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Past and present carbon accumulation in undisturbed boreal and subarctic mires: a review

Luonnontilaisten soiden pitkänajan- ja nykykertymät boreaalisella ja subarktisella kasvillisuusvyöhykkeellä: katsaus

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This review integrates the results from several recent studies on carbon (C) accumulation in undisturbed boreal and subarctic mire ecosystems in Finland, Sweden, Russia, Canada, and USA. Generally, a large variation in the average long-term apparent rate of carbon accumulation (LORCA) has been found among mires based on the mire type, age and geographical location. The differences in LORCA between the raised bog region and the aapa mire regions were found to be significant. The updated LORCA for undrained boreal and subarctic mire regions has been estimated at 13–20 g C m^{-2} a^{-1} throughout the Holocene, which is clearly lower than previous estimates for these northern mire regions. The age of the peat column is an important predictor of C accumulation and has to be taken into account when comparing results. The results indicate a rapid mire expansion in southern Finland from ca. 10 500 to 8500 cal. year BP, from 5000 to 3000 cal. year BP and around 2000 cal. year BP. In northern Finland the extensive mire expansion occurred from ca. 10500 to 8000 cal. year BP. The recent apparent rate of C accumulation (RERCA) in boreal and subarctic mire regions over the past 100 to 200 years ranges from 30 to 120 g C m^{-2} a^{-1}. The future C balance scheme of mires is also briefly discussed.

Key words: carbon accumulation, bogs, fens, boreal region, subarctic region, Holocene, climate change

Introduction

The role of mires in the global C cycle

Global concern over rising atmospheric CO_2 concentration has led to attempts to determine the role of terrestrial ecosystems in the global carbon (C) cycle. Forests and mires in the northern hemisphere have been identified as potentially large sinks for organic C (Tans et al. 1990, Gorham 1991, Kauppi et al. 1992, Houghton 1993). Organic peat deposits are characterized by a high C content, about 50% of the dry matter. Therefore, the high abundance of peat signals a significant net transfer of C to the soil. Mires generally accumulate C as partially decomposed plants because the rate of biomass production is greater than the rate of decomposition. About 2 to 15% of annual biomass production eventually makes it into long-term storage in the deeper, solely anoxic layer (catotelm) of a mire (Tolonen 1979, Gorham 1991, Gorham & Janssens 1992, Warner et al. 1993). Decomposition is inhibited by seasonal or permanent anoxia, associated with high water tables in mires. Overall, the accumulation of peat involves an interaction between plant production and C losses by decay, mire fires, leaching and deposition of C into the mineral soil beneath the peat.

On a global scale, the occurrence of mires is strongly related to topography and climate, with the greatest abundance found in flat areas with cool and moist climates, such as western Siberia, Russia and the Hudson/James Bay Lowlands of Canada (Figure 1, Sjörs 1959, Walter 1977, Botch & Masing 1979, Botch et al. 1995), but mires are also found in tropics. In the most northern latitudes, the low temperatures limit the distribution of bogs (e.g. Almquist-Jacobson & Foster 1995). The climate during the Holocene has generally favored peat accumulation and has maintained a large C sink. Total area of boreal and subarctic mires is estimated as 350 million hectares with 220–455 Pg C (1 Pg = 10^{15}g) stored as peat (Sjörs 1981, Gorham 1991, Lappalainen 1996). However, Turunen et al. (2002) estimate 270–370 Pg C is stored as peat. Despite the uncertainties in the global storage estimates, mires are a substantial reservoir of C in the boreal and subarctic regions, constituting at least one-fifth of the total soil C pool in the world (Post et al. 1982), and approximately half the amount of CO_2-C in the atmosphere (Houghton et al. 1990). While mires have been C sinks, they have also been a source of atmospheric CH_4. High latitude northern mires, most of which belong to the boreal and subarctic region, are suggested to contribute 34–60% of the wetland CH_4 emissions (Matthews & Fung 1987, Cicerone & Oremland 1988, Aselman & Crutzen 1989, Bartlett & Harriss 1993). The atmospheric cooling effect associated with a C sink in the past and also in the future depends essentially on the release of CH_4. However, in most climate-biosphere studies and climate change models, the dynamics of mires have been ignored (e.g. Cox et al. 2000) even though their importance in the global C budget has been recognized (e.g. Melillo et al. 1993).

