RATE OF APPARENT AND TRUE CARBON ACCUMULATION IN BOREAL PEATLANDS

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Abstract

The rate of carbon accumulation (RCA) was studied stratigraphically in 30 mires from Finland, Estonia and Maine, USA. Carbon 14-datings (308 in total) were used for dating long cores encompassing all or most of the Holocene: **apparent** long-term RCA. The apparent short-term (from 0 to c. 200 yr old) RCA was estimated by means of several methods including moss increment and pollen counts, dated fire layers in peat, and the so-called pine method.

The apparent long-term RCA (g m^{-2} a^{-1}) in Finnish raised bogs and fens ranged from 13 to 41 and from 8 to 25, respectively, and in Maine bogs from 20 to 26 and in a single fen 27. Between and within core variations were great. Both in Maine and in early ice- and water-free areas of Finland the early Holocene apparent RCA was high, slowed about 8000 years ago and accelerated in recent millenia. In hummocks the apparent short-term RCA varied from 20 to over 380; but in hollows and below the water table the rates came close to long-term averages. Some of the highest rates of recent apparent RCA were measured at suitable regrowth sites of *Sphagnum* both on cut-away trenches and on milled peat fields of mined peatlands in Finland (43 to 284) and in Maine (64 to 183).

In Finnish mires the **true** RCA, as derived from Clymo's peat accumulation model for long cores, was usually about 2/3 of the apparent long-term RCA. A change from intensive decay in the surface layers to very slow decay in deeper peat layers was dated to between some 300-500 years ago.

Keywords: climatic change, greenhouse effect, stratigraphy

INTRODUCTION

Accumulation of carbon in peat is characteristic of mire ecosystems. Therefore, determination of the rate of carbon accumulation (RCA) in peat strata should play a key role in any research on the carbon balance in peatlands. A preliminary evaluation of the role of peatlands in the biogeochemical cycles of the greenhouse gases CO_2, CH_4 and N_2O is given by Gorham (1991) and Rodhe et al (1991). The objective of the present paper is to study carbon accumulation in peat by means of paleoecological analyses within peat columns with known bulk density and age (equations 1 and 2). Depending on the time scales chosen, one may differentiate between **long-term** (over millenia) or **short-term** (over past decades or a few centuries) **rates of carbon accumulation**. These are, however, **apparent** values, that overestimate the real net accumulation of carbon, since carbon loss (albeit slow) is taking place in the whole peat column, including its thick anoxic part. The only way to estimate the **true rate of net accumulation** from peat stratigraphical data is to apply a mathematic model that takes continuous decay into account. In this study Clymo's (1984) peat accumulation model (eq 3) was used.

The model parameters p and α can be calculated, if the bulk density of peat and the age of the peat column for numerous enough levels are known. Although the model is simple and assumes decay is constant within the strata concerned, empirical tests show it is reliable enough on many dated peat cores, as verified by a comparison of observed and calculated distribution of cumulative dry mass versus age. In the "successful" case (when peat accumulation follows the model), it is possible to calculate both the total decay in the whole peat column and the developmental stages of the mire, viz. the present thickness of peat relative to the maximum thickness when decay in the whole peat strata equals the present fixation of carbon at the surface. The past few hundred years period is important, too, because during that time the plant litter originates in the oxic layer, where it is subjected to intensive decay (the acrotelm) and enters the anoxic layer (the catotelm; *sensu* Ingram, 1978).

(1) long-term and short-term (apparent) peat accumulation rate:
$A = r \times \sigma$, where
A = dry mass accumulation (kg m^{-2} a^{-1})
r = net rate of height increment (mm a^{-1})
σ = bulk density of peat, dry (g cm^{-3})

(2) long-term and recent loss of organic matter by decay: $L = 1 - M/(T \times P)$, where
L = loss (in fraction) of original organic matter produced
M = cumulative mass of organic matter above a given depth (g m^2)
T = age of the same level (M) (a)
P = rate of current or estimated production of organic matter (g m^{-2} a^{-1})

(3) net rate of peat carbon accumulation: $A = pe^{-\alpha t}$, where
A = net rate of dry mass accumulation (g m^{-2} a^{-1})
p = current rate of dry matter addition (g m^{-2} a^{-1})
α = decay coefficient as a proportion (a^{-1})
t = time (a).

For brevity, the terms long-term and short-term RCA have been used instead of long-term rate of apparent carbon accumulation and short-term rate of apparent carbon accumulation, respectively.

