

2.2.3 Peat carbon balance

The rate of C sequestration (C balance) to peat may in the long-term increase or decrease after drainage for forestry, depending on the peat nutrient level (mire site type) and climatic conditions (temperature sum).

Peat C stores decreased in the most nutrient-rich sites (RhSR, VSN-fertilized), especially in the north, but increased in the other, more nutrient-poor sites (VSR, TSR, LkR, IR, RaTR). The average values varied between -7 and +19 kg C m^{-2} over 60 years (II), and between -1.8 and 2.1 kg C m^{-2} over 30 years after drainage (III), giving thus annual values between -120 and +320 g C m^{-2} a^{-1}. The negative values mean C loss from peat (negative C balance) and positive values C sequestration into peat (positive C balance).

The change in peat C store was positively correlated with temperature sum and tree stand volume and negatively with peat nutrient level (site type; II, III). The increase in peat C stores (i.e. positive peat C balance) on the more nutrient-poor sites means that increased net primary production (NPP) and input of organic matter in the soil as litter on these sites had exceeded the simultaneously increased oxidation of organic matter. This negative correlation between peat C store change and nutrient level may be explained by the greater fine-root production and a slower decomposition rate at nutrient-poor sites. On such sites the decomposition rate is naturally slower than on the more fertile sites, because the decomposition rate depends on the availability of nutrients, especially nitrogen (Coulson and Butterfield 1978, Nilsson and Berg 1986, Aerts et al. 1995). Also, drainage on the poor sites is usually weaker than on the better sites and the oxidative, aerobic peat layer remains quite shallow even after drainage. When nutrient availability is low, trees have to allocate more C on the root systems to get the vital amount of nutrients, and the root production is greater than on fertile sites (Vogt et al. 1987, Finér and Laine 1998). The greater input of roots and slower decomposition rates thus enables higher C accumulation rates on the poor sites. Still another factor that may influence the differences in C accumulation between site types is the larger proportion of broadleaved trees (mainly birch, *Betula pubescens* Ehrh.) in the nutrient-rich sites (Keltikangas et al. 1986). In nutrient-poor sites a raw humus layer is often formed on the peat surface when the needle litter from trees is mixed with mosses growing height. In the nutrient-rich sites, however, the birch leaf-litter may cover the mosses and stop their growth quite effectively (Laine and Vanha-Majamaa 1992), thus preventing raw humus formation and consequent C accumulation on the original, pre-drainage peat surface.

The greater increase in the peat C stores in South Finland may be related to better tree growth in the south (Heikurainen 1973) and the consequent increase in tree stand biomass (IV), (Laiho and Laine 1997) and production of tree litter (Laiho and Finér 1996, Laiho and Laine 1996), which is resistant to decomposition processes because of its high lignin content (Berg 1984, Meentemeyer 1984, Berg and Lundmark 1987). The only statistically significant losses of peat C were found in the northernmost region (5-Lapland, I, II) where the impact of drainage on the growth of the tree stand is very small (Keltikangas et al. 1986), so that even a small increase in decomposition due to water-level drawdown may cause a reduction in the peat C store.

For comparison, there are only a few studies concerning the changes in peat C stores and C balance in tree-covered peatlands after drainage. Methodological difficulties and differences in climatological conditions make the results quite variable. Losses of peat C after drainage have been reported by Sakovets and Germanova (1992) and by Braekke and Finer (1991). Trettin et al. (1992) reported a rapid decrease in the C store of a histic soil (thin peated mire) after whole-tree harvesting and site preparation, including trenching and bedding. Increase in peat C store after drainage (although statistically insignificant) was reported by Anderson et al. (1992), who also stressed the importance of accuracy in the thickness measurements. In our study (II) the inaccuracy in peat thickness measurements was reflected by considerable C store variation between measurement points. However, because of the large number of measurements and the random distribution of measurement errors, the average values were considered reliable, at least in showing the trends between C balance and environmental variables.

Many studies (Silvola 1986, Glenn et al. 1993, Moore and Dalva 1993, Silvola et al. 1996a) have reported increased CO_2 fluxes after water-level drawdown, and it has been concluded that this eventually leads to losses in peat C store (Silvola 1986, Gorham 1991, Silvola et al. 1996a). However, because of the simultaneously increased NPP, this does not seem to be the case in most Finnish drained pine mires. Silvola et al. (1996a) concluded that a drop of 1 cm in the WT increases CO_2 emissions by 9.5 g C m^{-2} a^{-1} in Finnish mires, and that a drop of over 30 cm could not be compensated by the increasing NPP in boreal conditions. Our measurements in Lakkasuo (III) showed that the peat C store had indeed decreased at the site where the average drop in WT was highest (34 cm), and increased at the sites where the drop in the WT was clearly smaller (13 cm).

In practical forestry drainage areas the ditches often get blocked by vegetation, keeping the average drop in the WT rather small but still quite variable between sites (Laine 1986). This may partly explain the great variability in peat C balance values among peatlands in the extensive study material (II). Because of the rather small drop in the WT after drainage for forestry, the aerobic surface peat layer remains thin (Lähde 1969), offering still quite hostile conditions for oxidation processes and enabling C accumulation in peat even after drainage.

2.2.4 Vegetation carbon balance

Sequestration of C into peatland tree stands greatly increases after drainage. Changes in the ground vegetation C stores are insignificant in comparison to those of peat and tree stand, and may be left out of long-term calculations.

The C store in the ground vegetation increased (+2.4 g C m^{-2} a^{-1}) or decreased (-4 g C m^{-2} a^{-1}) slightly from the pre-drainage situation depending on the site type, whereas in the tree stand, the C store increased on all sites varying from 13

(RaTR) to 105 g C m^{-2} a^{-1} (VSN). The change in ground vegetation C store was 3-13% of that in the tree stand (III).

The C stores in ground vegetation (222-479 g C m^{-2}) were similar to those in biomasses reported by Kosonen (1981), Liedenpohja (1981), Lindholm (1981), Vasander (1981, 1982) and Laiho (1996), for pine mires and treeless fens in southern Finland. As the species composition radically changes with the succession following drainage (III, Laine and Vanha-Majamaa 1992, Laine et al. 1995a), the biomass distribution between different plant groups (e.g. mosses, shrubs, sedges, herbs) also changes (Laiho 1996). The changes in the total ground layer biomass may be proportionally very high during the succession (Laiho 1996), but as the biomass stays below 1 kg m^{-2} (c. 500 g C m^{-2}), its importance relative to the tree stand seems minor. However, although the C store remains small, the C fixed by the ground vegetation circulates rapidly (Reinikainen et al. 1984), and a considerable amount of C may flow into the peat through above- and below-ground litter production (Finér and Laine 1998).

In the simulated tree stands, the total C store increased by 6-12 kg C m^{-2} during the first rotation following drainage depending on the site type and macroclimatic region (IV). This would mean an average annual C sequestration rate of 45-140 g C m^{-2} a^{-1}. Averaged over two rotations, the increase in the total C store was 3-6 kg C m^{-2}, compared to the situation before drainage. In the unthinned stands the average C stores increased by 8-15 kg m^{-2} during the same periods. Of the total tree stand C store, 70-75% was in stems and crowns and 25-30% in stumps and roots (with diameter > 1cm). Coarse roots (diameter>1cm) alone contained 19-23% of the C store in the stand.

The sequestration of C in the tree stand seems to be an important sink for atmospheric C at least during the first post-drainage rotation. However, an even more important function of trees in the C balance of peatlands may be the increased C input to the peat through the production of litter (Finér and Laine 1998).

2.2.5 Methane emissions

Drainage reduces CH_4 emissions from peatlands radically. However, ditches emit CH_4 at a rate similar to undrained peatland surfaces.

The CH_4 fluxes from drained peatlands were always highest from the ditch bottoms (0 - 595 mg m^{-2} d^{-1}) and clearly decreased towards the ditch sides (0 - 78 mg m^{-2} d^{-1}) and strips (-3 - 33 mg m^{-2} d^{-1}) (V). The ebullition of CH_4 from ditch water was rather small, ranging from 3 to 37 mg CH_4 m^{-2} d^{-1}, less than 10% of the CH_4 flux from the ditch water measured by the chambers.

On minerotrophic sites, the CH_4 fluxes from the drained strips had stopped completely, and even a small uptake was detected; on ombrotrophic sites the strip emissions were 10-40% of that of the undisturbed conditions. This is largely caused by the oxidation of methane by methanotrophic bacteria in the aerobic surface peat layer, which is thicker in the minerotrophic sites than the ombrotrophic. Similar results, as to the drainage effect, have been reported by Glenn et al. (1993), Roulet et al. (1993), Martikainen et al. (1995) and Nykänen et al. (1998). The emissions from the ditches were similar to the emissions measured from the undrained parts of the mire (Martikainen et al. 1992). Thus the areal emission estimates of drained peatlands could be roughly corrected by regarding the ditch area (3-5% of the total area drained) as undisturbed mire surface. However, if the CH_4 fluxes from undrained mires were very low, as in more continental peatlands in Canada (Roulet and Moore 1995), the relative impact of the ditches may be much greater.

2.2.6 Radiative forcing

Drainage changes the C dynamics of mires and thus their radiative forcing. The increasing sequestration of C in tree stand and decreasing CH_4 emissions may cause a decrease in radiative forcing (a cooling effect) even on nutrient-rich mires, where losses of C from peat are evident.

