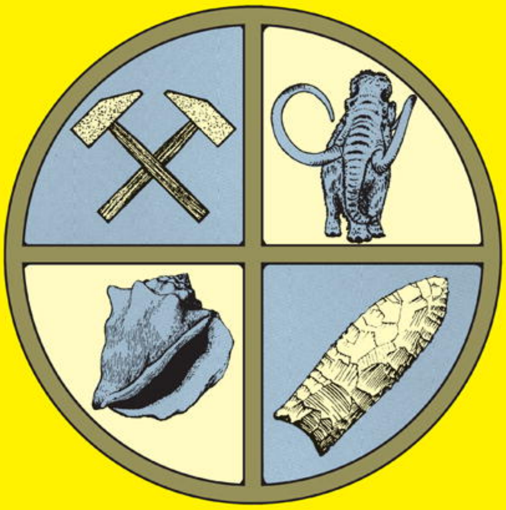
QUATERNARY SCIENCE REVIEWS
The International Multidisciplinary Research and Review Journal

Volume 26 Nos 13–14 July 2007 ISSN 0277-3791



Quaternary Science Reviews 26 (2007) 1871–1883

Climatic and environmental changes in north-western Russia between 15,000 and 8000 cal yr BP: a review

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Received 27 February 2006; received in revised form 19 March 2007; accepted 2 April 2007

Abstract

Multi-proxy palaeoenvironmental studies of nine sediment sequences from four areas in north-western Russia reveal significant changes in climate, lake productivity and vegetation during the Lateglacial and early Holocene that show some degree of correlation with changes reconstructed from sites throughout the North Atlantic region. At Lake Nero in the Rostov-Jaroslavl' area, which is outside the maximum limit of the Scandinavian Ice Sheet, sedimentation recommenced shortly after 15 cal ka BP in response to increases in temperature and humidity during Greenland Interstadial 1 (GI-1; Bølling-Allerød). However, climatic amelioration during GI-1 was slow to increase lake organic productivity or trigger large-scale changes in much of northwestern Russia. In general, this region was characterised by long-lasting lake-ice cover, low lake productivity, soil erosion, and dwarf shrub and herb tundra until the end of Greenland Stadial 1 (GS-1; Younger Dryas). At some sites, distinct increases in lake organic productivity, mean summer temperatures and humidity and the expansion of forest trees coincide with rapid warming at the beginning of the Holocene and the increasing influence of warm air masses from the North Atlantic. At other sites, particularly on the Karelian Isthmus, but also in Russian Karelia, the delayed response of limnic and terrestrial environments to early Holocene warming is likely related to the cold surface waters of the Baltic Ice Lake, the proximity of the Scandinavian Ice Sheet and associated strengthened easterlies, and/or extensive permafrost and stagnant ice. These multi-proxy studies underscore the importance of local conditions in modifying the response of individual lakes and their catchments.

While Lateglacial vegetation was dominated by *Betula nana* and *Salix* shrubs and various herbs, pollen and plant macrofossils suggest that *Betula pubescens* trees became established as early as 14–13 cal ka BP in the Rostov-Jaroslavl' area. In general, our data sets suggest that trees migrated from the southeast to the west and then spread later to the northeast and northwest, paralleling the direction of ice retreat, with *Betula pubescens* immigrating first, followed by *Pinus sylvestris* and *Picea abies*. However, palaeoecological records from Lake Terebenskoye in the Valdai Highlands suggest that the arrival of *Picea abies* preceded other trees in that area and that it colonised tundra communities as early as 12 cal ka BP. Since Lateglacial vegetation change in north-western Russia was time-transgressive, independent measures of palaeoclimate (e.g., chironomid-based palaeotemperature estimates) are needed for this region.

1. Introduction

The environmental response of Northern Hemisphere terrestrial and limnic ecosystems to the distinct climatic fluctuations at the end of the last glaciation varied both in

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doi:10.1016/j.quascirev.2007.04.005

time and space (e.g., Peterson, 1993; Harrison et al., 1996; Tarasov et al., 2000; Renssen and Isarin, 2001; Velichko et al., 2002), depending on local and regional climatic conditions and on the distance to the North Atlantic Ocean and adjacent ice sheets. Palaeoenvironmental and palaeoecological reconstructions of the response to these climatic fluctuations remain hampered by problems inherent with radiocarbon dating (Björck and Wohlfarth, 2001) and limited by the availability of high-resolution Lateglacial and early Holocene terrestrial records from many regions of the Northern Hemisphere. New investigations are now emerging from different regions, offering the possibility to address these issues in greater detail, but the western part of European Russia is among those areas where Lateglacial and early Holocene climatic and environmental conditions are still poorly understood.

To fill this gap, we performed multi-proxy palaeoenvironmental studies of eight lake sediment sequences and one section of varved clays along a NW–SE transect in northwestern Russia near the international borders with Estonia and Finland (Figs. 1A and B). We focussed specifically on areas which (i) were not covered by the Scandinavian Ice Sheet during the Last Glacial Maximum (region A); (ii) became gradually ice-free during the Last Termination (regions B–D); and, (iii) were influenced by the Baltic Ice Lake stage of the Baltic Sea (region D) (Figs. 2A and B). We speculated that the timing of the environmental response reconstructed at the different sites in each of the four regions would be in concert with the