MATERIAL AND METHODS

The material from Finland and Estonia consists of 21 radiocarbon dated long cores (chiefly unpublished peat data by

the authors and Dr. Mirjami Tolonen, University of Helsinki), and of about 300 short cores from virgin and drained mire sites in Finland. Valuable unpublished data were given by Ms. Liisa Ikonen, Geological Survey of Finland, Mr. Antti Huttunen, University of Oulu, and Mr. Heikki Seppä, University of Helsinki. The material from Maine, USA, includes five radiocarbon dated long cores and 40 dated short cores (Tolonen et al 1988).

The long-term RCA was studied on peat profiles, where both the datings and bulk density data are from the same cores (Table 1). Each site includes one peat core dated by ^{14}C-dating, and also almost always a pollen analysis. In nine profiles the carbon content was determined by IRGA-carbon analyzer (Salonen 1979) and on four by CHN (LECO) autoanalyzer. In the remaining profiles carbon content was estimated using the dry mass estimate of 0.50, which is a conservative estimate. The majority of these peats have a very low ash concentration.

Short-term RCA is stratigraphically difficult for several reasons. Separation of live plant material from peat is usually possible in *Sphagnum* peats, but it is very troublesome, if possible at all, in sedge peats (cf. Sjörs 1991). Sedge peat at any level is thus a mixture of organic matter of very different ages. Therefore the RCA in sedge mires can be determined as long-term averages only.

Among the numerous dating methods possible for the surface peats the following ones were found most useful for RCA.

(i) Moss increment counting as developed by Pakarinen and Tolonen (1977) and further improved to a statistical dating method by Tolonen et al (1988) is practically restricted to *Sphagnum* hummocks and covers at its best the past 170 years approximately.
(ii) The pine method (e.g. Ohlson and Dahlberg 1991) is useful for a much wider range of vegetation types, the main requirements being that they have relatively young living pines. Our experience is that there are often difficulties in correlating the root collar depth with the bulk density profile at the same site. The method provides only one fixed date per core, and within our study sites the temporal scale was almost always shorter than 80 years and only seldom over 100 years.
(iii) The best way to build up a reliable dating for a peat column encompassing both the very recent peat and the last 1000 or so years may be to combine (i) and (ii) with radiocarbon dating by the AMS-technique and "wiggle matching", which provides a precise dating for about 100 - 1000 B.P. (Clymo et al 1990). We are currently using this approach for two peat cores from Lakkasuo mire, Central Finland.
(iv) Pollen analytical dating and correlation is a good method for any peat types, provided there are some local or regional pollen analytical marker horizons of known age in the area. *Ambrosia* in North America was such a well-known marker for surface peats (Tolonen et al 1988), and in Finland the local features in the frequency of *Picea* pollen, after being dated by ^{14}C (preferably by using AMS from *in situ* material), can facilitate the determination of the short term RCA.

(v) Fire horizons, even very thin ones, can be detected easily in surface peats using advanced coring equipment. The recent bog fires can be dated by means of fire scars preserved in bog pines or pine stumps using the local dendrochronological master curve. In mire sites as in sedge fens, where charred particles can be observed macroscopically only with difficulty, microscopic counting is possible (Wein et al 1987).

RESULTS AND DISCUSSION

Apparent long-term accumulation and decay

Finland and Estonia

In Finland, the long-term accumulation rate of carbon (g m^{-2} a^{-1}, Table 1) were, in general, higher in *Sphagnum* peats (the average of the averages): 20.6, n= 13 (range 12.9 - 40.6) than in sedge peats: 14.1, n= 6 (range 8-24.9). In profile number 20 that comes from a drained spruce mire with woody peat, the average was 24.0 (S.D. 5.8).

The accumulation values were quite variable within the individual profiles. The total (sectional) variation in *Sphagnum* mires was 5-120, in sedge mires 4-60 and in the spruce mire 8-56 g m^{-2} a^{-1}. The rate of carbon accumulation appeared to be strongly controlled by the nitrogen concentration and pH of the original plant cover type and also, the decay susceptibility of the main peat-forming species. Those factors are most unfavourable for decay in *Sphagnum* bogs, particularly in hummocks (e.g. Farrish & Grigal 1988, Johnson & Damman 1991) and resulted in the largest accumulation values (cf. Svensson 1988, van Smeerdijk 1989). Within peat of the same type, the actual RCA is controlled mostly by conditions at the surface while the peat was in the acrotelm. This is, of course, because both a slower growth and a lower water table increase the time the peat remains within the biologically active surface layers (Clymo 1984, Damman 1988).