In our simulation study (VI), C was accumulated into the peat of an undisturbed minerotrophic pine fen at a rate of 21 g m^{-2}, while 7.3 g C m^{-2} a^{-1} was emitted into the atmosphere as methane. The tree stand C store was in a steady state (0.7 kg C m^{-2}).

Drainage stopped the CH_4 emissions completely and caused a small loss of C (-14 g C m^{-2} a^{-1}) from peat (as CO_2). The sequestration of C in the tree stand increased considerably, and the C store grew to 12-14 kg C m^{-2} in 100-150 years after drainage, depending on the tree stand scenario (cuttings/no cuttings). All merchantable wood obtained in the cuttings was manufactured into pulp and paper, which are very short-lived products; nearly all of the C store in these products was lost to the atmosphere during the first 10 years after cutting. This is in accordance with the average lifetime of wood products manufactured in Finland, as the major end-products in Finnish forest industry are, in fact, pulp and paper. According to Seppälä and Siekkinen (1993), 75-80% of the C bound in the raw wood in Finland is lost to the atmosphere in the first five years after cutting.

The pre-drainage C accumulation in peat and CH_4 emissions from the peat surface together caused negative radiative forcing (i.e. a cooling effect) of -0.3 nW m^{-2} per hectare of peatland. Drainage and the following forest succession on the mire further decreased the radiative forcing down to -0.8 nW m^{-2} during the first tree stand rotation. The decrease in radiative forcing was caused by the ceasing of CH_4 emissions together with the increased sequestration of CO_2 in the tree stand, but only a small decrease in the soil carbon storage (i.e. increase in CO_2 emissions). Wood products had only a minor, short-lived effect on radiative forcing, because of the short lifecycle of pulp and paper.

In the treated-stand scenario radiative forcing was raised above the pre-drainage level for 20 - 30 years after each clear-cutting, but was rapidly decreased again as C was sequestered from the atmosphere back into the tree stand. Expressed as time-integrated averages over 300 years, drainage of the mire decreased the radiative forcing by c. 40% for the tree stand scenario with cuttings and by c. 100% for the untreated stand scenario.

Radiative forcing calculations contain uncertainties, both in the determination of the C fluxes (II, III) and in the modelling of the atmospheric behaviour of the greenhouse gases (Houghton 1996). If a peatland was permanently changed from a C accumulator to a C source for the atmosphere, the effect of the mire on the radiative forcing would inevitably become positive at some stage in the future. However, over a potential greenhouse effect mitigation period of 100 years, (IPCC 1996c) drainage of peatlands for forestry does not appear to increase radiative forcing, even with small losses of peat C.

3 Forestry drainage in Finland and the greenhouse effect

3.1 The approach

In this section the changes caused by forestry drainage in the C balance and radiative forcing of Finnish peatlands from 1900 to 2100, are calculated. The information used is the changes in undrained and forestry drained peatland areas and the drainage-induced changes in C sequestration rates and CH_4 fluxes in the peatlands during the calculation period. The calculations thus include only undrained peatlands and those drained for forestry but the impacts of other main forms of peatland utilization (peat harvesting, agriculture) are also discussed.

3.2 Calculations

3.2.1 Peatland area

3.2.1.1 Inventories: 1900-2000

The calculations were made for 10 site-type groups and 5 regions: R1 - Southern Finland, R2 - Eastern Middle Finland, R3 - Western Middle Finland, R4 - Northern Ostrobothnia and Kainuu and R5 - Lapland. These selected regions represented different climatic conditions as well as the two major peatland zones, R1-R3 belonging mainly to the raised bog zone and R4-R5 belonging to the aapa mire zone (Seppä 1996) (Fig. 2).

The mire site types (Table 1) were grouped according to the post-drainage development of the vegetation (especially tree stand growth) (Laine 1989, Laine and Vasander 1996) and their similarity in greenhouse gas emissions, both of which are based on the nutrient availability, water table level and tree stand characteristics of the sites (Keltikangas et al. 1986, Silvola et al. 1996a, Nykänen et al. 1998). The site type grouping mainly follows the classification of forestry-drained peatlands (Laine 1989) in which the original, undrained site types are parallelled by drained site types, into which they develop after drainage (Table 1).

The initial areas for drained and undrained peatlands in different regions and site types were obtained from the results of the Third National Forest Inventory (NFI 3) in 1951-1953 (Ilvessalo 1957). In NFI 3, the areas of drained and undrained peatland are given by 20 forestry board districts and 25 mire site types (site type classification according to Lukkala and Kotilainen 1951). The total area of peatland on forestry land was 9.7 million hectares of which 8.8 mill. ha was still undrained. The changes in these areas from 1950 back to 1930 and forward to 1978 were calculated according to the forestry drainage area inventory by Keltikangas et al. (1986). The development from 1978 to 1998 was calculated using the annual forestry-drained area statistics in the various regions (Metsätilastollinen vuosikirja 1979). These statistics provided no information on peatland site types, and thus the same proportional change in site-type areas (within regions) as in 1970-78 (Keltikangas et

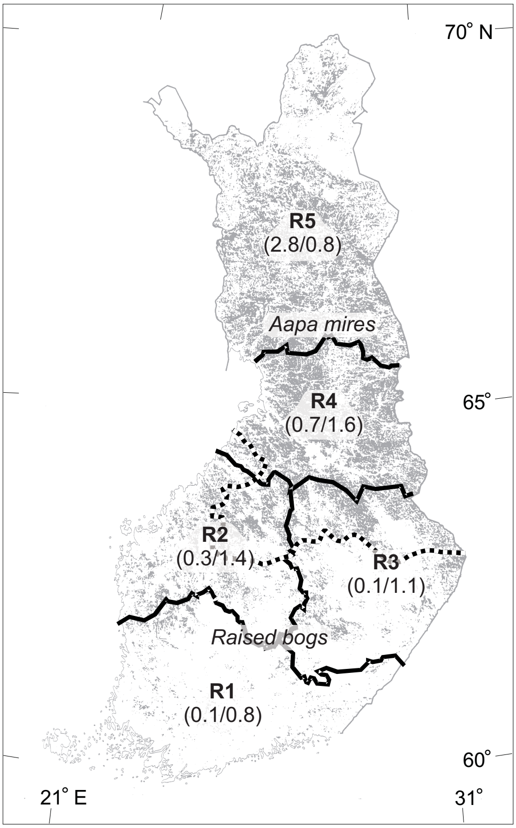

Figure 2. Peatlands in Finland (grey shading), the outlines of the study regions (R1-R5, black lines) and present areas of undrained / forestry-drained peatlands in the regions (million ha), and the borderline between raised bogs and aapa mires (dotted line). Map modified from Lappalainen (1982).

Table 1. The description of mire site-type groups. The names of the undrained and drained site types are from (Laine, 1989).

#	Name of site-type group	Undrained site type	Major tree species
1	Herb-rich type	LhK, RhK, VLK	Norway spruce / deciduous species
2	*Vaccinium myrtillus* type (I)	MK, KgK, (PK)	Norway spruce
3	*Vaccinium myrtillus* type (II)	RhSN, VL, RiL, RhRiN	treeless
4	*Vaccinium myrtillus* type (II)	RhSR, (RhSK), KoLK, LR, VSK	Scots pine / Norway spruce / decid. species
5	*Vaccinium vitis-idaea* type (I)	KR, KgR, PsR, PsK	Scots pine
6	*Vaccinium vitis-idaea* type (II)	VSN, VRiN	treeless
7	*Vaccinium vitis-idaea* type (II)	VSR,TSR	Scots pine
8	Dwarf-shrub type	IR, TR	Scots pine
9	*Cladina* type	RaN, LkN, (LkKaN)	treeless
10	*Cladina* type	RaR, KeR, (LkR)	Scots pine

al. 1986) was used. The proportion of drained paludified mineral soils was subtracted from all areas according to Keltikangas et al. (1986). In 1900 all peatlands (a total of 9.7 mill. ha; Ilvessalo 1957) were assumed to be undrained and the change from 1900 to the 1930 was assumed to be linear. The drainage activity on previously undrained peatlands was assumed to have ended by 1998.

In some regions and site types (especially nutrient rich fens) the areas derived from Ilvessalo (1957) and Keltikangas et al. (1986) were incompatible with each other. The differences may have been caused by subjectivity in the determination of site type and by various sampling errors. In these cases the calculations were done mainly after Keltikangas et al. (1986) by "moving" the area needed from one site type to another relatively similar one.

3.2.1.2 Scenario: 2000-2100

The drained peatland area maintained in production forestry may be expected to decrease in the future. Sites too poor for tree growth will be left out of forestry use and only the appropriate sites will be maintained by repetitive drainage operations. It is probable that in the poor sites the partly grown tree stand will be harvested and the site either abandoned or actively restored as a mire ecosystem. Thus all sites marginal for production forestry reverted from drained to undrained peatlands after the first (theoretical) tree stand rotation (see IV for rotation times). Such sites in the whole country were the most nutrient-poor ombrotrophic bogs (i.e. the *Cladina* types, site type groups 9 and 10) and half of the dwarf-shrub sites in regions 2 and 3 (group 8), all dwarf-shrub sites in region 4, and all other sites but herb-rich (group 1) and *Vaccinium myrtillus* sites (groups 2-4) in region 5 (see Table 1 for a description of site types). Altogether 1.7 million ha (30% of the present area) of forestry-drained peatlands would thus be abandoned, leaving c. 4 million ha for production forestry. These sites were assumed to undergo maintenance drainage at 40-year intervals.

