Lateral extension in *Sphagnum* mires along the southern margin of the boreal region, Western Siberia

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**Abstract**

Although recent studies have recognized Northern Eurasian ecosystems as an important carbon reservoir, little is known about the forest–peatland interactions in a boreal environment induced by ongoing climatic changes. This study focuses on the evaluation of both the long-term and contemporary trends of land-cover changes and rates of lateral extension of peat-accumulating wetlands toward the adjacent forests, estimated at the southern climatic range of the *Sphagnum*-dominated mires in Western Siberia. We used the radiocarbon dates and stratigraphy of peat sediments from seven peat cores, analyzed at two types of forest–peatland ecotones, which are located close to each other but differ by topography and composition of their plant communities. The rate of lateral extension was found in a wide range varying from 2.3 to \(791.7\) cm yr\(^{-1}\). It was observed to be rapid during the initial stage of mire development, but to have slowed down over the last 2000–3000 yr. Our results, therefore, strongly contradict the concept of progressive peat accumulation throughout the late Holocene and contribute to our knowledge about ongoing land-cover change in the natural ecosystems of the Northern hemisphere.

**Keywords:** *Sphagnum* mires, forest–peatland ecotone, lateral extension, Western Siberia

**1. Introduction**

Accurate estimates of long-term and contemporary carbon accumulation in boreal and northern ecosystems remain unresolved issues, although they are especially important in the context of the implementation of the terms of the Kyoto protocol. In particular, information on actual carbon accumulation is lacking for the vast peatland areas in Northern Eurasia (Russia), where shallow peat deposits are not included in the national carbon account, and land-cover changes associated with the conversion of upland forests into peatlands and/or the opposite processes, such as degradation of peat layers and reforestation, are unknown. It, therefore, leads to some uncertainty in the estimation of the potential response of natural ecosystems on forthcoming and ongoing climatic changes.

Wetlands in their natural state are generally net accumulators of organic matter, with \(\sim 192–455\) Pg C (1 Pg = 10\(^{15}\) g) stored as peat in boreal peatlands (Gorham 1991). Peatland carbon dynamics influence atmospheric gas concentrations and, thus, future changes in wetland/forest-covered areas and carbon storage have the potential to influence greenhouse gas-induced warming (Post et al 1992, MacDonald et al 2006). Overall, it has been suggested that the carbon stored in peatlands represents a reduction of approximately 50 ppm of atmospheric CO\(_2\) (Franzen et al 1996). However, during the same time that this removal was occurring there was a substantial increase in atmospheric CH\(_4\); this has been
attributed to the areal extension of peatlands (Blunier et al. 1995). Vast areas of the Northern peatlands were formed by means of paludification, the process by which dry land is converted to mire through progressive waterlogging and peat formation (Anderson et al. 2003), in North America (Alaska) (Reiners et al. 1970, Ugolini and Mann 1979), Finland (Korhola 1992, 1994, Mäkilä 1997, Turunen et al. 1999), and Western Siberia (Neustadt 1971, 1977, 1984, Walter 1977, Turunen et al. 2001). At present, 60% of all the peat deposits of the former USSR and 40% of those of the whole earth are found in Siberian peatlands, which represent a large carbon pool of 70.2 Pg, up to ~26% of all terrestrial carbon accumulated since the Last Glacial Maximum (Smith et al. 2004, Sheng et al. 2004).

Previous estimates suggest that peat accumulation processes vary substantially over time according to the climatic fluctuations during the Holocene, although the only two contemporary trends of development have been prospected in the boreal region of Western Siberia. One suggests a permanent increase of the peat carbon accumulation processes and a relatively rapid expansion of the West Siberian mires from the early Holocene up to the present (Walter 1977, Neustadt 1984, Gajevski et al. 2001). Furthermore, some evidence for the contemporary expansion of peatlands was observed recently using Remote sensing techniques (Mialon et al. 2005). Another concept supports the idea of a gradual extinction of Sphagnum mire development, attaining a stable equilibrium in contemporary carbon accumulation (Mäkilä et al. 2001, Turunen et al. 2001, Kremenetski et al. 2003). This speculation became more tangled under projected climatic changes. Present scenarios of climate change predict that currently dry mid-continental regions will become even drier due to increased evaporation (Cubasch et al. 2001). At the same time, other studies infer significant perturbations in the water balance, resulting in almost the entire Siberian region experiencing increased summer precipitation (Wetherald and Manabe 2002), and higher mean annual temperatures (Romanovsky et al. 2000, Prather et al. 2001). The climate change is most likely to affect the mass balance of carbon in shallow peatlands, at or near peat surfaces, where exposure to climatic variables is the greatest (Wieder 2001). Therefore, it becomes important to estimate the land-cover changes associated with transformation of upland forests into swamped forests, and subsequently into peat-accumulating wetlands. Presently, there are relatively few direct measurements of the rate of horizontal growth of peatlands in Western Siberia, even as compared with accounts of vertical growth.