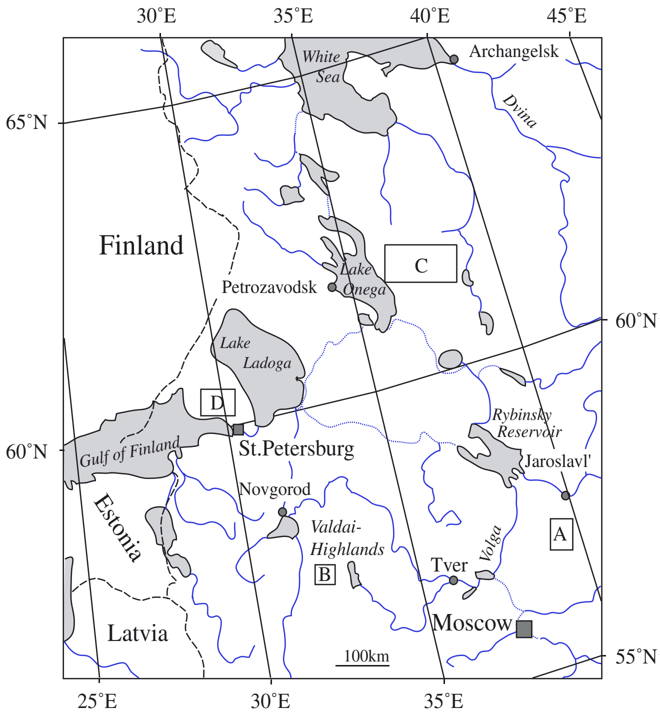

Fig. 1. (A) Map of central and eastern Europe and (B) Map of northwest Russia with the four study areas indicated. A = Rostov-Jaroslavl', B = Valdai Highlands, C = eastern Russian Karelia, D = Karelian Isthmus. Information on the nine investigated sites is given in Table 1.

established Northern Hemisphere climatic variations (Björck et al., 1998; Walker, 2001) and that local and extra-local conditions may have only had minor influence. Although the results of our studies show that this holds true for some time intervals and for some areas, they also indicate that local and extra-local conditions delayed and modified the environmental response and development. Here, we present a synthesis of these investigations (Wohlfarth et al., 1999, 2002, 2004, 2006; Subetto et al., 2002), including new studies of Lateglacial and early Holocene sediment from Lake Terebenskoye in the Valdai Highlands (Subetto, 2003) and examine the reconstructed climate, environmental, and vegetation histories between 15 and 8 cal ka BP for this part of northwestern Russia.

All age estimates for our study sites are based on calibrated AMS ^{14}C dates (cal) and are expressed in thousands of years BP (ka BP). For age estimates of other studies cited in the text it is indicated whether these are derived from OSL dating, exposure dating or varve chronology. We use the GRIP event stratigraphy (Walker et al., 1999; Lowe, 2001) to place our results within a wider geographical context.

2. Extent and retreat of the Scandinavian ice sheet

The most recent reconstruction of the maximum position of the Scandinavian ice sheet (SIS) in western Russia (Fig. 2A) indicates an ice margin terminating approximately between 32 and 34°E, south of 60°N, but extending further to the east north of 60°N (Demidov et al., 2006). OSL dating suggests that this maximum position was attained around 20–18 ka BP in the southern part of the region (Lunkka et al., 2001) and about 18–16 ka in the Archangelsk area to the northeast (Demidov et al., 2006). Numerous and extensive glacial lakes formed in front of the ice margin and during the subsequent melting (Lunkka et al., 2001; Saarnisto and Saarinen, 2001; Demidov et al., 2006). The age assignment and correlation of the different ice marginal features (Luga and Neva terminal belts), which formed during the retreat of the ice sheet in western Russia (Ekman and Iljin, 1991), is not well constrained. Studies by, e.g., Saarnisto and Saarinen (2001) date the formation of the Luga and Neva moraines to 14.2 and 13.3 varve ka BP, respectively, while Demidov et al. (2006) only describe Neva terminal belt features, which they place within the Older Dryas (≈13.9 cal ka BP) (Fig. 2B). These latter authors interpret the landscape between the Neva terminal belt and the maximum position of the SIS as a region characterised by down-wasting of dead ice, without clear signs of a still-stand of the ice margin. The Salpausselkä I terminal belt is generally associated with a still-stand and/or minor oscillations of the ice margin during the Younger Dryas cold phase. Recent age assignments for the formation of these ice marginal features are 11.8 ± 0.3 yr BP based on exposure dating (Tschudi et al., 2000) and 12.2–11.6 yr BP based on varve chronology (Saarnisto and Saarinen, 2001).