3.2.2 Carbon balance

3.2.2.1 Areal dynamics

The dynamics of the C balance and the net CO_2 and CH_4 fluxes on Finnish peatlands both drained for forestry and undrained were calculated for each site type group in each region by multiplying the undrained and drained areas by the corresponding C balance and gas flux values. Calculations were done in 5-year periods for the period 1900-2100.

3.2.2.2 Peat C balance values

The peat C balance values for the undrained peatlands were derived from the long-term C accumulation rates for undrained mires in Finland given by Turunen et al. (1999b). As these values were calculated assuming a C content of 50% of dry matter, they were corrected to the C content of 54% (I, II, Lappalainen 1996).

The corresponding peat C balance values for drained peatlands were derived from the data in substudy (II), using values predicted by a multilevel regression model (*y=constant+region +site type+random errors*; the common structure of the model is defined more closely in the substudy II). These values represent the average C balance for the area between the ditches and were thus corrected by ditch area (5%), assuming zero C balance values for ditches.

The annual C balance values (g C m^{-2} a^{-1}) for different regions and site type groups are shown in Table 2. Similarity in average tree stand and peat properties and WT levels were used as the guideline for extrapolating values for the drained pine-dominated site types (i.e. the originally treeless site types 3 and 6) no direct measurements of which were done. As no information from spruce-dominated, shallow-peated mires was available (site type groups 1, 2 and 5), the change in C balance was assumed to be zero, i.e. the same values were used for both drained and undrained sites. As similar assumption was made with the most nutrient-poor ombrotrophic bogs (site type groups 9 and 10), where drainage-induced changes in peat properties and tree growth (Keltikangas et al. 1986) are quite small. Thus, the effect of forestry drainage on peat C stores and C balance is based on the changes in only five site-type groups out of ten, which must be remembered in interpreting the results. The reasons for and consequences of these assumptions will be discussed.

3.2.2.3 Total peat C store

The total peat C store in Finnish peatlands in 1950 was calculated using the areal distribution and mean depths of peatlands given by Ilvessalo (1956, 1957), the mean mass of dry organic matter per unit area for these peatlands given by Turunen et al. (1999b) and the C concentrations in dry organic matter (mean 54%, I, II). The peat C store was first calculated for all peatlands *without the impact of drainage* for the year 1950. The C store in 1900 was then calculated by subtracting from the 1950s value the estimated amount of C accumulated in these peatlands in the past 50 years. The peat C store development of all peatlands (forestry drained and undrained together) from 1900 to 2000 was integrated in one-year periods.

3.2.2.4 Impact of ditch spoil banks

Drainage on peatlands has an impact which has not been considered before in this thesis, the decomposition of ditch spoil banks. When peat which has been in anaerobic conditions is lifted onto the soil surface and effectively disturbed by machinery, it may be expected to decompose aerobically much quicker than in the quite limited aerobicity in the undisturbed peat layers. The impact of ditch spoil bank decomposition on the total peat C balance was estimated by using a simple exponential decay model, y=y0*exp(-kt), (Olson 1963), in which the remaining mass (y) is dependent on the original mass (y0), time (t), and a specific decay constant (k). As there are no measurements of the decomposition rate of ditch spoils, the decay constant for pine logs (k=0.033) suggested by Krankina and Harmon (1995) was used. This means that half the ditch spoils would be decomposed in 20 years and 90% in 70 years. The study by Krankina and Harmon (1995) has been conducted in conditions similar to southern Finland (region 1, T_{mean} 4 °C). Since aerobic decomposition is temperature dependent, k was corrected for other study regions using the equation given by Liski et al. (1999): $k_i=k_0*(1+0.079*(T_{mean}-4))$, where k_0 is the original k-value (region 1) and T_{mean} is the mean annual temperature of the region specified.

The original mass of C in ditch spoils was estimated using the normal ditch dimensions (depth 80 cm, width 136 cm; Paavilainen and Päivänen 1995). The volume of peat lifted would thus be 0.76 m^3 m^{-1}, making c. 10 000 kg C ha^{-1} with normal ditch spacing of 35 m (Sevola 1998), bulk density of 82 kg m^{-3} (I) and C concentration of 54% (I). Since a large proportion of undrained mires have had thinner peat layers than the normal ditch depth (85cm), the mass of C in ditch

Table 2. Peat carbon balance values (g C m^{-2} a^{-1}) used in the calculations (1900-2100) for different regions and site-type groups. Positive values indicate C sequestration to peat, and negative values C loss from peat. UD=undrained, DR=drained.

	Region 1		Region 2		Region 3		Region 4		Region 5	
Site type group	UD	DR	UD	DR	UD	DR	UD	DR	UD	DR
1	29	29	29	29	29	29	24	24	23	23
2	29	29	29	29	29	29	24	24	23	23
3	18	183	18	14	18	-2	17	-27	17	-127
4	18	183	18	14	18	-2	17	-27	17	-127
5	16	16	21	21	21	21	28	28	27	27
6	19	298	19	129	19	113	16	88	17	-12
7	18	298	20	129	20	113	18	88	17	-12
8	33	349	38	180	38	164	22	139	22	39
9	21	21	21	21	21	21	17	17	17	17
10	32	32	35	35	35	35	17	17	17	17

spoils was calculated by using the information on peat thickness on different mire site types (Ilvessalo 1956). This data was used for first-time drainage. In maintenance drainage operations the mass of ditch spoils is smaller, since a large part of the drainage is merely cleaning of old ditches (Sevola 1998). For ditch cleaning, 1/3 of the mass of new ditches was used.

An example of ditch spoil bank decomposition is shown in Figure 3. The impact of the ditch spoil bank decomposition on the total peat C balance was calculated separately and is taken into account as a separate option later in this study in the total C balances and radiative forcing values.

3.2.2.5 Tree stand simulations

The tree stand C balance was derived from simulations using the technique described in substudy (IV). The development of the tree stand after drainage was simulated using the tree-level growth models of Hökkä (1997) and Hökkä et al. (1997) in the MELA stand simulator system (Siitonen et al. 1996). Data from Heikurainen (1971), Gustavsen and Päivänen (1986) and Hökkä and Laine (1988) were used to form the initial diameter and stem frequency distributions for different site-type groups and regions, and the corresponding tree heights were calculated using models developed by Hökkä (1997). Tree stands were grown, thinned and regenerated as in (IV), in which thinning and regeneration intervals were based on the fertility of the site type and the geographical location in Finland. Tree stands on undrained peatlands were assumed to remain unchanged.

The above-ground biomasses of the trees were calculated separately for merchantable stem and crown (logging residues) using stand-level biomass models (IV) derived from the tree-level biomass models of Marklund (1988). The biomasses were transformed to carbon by an average pine tree C ratio of 0.52 (Laiho and Laine 1997).

After cuttings, the C in the merchantable stemwood was removed from the peatland and processed into wood products. The C store development of wood products was calculated according to the model by Seppälä and Siekkinen (1993), in which the total C balance of all wood products manufactured in Finland in 1990 is given as a function of time after cutting. This model indicates that 92% of the C store is lost to the atmosphere during the first 10 years, but after that the decomposition is very slow, since the remaining C is bound in very long-lived wood products (Fig. 4).

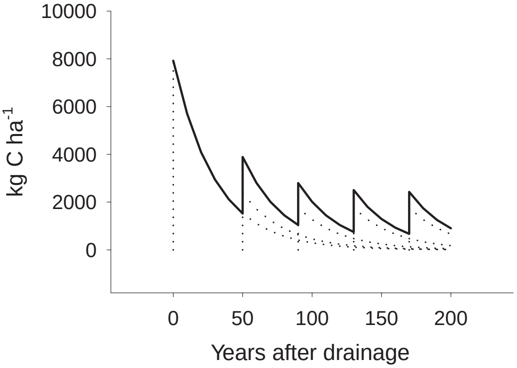

Figure 3. An example of the calculation of ditch spoil bank decomposition in the VSR (tall sedge pine fen) site type in southern Finland, with first-time drainage and four maintenance drainages. The mean thickness of peat in this site type in the undrained state is 70 cm, totalling 8000 kg C ha^{-1} in ditch spoil banks in first-time ditching. The corresponding masses of C in the succeeding maintenance drainages are 2400 and 1800 kg C ha^{-1}. Decomposition of the spoil bank was calculated at a rate of 0.033 a^{-1} of the original mass (see the methods section). The solid line indicates the total C and the dotted line the C from the succeeding ditchings.