The greatest height increment of peat varied up to 20 fold within individual peat profiles. This is the primary factor determining accumulation rate according to eq. 1, since bulk density varies much less. The greatest values (1.36 mm a^{-1} and 3.3 mm a^{-1}) were found in the southern plateau bog Munasuo, where the average RCA value of 35.3 g m^{-2} a^{-1} exceeded that of the raised bog Nigula in southern Estonia (29.5). In the raised bog Kurkisuo in southern Finland, the average RCA was still greater (40.6). In Munasuo and Kurkisuo the values exceeded 60 g m^{-2} a^{-1} and in Pesänsuo (according to the very numerous successive ^{14}C-datings by the Geological Survey of Finland) they exceeded 120 g m^{-2} a^{-1} within individual sections. In other Finnish mires, long term averages rarely reached such high values within any section.

The long-term average in Ylimysneva bog in Parkano was 13 g m^{-2} a^{-1} or slightly more than half that in the Häädetkeidas bog in

Table 1. Preliminary values of carbon accumulation in mires based on peat profiles studied in Finland, Estonia and Maine, USA. Finnish abbreviations of the site types, cf. Eurola et al 1984. Explanation of the columns: Thickness of peat (1); mean height increment (2); mean (S.D. in parantheses) long- term accumulation rate of carbon (3); and its range (4) in the different dated sections within the core, both according to eq.1; current net rate of carbon accumulation (5) and decay (6); both according to eq 3. Profiles 1-6 and 24 are from sedge mires, 7-19, 21-23 and 25-27 from *Sphagnum* mires, site 20 is from a drained spruce mire. Pesänsuo according to unpublished results by Ms. Liisa Ikonen, Geological Survey of Finland.

	Miro	Locat. N.lat	Site type	(1) m	(2) mm a^{-1}	(3) g m^{-2}a^{-1}	(4) g g m^{-2}a^{-1}	(5)	(6) g m^{-2}a^{-1}
1	Silmäsvuoma	67°33'	RiL	1,7	0,18	9,6 (0,9)	4 - 60	10.7	0,4
2	Ahvenjärvenvuoma	67°34'	RaN	3,7	0,35	16,8 (4,7)	10 - 22	-	-
3	Haukkarimpi	66°21'	RiL	1,9	0,18	10,3 (2,6)	5 - 20	-	-
4	Puohtiinsuo	62°45'	RhRiN	4,3	0,43	15,8 (3,3)	8 - 37	-	-
5	Häädetkeidas lagg	62°03'	LkN	1,6	0,19	8,0 (1,4)	6 - 15	-	-
6	Suurisuo	61°00'	RhSN	3,7	0,73	24,9 (7,8)	15 - 30	17,7	14,3
7	Korkianeva	62°45'	RaLkN	3,4	0,57	20,2 (8,9)	13 - 31	9,3	19,8
8	Unnansuo	62°32'	KeR	3,1	0,32	13,9 (4,9)	11 - 16	-	-
9	Ylimysneva	62°08'	RaTR	2,4	0,26	12,9 (3,1)	11 - 44	-	-
10	Häädetkeidas	62°03'	KeR	5,4	0,54	20,8 (5,9)	11 - 40	-	-
11	Kunonniemensuo	62°05'	IR	4,3	0,60	18,1 (11,0)	7 - 24	8,1	9,8
12	Pesänsuo	61°16'	KeR	6,1	0,66	25,0 (11,0)	9 - 118	-	-
13	Lakkasuo	61°47'	RaR	3,3	0,53	14,6 (2,6)	11 - 20	-	-
14	Kaurastensuo	61°01'	KeR	5,2	0,53	18,3 (6,9)	5 - 42	10,9	7,1
15	Laaviosuo	61°01'	RaR	5,4	0,53	20,8 (10,3)	5 - 30	12,8	17,2
16	Varrassuo	61°00'	KeR	4,4	0,66	17,2 (4,7)	6 - 50	11,1	17,5
17	Kurkisuo	60°34'	RaTR	4,7	1,15	40,6 (13,3)	22 - 71	-	-
18	Punassuo	60°14'	KeR	4,9	0,56	19,5 (7,0)	16 - 40	-	-
19	Munasuo	60°05'	RaN	6,4	1,36	35,3 (8,6)	14 - 66	10,3	28,7
20	Pukkilansuo, Salo	60°20	VK, oj.	2,1	0,32	24,0 (5,8)	8 - 56	-	-
21	Torvströmossen	60°11	IR	4,5	0,57	20,1 (4,0)	16.- 60	-	-
22	Nigula Raba	57°40'	KeR	5,3	0,66	29,5 (6,9)	9 - 112	23,0	12,5
23	Crystal Bog	45°18'	"KeR"	6,0	0,66	23,5 (10,4)	15 - 58	-	-
24	Crystal Fen	45°18'	"VL"	4,1	0,44	26,9 (9,8)	13 - 58	-	-
25	Caribou Bog	45°02'	"IR"	6,4	0,64	23,1 (10,8)	12 - 93	-	-
26	Great Heath	45°00'	"RaN"	7,8	0,76	25,8 (11,0)	13 - 33	-	-
27	Big Heath	44°06'	"TR"	4,9	0,63	20,5 (9,1)	14 - 67	10,1	20,9