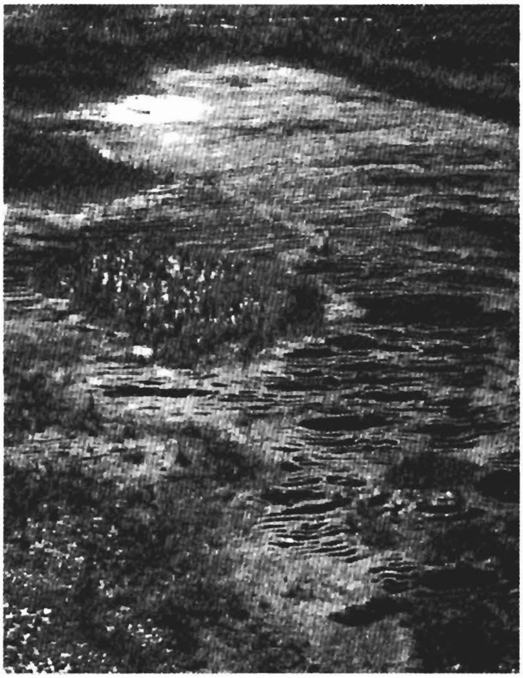

Figure 1. A patterned rich fen, James Bay, Québec, Canada (photograph by Jukka Turunen).

Kuva 1. Eutrofinen rimpineva, James Bay, Québec, Canada (kuva Jukka Turunen).

This review will primarily focus on the long-term (LORCA) and short-term (RERCA) rates of C accumulation in boreal and subarctic regions. Factors causing variation in the C accumulation, like climate, mire type, the age of the mire deposition, topography and fires will be discussed. This review will not discuss the vegetation succession of mire deposits, the mineral subsoil C accumulation, the development history of mire microforms (e.g., strings and flarks of aapa mires, hummocks and hollows of raised bogs) and their relation to C accumulation rates. Various studies underline that mires are complex ecosystems with a structure and dynamics that can be influenced by allogenic (climate) and autogenic (e.g. topography, substrate and hydrology) factors (Sjörs 1961, Aaby & Jacobson 1979, Elina 1987, Foster et al. 1988, Korhola 1992, 1996, Korhola et al. 1996, Vardy et al. 1997, Hilbert et al. 2000). Discrimination between individual factors is often difficult.

Terms and abbreviations

There are three different definitions to describe C accumulation. The long-term apparent rate of C accumulation (LORCA, g C m^{-2} a^{-1}) can be estimated at a given mire site from peat columns of known dry bulk density, C concentration and age of the basal peat. Similarly, the recent apparent rate of C accumulation (RERCA) is based on the column section between the surface and a given dated horizon in the surface peat column. Both these definitions are apparent values because of the continuous plant decay in the upper oxic acrotelm and the thicker anoxic catotelm (Clymo 1984, 1992, Tolonen & Turunen 1996, Clymo et al. 1998). The actual net rate of C accumulation (ARCA) can only be estimated by peat accumulation models like Clymo (1984), where the rate of organic matter addition and the decay coefficient are calculated based on cumulative dry peat mass versus age from several levels of the peat column. Due to decay, ARCA is always lower than LORCA.

Reliability of the estimates in C accumulation studies

Depth and areal distribution of mires

There have been several calculations of the average long-term apparent rate of carbon accumulation (LORCA) and the actual net rate of carbon accumulation (ARCA) in boreal and subarctic mires, as defined in Tolonen and Turunen (1996). LORCA has been estimated at 30 g m^{-2} a^{-1} in the former Soviet Union (Botch et al. 1995), 20–35 g m^{-2} a^{-1} in Canada and USA (Tolonen et al. 1988, Ovenden 1990, Zoltai 1991, Gorham 1991), and 21–26 g m^{-2} a^{-1} in Finland (Tolonen & Turunen 1996, Clymo et al. 1998). However, the material used in all these studies is biased because most of the profiles are from deep deposits as chosen for analysis by mire paleoecologists, which under-represents shallower mires. The dataset collected in most studies is small and does not represent the mean depths of mires and does not take into account areal information of different mire types (Table 1). The bias in mean depths is also evident through the mire classification in northern latitudes based on the artificial minimum depth of peat deposits. The minimum depth for geological mires in Finland, Canada and Russia is 30, 40 and 50–70 cm (Zoltai et al. 1975, Botch & Masing 1979, Lappalainen & Hänninen 1993, Kremenetski et al. 2003), respectively. Also, peat depth data of permafrost areas is scarce because of difficulties coring frozen peat (Kremenetski et al. 2003). In Russia, the average peat depth is reported to be 2.2–2.6 m (Botch et al. 1995, Kremenetski et al. 2003). Riley (1994) gives an average depth of 2.2 m for mires in northeastern Ontario, and Gorham (1991) used a mean of 2.3 m for boreal and subarctic mires. However, uncertainty arises from the representativeness of these depth estimates for all boreal and subarctic mires. Sims et al. (1982), for example, showed that fens of the Hudson Bay Lowland coastal region are relatively shallow (mean 104 cm, n=47). The mean depth measured at 900 000 sites spread over 5.1 Mha of Finnish mires is 1.52 m (Lappalainen & Hänninen 1993). However, the question of mean/median depths remains open until more systematically surveyed data becomes available for comparison.