3.2.3 Greenhouse effect

3.2.3.1 Gas flux calculations

The peat C balance values determined (Table 2) include the net C exchange as CO_2-C, CH_4-C and DOC (leaching of C) during the measurement period. The net leaching of dissolved organic carbon (DOC) from undisturbed mires has been quite small (Sallantaus 1992, Sallantaus and Kaipainen 1996) and has been assumed to remain unchanged after drainage (Ahtiainen 1988, Sallantaus 1994), whereas CH_4 fluxes are known to change drastically (e.g. Nykänen et al. 1998). Thus the net CO_2-C fluxes needed for radiative forcing simulations were calculated by adding the C lost from peat

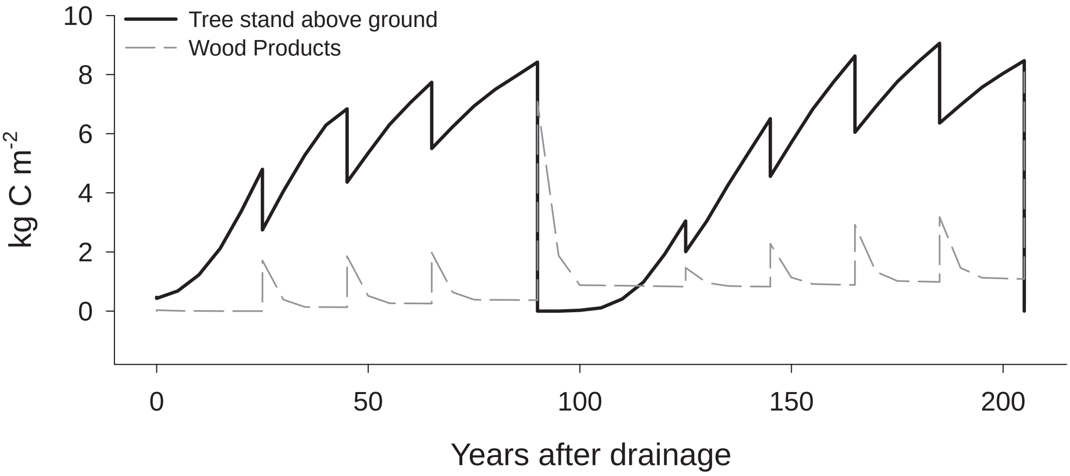

Figure 4. An example of the calculation of C store dynamics in a forestry-drained tree stand (VSR, southern Finland) undergoing normal harvesting procedure. When harvested, some of the C in the tree stand biomass (merchantable stems) enters wood products from which C is lost to the atmosphere in decomposition processes. The data for the figure was derived by simulating VSR stands in southern Finland using the MELA stand simulator (Siitonen et al, 1996; IV). The C stores in the trees were calculated using the tree-level biomass models of Marklund (1988) and an average C ratio of pine trees, i.e. 0.52 (Laiho and Laine 1997). The decomposition of wood products was calculated according to the model by Seppälä and Siekkinen (1993).

as CH_4-C (Table 3) to peat C balance values (Table 2), and leaching as DOC was omitted. The data from Nykänen et al. (1998) was used for CH_4 fluxes (Table 3), but the flux estimates were first corrected by the ditch area according to substudy (V). For the tree stand, all the C sequestered was converted to CO_2.

Table 3. Net CH_4-C flux values (g C m^{-2} a^{-1}) used in the calculations for different site-type groups for the whole country. The negative values indicate CH_4-C emissions from peat into the atmosphere.

Site type group	Undrained	Drained
1	-0.1	0.0
2	-0.1	0.0
3	-8.2	-1.0
4	-20.3	-0.9
5	-4.4	-1.0
6	-20.3	-0.9
7	-20.3	-0.9
8	-4.4	-1.0
9	-9.6	-6.1
10	-4.0	-1.9

3.2.3.2 Radiative forcing simulations

Radiative forcing resulting from the net CO_2 and CH_4 fluxes was calculated in two stages using the REFUGE model – a computer program designed to calculate global average radiative forcing caused by greenhouse gas fluxes (Korhonen et al. 1993, Savolainen and Sinisalo 1994, Sinisalo 1998). The fluxes were first converted into atmospheric concentration change. This change depends on the flux rate and the mean lifetime of the gas, and can thus easily be calculated for gases like CH_4, which have a specified lifetime in the atmosphere. Since CO_2 has no specified lifetime, modelling approaches in which transport of CO_2 to the oceans is taken into account are used. In REFUGE, the pulse response function corresponding to the background situation of 25% of extra carbon dioxide in the atmosphere (Bern-model without biosphere; IPCC 1997) was used for CO_2. The concentration changes were then converted into radiative forcing using the gas-specific functions given by IPCC (1997). Only the direct radiative forcing of CO_2 was taken into account, but the indirect impact of CH_4 was also calculated . Increased CH_4 concentrations enhance the formation of tropospheric ozone and the decay of CH_4 produces water vapour in the stratosphere, which together increase the radiative forcing of methane by 20-30% (IPCC 1994).

3.3 Results

3.3.1 Areal development of forestry drainage

Drainage of peatlands for forestry purposes remained at a relatively low level until 1960, when 8.3 mill. ha, i.e. 86% of the total area of 9.7 mill ha was still undisturbed. A big leap was taken during the next two decades when an additional area of 3.6 mill. ha was drained for forestry. This meant that half (5 mill. ha) of the total peatland area in Finland, and nearly all potential sites for forestry use, had been drained by 1980. Since an additional peatland area of 0.5 mill ha was reserved for conservation (Valtakunnallinen soidensuojelun ... 1981), the drainage activity slowed down rapidly in the 80s.

At present a total of 5.7 mill ha, i.e. almost 60% of the peatland area in Finland has been drained for forestry. This area may be expected not to increase further, because rare biotypes, such as fertile or treeless mires, are nowadays conserved by law and no more grants are given for the first-time drainage of peatlands (Metsätalouden säädökset 1997). The scenario of the drainage area development shows instead that c. 30% of presently drained areas would be left out of production foresty. However, as appropriate drainage must be maintained in the areas remaining in production forestry (c. 4 mill. ha), this would mean an average yearly area of 70 000 – 80 000 ha undergoing drainage measures (Sevola 1998).

Most of the drained peatlands are situated in northern (R4; 1.6 mill. ha) and western (R3; 1.4 mill.ha) Finland (Fig. 5) , where the peatland proportion of the land area is high as well (Fig. 2). However, drainage has been most intensive in the southern and eastern Finland, where c. 90% of the peatland area has been drained, whereas only a little more than 20% has been drained in Lapland.

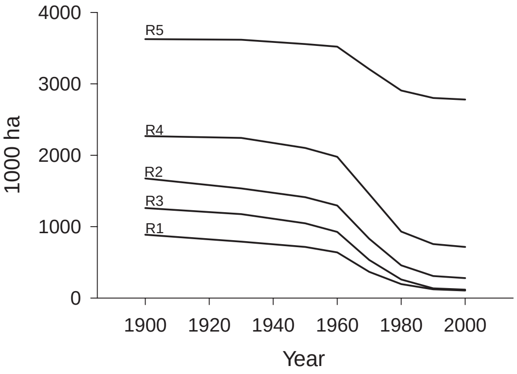

Figure 5. Undrained peatland area by study region. See Fig. 2 for location of regions in Finland.

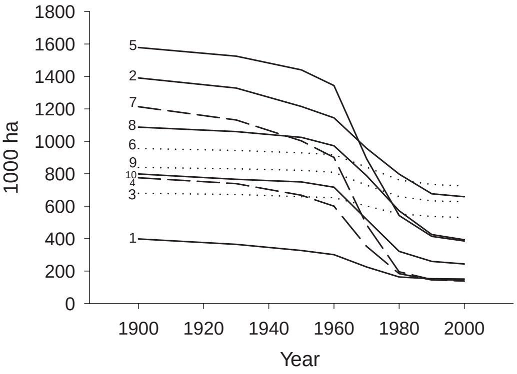

Figure 6. Undrained peatland area in Finland by site type group. The dotted line depicts treeless mires and the hatched line composite types. See Table 1 for descriptions of site type groups.

The site-type groups most commonly drained are the treed *V. vitis-idaea* site types (groups 5 and 7, Fig. 6), consisting mostly of pine mires (Table 1). Their combined area is 2.3 mill. ha, which is c. 40% of the total peatland area under drainage and c. 80% of their original area before drainage operations. Somewhat less drained site type groups include the *Vacc. myrtillus* types (spruce mires, groups 2 and 4) and the most infertile pine mires (Dwarf-shrub and *Cladina* types, groups 8 and 10). Drainage activity has been least on the originally treeless mires of which c. 80% has remained in its natural state (Fig. 6).

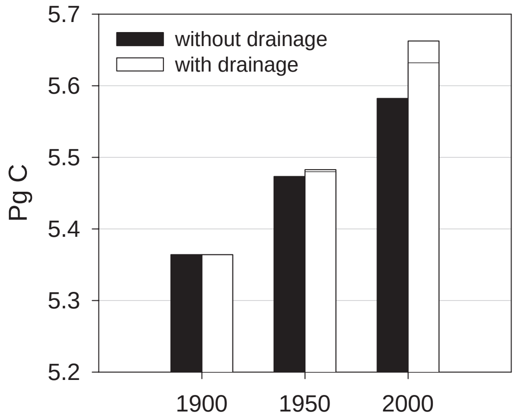

Figure 7. The peat C store in Finnish peatlands (undrained and forestry-drained together). The value for 1950 is based on inventory data (Ilvessalo 1956, 1957) and peat sample material (I; Turunen et al. 1999b). The values for 1900 and 2000 have been calculated from the 1950 value using the annual C balance values for Finnish peatlands with and without the impact of forestry drainage (Fig. 7). The horizontal line in the white bars depicts the C store with the inclusion of the estimated C loss from decomposing ditch spoil banks (Fig. 8).