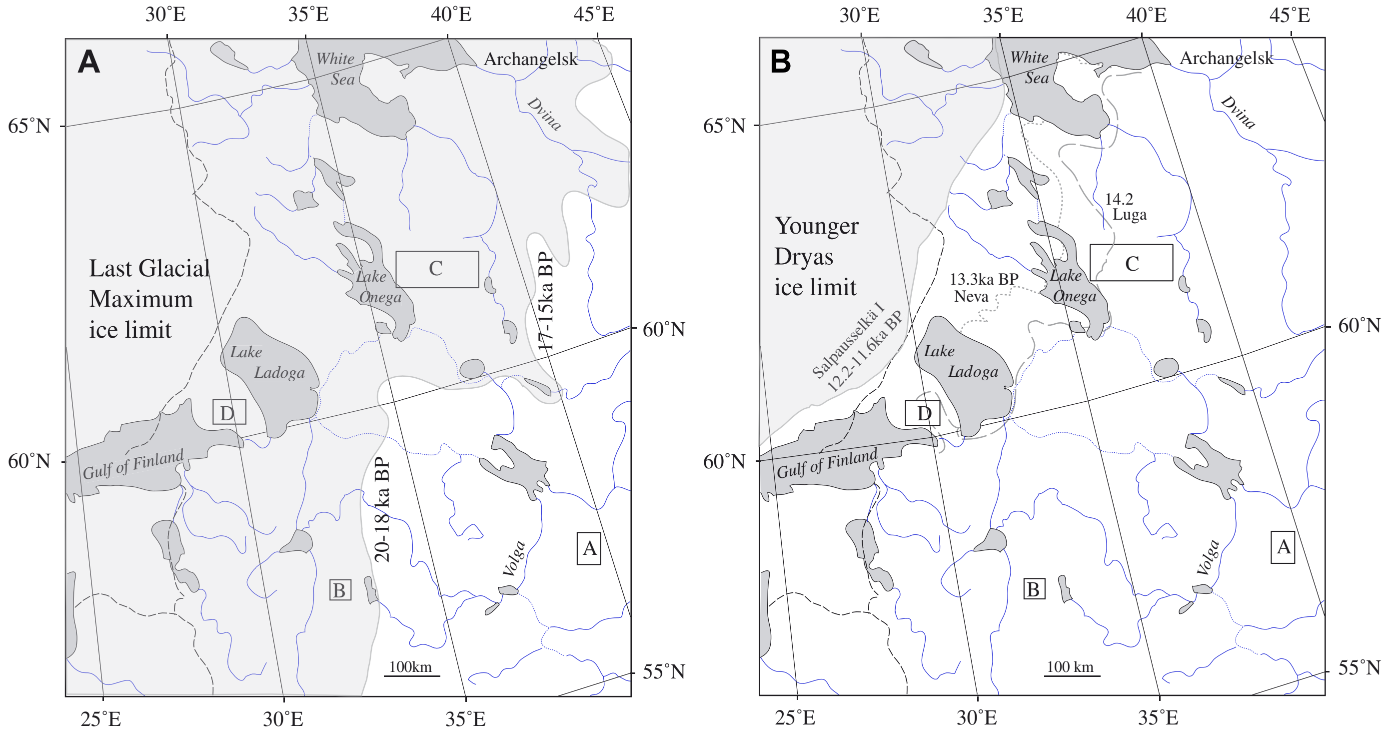

Fig. 2. (A) The Last Glacial Maximum extension of the scandinavian ice sheet (SIS) and (B) the Older Dryas (Neva) and Younger Dryas (Salpaussälka) terminal belts in the study area, according to Demidov et al. (2006). The dotted areas indicate regions where dead ice remained after deglaciation. The four study regions are: A = Rostov-Jaroslavl', B = Valdai Highlands, C = eastern Russian Karelia, D = Karelian Isthmus.

Independent of these different age estimates it is evident that our site in the Valdai Highlands (region B in Fig. 2B) should have become ice-free some time after the deglaciation from the maximum position i.e., after 20–18 ka BP. The sites in eastern Russian Karelia (C) are located in a former dead-ice terrain, where stagnant ice may have remained for several thousand years (Demidov et al., 2006), while the study area on the Karelian Isthmus (D) could have become ice free between 13.9 and 12.7 ka BP.

3. Study regions

3.1. Rostov-Jaroslavl' area

Three lake sediment sequences (Table 1) from north of Moscow (region A in Figs. 1B and 2A and B) were analysed for pollen, macrofossils, and lithological and geochemical parameters (Wohlfarth et al., 2006). Age was assigned based on calibrated AMS ^{14}C measurements on terrestrial plant macrofossils consisting mostly of wood fragments. At Lake Nero, which is the largest of all the lakes studied and from which a sedimentary record comprising the Last Interglacial–Glacial cycle has been described by Tarasov et al. (1996), a shallow, but productive lake developed about 15 cal ka BP (Wohlfarth et al., 2006). The compacted sediments with root structures in the bottom of the cores suggest that portions of the basin dried out prior to 15 cal ka BP. Between 15 and 13 cal ka BP, the local vegetation was dominated by *Betula* and *Salix* shrubs, sedges, grasses and other herbs such as *Artemisia*. Pollen concentrations and macrofossils suggest that *Betula pubescens* (referred to as *Betula* sect. *Albae* in Wohlfarth et al., 2006) may have grown in the Rostov-Jaroslavl' area as early as 13–14 cal ka BP; however, a hiatus in the sediment sequence at the transition between *Betula nana* and the first occurrence of *B. pubescens* macrofossils makes it difficult to determine exactly when *Betula* trees first grew in the lake's catchment (Wohlfarth et al., 2006).

Lithological and macrofossil evidence indicate lake-level fluctuations between 14 and 13.5 cal ka BP, which were followed by a low lake-level phase and possibly a dried-out lake between ca 13 and 8.2 cal ka BP (Wohlfarth et al., 2006). In contrast, lakes Zaozer'e and Chashnitsy started to fill in after 12 cal ka BP, possibly in response to melting of permafrost (i.e., a thaw or thermokarst lake). After a shallow lake phase with increased organic productivity (ca 12–10.5 cal ka BP), water levels in these lakes decreased and peatland expanded over the coring sites between 10.5 and 9 cal ka BP. The ongoing degradation of permafrost due to warmer air temperatures likely led to subsurface drainage of these basins (e.g., Burn, 1997; Smith et al., 2005). The presence of *Pinus sylvestris* and *Betula pubescens* in local forests is shown by plant macrofossils in Lake Chashnitsy sediments that date to around 11 and 10.6 cal ka BP, respectively, and imply that minimum mean summer temperatures were $>12\,^{\circ}C$ (Iversen, 1954).