the same area (21 g m^{-2} a^{-1}). The difference is probably due to repeated (at least seven) fires that burned the bog prior to the end of Subboreal time (Huttunen 1990). In the "geologically old area" of Finland or around the area that lies below the *Ancylus* limit, the role of bog fires on the RCA seems to have been significant, especially between 7000-3000 ^{14}C -years ago. In the same area, the early Holocene RCA was very rapid, typically in wet rich fens with reed, sedges, *Scorpidium* and other Bryales mosses plus *Sphagnum teres* as characterestic species. The RCA was very high in eastern Karelia too at the same time (Elina et al 1984). About 8000 calendar years ago, the height increment of peat and the RCA decreased to a third or less in the same area, and it was not until some two or tree millenia ago that it accelerated again. In the mires of western Finland below the *Ancylus* limit, the long-term RCA has varied irregularly controlled by forces other than climate (Aario 1932).

The strong decrease in the RCA northwards seems to be steeper than expected if it resulted only from a decrease in primary production. Another factor is increased decay because the plant material of northern aapa-mires decays more easily. In southern Lapland the long-term height increment of peat usually ranged from 0.1 to 0.4 mm a^{-1}, resulting in very low RCA. The average accumulation values in eastern Finland were generally only about half those in similar mires in western Finland at comparable latitudes. Perhaps the lower summer water tables in the mires of eastern Finland, increase decay by lengthening the residence time of peat in the acrotelm. This would reduce the amount of carbon added to the catotelm. Slow height growth under these conditions during the past about 7000 ^{14}C -years would further reduce RCA.

Maine

The long-term RCA for bogs and fens in Maine came close to the Southern Finnish ones, being on average 20.5 to 25.8 g m^{-2} a^{-1} in four ombrotrophic bogs and 26.9 g in one sedge fen (Table 1). The within-section variation was great: in raised bogs 12 to 93 and in the fen sites 13 to 58 g m^{-2} a^{-1}. Partly, this was due to frequent bog fires that were, generally, more frequent in Maine than in Finland. Another common pattern among all the cores was the greater RCA prior to about 8000 calendar years ago. After that, the height increment of peat slowed for about 6000 years until it increased considerably. Similar changes were found by Zurek (1976) in Eurasian mires. This common pattern in the development of mires is due to a change in peat-forming processes in the Hypsithermal and the subsequent accelerated deterioration of climate (cooler and/or moister) in recent millenia.

Comparison with other countries

Many published RCA data from other countries are available for comparison (for early papers ,see Tolonen 1979). From the data of Elina et al. (1984) comprising radiocarbon dated profiles from 63 peatlands in Eastern Karelia one can calculate the average long-term RCA for the whole Holocene, 20 g m^{-2} a^{-1}. In the Ramna bog, Halland, Southern Sweden (Mattson and Koutler-Anderson 1954) the RCA varied from 20 to 25. For a southern Swedish bog, Store Mosse, (Svensson 1988) the maximum value for the past 950 years was 30 to 45 g m^{-2} a^{-1} of carbon.

A greater long-term value, about 74 g m^{2} a^{-1}, was recorded for a reed fen and raised bog peat in western Netherlands (van Smeerdijk 1989). RCA values as high as 23 to 35 and 64 to 104 g m^{-2} a^{-1} have been calculated for the blanket bogs in central and northern England, respectively (Jones and Gore 1975). In contrast, lower values of RCA in *Sphagnum imbricatum* hummocks of Dutch raised bogs were reported by Middeldorp (1982, 1986; from 38 to 46) and van der Molen and Hoekstra (1988; from 31 to 37). For *Sphagnum cuspidatum* hollows, the latter authors obtained much lower values, 10 to 14 g m^{2} a^{-1} (corrected units agree with the published data). Reader & Stewart (1972) gave values about 18, 13 and 26 g m^{-2} a^{-1} of carbon for a bog forest, muskeg and lagg, respectively in a mire from southeastern Manitoba, Canada. In the centre of the dome of Point Escuminac bog, New Brunswick, Canada (47° 04' N), the long term RCA during the past 8100 years was estimated at about 70 g m^{-2} a^{-1} according to Warner et al. (1992). In all these cases, the RCA (carbon) was estimated from the original dry matter values (multiplier 0.5). Gorham's (1991) RCA estimate for the whole boreal and subarctic peatland area, based mainly on data from interior North America is 29 g m^{-2} a^{-1} of carbon. Thus, there seems to be an overall trend that the long term RCA decreases northwards, even outside the boreal peatlands proper, i.e. in the whole area of ombrogenous bogs and aapa fens. This may be true at least for the dominant hydrologic levels within both mire complex types (hummock level in raised bogs and rimpi/flark level in aapa mires).