3.3.2 Carbon balance of Finnish peatlands

3.3.2.1 Peat

The total C store in peat was calculated at 5.5 Pg in 1950, 5.4 Pg in 1900 and 5.6 Pg in 2000 (Fig. 7). The rate of C sequestration into peat in Finnish peatlands has increased because of forestry drainage from 2.2 Tg a^{-1} (22 g m^{-2} a^{-1}) in 1900, when all peatlands were still undrained, to 4.2 Tg a^{-1} (44 g m^{-2} a^{-1}) at present (Fig. 8). The present values for undrained and forestry drained peatlands are 0.8 Tg a^{-1} (21 g m^{-2} a^{-1}) and 3.4 Tg a^{-1} (60 g m^{-2} a^{-1}) respectively. Inclusion of the CO_2 emissions from decomposing ditch spoil banks would decrease the total value by 0.9 Tg a^{-1}, so that the present C balance would be 3.4 Tg a^{-1} (35 g m^{-2} a^{-1}) for the whole country and 2.5 Tg a^{-1} (45 g m^{-2} a^{-1}) for drained peatlands and the increasing effect of drainage would thus be only 1.0 Tg a^{-1}. Forestry drainage would thus have increased the peat C store by 0.08 Pg (=80 Tg) compared to the undrained situation during this century or by 50 Tg accounting ditch spoil bank emissions (Fig. 7).

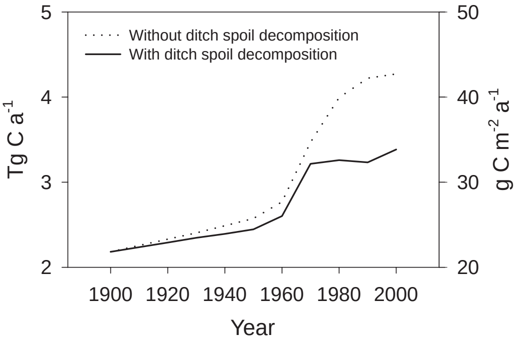

Figure 8. Total peat C balance of undrained and forestry drained Finnish peatlands 1900-2000 with and without the impact of ditch spoil bank decomposition.

The C sequestration rate has decreased in Lapland (R5) but increased in all other regions (Fig. 9). The increase in C sequestration has been highest in the nutritionally oligotrophic site-type groups 7 and 8 (sparsely-treed pine mires) (Fig. 10), in which the increases in C balance values and drained areas were also high (Table 2, Fig. 6). The increase in the C sequestration rate over undrained conditions was six-fold (from 0.22 to 1.16 Tg a^{-1}) on site-type group 7 and four-fold (from 0.33 to 1.37 Tg a^{-1}) on group 8. On the site-type group 6, with the same C balance values as group 7 but a proportionally much smaller drained area, the C sequestration rate has “only” doubled from the undrained conditions. On the more nutrient-rich site-type groups 3 and 4 (mesotrophic, treeless and sparsely-treed composite types) the sequestration rate has decreased from the original value and group 4 has even become a net source of peat C to the atmosphere (Fig. 10). On other site-type groups no change in C sequestration rate was assumed, as mentioned in the “calculations” section.

3.3.2.2 Tree stand

The C store in the above-ground tree stand was estimated at 63 Tg in 1900, when all peatlands were undrained. Forestry drainage has increased the C store to 170 Tg at present and the C store is predicted to keep increasing until the 2040s when

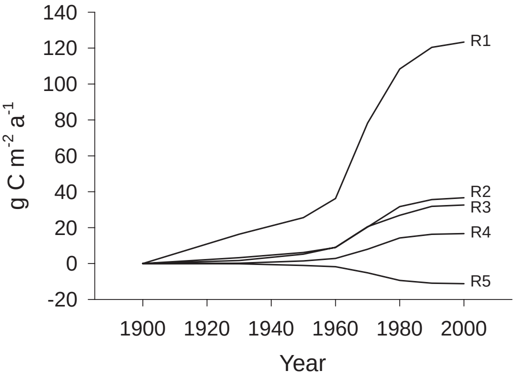

Figure 9. The effect of forestry drainage on the peat C balance by study region (without the impact of ditch spoil bank decomposition). See Fig. 2 for the location of the study regions in Finland.

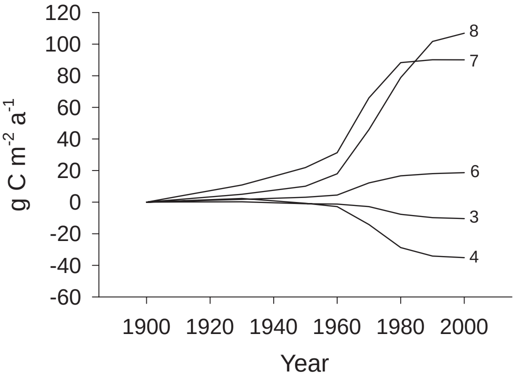

Figure 10. The effect of forestry drainage on the peat C balance by site-type group (without the impact of ditch spoil bank decomposition). Unmarked site-type groups were assumed to have no impact on peat C balance.

it will exceed 230 Tg (Fig. 11). It will then start to diminish because of increasing cuttings and will fall to 135 Tg in 2100. The C store in wood products, 10 Tg at present, is calculated to rise steadily during the whole period, reaching 38 Tg in 2100 (Fig. 11).

Most C is sequestered in the tree stands of site-type group 2 (*Vaccinium myrtillus* type I), although the greatest increase has occurred in group 7 (*Vaccinium vitis-idaea* type II) (Fig. 12). Tree stands on *Vaccinium myrtillus* type I are already rather dense in their natural state, whereas *Vaccinium vitis-idaea* II site-types are quite sparsely-treed when undrained. If site-type groups are combined by nutrient level but keeping originally treeless sites separate, it can be seen that the C store in *Vaccinium vitis-idaea* sites is on a par with *Vaccinium myrtillus* types, Dwarf shrub types are clearly lower and *Cladina* types have remained unchanged (Fig. 13). The impact of the originally treeless sites and the most fertile site type groups (Herb-rich type) has been quite small because of the small areas of drainage on these site types (Fig. 6).

The increase in the tree stand C store has been clearly greater than that in the peat (Fig. 14). However, if the sequestration of C in peat remains linear, the impact of forestry drainage on the peat C stores would eventually exceed the impact on the tree stand, even if some C is always being sequestered in very long-lived wood products (Fig. 14).

3.3.3 Greenhouse impact of forestry drainage

3.3.3.1 Changes in the CH_4 and CO_2 fluxes

Methane emissions from peat into the atmosphere have decreased from 0.9 to 0.4 Tg CH_4-C a^{-1} (i.e. the net CH_4-C exchange between peat and the atmosphere has changed from –0.9 to –0.4 Tg CH_4-C a^{-1}, Fig. 15) because of forestry drainage during this century. The corresponding CH_4-C emissions from the undrained peatlands are 0.35 Tg a^{-1} and from the drained 0.06 Tg a^{-1} at present (Fig. 16). In the future the total CH_4 emissions are predicted to rise again slightly because of the abandonment of nutrient-poor peatlands and the consequent rise in the WT level at those sites (Fig. 15).

The net changes in the peat CO_2–C fluxes are a bit higher than the changes in C sequestration in peat since they were calculated by adding the C lost from peat as CH_4-C to peat C balance values. The rate of CO_2-C sequestration into peat has thus increased because of forestry drainage from 3.1 Tg a^{-1} in 1900 to 4.6 Tg a^{-1} at present, and is predicted to decrease slightly to 4.4 Tg a^{-1} in 2100 (Figs. 15 and 16). Inclusion of ditch spoil bank emissions would drop the present value by 0.6 Tg a^{-1}, but by 2100 this ditch spoil bank contribution would decrease to less than 0.2 Tg a^{-1} (Fig. 15).

The rate at which CO_2-C is sequestered into

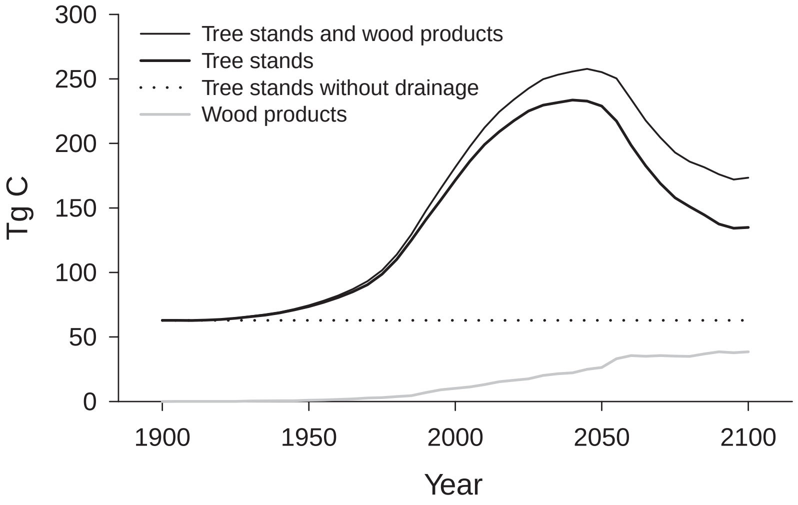

Figure 11. C stores in the tree stands and wood products of Finnish peatlands. The dotted line shows the assumed situation without the impact of drainage (i.e. a constant C store of 63 Tg).

tree stand and wood products and released from them back into the atmosphere varies considerably with time (Fig. 15). At present the sequestration is at its highest, i.e. over 3 Tg CO_2-C a^{-1} (3.0 Tg a^{-1} in the above-ground tree stand and 0.2 Tg a^{-1} in wood products) but it will start to decrease after increasing removals of timber at the beginning of the 21st century. Around 2045 more CO_2 will be released than sequestered, but before the end of the century the total CO_2-C balance between tree stands and wood products will be positive again (Fig. 15).