Table 1
Details on the palaeoenvironmental sites studied in northwest Russia

Site	Elevation (m a.s.l.)	Latitude longitude	Surface area (km^2)	Water depth (m)	Chronology[a]	Analysed proxy data[b]	Reference
A. Rostov-Jaroslavl'							
Lake Nero	93	57°10′N 39°26′E	52	4	8 AMS ^{14}C (4)	TC, TN, TS, mineral magnetics, pollen, macrofossils	Wohlfarth et al. (2006)
Lake Zaozer'e	147	56°50′N 39°21′E	0.3	18	5 AMS ^{14}C (4)	TC, TN, TS, mineral magnetics, macrofossils	Wohlfarth et al. (2006)
Lake Chashnitsy	163	56°56′N 39°23′E	0.7	>6	7 AMS ^{14}C (5)	TC, TN, TS, mineral magnetics, macrofossils	Wohlfarth et al. (2006)
B. Valdai Highland							
Lake Terebenskoye	153	58°08′N 32°59′E	0.3	1.5–2	6 AMS ^{14}C (6)	TOC, TN, mineral magnetics, pollen, macrofossils	Subetto (2003); this paper
C. Eastern Russian Karelia							
Lake Tambichozero	122	61°56′N 37°54′E	~0.7	—	Varve measurements, 4 AMS ^{14}C (4)	TC, mineral magnetics, grain size, pollen, macrofossils	Wohlfarth et al. (2002)
Lake Pichozero	117–118	61ǫ47′N 37ǫ25′E	~2.3	—	Varve measurements, 6 AMS ^{14}C (6)	TC, TIC, OC, TS, TN, Rock-Eval, mineral magnetics, pollen, macrofossils	Wohlfarth et al. (2004)
Pudozh	37–45	61°48′N 36°28′E	N/A	N/A	Varve measurements, 17 AMS ^{14}C (17)	macrofossils	Wohlfarth et al. (1999)
D. Karelian Isthmus							
Lake Medvedevskoye	102	60°31′N 29°54′E	~0.5	<4	Tephra, 5 AMS ^{14}C (6)	TOC, mineral magnetics, pollen, diatoms	Wastegård et al. (2000), Subetto et al. (2002)
Lake Pastorskoye	77	60°13′N 30°02′E	0.18	<4	Tephra, 7 AMS ^{14}C (4)	TOC, mineral magnetics, pollen, diatoms	Wastegård et al. (2000), Subetto et al. (2002)

[a]Numbers in brackets indicate the number of ages, not including varves, for the period between 15 and 8 cal kyr BP.
[b]TC = Total carbon; TN = Total nitrogen; TS = Total sulphur; TOC = Total organic carbon; TIC = Total inorganic carbon.

3.2. Valdai Highlands

Calibrated AMS ^{14}C measurements (Table 2) and lithological, geochemical and plant macrofossil analyses for the sediment sequence from Lake Terebenskoye in the Valdai Highlands (region B in Figs. 1B and 2A and B) (Subetto, 2003) suggest that sedimentation in the basin started around 14 cal ka BP (Fig. 3). Given the large temporal lag between the likely retreat of the ice margin (i.e., <18 cal ka BP) and the beginning of sedimentation in the basin, we assume that stagnant ice and permafrost remained in the area for several thousand years (cf. Velichko et al., 2002; Demidov et al., 2006).

Plant macrofossils in the lowermost part of the sequence (7.0–5.9 m; ~13.8–12.5 cal ka BP) consist of *Betula nana* and *Dryas octopetala*, and low total carbon (TC) values indicate a low productivity lake (Fig. 3). Mineral magnetic parameters, TC values and the carbon/nitrogen (C/N) ratio increase at 5.9 m (~12.5 cal ka BP), suggesting increased in-wash of minerogenic and organic material from the surrounding slopes and/or a minor increase in lake productivity. Plant macrofossils are scarce between 5.9 and 5.2 m, but three *Picea abies* needles and two *P. abies* seeds appear at 5.8 m (~12 cal ka BP). This is the earliest macrofossil record of *P. abies* in northwestern Russia (cf. Giesecke and Bennett, 2004). The combination of *P. abies* with *Betula nana* shrubs and cold steppe herbs (T. Sapelko, unpublished pollen data) suggests a mosaic of environments including tundra and taiga elements before 11.5 cal ka BP. The presence of *P. abies* suggests a continental climate with warm summers (~10 °C) and moist soil conditions (Giesecke and Bennett, 2004). The first *Pinus sylvestris* and *Populus tremula* remains occur at about 5.4 m (~11.4 cal ka BP) and *Betula pubescens* remains first appear at 5.2 m (~11.2 cal ka BP) (Fig. 3). These results show that *Pinus sylvestris*, *Populus tremula*, and *Betula pubescens* became constituents of the local vegetation shortly after 11.5 cal ka BP, presumably associated with early Holocene warming. However, since organic sedimentation begins gradually at about 5.2 m (~11.2 cal ka BP) i.e., coincident with the arrival of *Betula pubescens*, plant communities were likely open with unstable soils until about 11 cal ka BP. *Pinus sylvestris* suggests that minimum mean summer temperatures may have exceeded 12 °C after 11.4 cal ka BP (Iversen, 1954).

A palaeosol observed in the stratigraphic record at 5.18–5.16 m (~11 cal ka BP) (Fig. 3), could be interpreted in two ways. It may indicate a brief hiatus caused by a lowering of the water level and the subsequent overgrowing of the lake; however, true soil horizons are typically associated with relatively high C/N ratios, given their greater proportion of terrestrially-derived organic material (Meyers and Lallier-Vergès, 1999). Instead, this apparent soil, with a C/N ratio of 11.5 (Fig. 3), is likely linked to soil instability and increased erosion from the surrounding slopes, due to rapid melting of stagnant ice and/or permafrost in response to increased temperatures in the early Holocene. Mineral magnetic values decrease upwards in the sequence and TC and total nitrogen (TN) contents rise gradually between 5.2 and 3.6 m (~11.2–8.5 cal ka BP). High values thereafter indicate a high productivity lake (Fig. 3). Plant macrofossils are more frequent from 4.75 m (~10.5 cal ka BP) upwards. Increased lake organic production, decreased in-wash of minerogenic material and the establishment of closed forests suggest that soils in the catchment stabilised.