The objectives of this study were (i) to estimate the rates of long-term extension of Sphagnum mires at their southern climatic range in Western Siberia with the aid of peat stratigraphic investigations based on radiocarbon dating, (ii) to compare the lateral growth in the marginal versus the central areas of the mire, and (iii) to understand the contemporary trends in Sphagnum mire development.

2. Materials and methods

2.1. Study area

Western Siberia refers to the area bordered by the Ural Mountains in the west, the Yenisey River in the east, the Kara Sea in the north and the Altai Mountains and Kazakh Hills in the south (figure 1). The largest part of Western Siberia is occupied by the Ob–Irtyskh Basin, a nearly level plain lying some 25–95 m above sea level. Earlier studies, collated by Walter (1977), have found that the formation of peatlands in the area between the Ob and Irtyskh rivers started at the beginning of the postglacial age (Holocene), i.e. from 10 000 up to 12 000 years BP.

Our field observations were conducted on the southern slope of the Great Vasyugan Mire system (56°50′N, 78°30′E) which is located on the border between the southern boreal and boreonemoral vegetation zones (Tuwhanen 1984). The Great Vasyugan Mire is a natural phenomenon, the largest swamp system in the northern hemisphere, covering over 55 000 m², which is about 2% of the whole area of the Earth’s peat bogs (UNESCO World Heritage list). This area represents the southern limit of Sphagnum-dominated wetlands. The peats are underlain by relatively impermeable substrates thus favoring waterlogging (Walter 1977). There is a strongly pronounced inter-annual variability observed in climatic conditions at the study area, with cycles of alternating droughts and excessive moistening, although the latter predominates. Mean annual precipitation ranges from 450 to 560 mm yr⁻¹, 2/3 of which comes as summer rain, and total evaporation is 500 mm (Sergeev et al. 1977).

Our study focused on two raised peatlands located in relatively small, isolated basins with similar forested bog communities, dominated by pine trees (Pinus sibirica) and dwarf shrub-Sphagnum vegetation (a so-called, rymn). Two types of interaction between the upland forest and peatland (ecotones, e.g. Weber 1897) are present at the study area, as shown in figure 2. One ecotone (figure 2(A)) is located on flat terrain and consists of ecosystems ranging from automorphic deciduous forests to forested bogs. Another ecotone (figure 2(B)) is formed by a similar series of forest ecosystems, although it additionally contains herbaceous (sedge–reed) communities. Accordingly, we will refer to ‘forest’ (figure 2(A)) and ‘reed–forest’ (figure 2(B)) ecotones hereafter in the text, with special emphasis on the differences in plant communities corresponding to these ecotones. The forest ecotone is situated 12 km northward of the reed–forest ecotone. The peatland surface was instrumentally leveled and the peat depth measured at both ecotones to examine the shape of the mire basins.

2.2. Peat sampling and laboratory analysis

The modern vegetation and the rate of lateral extension of bog ecosystems were examined at seven study sites (figures 2(A) and (B)) by detailed field surveys and laboratory analysis of the peat samples. Peat columns were extracted using a Russian peat sampler across all types of vegetation communities, from the deepest sites (their locations were found out beforehand)
Figure 1. Study area of the Ob–Irtysh watershed (asterisk) in the southern part of West Siberia, Russia (56°50′N; 78°30′E). Forest–peatland ecotones in LANDSAT-TM imagery: A—forest, B—reed–forest. Red corresponds to small-leaved deciduous forest, bright green corresponds to grasslands and agriculture lands, and brown corresponds to Sphagnum mires.

Figure 2. Forest–peatland ecotones: (A) series of forest ecosystems, (B) series of forest ecosystems with a treeless (reed- and sedge-dominated) border between upland forest and forested bog. Ecosystems: R1—pine dwarf shrubs-Sphagnum bog (ryam), R2—tall ryam, Pf1—marginal carr (pine forest over peat), Pf2—birch sapling (swamped forest), Rd—treeless reed- and sedge-dominated marsh, F—small-leaved deciduous (birch and aspen) forest.

as well as the marginal parts of the mire. For analysis, 67 continuous 10 cm peat samples were taken from the cores.