3.3.3.2 Change in radiative forcing

Forestry drainage has already decreased the radiative forcing of Finnish peatlands by 2.4 mW m^{-2} since the beginning of the century and the decrease will be at its highest value of -2.8 mW m^{-2} from 2030 to 2050. The decrease is caused by increases in the CO_2 sequestration into peat (-0.2 to -0.3 mW m^{-2}) and into tree stands and wood products (-0.8 to -0.9 mW m^{-2}) and by the decrease in CH_4 emissions from peat to the atmosphere (-1.4 to -1.5 mW m^{-2}) (Fig. 17). Inclusion of ditch spoil bank decomposition would raise radiative forcing by 0.1 – 0.2 mW m^{-2}. Increased CO_2 emissions from wood products after 2050 and the decrease in the drained peatland area will diminish the impact of forestry drainage to -2.0 mW m^{-2} by 2100.

3.4 Discussion

3.4.1 Peatland area

The third National Forest Inventory (NFI 3) in 1951-1953 (Ilvessalo 1956, 1957) is the most accurate inventory covering undrained peatlands in Finland. This was also the last NFI in which drained and undrained peatland site types were accurately determined, thus giving the best reference point for calculations.

According to NFI 3 the total area of peatland on forestry land was 9.74 mill. ha in the 1950s. According to the last NFI (NFI 8; 1986-1996, Sevola 1998) the area of undrained mires was 4.25 million ha, indicating that peatlands drained for forestry or otherwise utilized would have covered altogether 5.49 million ha at the beginning of the 1990s. Since NFI 8, 0.104 mill. ha of previously undrained peatlands have been drained for forestry (Sevola 1998), giving areas for drained and undrained peatlands of 5.59 mill. ha and 4.15 mill. ha respectively. As c. 0.15 mill. ha of peatlands have been put to uses other than forestry (peat harvesting, agriculture, construction of roads and water reservoirs) after NFI 3 (Paavilainen and Tiihonen 1988, Vasander 1996), 5.44 mill. ha is left for forestry-drained peatlands.

This area is somewhat smaller than the 5.7 mill. ha, calculated as forestry-drained peatland area in this study, but clearly greater than the area

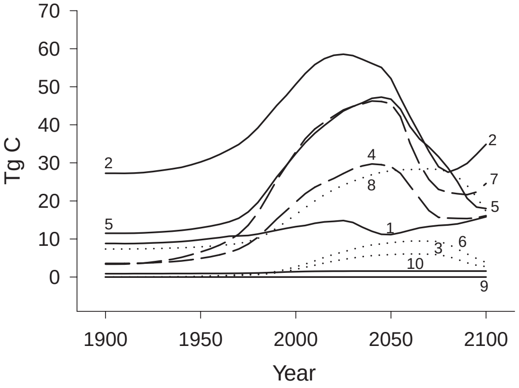

Figure 12. Tree stand C stores in Finnish peatlands by site-type group. The dotted line depicts treeless mires and the hatched line composite types. See Table 1 for descriptions of site type groups.

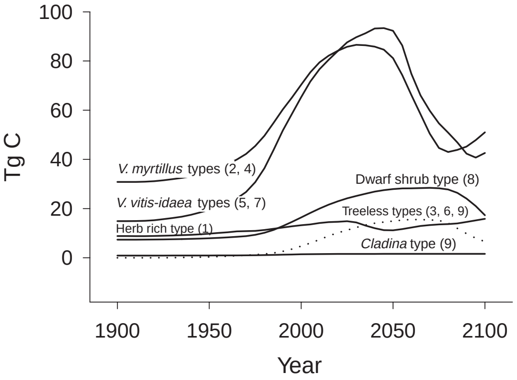

Figure 13. Tree stand C stores in Finnish peatlands by site type group, combined by similar nutrient levels. Originally treeless types are shown as a separate group (dotted line).

of forestry-drained peatland given in NFI 8 (4.67 mill. ha). This figure from NFI 8 is clearly an underestimate, since some drained peatlands have been classified as mineral soils in NFI 8 because of the shallow peat layer at those sites (Päivänen and Paavilainen 1996, Tomppo 1999). It is also probable that the forestry-drained area calculated in this study (5.7 mill. ha) is an overestimate. In the annual drainage statistics used in the study by Keltikangas et al. (1986) some maintenance drainage operations had been classified as first-time drainages, i.e. some drainage areas had been counted twice (or several times) in the drainage statistics. The effects of drainage on C balance and radiative forcing in Finnish peatlands may thus also be slightly biased in this sense.

3.4.2 Carbon balance

The total peat C store in Finnish peatlands in 1950 was calculated at 5.5 Pg. This value may be considered the best estimate possible, since it is based on the most accurate areal inventory of peatlands (Ilvessalo 1956, 1957) and the most representative sample material available (Turunen et al. 1999b, and substudy II). The value is somewhat smaller than that provided by Ahlholm and Silvola (1990), who estimated the store was as much as 6.25 Pg. Lappalainen (1996) has calculated the C store at 3.4 Pg, from a large inventory material of geological peatlands (peat thickness >30 cm, peatland area > 20 ha), with a corresponding area of 5.1 mill. ha. Combining that data with results of this study, peatlands smaller than 20 ha would cover 4.6 mill. ha and store 2.3 Pg of carbon.

The dynamics of the areal peat C balances were calculated as the change in the area (m^2) and corresponding C balance estimates (g C m^{-2} a^{-1}). The change in areas is considered relatively reliable, whereas the changes in the measured C balance values involve much more uncertainty, as discussed in II. The extrapolation of these values to the other site types introduces further uncertainty into the results.

Some site types were assumed not to alter their peat C sequestration rates following drainage. This was done mainly because no C balance measurements from these sites were available. On the most nutrient-poor, ombrotrophic sites (groups 9 and 10) drainage usually results in only insignificant changes in the vegetation, justifying the zero-effect for those sites. However, the general trends in C balance studies (II, III, Silvola et al. 1996a) suggest that the site-type groups 1 and 2 as nutrient-rich ones (Table 1) might increase their net C emissions after drainage. Also, the rate of post-drainage vegetation succession has been shown to be rapid on such sites (Hotanen et al. 1999). However, the change in the peat properties caused by drainage might not be as drastic as in the vegetation cover, since the tree stand on

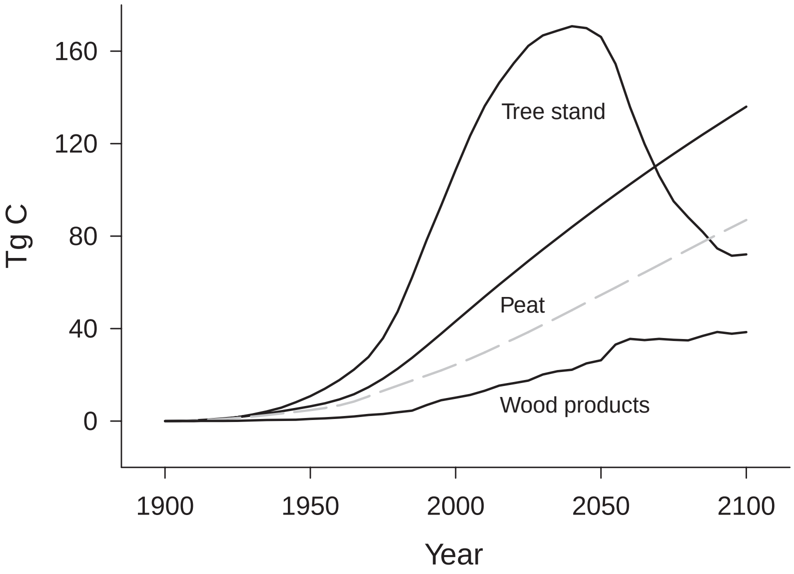

Figure 14. The effect of forestry drainage on the C stores in peat, tree stands, and wood products in Finnish peatlands 1900-2100. The hatched line depicts the situation with the estimated ditch spoil bank CO_2 emissions included in the total peat C balance (Fig. 8).

these sites is quite dense and already forest-forming in their natural state, and the peat may also be moderately well decomposed. We may therefore justifiably assume that drainage would not affect the peat properties of these sites as much as the wetter and thick-peated pine mires, and thus the zero-effect for these sites was considered the most reasonable one. The use of the same C balance values for these site-type groups (1 and 2) as for the most nutrient-rich pine mires (groups 3 and 4, Table 2) would also have decreased the present peat C sequestration value only by 0.07 Tg a^{-1} (from 4.24 to 4.17 Tg a^{-1}), indicating the insensitivity of the results to the change in parameter values in this case.