3.3. Eastern Russian Karelia

The sites analysed in eastern Russian Karelia (region C in Figs. 1B and 2A and B) consist of a section with laminated sediments at Pudozh that date to 12.9–11 cal ka BP (Wohlfarth et al., 1999) and two lake sediment sequences (Tambichozero and Pichozero) from higher elevations (Wohlfarth et al., 2002, 2004). The latter two were analysed for a variety of proxy data, whereas only macrofossils were analysed at Pudozh (Table 1). Chronological control is particularly strong at these sites since age assignment for all three sequences is based on a combination of varve counting and calibrated AMS ^{14}C measurements on terrestrial plant macrofossils. Sedimentation started at 14 cal yr BP in Lake Tambichozero and at 12.9 cal ka BP in Lake Pichozero, which shows that

Table 2
AMS ^{14}C measurements and calibrated ages from Lake Terebenskoye, Valdai Highlands, Russia

Depth (cm)	Material	Lab no.	Radiocarbon age (^{14}C yr BP $\pm 1\sigma$)	Calibrated age[a] (cal yr BP $\pm 2\sigma$)
373–378.5	*Pinus sylvestris* (N), bark (indet.)	Poz-588	7870±40	8683 (8550–8970)
415–425	*Betula* sp. (S, C, B), *Populus tremula* (B)	Ua-16771	8630±95	9656 (9460–10,110)
460–465	*Betula* sp. (L, C, S) *Populus tremula* (B)	Poz-591	9320±45	10,521 (10,300–10,670)
494–505	*Picea abies* (N), *Betula pubescens* (S), *Populus tremula* (B)	Poz-586	9660±60	11,008 (10,780–11,210)
545–548	Twigs (indet.)	Poz-584	9950±100	11,472 (11,200–11,820)
692–697	*Betula*/*Salix* (L, B), *Dryas octopetala* (T)	Ua-16772	11,910±180	13,769 (13,360–14,150)

N = needles; S = seeds; C = catkin scales; B = bract; L = leaf; T = twig.
[a]Weighted average of the probability distribution calculated with CALIB 5.0 (Reimer et al., 2004). Age range is the 95% confidence interval ($\pm 2\sigma$) rounded to the nearest 10 yr.

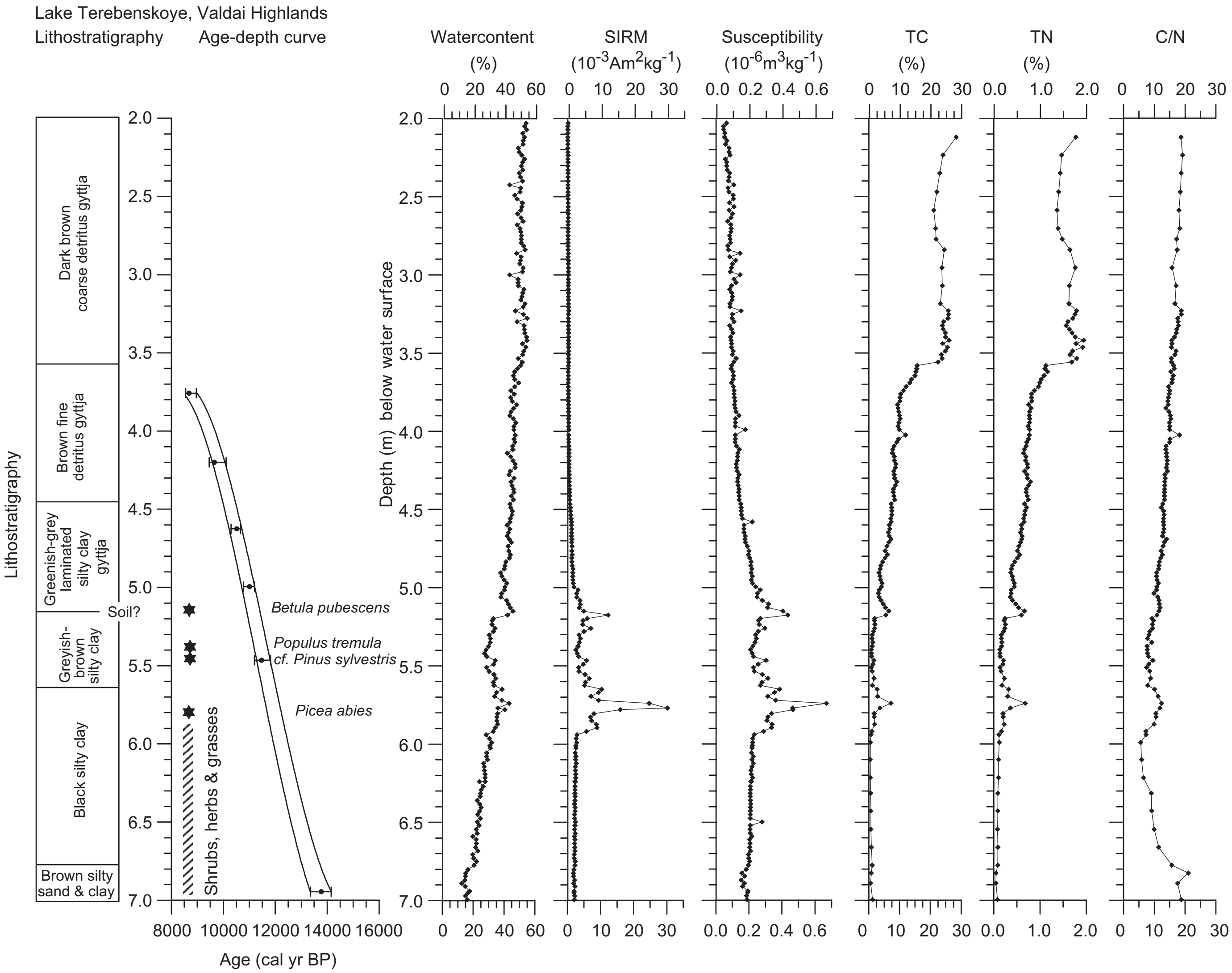

Fig. 3. Lithological and geochemical parameters and age-depth curve for Lake Terebenskoye, Valdai Highlands, Russia. Plant macrofossil evidence is summarised within the age-depth panel. Stars mark the stratigraphic positions of the first occurrences of plant macrofossil taxa. The age-depth curve is based on calibrated ages (Table 2) and third degree polynomial functions. SIRM = Saturation Isothermal Remnant Magnetisation; TC = total carbon; TN = total nitrogen; C/N = carbon/nitrogen ratio.

stagnant ice remained in the area for several thousand years after deglaciation (Demidov et al., 2006).