The peat samples were washed and examined under an optical microscope (magnification 40–250×) to identify a plant’s macrofossil remains (Katz et al 1977). Microfossil contents were estimated by determining the fractional area of the remaining vascular plant tissue and mosses. Then, peat was classified into three groups corresponding to successive stages of mire development: oligotrophic, mesotrophic, and eutrophic. The oligotrophic and eutrophic stages were classified as having more than 95% abundance of plant species growing in respective conditions. Otherwise, the sediment was considered to be in the mesotrophic stage of mire development.

AMS 14C dating for peat samples was acquired from the NIES-TERRA AMS facility at the National Institute for Environmental Studies in Tsukuba, Japan (Tanaka et al 2000). The dates were determined in conventional 14C years before present (B.P.–AD 1950), with appropriate standard errors (1σ) calculated by the laboratory. We converted the radiocarbon dates (14C yr BP) to calibrated ages (cal yr BP) using the INTCAL04 calibration curve (Reimer et al 2004). The rates of lateral extension were calculated based on calibrated (median value) radiocarbon dates of basal peat samples for each pair of adjacent sampling points along the transects.

3. Results and discussion

In spite of the substantial resemblance among peat-forming processes at the central part of the two ecotones, considerable differences in the rate of vertical growth were found in marginal shallow deposits. Estimated rates of vertical peat accumulation at analyzed transects have been published earlier (Peregon et al 2007). In figure 3 we show the peat stratigraphy (microfossil plant remains).
Figure 3. Microfossil plant remains in forest (A) and reed–forest (B) ecotones. *Sphagnum* mosses: 1—*S. fuscum*, 2—*S. angustifolium*, 3—*S. magellanicum*, 4—*S. fallax*, 5—mesotrophic mosses (*S. centrale*, *S. russowii*); sedges (*Carex*): 6—*C. globularis*, 7—*C. lasiocarpa*, *C. rostrata*, 8—*C. elata ssp. omshkiana*, *C. cespitosa*; 9—*Eriophorum vaginatum*, 10—*Scheuchzeria palustris*, 11—brown mosses; grasses: 12—reed (*Phragmites australis*), 13—*Calamagrostis*; 14—shrubs, 15—birch leaves, 16—wooden remains. The framed numbers below the columns indicate radiocarbon ages of the basal peat samples (years BP).

Overall, the mire development in the forest ecotone was initiated through conversion of upland forest to sedge fen, either directly or via a brief marsh phase resulting from local or seasonal flooding. Wooden remains are presented along the whole depth of the core, suggesting that this mire has been tree-covered for the entire period of mire development. No evidence of peat degradation or fire activity was found in the analyzed samples. The shallowest core analyzed in this study, about 20 cm depth (A4), was initiated by an invasion of *Sphagnum* into adjacent upland forest (i.e. paludification: e.g. Anderson et al 2003). Its history is recorded by mesotrophic wood-*Sphagnum* sediments directly overlaying the parent loamy soil. All observations indicate persistent peat accumulation in peat deposits related to the forest ecotone. In contrast, sediment stratigraphy in core B3 of the reed–forest ecotone provides some evidence of ‘intermittent’ peat accumulation. The uppermost 10 cm thick layer of the deposit is composed of turf that may indicate peat degradation. In contrast to underlying peat deposits the turf contains a great amount of live and undecomposed roots of vascular plants. The fair amount of wooden residue found implies dry conditions which are favorable for growing trees.

Radiocarbon dates for basal peat samples span about 3000 yr. The $^{14}$C dates and calibrated ages for each core are depicted in greater detail in table 1.

The oldest date, 3278 ± 7 cal yr BP (3110 $^{14}$C years BP), was measured in the reed–forest ecotone (core B1). Peat formation in a forest ecotone area initiated about 1100 yr later as compared with a reed–forest ecotone. Our analysis suggests that both peatlands were initiated in topographical depressions and have extended their margins toward adjacent forests, i.e. the mires were formed via paludification. Although these sampling sites were rather sparsely distributed over the forest–peatland transects, they do allow certain obvious trends to be distinguished in lateral growth. Mean rates of lateral extension (cm yr$^{-1}$) calculated from the basal peat dates and distances between the sampling sites are presented in figure 4.