True rate of carbon accumulation and decay

Finland and Estonia

In *Sphagnum* bogs and in one aapa fen (numbers 6,14,15,16 and 22 in Table 1), the true accumulation values of carbon (eq 3) were about 2/3 of the long term averages in the same profiles. Bogs Munasuo and Korkianeva were excluded, because in the former the long-term and the current RCA data were from different cores and in the latter the model fit was not good; in Kunonniemensuo (no. 11) the time period spanned less than 2000 years. The model fit was poor in profile 1, due to some erratic values. This factor of 2/3 reflects the approach to a steady state, and may be compared with 4/5 used by Gorham (1991). Applying the factor 2/3 for all long term accumulation values, gives a mean of the true carbon accumulation as follows (S.D. in parentheses):

Sphagnum bogs 14.7 g m^{-2} a^{-1}, (5.4, range 8.6-27.2)
Sedge mires 9.5 g m^{-2} a^{-1}, (4.2, range 5.4-16.7)

For the data of Häädetkeidas bog (dome), Ylimysneva bog, and Ahvenjärvenvuoma aapa fen the figures for α did not differ significantly from 0, and consequently the fitted age/mass curve did not differ significantly from a straight line. In other profiles the model resulted in decay values between 0.4 and 29 g m^{-2} a^{-1} ($n = 9$), which is about 2/3 of the calculated input of carbon into the catotelm layer. Hence the studied mires might be expected to maintain their positive carbon balance though the balance would decrease in size as millenia passed. Their present peat layer is 35 to 73 % (mean 67 %) of their maximal, steady state thickness, when decay in the whole peat stratum equals the input of organic matter into the catotelm.

A change from intensive decay in the surface layers to almost constant slow decay in the catotelm was dated to between some 300-500 years (Fig. 1). It is likely that the acrotelm/catotelm limit, if defined approximately at the depth of prevailing or even at the lowest water level during the vegetation period, does not coincide with the layer of intensive decay, but is deeper and older. The age of the acrotelm *sensu* Ingram (1978) has been estimated in a few studies to be between 50 to 200 years and older (eg. Pakarinen and Tolonen 1977, Aaby et al 1979, Oldfield et al 1979, Hemond 1980, Clymo 1984, Malmer and Holm 1984, Tolonen et al 1988, Ohlson and Dahlberg 1991).

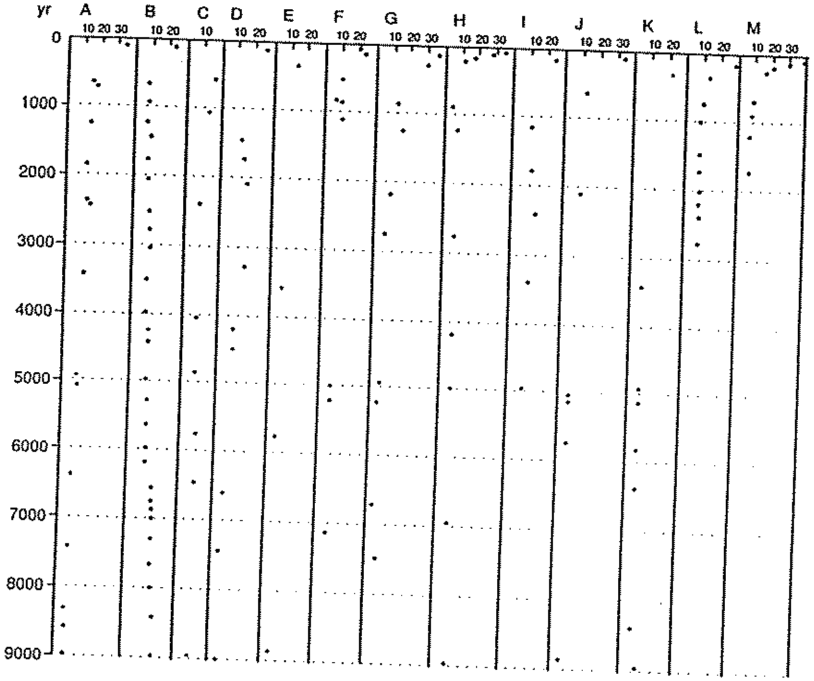

Fig. 1. Dry matter residue (as % of the assumed constant production) *versus* age according to eq 2 in thirteen long cores. A = Laaviosuo, B = Pesänsuo hollow, C = Häädetkeidas dome, D = Kaurastensuo, E = Ylimysneva, F = Varrassuo, G = Big Heath, H = Ahvenjärvenvuoma, I = Suurisuo, J = Haukkarimpi, K = Crystal Fen, L = Pesänsuo hummock, M = Kunonniemensuo (cf. Table 1). Dating was by dendrocalibrated ^{14}C-dating (dots) and by moss-increment -dating (asterisks). The production values used are 430 g m^{-2} a^{-1} for all cores, but 500 g m^{-2} a^{-1} for G, I, K and M, and 350 g m^{-2} a^{-1} for J.