The peat C accumulation rates (i.e. C balance values, Table 2) were assumed to be static on both undrained and drained sites, which may not be true. On undrained mires this rate depends on climatic conditions as well as on the autogenic processes of the mire and on drained sites on the tree stand development as well (II). It has been suggested that the peat C accumulation rate would decrease with the peat bog development so that the long-term rate (LORCA), which is the average rate of C accumulation into peat during the history of the mire, is always greater than the present (=ARCA) rate (Clymo 1984, Clymo et al. 1998). This theory has been shown to apply to some mires but not others. The discrepancy may be explained by the fact that this model assumes a static input of C into the peat which is not valid, since it can change with alterations in climate and autogenic changes in the mire development. Thus the rate of C accumulation at present may be lower or higher than the measured long-term rate. In dry summers mires may even be net sources of C to the atmosphere (Alm et al. 1999a).

Peat C balance values for drained peatlands were based on linear C store change over the 60 years since drainage. It is impossible to say whether the C balance values will remain at the same level in the future as well, even if climatic conditions remain the same. Some reductions in peat C sequestration may, however, be expected in connection with the final harvesting and site preparation needed for tree-stand regeneration (Trettin et al. 1995).

The total rate of C sequestration into peat in Finnish undrained and forestry-drained peatlands together was calculated to have increased from 2.2 to 4.2 Tg C a^{-1} because of forestry drainage (Fig. 8). This value was derived from parameters measured from the area between ditches, as explained in II, and the values were corrected by giving zero C balance values for the area covered by ditches. With standard ditch measures this

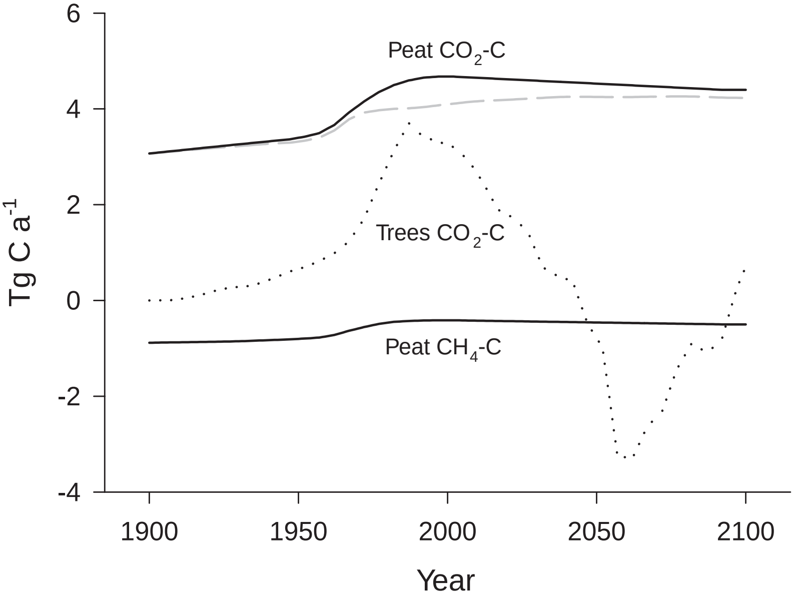

Figure 15. The net CO_2 and CH_4 fluxes in Finnish peatlands 1900-2100 (undrained and forestry drained together). Positive values mean C sequestration from the atmosphere to peatlands and negative values C loss from peatlands to the atmosphere. The trees CO_2-C line also includes the sequesteration of C in wood products. The hatched line depicts the situation with ditch spoil bank emissions included in the total peat CO_2 fluxes.

meant a 4% lowering of C sequestration rates on the drained peatlands and consequently a 3% lowering of the rate of all peatlands together.

Ditch spoil bank decomposition was calculated as a separate component in C balance, and it seemed to have quite a significant impact on the total C balance. The inclusion of ditch spoil bank emissions would decrease the total peat C balance of Finnish peatlands by 0.9 Tg a^{-1} (Fig. 8), i.e. by 16 g C m^{-2} a^{-1}, calculated for forestry-drained areas. However, it is probable that a significant part of C is not lost directly to the atmosphere as CO_2 since it may be leached down as DOC and retained in deeper peat layers (Domisch et al. 1998). Some of the leached and retained C could then actually be included in our measured C balance values (II), even though peat samples were taken beyond ditch banks. Quite often the banks were, however, no longer visible 60 years after the drainage.

The decomposition was calculated using a single decay constant model (Olson 1963). This kind of model is nowadays known to overestimate the decomposition rate, because when the decomposition proceeds, the proportion of more stable (decay-resistant) compounds increases and the decay rate thus decreases (Harmon et al. 1986). However, in this study a single decay constant model was used both for simplicity and because other more crucial assumptions were made (like the value of decay constant, k).

3.4.3 Tree stand

The present rate of sequestration of C into aboveground tree stand was calculated at 3 Tg a^{-1}. The rate for stemwood C is c. 2 Tg a^{-1}. This is 35% of the C sequestration rate of all Finnish forests in 1990 (5.5 Tg a^{-1}) reported by Karjalainen et al. (1995). As the total area of drained peatlands is c. 28% and that of the “satisfactory” sites only c. 20% of the forest land in Finland, it would seem that peatland forests sequester C at a faster rate than Finnish forests in general. This may be partly explained by the fact that the major part of the drained forests is still young, measured as drainage age, and are still experiencing a good growth rate. However, according to Tomppo (1999) the annual increment of the growing stock in peatland forests (including earlier shallow-peated peatland sites nowadays classified as mineral soils; 20.3 mill. m^3 a^{-1}) was only 27% compared to Finnish forests in total. The volume of the growing stock on these peatlands was 449 mill. m^3, which makes c. 98 Tg C, stored in the stemwood. The corresponding value in this study was 103 Tg C, which

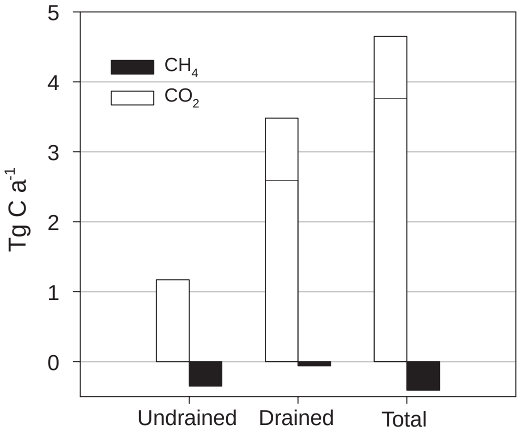

Figure 16. The calculated peat CO_2-C and CH_4-C balance in the undrained and forestry drained peatlands in Finland at present (1999). Negative values mean a loss of C from peat and positive C sequestration in peat. The horizontal lines in the white bars depict the situation with the estimated ditch spoil bank CO_2 emissions included in the total peat CO_2 fluxes.

indicates that the simulation of the tree stands may have slightly overestimated the growth rate of peatland stands. Part of the difference may also have been generated by overestimating the drained peatland area in this study. However, bearing in mind that the tree stand simulation period before this comparison was already over 90 years long, the simulated values seem to fit the measured ones rather well.

The pattern of tree stand growth and C sequestration over the next century is based on the straightforward assumption that the stands will be treated according to approved management strategies. The failure of this assumption, e.g. a change in land use policy among forest-owners, might greatly affect the rates of future sequestration of C into the tree stands.

3.4.4 Methane

Methane emissions were calculated to have decreased over 50% (from 0.9 to 0.4 Tg a^{-1}) as a result of forestry drainage this century. This large decrease was mainly caused by the considerable drainage activity on the originally minerotrophic and very wet, high CH_4 flux sites (site type groups 4, 6 and 7, see Table 3 and Fig. 6). The magnitude of the decrease in CH_4 fluxes is therefore very much dependent on the site-type distribution, stressing the importance of correct determination of the drainage area development.

The values for CH_4 fluxes were derived from the study by Nykänen et al. (1998), which is the most extensive available for Finnish peatlands, covering 17 peatland sites in the southern and middle boreal zone in Finland. However, the sites are concentrated only on two locations in Finland and geographical variation is therefore poorly represented.

The same CH_4 emission values were used for all regions (Table 3). This was done since no evidence of any possible trends between the regions was available. Mikkelä (1999) found no significant differences in CH_4 flux rates between different regions (from the south to the north) in Sweden but she found that CH_4 flux correlated strongly with coverage of sedges and WT level. While CH_4 production is temperature-dependent (Granberg et al. 1997), the oxidation of CH_4 is less so (Dunfield et al. 1992), and CH_4 emissions are probably more dependent on the WT level and the vegetation cover (e.g. Bubier 1995). The presence of sedges is crucial in this sense since they transport methane very effectively through the oxidative layer in peat (e.g. Frenzel and Rudolph 1998, Rusch and Rennenberg 1998). The length of the growing season is longer in the south but no clear differences within site types have been found in the peat accumulation rates between the south and the north (Turunen et al. 1999b). Thus the mire site type, which is a quite good description of the vegetation cover, was chosen as the only predictive variable, and no corrections were made on the grounds of, for example, mean temperature.

3.4.5 Radiative forcing

Forestry drainage was calculated to have considerably decreased the radiative forcing of Finnish peatlands and was predicted to continue to do so for at least the next 100 years (Fig. 17). This was caused by increases in peat and tree stand CO_2–C sequestration and a decrease in CH_4 emissions after drainage.