Estimated rates of areal extension differ from one analyzed ecotone to another. According to radiocarbon dates, peat formation in a ‘forest’ ecotone began about 2189 ± 5 cal. yr BP (2270 $^{14}$C yr BP), and during an initial stage of paludification the mires invaded the surrounding mineral soils at a mean rate of 7.92 m a year. Although the rate of horizontal growth appears to have obviously decreased (down to 9.9 cm yr$^{-1}$) from about 2200 to 550 cal. yr BP, it slightly increased again thereafter (up to 15.4 cm yr$^{-1}$). These variations could be explained by the undulation in the topographical profile of the mire basin corresponding to the location of the core A2 (see figure 2).

Analogous to the forest ecotone, our analysis in the reed–forest ecotone revealed a significantly higher rate of extension...
recent millennia. According to Sjörs (1982), the main period of more rapid growth do not coincide with a period of increased lateral extension. The evidence for present expansion is scant, and our results, however, suggest that wetland extension rates are usually terrestrialized basins, and so under-represent shallower environments. Thus, the mires reached practically their present extent. Our results clearly demonstrate the highly expansive nature of mire ecosystems, which means that they can advance at a rate of more than two meters a year under favorable conditions. Thus, the mires reached practically their present area within only a few hundred years. Since about 40% of mire area was formed during less than 100 yr after initiation of the mire development at our test sites, another 2000–3000 yr were required for paludification to create the last 60% of its present extent.

How do our estimates compare with results obtained by other studies in boreal regions, and in Western Siberia in particular? First of all, the data used in previous studies is biased because most of the cores came from deep and usually terrestrialized basins, and so under-represent shallower mires. The evidence for present expansion is scant, and some boreal peatlands have shown very little increase in recent millennia. According to Sjörs (1982), the main period

during the initial stage of mire development, which is estimated at a rate of 2.42 m a year corresponding to the period of 3278–3212 cal. yr BP (3110–3010 $^{14}$C yr BP). Then, the rate of extension decreased to 8.9 cm yr$^{-1}$ from 3212 to 2363 cal. yr BP. In addition, it may be seen that lateral extension has been very slow indeed over the last 2300–2400 yr, advancing only 2.3 cm yr$^{-1}$. Periods of more rapid growth do not coincide in time between two mires: in fact when the mire in a forest ecotone is going through a period of exceptionally rapid lateral growth, it has already decelerated in a reed–forest ecotone (figure 4). Overall, the climate has often been put forward as a driving force of variations in Holocene peat accumulation (e.g., Ovenden 1990, Korhola et al 1996, Turunen et al 2004).

Our results, however, suggest that wetland extension rates are caused by local internal environmental factors, such as site topography, substrate conditions, etc rather than by external (allogenic) factors, such as climatic fluctuations only. This conclusion is similar to that reported by Mäkilä et al (2001). In this context, we agreed with the arguments of Borren et al (2004) saying: ‘If climate is the major force behind variations in peat accumulation, these variations should turn out to be similar for all peatland types within one climatic zone’. In this study, we do not consider a whole range of non-climatic factors controlling peat accumulation (e.g. acidification of the environment, the chemical and physical composition of the subjacent strata, etc), although the general restriction of Sphagnum to these sites is only partly determined by the environment, with Sphagnum playing a considerable role in creating a habitat in which few other plants can flourish: an environment with high acidity, low nutrient availability, anoxia and low temperatures (Andrus 1986, van Bremen 1995).

Table 1. Radiocarbon dates/calibrated ages of basal peat samples and rates of lateral extension along the transects.

| Core No. | Sample depth (m) | Laboratory number | Basal peat age ±1σ ($^{14}$C yr BP) | Calibrated age; lower (median) (cal yr BP) | Material dateda | Distance along the transect (m) / rate of extension (cm yr$^{-1}$) |
|----------|------------------|-------------------|-----------------------------------|------------------------------------------|---------------|-------------------------------------------------|
| A4       | 0.17–0.2         | Terra-060307a04 Modern | —                                 | —                                       | M            | 85/15.4 ± 0.9                                    |
| A3       | 0.3–0.4          | Terra-060307a11     | 580 ± 30                          | 543 (552) 561 E                         | M            | 160/9.9 ± 0.1                                    |
| A2       | 0.8–0.9          | Terra-060307a05     | 2190 ± 30                         | 2147 (2165) 2183 E                      | E            | 190/791.7 ± 612.1                                |
| A1       | 1.6–1.7          | Terra-060307a06     | 2270 ± 30                         | 2184 (2189) 2193 E                      | E            |                                                  |
| B0       | 0                | —                  | —                                 | —                                       | —            | 55/2.3 ± 0.03                                    |
| B3       | 0.4–0.5          | Terra-060307a07     | 2400 ± 30                         | 2353 (2365) 2376 E                      | E            | 75/8.9 ± 0.5                                    |
| B2       | 0.8–0.9          | Terra-060307a08     | 3010 ± 30                         | 3161 (3212) 3263 E                      | E            | 160/242.4 ± 189.1                               |
| B1       | 1.9–2.0          | Terra-060307a09     | 3110 ± 30                         | 3271 (3278) 3285 E                      | E            |                                                  |

* Material dated: M—mesotrophic peat, E—eutrophic peat.