The possible bias in the global C accumulation estimates also arises from the uncertainty in the distribution of bogs and fens in northern countries. Also, a serious problem in mire mapping may be the uncertain identification of forested mires from upland forest sites in vast remote areas of Canada and Russia. In West Siberian mire mapping this uncertainty has been recognized (Kremenetski et al. 2003). Detailed results of different mire types are available only for few countries such as Finland based on National Forest Inventories (see Turunen et al. 2002). The coarse distribution of bogs and fens in the Former Soviet Union have been estimated as 48% and 52% (Botch et al. 1995) and in Canada 66% and 34% (Tarnocai et al. 2000), respectively. Therefore, more accurate investigations of total areal distribution and the mean depths of different mire types (including forested/unforested mires) are required.

Dry bulk density and C concentration

A significant source of overestimation in C accumulation and the total C storage calculations of northern mires may have been the estimates used for dry peat bulk density. The estimate most often referred to from Gorham (1991) of 455 Pg stored as peat is based on the value of 112 g dm^{-3}. This estimate is a significantly higher estimate for dry bulk density for boreal and subarctic mires

Table 1. Mean of dry bulk density, carbon concentration and the long-term apparent rate of C accumulation (LORCA) of mires in North America, Asia and Europe. * = C concentration estimate used for LORCA calculations. ** Values based on Figure 7, pp. 60–67 (n=total for bog and fen sites).

Taulukko 1. Kuiva-ainetiheyden (dry bulk density), hiilipitoisuuden (Carbon concentration) ja hiilen pitkäaikaiskertymän (LORCA) keskiarvot Pohjois-Amerikan, Aasian ja Euroopan soilla.

Region	Mire type	Dry bulk density (g dm^{-3})	Number of sites (n)	Carbon concentration (%)	LORCA (g C m^{-2} a^{-1})	Reference
North American sites						
USA	bogs	71	4	50*	22.9	Tolonen et al. (1988)
Canada		100	159	50*	10–35	Ovenden (1990)
Canada	bogs and fens	112	?	51.7	29.0	Gorham (1991)
Canada	bogs	–	2	45.2	25.6	Kuhry et al. (1992)
Canada	bogs	102	109	51.0		Riley (1994)**
	fens	140		50.1		
Canada	bogs	–	9	–	20.2	Kuhry & Vitt (1996)
Canada	bogs	94	40	45.7	17.6	Robinson & Moore (1999)
	fens	88	60	46.2	17.0	
Canada	bogs, open / wooded fens	94/105	475	51.8	19.4	Vitt et al. (2000)
Canada	bogs	64	13	50*	20.9	Turunen et al. (unpublished)
Canada	bogs	98	12	49.3	6.3	Turunen &Turunen (2003)
Asian/ European sites						
Russia	bogs	80	?	56.0	31.4	Botch et al. (1995)
Russia	bogs	93	11	52.7	17.2	Turunen et al. (2001)
Russia	fens/bogs	–	2	51.6	13.0	Oksanen et al. (2001)
Sweden	bogs	81	5	40.0–51.0	–	Malmer & Holm (1984)
Sweden	fens	66	11	52.0	16.0	Klarqvist (2001)
Finland	bogs	89		50.3***	–	Mäkilä (1994)
	fens	93		50.3***	–	Virtanen et al. (2003)***
Finland	bogs	74	548	50.0*	24.0	Tolonen & Turunen (1996)
	fens	81	373	50.0*	15.1	
Finland	bogs	72	6	44–58	16.7–22.3	Mäkilä (1997)
Finland	fens	82	180	53.9	–	Minkkinen & Laine (1998)
Finland	bogs	80	20	50*	10.2	Pitkänen et al. (1999)
	fens	78	7	50*	5.6	
Finland	bogs	74	927	50.0*	20.8	Turunen et al. (2002)
	fens	81	375	50.0*	16.9	
Ireland	bogs	69	11	51.1	–	Tomlinson & Davidson (2000)

when compared to most published studies (Table 1). According to Mäkilä (1994, based on 49 953 samples), the mean dry bulk density of Finnish geological mires is 91 g dm^{-3}, similar to those obtained for other peat deposits in the boreal region (Table 1). C concentrations of different peat types are relatively well studied in the boreal and subarctic mires and range from 45% to 56% (Table 1). *Sphagnum* and *Carex* are the most common peat-forming genera in northern mires and the C concentration of these peat deposits depends mainly on the decomposition rate and plant remains in peat, being lowest in weakly decomposed *Sphagnum* peat and highest in well-decomposed *Carex* peat or peat with high lignid content.

Long-term C accumulation

The net transport of C between the atmosphere and peat is determined by the balance between the annual input of organic matter into the anoxic catotelm and the C loss from the peat. The results from Finland and the boreal region of Canada (Clymo et al. 1998) indicated a rather clear relationship between the long-term rate of carbon accumulation and climate. The rate of addition of dry mass (p) into the catotelm was related to the degree-days above zero, and the decay coefficient (a) logarithmically to mean annual temperature (Clymo et al. 1998), i.e. both p and a are larger in the south than in the north. Naturally, the moisture surplus (precipitation minus evapotranspiration) and the local basin hydrology influences plant species composition and rates of net ecosystem production (Hilbert et al. 2000).