Maine

In the raised bog Big Heath the actual RCA was 10.1 g m^{-2} a^{-1}, which was about 50 % of the long-term RCA for the past 7500 years (Table 1). The calculated decay, 20.9 g m^{-2} a^{-1}, was about 69 % of the carbon input into the catotelm.

Comparison with other countries

According to parameter values in Clymo (1984) for the raised bog Agerӧds Mosse in southern Sweden, the actual RCA was about 16.6 and decay about 8.4 g m^{-2} a^{-1}, which is 34 % of the carbon supply into the catotelm. For the plateau bog Draved Mose, southern Denmark, the corresponding values were 17.6 (RCA), 8.9 (decay) and 34 %. For a Dutch raised bog, van der Molen and Hoekstra (1988) calculated the production and decomposition rates in the catotelm with a reasonably good fit to the model. Accordingly, the actual RCA was only about 4 g m^{-2} a^{-1} which was about 20 % of the long-term grand average in the core (about 17 g m^{-2} a^{-1}, calculated from the data in the present article). The present decay rate was high, 39 g, being about 92 % of the catotelm carbon input. In Point Escuminac Bog, Canada, mentioned above, the actual RCA was 38.4 and the current decay 78.1 g m^{-2} a^{-1}, the latter being 67 % of the catotelm input. The actual RCA was about 55 % of the long-term RCA and the mire is at least 66 % of the way to its maximum thickness (Warner et al. 1992). As an average actual RCA for 38 boreal peatlands from North America, about 23 g m^{-2} a^{-1} is given by Gorham (1991). According to the parameter values of the model used in that article, the decay in the same data set would be about 18 g m^{-2} a^{-1} of carbon , which was about 44 % of the input into the catotelm.

Apparent short term carbon accumulation and decay

Short-term RCA

A clear fire horizon was found in the southern and western part of the eccentric ombrotrophic bog Lakkasuo, central Finland. Preliminary dates based on the moss increment dating method and pollen zone correlations to about 260 years back, served as time markers for calculation of the short-term RCA above this level. Peat cores, with known values for volume, were obtained from sites representing different virgin and drained mire site types (Table 2). The results are expressed as dry mass figures.

Table 2. The average accumulation rate of dry matter (g m^{-2} a^{-1}) at some sites representing different virgin and drained mire site types in an eccentric bog complex Lakkasuo in central Finland above the fire horizon, preliminary dated to 260 years. The drainage took place 30 years ago. S.D. in parentheses after the mean. For the Finnish mire site types, see Eurola et al. (1984).

Site type	n	Accumulation rate g m^{-2} a^{-1}	
Mesotrophic sedge pine fen (RhSR)	1	112.6	
Spruce-pine mire (VK)	4	111.1	(6.2)
Short sedge bog with S. fuscum (LkN)	5	90.6	(5.7)
Spruce-pine mire (KR)	2	90.3	(19.5)
Cottongrass pine bog with S. fuscum (RaTR)	4	85.1	(12.8)
Short sedge bog with S. fuscum (LkN), drained	3	82.4	(5.9)
Herb and grass birch-spruce mire (RhK)	4	75.8	(16.6)
Dwarf shrub pine bog (IR)	9	62.9	(14.5)
RaTR, drained	5	62.4	(9.6)
Short sedge S. papillosum pine fen (LkR)	6	55.4	(14.9)
Cottongrass pine bog (TR), drained	4	51.0	(7.4)
IR, drained	15	44.4	(13.0)

Mesotrophic sedge pine fen (RhSR), virgin spruce mire (VK), short sedge bog (LkN) and spruce-pine mire (KR) had the greatest dry matter accumulation values at this time scale. Smaller than the accumulation values at two site types, LkN and VK, were those statistically ($p < 0.01$) at TR and IR, and similarly smaller than those at VK also were those in RaTR. The average accumulation values were in all cases greater for the virgin than for the drained part of the same mire site type, but in the pairs compared this difference was statistically significant ($p < 0.05$) in IR and RaTR only. The short-term accumulation rates have not yet been calculated for corresponding virgin and drained tall-sedge fen and tall-sedge pine fen. However, Laine et al. (1992), using another approach, concluded that the carbon accumulation in peat was higher on the drained part of these sites.