Lithological, geochemical, pollen, and plant macrofossil data indicate low productivity lakes with long-lasting ice cover, tundra communities with barren ground, unstable soils, and soil erosion in the catchment prior to 11.5 cal ka BP (Wohlfarth et al., 1999, 2002, 2004). Arctic and subarctic vegetation consisting of *Betula nana* shrubs and various herbs, grasses and mosses occupied the area. The presence of *Betula nana* shrubs suggests mean minimum summer temperatures of 3–4 °C (Hultén and Fries, 1986; Bos et al., 2001). The immigration of *Betula pubescens* and *Populus tremula* into the catchment around 11.5 cal ka BP coincided with an increase in lake productivity, but also with enhanced soil erosion and rapid degradation of stagnant ice and/or permafrost. Pollen and plant macrofossils suggest that open forests composed of *Betula pubescens* and *Populus tremula* and perhaps scattered *Picea abies* and *Pinus sylvestris* developed shortly after 11.5 cal ka BP (Wohlfarth et al., 2002, 2004), i.e., coinciding with the beginning of the Holocene. The presence of *Picea abies* close to Lake Pichozero at 10.7 cal ka BP is confirmed by *Picea* macrofossils, although *Picea* pollen concentrations rise continuously from 11.4 cal ka BP onwards (Wohlfarth et al., 2004). The establishment of forests, which also included *Corylus* from 9.6 cal ka BP onwards, would have contributed to the stabilisation of the surrounding soils. Expansions of herb and grass communities around 11.2–10.9 cal ka BP at Lake Pichozero and 10.2–9.9 cal ka BP at Lake Tambichozero could have been caused by drier/colder climatic conditions, but more probably reflect gradual infilling of the lakes and/or expansion of herbs and grasses around the lakes' margins. Lake organic productivity increased steadily in

Lake Tambichozero (Wohlfarth et al., 2002), but declined again around 11 cal ka BP in Lake Pichozero, where it remained low until 9.6 cal ka BP. This is surprising, since early Holocene increases in temperature should have led to an increase in lake-water temperature and lake organic productivity. Local conditions such as influx of cold meltwater from degrading stagnant ice and/or permafrost may have kept the lake water cold and turbid and rapid sedimentation could have led to anoxic conditions, resulting in low lake productivity (Wohlfarth et al., 2004). A second major increase in lake productivity at ~10 cal ka BP in Tambichozero and at 9.6 cal ka BP in Pichozero may have been favoured by stable soil conditions in the catchment. Pollen-based temperature and precipitation reconstructions (Wohlfarth et al., 2004) suggest variable conditions in the area but support cold dry conditions prior to 11.5 cal ka BP with increasing temperatures and precipitation in the early Holocene. Minimum mean July temperature estimates based on plant macrofossils point to a gradual rise from >10 °C between 11.5 and 10 cal ka BP to >12–13 °C at 9.7 cal ka BP.

3.4. Karelian Isthmus

The two lake sediment sequences studied on the Karelian Isthmus (lakes Pastorskoye and Medvedevskoye) (region D in Figs. 1B and 2A and B) were analysed for pollen, diatoms, tephra, mineral magnetic parameters and total organic carbon (TOC) (Wastegård et al., 2000; Subetto et al., 2002) (Table 1). Age assignment at both sites is based on the Vedde Ash and AMS ^{14}C measurements on terrestrial plant macrofossils, aquatic mosses, and bulk sediment. Sedimentation in these lakes started between 13.5 and 13 cal ka BP, only a few hundred years after deglaciation of the area. Both lakes were initially shallow with low productivity. Although the lakes are located within 40 km of each other, their early development diverges to some extent. Lake organic productivity increased in a stepwise fashion in Lake Pastorskoye with an initial rise starting around 11.6 cal ka BP, followed by a second rise at 11.1 cal ka BP. The lake developed into a deeper, high productivity lake after 10.7 cal ka BP. In Lake Medvedevskoye, on the other hand, lake organic productivity seems to have increased gradually after 12.4 cal ka BP, developing into a deep, productive lake between 11 and 10.2 cal ka BP. Since the chronology for Lake Medvedevskoye is uncertain between 11 and 10.2 cal ka BP and may be complicated by a hiatus caused by melting of stagnant ice and unstable soils around the lake (Subetto et al., 2002), the apparent age differences in lake development may be an artefact of poor chronological control and/or differential sedimentation.

The pollen stratigraphies suggest that open vegetation with abundant *Artemisia* and sedges and areas with barren soils characterised the local landscape until about 11 cal ka BP. The establishment of open forest with *Betula pubescens*, *Pinus sylvestris*, and *Picea abies* around 11 cal ka BP, which also contained *Alnus* and *Corylus* after 10.7 cal ka BP, led to soil stabilisation in the catchment (Subetto et al., 2002). Inferred climatic conditions before 11 cal ka BP were cold and dry, and warmer and more humid thereafter.

4. Climatic and environmental development 15,000–8000 cal yr BP

The sites which we have studied in northwestern Russia have comparably good chronologies, based on AMS ^{14}C measurements, tephra horizons and annual laminations (Tables 1 and 2). However, sedimentary hiatuses of varying length in several of the sequences (lakes Nero, Zaozer'e, Chashnitsy, and Tambichozero) complicated the establishment of precise, site-specific chronologies. The sites also partly diverge in the type of analyses performed on the different sediment cores (Table 1). Some sites were only investigated for diatoms and pollen (lakes Medvedevskoye and Pastorskoye) or for plant macrofossils (lakes Zaozer'e and Chashnitsy, and at Pudozh), while pollen and plant macrofossil analyses were combined at other sites (lakes Nero, Terebenskoye, Tambichozero, and Pichozero). Since each pollen percentage diagram was complemented by pollen concentration values for different taxa, their presence in the local vegetation can be more precisely evaluated. Pollen accumulation rates were not calculated due to variable sedimentation rates.