The study of Turunen et al. (2002) quantified detailed LORCA in different mire vegetation regions in boreal and subarctic Finland. This study was based on extensive dataset of 1302 undrained mire sites and the LORCA was connected to the mean depths and the areal information of different mire type groups within the Finnish mire vegetation regions. The area-weighted LORCA for the entire Finnish undrained mire area (4.25 million ha) was estimated at 18.5 g m^{-2} a^{-1} throughout the Holocene, which is lower than earlier estimates of 26.1 and 21.0 g m^{-2} a^{-1} for Finnish mires (Tolonen & Turunen 1996, Clymo et al. 1998). The estimated LORCA of Finnish mires was also clearly lower than previous estimates for other boreal and subarctic regions (Gorham 1991, Botch et al. 1995, Table 1), but close to the most recent estimates in western Canada (Robinson & Moore 1999, 2000, Vitt et al. 2000), in western Siberia, Russia (Turunen et al. 2001) and in northern Sweden (Klarqvist 2001, Table 1).

The differences in LORCA between the raised bog region and the aapa mire regions in Finland have been found to be significant (Tolonen & Turunen 1996, Turunen et al. 2002). LORCA is highest in the eccentric bog region, 27.4 g m^{-2} a^{-1} and lowest in northern aapa mire, palsa and orohemiarctic mire areas, 16.9 g m^{-2} a^{-1} (Turunen et al. 2002), similar to the results of Klarqvist (2001). However, a considerable variation has been found within and between different mire type groups. Generally, ombrotrophic and ombro-oligotrophic bogs (dwarf-shrub pine bogs, cottongrass pine bogs, *Sphagnum* fuscum pine bogs, ridge-hollow pine bogs) are the most efficient at C accumulation, with a LORCA up to 30–35 g m^{-2} a^{-1}. Under wet conditions, for example, *Sphagnum* apparently has a high net productivity, and the peat passes into the anoxic catotelm without being strongly decayed (Aaby & Tauber 1974). The lowest rates, about 10 to 15 g m^{-2} a^{-1}, have been found in oligotrophic and mesotrophic open fens (tall-sedge fens and flark fens) (Klarqvist 2001, Turunen et al. 2002). Total aboveground net primary production generally increases from bogs to poor-moderate rich fens (Szumigalski & Bayley 1996b, 1997) but so does the decay of organic matter because *Sphagnum* species are more resistant to decay than *Carex* species (Johnson et al. 1990, Johnson & Damman 1991, Malmer 1992, Malmer & Wallen 1993, Szumigalski & Bayley 1996a, Scheffer et al. 2001).

The results of large datasets show that the age of the peat column is an important predictor of C accumulation (Tolonen & Turunen 1996) and has to be taken into account when comparing results (Figure 2, Turunen et al. 2002). A very clear increase in LORCA with decreasing mire age is observable. The most pronounced increase in accumulation rates occurred about 5000 cal. year BP (Figure 2), likely explained by the climate

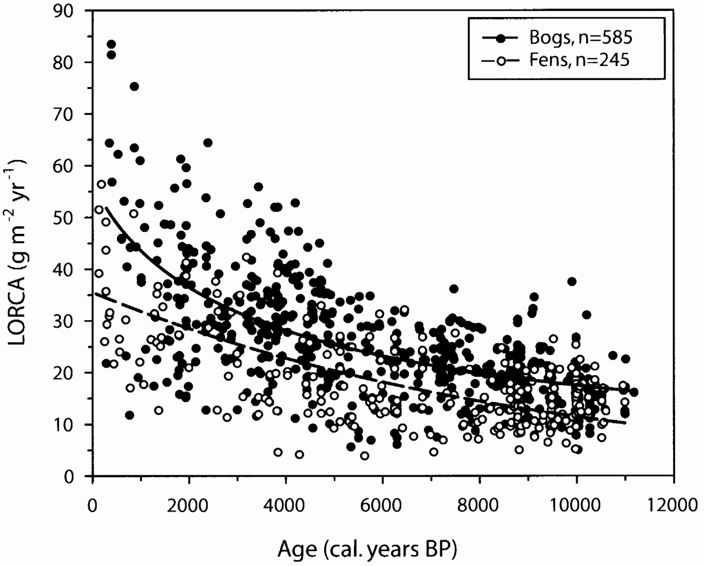

Figure 2. The average long-term apparent rate of carbon accumulation (LORCA) in Finnish bogs and fens (datasets 1 & 3 in Turunen et al. 2002).