Figure 4. Lateral extension rates of mires: A—forest ecotone, B—reed–forest ecotone.
of peatland spreading (paludification) has happened between 5000 and 2000 yr BP. Some recent studies determined that lateral extension of peatlands of the West Siberian lowlands has slowed or stopped within the past 3000 yr (Kremenetski et al. 2003). However, Neustadt (1984), taking the large (2268 km²) Bakchar Bog in western Siberia, which also belongs to the Great Vasyugan mire complex, as typical, and assuming an acceleration rate of 0.5 mm yr⁻¹, suggests that spreading has continued fairly rapidly up to the present time. Our results, however, do not provide evidence of progressive lateral extension of the mire ecosystems, but rather indicate that both slow and very rapid phases in lateral growth have occurred. The actual filling-in process, which advanced from the center of the basin toward the edges, took place very rapidly in both mire basins at a time of initiation, when they were still entirely mesotrophic or even eutrophic (see table 1). This fact is consistent with data published from raised bogs in Finland, indicating that the mire reached its present extent in the early mesotrophic stage and has mainly grown vertically since then, even though there are no obstructions to lateral extension (Ikonen 1993). According to Korhola (1992, 1994), very little horizontal extension has taken place over the last two thousand years in five raised bogs in southern Finland. The reason for this is the steepening of the bottom gradient toward the marginal areas of the present mires. It was also the case of our study, where the lateral extension was found to be slower at the steep margins of the basin, such as in the reed–forest ecotone (core A2), as compared to that on gently sloping margins in the forest ecotone. Water table levels in the studied mires showed a decrease of up to 40–50 cm in peat deposits of 90 cm depth after a series of dry years (1997–2000) compared to a wet year (2002) (our field observations), leading to significant vegetation drought stress and exposure of the peat column to aerobic conditions, providing favorable conditions for growing trees at the marginal parts of mire basin, as is observed in the reed–forest ecotone–ecosystem P1 (pine forest over peat) (figure 2).

There is a further question as to what will happen to the Sphagnum wetlands in their present distribution areas under the impact of climate changes: whether they will spread laterally or, alternatively, contract in area. The answer depends on precipitation and its seasonal distribution patterns (Tolonen and Turunen 1996). The warmer and drier climates, predicted in all climatic parameters. of peatland spreading (paludification) has happened between 5000 and 2000 yr BP. Some recent studies determined that lateral extension of peatlands of the West Siberian lowlands has slowed or stopped within the past 3000 yr (Kremenetski et al. 2003). However, Neustadt (1984), taking the large (2268 km²) Bakchar Bog in western Siberia, which also belongs to the Great Vasyugan mire complex, as typical, and assuming an acceleration rate of 0.5 mm yr⁻¹, suggests that spreading has continued fairly rapidly up to the present time. Our results, however, do not provide evidence of progressive lateral extension of the mire ecosystems, but rather indicate that both slow and very rapid phases in lateral growth have occurred. The actual filling-in process, which advanced from the center of the basin toward the edges, took place very rapidly in both mire basins at a time of initiation, when they were still entirely mesotrophic or even eutrophic (see table 1). This fact is consistent with data published from raised bogs in Finland, indicating that the mire reached its present extent in the early mesotrophic stage and has mainly grown vertically since then, even though there are no obstructions to lateral extension (Ikonen 1993). According to Korhola (1992, 1994), very little horizontal extension has taken place over the last two thousand years in five raised bogs in southern Finland. The reason for this is the steepening of the bottom gradient toward the marginal areas of the present mires. It was also the case of our study, where the lateral extension was found to be slower at the steep margins of the basin, such as in the reed–forest ecotone (core A2), as compared to that on gently sloping margins in the forest ecotone. Water table levels in the studied mires showed a decrease of up to 40–50 cm in peat deposits of 90 cm depth after a series of dry years (1997–2000) compared to a wet year (2002) (our field observations), leading to significant vegetation drought stress and exposure of the peat column to aerobic conditions, providing favorable conditions for growing trees at the marginal parts of mire basin, as is observed in the reed–forest ecotone–ecosystem P1 (pine forest over peat) (figure 2).

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