In the Maine peatlands the short-term RCA varied from 21 to 384 g m^{-2} a^{-1} in the layers of bog hummocks, that are usually lying well above the water table (WT). For peats both slightly above the WT and below it, RCA values close to the long-term averages for the same cores were obtained: from 20 to 37 g m^{-2} a^{-1}. In hollows and on a lichen-covered depression values ranged from 23 to 48 and was 22 g, respectively, (averages for 135- and 150-year-long periods, Tolonen et al. 1988).

For comparison, the RCA of *Sphagnum* over the four years in the study of Rochefort et al (1990) was 51 g m^{-2} a^{-1} in minerotrophic and 55 in the oligotrophic zone of a poor fen in Ontario. In the floating-mat of *Sphagnum* in a kettle hole mire, Massachusetts, the RCA for about 50 years old peat was some 90 g m^{-2} a^{-1} (Hemond 1980).

Short-term decay

The short-term RCA in Lakkasuo mire can be compared with the long-term rate obtained from the ^{14}C-dated core from the same mire (Table 1). In the case of the types *Sphagnum fuscum* pine bog and *Alnus glutinosa* sedge swamp, the former had a long term average (with S.D) of 39.5 (8.3) g m^{2} a^{1} during the time period 0 - 5317 B.P., and the latter had 22.7 (2.8) g m^{-2} a^{-1} of dry matter, respectively during the period 5317 - 7179 B.P. Considerable loss of organic matter has thus taken place in peats older than about 260 years in the sites representing both types of vegetation in Lakkasuo mire.

Decay in the acrotelm is shown in Figs 2 and 3. It appeared that the "constant initial productivity" concept of eq 2 can be valid for *Sphagnum fuscum* in a hummock core during a 150 years period (Fig. 2, left, Fig. 3, core 1). There eqs 2 and 3 were applied for "pure" moss material. In the other cores the relative decay during the given times was smaller. In these cores, however, the estimated initial productivity was very conservative as the unknown productivity of vascular plants was not included.

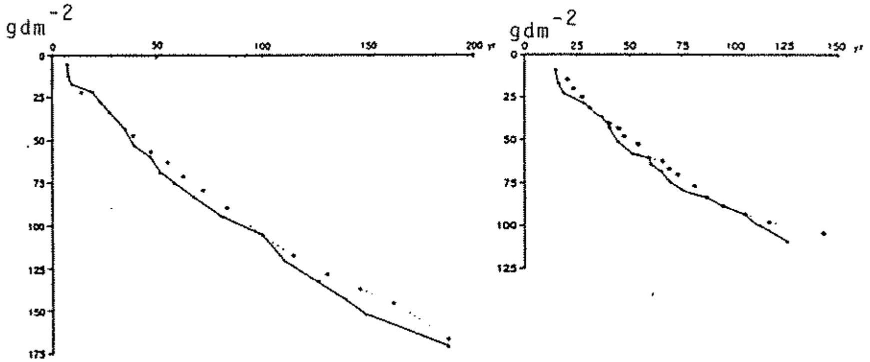

Fig. 2. Cumulative peat dry mass (g dm^{-2}) *versus* time according to eq.3 (dots) and measurements (line) in two *Sphagnum* hummocks, Kärpänsuo Bog, Finland (Pakarinen & Tolonen 1977, El- Daoushy et al 1979, left figure) and Caribou Bog, Maine, USA (Tolonen et al 1988, right figure). Dating was by the moss-increment method and by ^{210}lead dating (Kärpänsuo). The parameter values for Kärpänsuo are: $p = 154$ g m^{-2} a^{-1}, $\alpha = 0.00592$ a^{-1} and those for Caribou bog: $p = 159$ g m^{-2} a^{-1}, $\alpha = 0.0128$ a^{-1}. These values give for decay in the whole core 67 % in Kärpänsuo and 80 % in Caribou Bog. The corresponding values according to eq 2 are 68 % for Kärpänsuo and 54 % for Caribou bog.