Kuva 2. Pitkänajan keskimääräinen hiilikertymä (LORCA) tutkituilla rämeillä ja nevoilla Suomessa (materiaali Turunen et al. 2002).

change towards wetter and cooler conditions after the mid-Holocene temperature optimum (e.g. Korhola 1995, Korhola et al. 1995). Also, older mires have obviously experienced more C loss by leaching and fires (Hogg et al. 1992). Mire fires can slow the progress of vertical peat accumulation and result in great C losses, up to 1.5 to 4 kg m $^{-2}$ in an individual fire (Kuhry 1994, Pitkänen et al. 1999, Robinson & Moore 2000).

The true average accumulation rate of carbon (ARCA) has been estimated through theoretical peat accumulation models, in which the concave shape of the peat age versus depth (as cumulative C mass) curve has been observed in many mire sites (Clymo 1984, Clymo et al. 1998). ARCA for long cores has been estimated from $^{2}/_{3}$ to $^{3}/_{4}$ of the LORCA (Gorham 1991, Korhola et al. 1995, Tolonen & Turunen 1996, Mäkilä 1997). The average net accumulation rate of C decreases with time because slow decay takes place in the anoxic, deeper peat layers (Clymo 1984, 1992, Gorham 1991, Tolonen et al. 1992, Warner et al. 1993, Tolonen & Turunen 1996, Clymo et al. 1998). However, there are some serious problems in Clymo's (1984) model. An increasing number of peat deposits with a significantly convex peat age versus depth curve have been found to contradict the concept of constant input from the acrotelm and decay proportional to the amount of matter remaining as presented by Clymo (1984). This result has been found in several mires (e.g. Ikonen 1993, Korhola et al. 1995, Kuhry & Vitt 1996, Kilian et al. 2000, Turunen et al. 2001, Muller et al. 2003). The incorrect assumption of constant input and decay throughout the millenia ignores the systematic changes in peat stratigraphy as much as the impact of species on productivity and decay (Kilian et al. 2000). For example, about 50% of the current C storage at ca. 8500 years old Reksuo Bog was accumulated during the last 3000 BP during the ombrotrophication (Korhola et al. 1996). Normally, only few single vertical cores are analyzed for C accumulation at each mire and the horizontal expansion is ignored. Both vertical growth and lateral expansion should be considered (Korhola 1994, Korhola et al. 1995, Mäkilä 1997). The results indicate that both slow and rapid phases of lateral growth have occurred depending mainly on the topography of the mineral substrate. The fastest expansion rates are usually associated with mires having confining layers such as clays, whereas slow expansion is typical of mires on more permeable soils (Foster et al., 1988, Korhola, 1994, 1996, Mäkilä 1997, Turunen & Turunen, 2003). However, progressive lateral expansion of mires has also occurred (Foster & Wright 1990, Foster & Jacobson 1990).

Figure 3 shows a histogram of calibrated radiocarbon basal dates in southern and northern

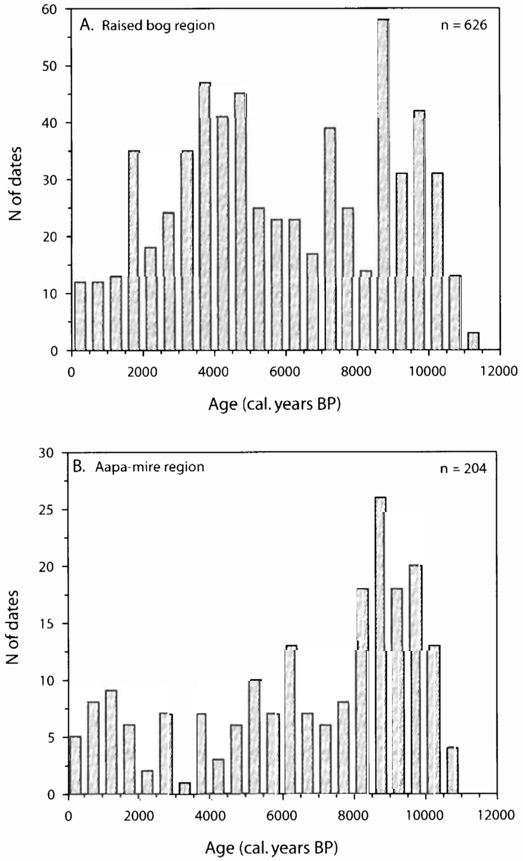

Figure 3. The histogram of calibrated radiocarbon dates of basal peats for a) the southern raised bog region and b) the northern aapa mire region of Finland (datasets 1 & 3 in Turunen et al. 2002).

Kuva 3. Histogrammi tutkittujen soiden pohjaturpeen radiohiili-ijistä a) Etelä-Suomen keidassuovyöhyke ja b) Pohjois-Suomen aapasuovyöhyke (materiaali Turunen et al. 2002).