4.1. Climate and environment 15,000–11,500 cal yr BP (≅ Greenland Stadial [GS] 2–GS 1)

The Last Glacial Maximum (LGM) ice margin in western Russia attained its maximum position in the southern part of the area at 20–18 ka BP (Lunkka et al., 2001) and at around 18–16 ka BP in the northern part (Demidov et al., 2006) (Fig. 2A). Continuous permafrost reached 53°N during and after the LGM and scattered permafrost may have extended as far south as 46°N (Morozova and Nechaev, 2002; Velichko et al., 2002). Periglacial tundra and steppe communities were the dominant vegetation south and east of the ice sheet (Frenzel et al., 1992; Tarasov et al., 2000), but it has been speculated that boreal trees may have existed in habitats with favourable climatic conditions. Refugia for broad-leaved, temperate tree species may have been located to the southeast of our study area within the Volga River valley, the Southern Urals and the southern part of the Middle Russian Upland (Grichuk, 1984; Velichko, 1984; Velichko et al., 2002); however, this was not corroborated by the biome reconstruction of Tarasov et al. (2000), perhaps because of the scarcity of available LGM data. The retreat of the SIS from its maximum position in Russia was rather slow, given that lakes Onega and Ladoga, which are situated at a relatively short distance from the LGM margin, only became ice-free several thousand years after deglaciation (Demidov et al., 2006) (Fig. 2B).

Sedimentation in the Lake Nero basin recommenced around 15 cal ka BP (Fig. 4A), after a phase with no or little deposition, which compares well with the age of the bottom sediments in lakes Tatishchevo (Aleshinskaya, 1998) and Dolgoe (Borisova et al., 1998), located some 130 km to the southwest. The renewed infilling of the basin and the subsequent development of a shallow, productive lake indicates higher run-off, likely as a result of higher air temperatures, higher precipitation, and/or melting permafrost. The change in climatic conditions from dry and cold before ~15 cal ka BP to warmer and more humid after ~15 cal ka BP coincides with the first marked temperature increase seen in many North Atlantic records 15–14.5 cal ka BP (GI-1e) (e.g., Björck et al., 1996, 1998; Walker et al., 1999; Lowe, 2001; Renssen and Isarin, 2001; Walker, 2001; Renssen and Bogaart, 2003), which shows that the atmospheric signal was rapidly transmitted to areas distant from the North Atlantic. While Lateglacial vegetation was dominated by *Betula* and *Salix* shrubs and various herbs, it appears that *Betula pubescens* trees became established as early as 14–13 cal ka BP in the Rostov-Jaroslavl' region (Fig. 4B). Minimum mean summer temperatures based on plant macrofossils were above 4 °C and may have been as high as 10 °C on a local scale, if indeed *Betula pubescens* was present (Fig. 4C).

In the Rostov-Jaroslavl' region, the sedimentary hiatus in Lake Nero and the delayed start of sedimentation in lakes Zaozer'e and Chashnitsy prevent a palaeoenvironmental reconstruction for the area between 13 and 12 cal ka BP. Since water levels in Lake Nero dropped dramatically around this time and smaller lakes did not start to form until ca 12 cal ka BP but were also characterised by distinct water-level changes later (Fig. 4A), marked hydrological changes must have occurred in the region and permafrost degradation may have been rather slow. The relatively dry climatic conditions reconstructed for regions B–D between 13 and 11.5 cal ka BP could have had an influence on the water balance in the Rostov-Jaroslavl' area (region A) and could have delayed melting of permafrost. On the other hand, it is also possible that the drainage of large ice-dammed lakes (Lunkka et al., 2001; Saarnisto and Saarinen, 2001; Demidov et al., 2006) during deglaciation may have altered the hydrological balance in the region.

In areas formerly covered by ice, lake sedimentation started between 14 and 13 cal ka BP (Figs. 2B and 4A). The time lag between deglaciation (Lunkka et al., 2001; Saarnisto and Saarinen, 2001; Demidov et al., 2006) and the start of sedimentation in the investigated basins supports the idea that stagnant ice remained for several hundred to thousands of years. Gradual melting was possibly triggered by warmer Atlantic air masses reaching this part of western Russia and by higher air temperatures during Greenland Interstadial 1 (GI-1; Bølling-Allerød). However, warmer temperatures did not increase lake organic productivity or trigger large-scale vegetation change immediately. Indeed, environmental conditions in regions B–D were characterised by long-lasting lake-ice cover, erosion from unstable soils, and tundra vegetation dominated by *Betula* shrubs and various herbs until after 11.5 cal ka BP (Figs. 4A and B). Reconstructed minimum mean summer temperatures of 3–4 °C, as indicated by plant macrofossils (Fig. 4C), are considerably lower than pollen-based summer temperature estimates of 10–15 °C for the Rostov-Jaroslavl' region (Wohlfarth et al., 2004; P. Tarasov, unpublished data), which suggest that summers would have been warm enough to support trees. It is possible that scattered *Betula pubescens* and *Picea abies* were present in the Rostov-Jaroslavl' region and in the Valdai Highlands, respectively, before 11.5 cal ka BP (Fig. 4B). If summer temperatures were in fact ⩾10 °C, low winter temperatures, precipitation and run-off, unstable soil conditions, and the presence of permafrost and remnant ice, which could have kept summer temperatures relatively cold on a local scale due to wet soil conditions (Renssen et al., 2000) and strong winds, could have limited tree establishment. Moreover, the cold Baltic Ice Lake, which then extended into the Lake Ladoga basin (Björck, 1995; Saarnisto and Saarinen, 2001; Subetto, 2003) and the proximity of the Scandinavian Ice Sheet (Fig. 2B) would have influenced atmospheric circulation regionally before 11.5 cal ka BP.