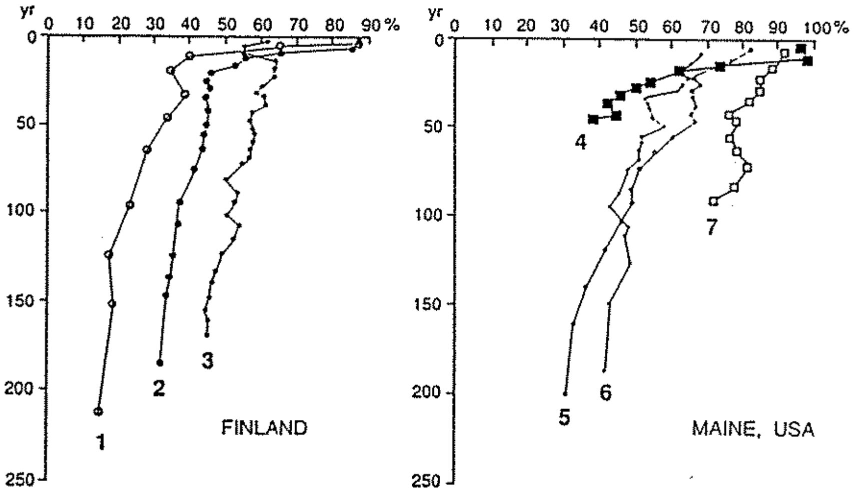

Fig. 3. Distribution of dry matter residue *versus* age (as % of the assumed constant productivity) as derived from eq 2 in some short cores from *Sphagnum* hummocks dated by moss-increment method, pollen correlations and lead-210 dating (cores 1 and 2 as shown in the figures); core 4 is from above a historically documented fire horizon (see Tolonen et al 1988). Cores 2 and 3 refer to moss material, and the remaining five refer to bulk material. Initial productivity was estimated for core 1 (Kunonniemensuo bog) and core 4 (Carrying Place Cove Bog) at 500 and 700 g m^{-2} a^{-1}, respectively. In the remaining sites the following measured moss productivity (g m^{-2} a^{-1}, in parentheses) were used: 2. Kärpänsuo (276), 3. Lakkasuo IV L 27 (240), 5. Great Heath D (240), 6. Caribou Bog 1A (221) and 7. Crystal Bog HH (228).

Mined mire sites

The after-mining regrowth of peat as reported for 27 short cores from both cut-away depressions and the milled peat field in a domed raised bog, Denbo Heath and from trenches in two further peat bogs in Maine, resulted in short-term RCA values for 29 and 46 years (Tolonen et al 1988). They varied from about 60 to 183 g m^{-2} a^{-1} (excluding one deviating core). Similar post-mined RCA was found using thirty short cores from cut-away trenches in the raised bog Aitoneva, Central Finland (Lainevesi and Tolonen 1985). For the periods that varied from a few years to 38 years, the RCA ranged between 43 and 289 g m^{-2} a^{-1}, but was usually about 100 g m^{2} a^{-1}. At certain mined sites of both areas, regeneration was slow or non-existent, mainly due to water erosion on sloping surfaces.

CONCLUSIONS

1) The true (actual) rate of carbon accumulation (or loss) in peat can be estimated only when both the input of carbon into the catotelm and decay *versus* time in the whole peat colum is considered. For this purpose, it is necessary to obtain data from a much larger number of well-dated peat profiles, especially from aapa mires, from spruce mires, and from different thinner peat strata in general. In terms of the representativeness, the present data is obviously skewed. There is an apparent need for more complex models of peat accumulation. This work is possible only if there is a solid understanding of primary production from the most common mire vegetation site types. The importance of international cooperation and collaboration must be stressed in solving these problems.

2) Short-term accumulation rates based on peat produced during the last few centuries do not give any indication of true carbon accumulation rates. Microsite variation for apparent short-term carbon accumulation rate is enormous within seemingly homogeneous sampling plots. For a better understanding of processes in the acrotelm, the real variation and differences between different mire site types must be known.

3. The apparent long-term accumulation rates differ quite a lot. Apparent long-term carbon accumulation rates for peat in the catotelm appear to be 1.25-1.50 times the true carbon accumulation rates. The only way for any generalization for the whole boreal area, is to establish useful and practical models that explain the regularities both in the bulk density and height increment of peat. The models should be constructed on the basis of both mire complex zones and vegetational peat types. In Finland, the potential for such studies is exceptional using both published material (e.g. Tolonen and Ijäs 1990) and the peat data base of Finnish Geological Survey and Vapo Oy.

4) The impact of the greenhouse effect on the net rate of carbon accumulation in peats can be estimated independently by means of paleoecology provided that the zonation/climate relationships and the history of mires are known and the controlling factors are understood. The former relationships are reasonably well known by now (Solantie 1986). The current research program SUOSILMU, "The Carbon Balance of Peatlands and Climate Change" in Finland is producing much new information about the less well-known function of mire ecosystems.

5) Presumably the proposed warming will move the common area of *Sphagnum* bogs (raised bogs) northwards and result in an increase in the total accumulation of carbon, provided precipitation stays similar to the present conditions. However, we do not know, how much the increase in decay in southern peatlands could compensate for this probable increase in the north.

Acknowledgements: We thank Dr. Mati Ilomets (Tallinn, Estonia) for contributing data for the Estonian mires and logistic support.

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