Finland (data from Turunen et al. 2002). The data set includes mires formed through primary mire formation, paludification and terrestrialization. The results indicate a rapid mire expansion in southern Finland from ca. 10 500 to 8500 cal. year BP, from 5000 to 3000 cal. year BP and around 2000 cal. year BP. The results are supported by changes in lake levels in southern and central Sweden, where a major dry period occurred between 7000 and 4500 cal. year BP, resulting in decreased water levels (Digerfeldt 1988, Almquist-Jacobson 1995). The relatively clear decrease of basal peat dates in southern Finland from 8000 to 5000 cal. year BP indicating a climatic change can be seen in Figure 3A. According to Korhola (1992), the lateral expansion of five raised bogs in southern Finland was slow from ca. 7000 to 4500 cal. year BP, and it is possible that most of the basal dates between this time interval are from mires formed through terrestrialization (Figure 3A). Around 4500 cal. year BP the water levels started to rise again (Donner et al. 1978, Digerfeldt 1988) and this is reflected in both the rapid mire expansion and increased rates of C accumulation (Figures 2 and 3A).

In northern Finland the extensive mire expansion occurred from ca. 10500 to 8000 cal. year BP. Klarqvist (2001) indicates similar pattern in northern Sweden. According to pollen data of Seppä & Birks (2001), the early Holocene was cool and moist, corresponding with the present climate of the Norwegian north coast. Climate conditions were favorable for mire expansion due to the high primary production and low decay rates throughout the peat deposits. During the mid-Holocene ca. 8200 to 6700 cal. year BP, the July mean temperatures in northern Finland reached their Holocene maxima, about 1.4–1.7 °C higher than at present. During this time, there is a clear decrease in the total number of basal dates in northern Finland (Figure 3B) despite the annual precipitation remaining at a higher level compared to the present (Seppä & Birks 2001). Lake-level records from northern Finland and Sweden (Hyvärinen & Alhonen 1994, Eronen et al. 1999, Rosen et al. 2001) showed evidence of a distinct dry period ca. 8000–4000 cal. year BP. However, Figure 3B indicates that mires of northern Finland have expanded at a fairly constant rate over the last 6000 cal. year BP. The reason for this apparent contradiction in climatic data may be due to the fact that lake levels are more dependant on winter precipitation (Carcaillet & Richard 2000, Muller & Richard 2003). Summer precipitation and/or evapotranspiration was evidently high enough to promote peat growth. However, the proportion and intensity of different mire formation processes may have changed greatly during the middle and late Holocene. The results illustrate that possibly both autogenic and allogenic factors have strongly controlled the mire development in northern Finland.

Short-term C accumulation

An important consideration is that many estimates of the present day CO_2 sink of mires are based on LORCA during the entire Holocene but it is not clear how these values reflect on the present day CO_2 exchange processes (Crill et al. 2000). The past ~200 years are important in C dynamics of the mire, because during that time the plant biomass in the upper aerobic (acrotelm) layer has undergone intensive decay, entering the thicker, anaerobic layer (catotelm), which has low hydraulic conductivity and a lower rate of decay (Clymo 1984). Thus, the catotelm is the true site of peat accumulation, where slow anaerobic decomposition results in additional C loss. Belyea & Clymo (2001) have also presented a study of feedback mechanisms for oceanic bogs, which may explain how short-term variability in peat-forming processes is constrained to give relatively steady rates of long-term peat accumulation. The feedback mechanism is based on the relationship between the rate of peat formation and acrotelm thickness so that the microforms (i.e. hummocks and hollows) expand or contract vertically in response to the water table fluctuations (Belyea & Clymo 2001).

The C accumulation in Finnish mires over the past 100 to 200 years ranges from 40 to 81 g C $m^{-2} a^{-1}$ (Tolonen & Turunen 1996, Pitkänen et al. 1999). This is of the same magnitude as unpublished results of Turunen et al. in eastern Canadian ombrotrophic bogs, where C accumulation over the 150 years varied from 30 to 122 g C $m^{-2}a^{-1}$, with an average of 76 g C $m^{-2} a^{-1}$, and also for boreal *Sphagnum* dominated peat deposits elsewhere in North America (Tolonen et al. 1988, Wieder et al. 1994, Belyea & Warner 1994). The highest RERCA values in the surface layers of ombrotrophic *Sphagnum* bogs are as expected, because *Sphagnum* species are more resistant to decay than *Carex* species (Johnson et al. 1990, Johnson & Damman 1991, Malmer & Wallen 1993, Szumigalski & Bayley 1996a, Scheffer et al. 2001). However, the accumulation and decomposition rates also vary among *Sphagnum* species (Van der Molen & Hoekstra 1988, Johnson et al. 1990, Johnson & Damman 1991). As well, the development stage of the mire seems to be a very important factor controlling C accumulation. The young mires are considerably effective C accumulators due their optimal moisture regime for production of wetland species such as Phragmites and *Carex*, but suppressed decay due to the thin acrotelm (Malmer 1992, Tolonen & Turunen 1996). Increased rates of RERCA have also been found in mires of eastern Canada (Turunen et al. unpublished data). The highest RERCA during the last 50 years occurred in the high atmospheric N deposition region (0.8 g N $m^{-2} a^{-1}$), possibly due to a combination of climate and high N deposition. The correlation between the measured LORCA and RERCA was low.