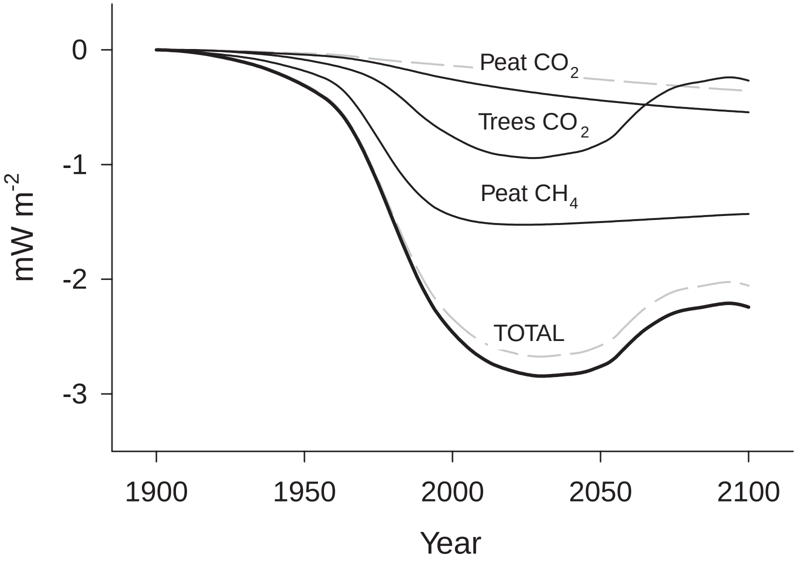

Figure 17. The effect of forestry drainage on the radiative forcing of Finnish peatlands 1900-2100. The hatched line depicts a situation with ditch spoil bank emissions included in the total peat CO$_2$ fluxes. The trees CO$_2$-C line also includes the sequesteration of C in wood products.

Peat CO$_2$ balance seemed to be the least important factor in the effect of forestry drainage on the total radiative forcing of Finnish peatlands during the period of 200 years under consideration, although the changes in peat C balance seemed very high compared to the pre-drainage situation (Fig. 8). A more important a factor was the sequestration of C into tree stands and wood products. The C sequestration into wood products was modelled according to Seppälä and Siekkinen (1993), whose study showed the very short average lifetime of Finnish wood products. The use of longer lifetimes, as in the study by Karjalainen et al. (1995), would have significantly increased the C storage in wood products.

The greatest effect of forestry drainage on radiative forcing was obviously the decrease in CH$_4$ emissions, being as great as the effect of increased C sequestration into peat, trees and wood products taken together. The decrease in net CH$_4$-C fluxes from peat to the atmosphere seems small compared to the sequestration of CO$_2$-C into tree stand (Fig. 15). However, the importance of CH$_4$ is explained by its 58 times greater ability to absorb infrared radiation than that of CO$_2$, compared on a mass-to-mass basis (IPCC 1990). The indirect effects of CH$_4$ in the atmosphere increase the radiative forcing by a further 20-30%.

Agricultural use of peatlands and peat harvesting have been suggested to increase the greenhouse gas emissions (Nykänen et al. 1995, Regina et al. 1996) and radiative forcing (Savolainen et al. 1994) of the system compared to an undisturbed mire. However, direct comparison of the greenhouse impact of these uses of peatlands with forestry drainage in Finland are not possible, since radiative forcing calculations similar to those in this study are not known to the author. Some estimates of the present-day CO$_2$ emissions from peat harvesting and agricultural cultivation areas have, however, been published. The use of peat for energy in Finland is calculated to release 2.3 Tg CO$_2$-C into the atmosphere annually (Tilastokeskus 1998). Since CO$_2$ emissions from the drained peat production fields, stockpiles and from the use of horticultural peat have been estimated to further increase the C release by 0.33 Tg a^{-1} (Laine et al. 1996a) and agricultural use of peatlands is estimated to release c. 1 Tg CO$_2$-C a^{-1} into the atmosphere (Nykänen et al. 1995, Laine et al. 1996a), the total annual C flux from peat harvesting and agricultural use of peatlands in Finland would amount to c. 3.6 Tg a^{-1}, which is c. 85% of the rate of C sequestration into the peat of undrained and forestry drained peatland in Finland (Fig. 8).

Compared to the greenhouse gas emissions from fossil fuels and other anthropogenic sources, the total effect of peatland drainage on radiative forcing seems quite high. Using the same REFUGE model and calculation methods Korhonen (1998) has reported a total radiative forcing of 3.5 mW m^{-2} from anthropogenic CO_2, CH_4 and N_2O gas emissions (mainly from energy production and use, waste management and agriculture, but excluding peat harvesting) in Finland in 1990. The effects of the various gases in fossil fuel emissions were 2.63 mW m^{-2}, 0.60 mW m^{-2} and 0.24 mW m^{-2} for CO_2, CH_4 and N_2O respectively. Sinisalo (1998) reported a total radiative forcing of 3.8 mW m^{-2} for the same year in Finland. This value included the effect of halocarbons and CO_2 emissions from peat harvesting. In this thesis the radiative forcing impact of peatland drainage for forestry in 1990 was calculated at –2.1 mW m^{-2}, and the effects of CH_4 and CO_2 fluxes were –1.3 mW m^{-2} and –0.8 mW m^{-2} respectively. The impact of forestry drainage would thus be large enough to decrease the total radiative forcing of anthropogenic greenhouse gas emissions by c. 55-60% in Finland. N_2O emissions from peatlands were not considered in this study, but their importance in total radiative forcing has previously been found to be minor (Martikainen et al. 1993, Laine et al. 1996b).

Kanninen et al. (1994) reported a decrease in radiative forcing of c. 1.1 mW m^{-2} in 1990 caused by the increased growth of Finnish forests this century, over half of which is due to forestry drainage of peatlands (Tomppo 1999). The radiative forcing impact of all managed forest ecosystems in Finland would thus have been c. 2.6 mW m^{-2} in 1990, having decreased the total radiative forcing from anthropogenic sources by c. 75%. In the future this situation may change, since the emissions from fossil fuels are predicted to grow steeply without a strict policy to actively reduce them (Korhonen et al. 1993), whereas the C sequestration in the tree stands is predicted to start to decrease around 2030 (Fig. 11; Kanninen et al. 1994). This would be caused by increased cuttings or/and decreased growth because of tree stand ageing.

Radiative forcing calculations include uncertainties, which in absolute values may be quite high (c. 40%; Sinisalo 1998). However, when the model is used to provide comparative figures, for example between different gases or emission sources, with the same basic assumptions, the level of uncertainty is much less (c. 10%; Sinisalo 1998). In this study no numerical estimates for the uncertainties of various C emissions were provided, since in many cases these were unmeasurable. The largest uncertainties are probably included in the peat C balance values, which include many possibilities for errors, as mentioned before. CH_4 emission estimates were extrapolated to other site types and regions, which increased uncertainty by an unmeasurable quantity. The tree stand development may be considered relatively accurately determined, as may the areal development of forestry-drained peatlands, at least during this century. The uncertainties in all C flux rates increase considerably in predictions for the future.

4 Conclusions

Forestry drainage of peatlands significantly changes the C fluxes between the ecosystem and the atmosphere. It was found in this study that the C stores in the tree stand and on average in peat at least temporarily increase after drainage. This means increased sequestration of C into these ecosystems. CH_4 emissions decrease after forestry drainage at all sites where permanent water-level drawdown is achieved. Taken together the altered exchange rates of these gases have decreased radiative forcing (i.e. the greenhouse impact) of peatlands in Finland.

Further research is still needed. Better estimates of peat C balance should be sought to provide for the sites where direct measurements do not exist at the moment. The general trends in peat C balance between site types and regions, determined in this study by geological methods, could be tested using direct gas exchange measurements. In treed peatlands this could be accomplished by measurement of net C fluxes above the canopy using towers (the eddy covariance method), combined with simultaneous chamber measurements of soil C fluxes and recording of vegetation biomasses. Such information would provide better keys for modelling C fluxes at ecosystem level and predicting the C balance of peatlands in the changing climate.

From the greenhouse effect point-of-view, the most important task is to expand the CH_4 measurements to cover the country better regionally and to provide more information for CH_4 flux models. Measuring CH_4 fluxes is methodologically less problematic than measuring CO_2 since the static chamber method is usable at all sites, including treed ones.

Tree stand dynamics in drained and especially undrained peatlands, are still poorly understood, which limits the usability of simulation models. However, compared to other C fluxes in peatlands, the C store development of tree stands can nowadays be estimated relatively accurately. Further research is needed especially in the field of tree-litter production and decomposition processes in peat soils. The input of C into the soil through root litter is probably of the utmost importance to peat C balance in drained peatlands, but the litter dynamics are still poorly understood because of methodological difficulties in below-ground production studies.

The calculations presented here include many uncertainties involved in the actual parameter values, both in the models used and in the numerous assumptions. Despite all these uncertainties, the finding that drainage of peatlands for forestry in Finland appears to have decreased the greenhouse effect of these ecosystems can be considered quantitatively reliable. However, further drainage of natural mires is not recommended, since these ecosystems may contain values which might be considered even more important than the mitigation of predicted changes for Finland in climatic variables.

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