C sink and pool

The present total LORCA for all boreal and subarctic mires is estimated at 66 Tg a^{-1} (Turunen et al. 2002), which is about 31% lower than the previous estimates of 96 Tg a^{-1} by Gorham (1991) and even lower than the estimate of 70 Tg a^{-1} for the true rate of C accumulation by Clymo et al. (1998). However, Clymo et al. (1998) suggested that the mean sequestering rate might be 30–40% less than 70 Tg a^{-1} obtained in their calculations because of the possible over-representativeness of deep mires in the dataset.

The updated C pool of northern mires has been estimated at 270–370 Pg C (1 Pg = 10^{15}g) (Turunen et al. 2002), which is very similar to earlier estimates of 300 Pg for global mires (Sjörs 1980), 249 Pg for boreal and subarctic mires (Armentano & Menges 1986), 210 Pg for boreal mires (Oechel 1989), and 234–252 Pg by Lappalainen (1996). The estimate of 455 Pg given by Gorham (1991) is the only significantly higher estimate for boreal and subarctic mires. The average dry bulk density of 112 g dm^{-3} used by Gorham (1991) may be too high and the main source of differences in C pool estimates. Using a mean bulk density of 91 g dm^{-3} instead of 112 g dm^{-3} used in Gorham's (1991) calculations, the C pool of northern mires will decrease from 455 to 370 Pg. This correction is justified because of the improved peat sampling methods and the increased number of reliable samples available for dry bulk density measurements.

Using an average depth of boreal and subarctic mires as the basis of calculations for the total C pool gives varied results depending on the depth used. Using a mean bulk density of 91 g dm^{-3} and for example, a mean depth of 1.7 m for all boreal and subarctic mires, the C pool of northern mires can be estimated at 274 Pg, similar to the estimate of Turunen et al. (2002). The possible bias in the data used in the previous estimates has been recognized, and the large range in the C storage estimate mainly reflects uncertainty in the depth of global peat deposits (Gorham 1991, Botch et al. 1995, Clymo et al. 1998). However, to improve the total C pool estimates a more accurate age-depth distribution of mires from North America and Russia is needed.

Future C balance?

Generally, the climate during the Holocene has favored C accumulation in boreal and subarctic mires. The anthropogenic influences on climate will cause both positive (warming) and negative (cooling) feedbacks in the terrestrial biosphere (Gorham 1991, Alm et al. 1999c). The predictions of these feedbacks are still quite speculative. The crucial question of the future is whether mires will act as sinks or sources of C-containing gases to the atmosphere. Possible climatic changes in temperature, precipitation, irradiation and evapotranspiration in northern latitudes will affect the hydrology and the future gas balance of mires. For example, a 1% loss of the mire C store from drying would result in a source of 2.7–4.5 Gt C to the atmosphere. Most general circulation model (GCM) -based projections indicate that there may be an overall increase in annual temperatures in the boreal and subarctic region (IPCC 1995, 2001). The rise of the annual mean temperature, according to the model used, is 2.5–10.0°C for northern latitudes for the next 100 years. Projected precipitation patterns are more uncertain. Most models show an increase in precipitation as a whole due to a higher content of water vapor in the atmosphere. However, frequencies and intensities of summer heat waves may increase, resulting in longer dry periods (IPCC 2001).

There would be consequences for total CO_2 and CH_4 fluxes from northern mires if the extent of mire areas changes, the duration of the biologically active period is modified, or the production or oxidation of CH_4 per unit area changes. In areas of predicted decreased annual soil moisture content (such as central Russia and Canada, Hadley Centre Atmospheric Model, http://www.meto.gov.uk/index.html) the lowered water tables will cause increased CO_2 release rates from peat through decomposition (Moore & Dalva 1993, Silvola et al. 1996), and will likely cause a net C loss in natural mires (Shurpali et al. 1995, Waddington & Roulet 1996, Carroll & Crill 1997, Alm et al. 1999b). These C losses can, however, be compensated for in more humid years, when the annual accumulation greatly exceeds the long-term averages (Alm et al. 1997). Some studies have also demonstrated how artificially induced water table drawdown has the capacity to increase CO_2 and decrease CH_4 emissions under a warmer climate (Laine et al. 1996, Nykänen et al. 1998). If the duration of a summer drought period approaches two months, methanogens decrease to such a low level that the flux may not recover during the remaining growing season, which would reduce the potential climatic feedback of boreal mires (Kettunen 2003). Also, if the water level will stay permanently low, increased tree and scrub growth could compensate for these respiratory losses, mainly due to increased above- and below-ground litter production in minerotrophic fens (Laine et al. 1996, Laine & Minkkinen 1996, Minkkinen & Laine 1998a, Minkkinen et al. 2002). In bogs, there are indications of plant community composition changes; increases in soil temperature and decreases in water table elevation increased cover of shrubs and decreased cover of graminoids (Weltzin et al. 2003). However, nutrient-poor bogs can support only limited tree growth. Further, the role of mire fires in remote northern areas may become crucial (Kuhry 1994, Pitkänen et al. 1999, Robinson & Moore 2000).

Studies like Korhola et al. (1996) indicate that mires have been acting both as sinks and sources during their development history. Modern bogs generally have a net cooling greenhouse effect, while the fens still support the natural atmospheric warming in spite of their role as C sink (Alm et al.1999c). Since the evaporation surplus ultimately controls the regional distribution of the main hydrological mire complex types, it is possible to predict that the increased water table in summer would promote the occupation and growth of *Sphagnum* mosses. The proposed warming could shift the existing climatic mire complex regions northward, and the southern aapa mire region would partially change to *Sphagnum* bogs that are more effective in sequestering C (Tolonen & Turunen 1996). This would strengthen the role of boreal mires as a C sink. In areas of increased annual soil moisture content, the primary productivity would increase due to increased temperature and atmospheric CO_2 content (e.g. Melillo et al. 1990), which would enhance C sequestration from the atmosphere. On the other hand, anaerobic decomposition could increase with more substrates supplied, and CH_4 emissions might rise (Guthrie 1986, Dacey et al. 1994, Hutchin et al. 1995). Also, raised CO_2 has been observed to increase CH_4 efflux rate 10–20% (Saarnio et al. 1998, Saarnio & Silvola 1999). An increase in temperature has been shown to promote plant and microbial respiration, which could turn northern mires from sinks to sources for atmospheric CO_2, especially if precipitation is decreased (Billings et al. 1982, Lashof 1989, Melillo et al. 1990). The change in winter CO_2 emissions will probably be relatively minor compared to the fluxes during the growing season (Alm et al. 1999a).

Northern mires are sensitive ecosystems, reacting rapidly to variations in climate. The expansion of boreal mires has evidently had a two-way atmospheric effect during the Holocene through warming by increasing landscape CH_4 release and cooling by C accumulation. The annual distribution of drought, precipitation and its seasonal distribution pattern will have a key role in the C balance of northern mires in the future (e.g. Alm et al. 1999c). Climate change will have a varying impact on different geographical regions making predictions about the effect of climate change on the net C dynamics difficult. These uncertainties include the influence of climate (including N deposition) on hydrology, mire plant community composition and possible acclimation (e.g. Weltzin et al. 2003), rates of plant production and decomposition and disturbances such as fire.

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Tiivistelmä

Luonnontilaisten soiden pitkänajan- ja nykykertymät boreaalisella ja subarktisella kasvillisuusvyöhykkeellä: katsaus

Tässä yhteenvedossa tarkastellaan luonnontilaisten soiden hiilen pitkänajan- (LORCA) ja nykykertymiä Suomen, Ruotsin, Venäjän, Kanadan ja Yhdysvaltojen boreaalisella ja subarktisella kasvillisuusvyöhykkeellä. Keskimääräinen pitkän ajanjakson hiilikertymän vaihteluväli on varsin suuri riippuen mm. suotyypistä, suon iästä ja maantieteellisestä sijainnista. Pitkän ajanjakson hiilikertymien ero oli merkitsevä eteläisen keidassuovyökkeen ja pohjoisen aapasuovyöhykkeen välillä. Keskimääräinen pitkän ajanjakson hiilikertymä viimeisimmän jääkauden jälkeen on ollut noin 13–20 g C m^{-2} a^{-1}, mikä on selkeästi alhaisempi kuin useat aikaisemmat arviot. Suon ikä on erityisen tärkeä hiilikertymän suuruuteen vaikuttava tekijä ja tulisi ottaa huomioon aina hiilikertymiä arvioitaessa ja/tai verrattaessa. Tulokset osoittavat myös soiden nopeaa laajuuskasvua Etelä-Suomessa noin 10 500–8500 cal. v. BP, 5000 – 3000 cal. v. BP ja 2000 cal. v. BP. Pohjois-Suomessa soiden intensiivisin laajuuskasvu ajoittuu välille 10500 – 8000 cal. v. BP. Soiden näennäisesti korkeammat nykykertymät viimeisimpien 100–200 vuoden aikana vaihtelevat välillä 30–120 g C m^{-2} a^{-1}. Boreaalisten ja subarktisten soiden tulevaisuuden hiilikertymänäkymiä on yhteenvedossa myös lyhyesti pohdittu.

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