4.2. *Climate and environment 11,500–10,000 cal yr BP (Early Holocene)*

Distinct changes in lake organic productivity, catchment soils and vegetation occurred at most sites at the beginning of the Holocene (Fig. 4A). The increase in lake organic productivity and the immigration and establishment of trees in eastern Russian Karelia and in the Valdai Highlands show that limnic and terrestrial environments responded rapidly to the temperature increase seen in numerous archives around the Northern Hemisphere at this time (Björck et al., 1996). Pollen-based climate reconstructions for Russian Karelia indicate that winter temperatures rose from −25 °C to −20 °C and summer temperatures from 12 °C to 16 °C at ~11.5 cal ka BP (Wohlfarth et al., 2004). This is in good agreement with the rise in minimum mean July temperatures from 3–4 °C to >10 °C inferred from plant macrofossils (Fig. 4C). A sedimentary hiatus of about 300 cal yr in the Lake Tambichozero sequence suggests a higher degree of catchment erosion, possibly caused by melting of stagnant ice and/or permafrost as a result of higher air temperatures.

Betula pubescens and *Populus tremula* were the pioneer trees in eastern Russian Karelia, appearing close to the studied lakes 11.5 cal ka BP, while *Picea abies* and *Pinus sylvestris* became established after 11 cal ka BP (Fig. 4B). Tree immigration may have been delayed on the Karelian Isthmus, since shrub and herb communities remained dominant until *Betula*, *Pinus* and *Picea* trees appeared at ca 11 cal ka BP, followed by *Alnus* and *Corylus* at ca 10.7 cal ka BP.

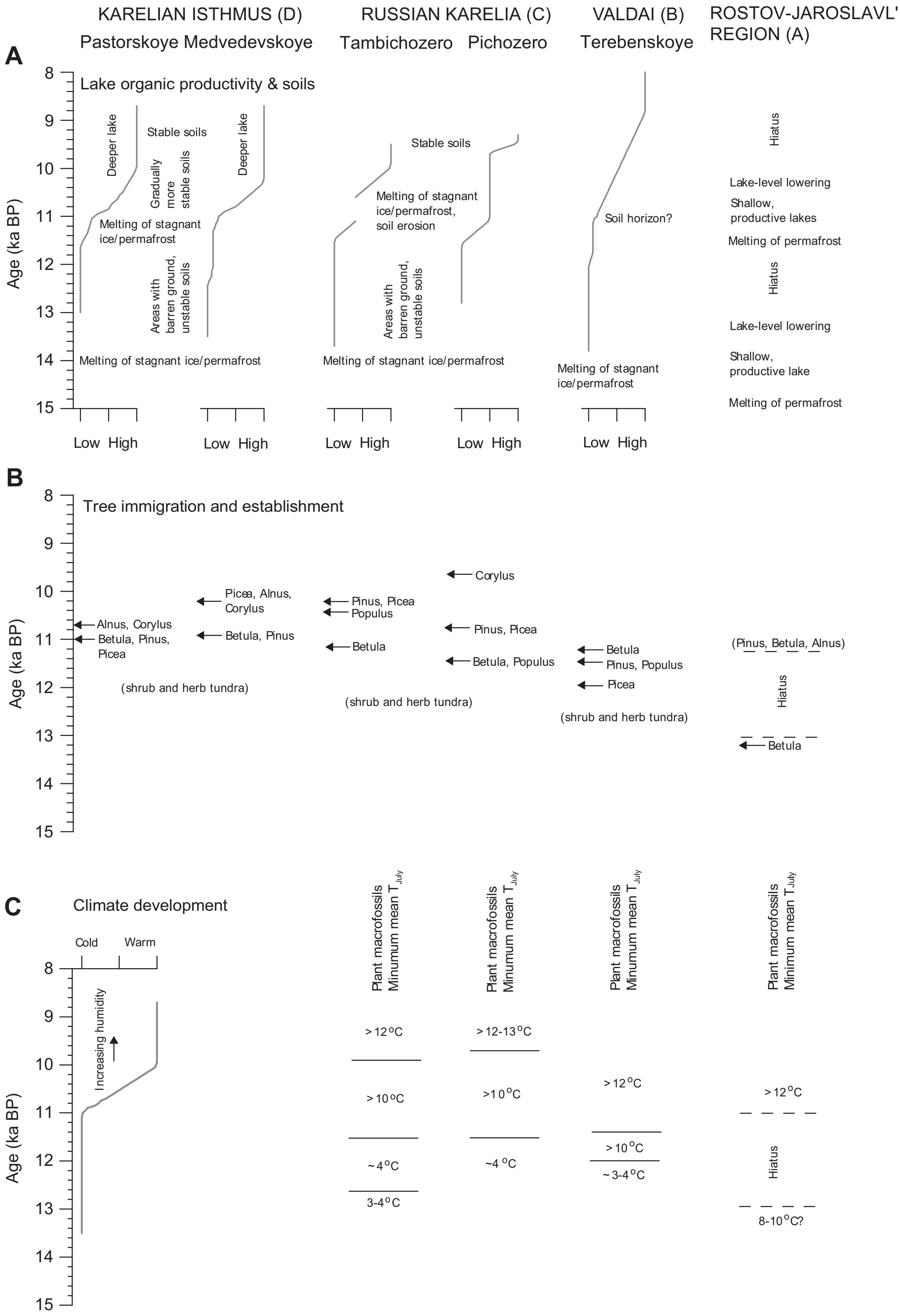

Fig. 4. Summary of the environmental and climatic development along a NW–SE transect in northwest Russia, based on Wohlfarth et al. (1999, 2002, 2004, 2006), Subetto et al. (2002) and Subetto (2003). (B) Minimum tree arrival times are estimated primarily from plant macrofossils. Estimates based on increases in pollen percentages and concentrations (presented in italics) were used where macrofossil data were not available. (C) Inferred temperature estimates are based on plant macrofossils of indicator species.

The slight rise in lake organic productivity in the Valdai Highlands and on the Karelian Isthmus around 11.5 cal ka BP was followed by a more distinct increase around 11 cal ka BP (Fig. 4A), which also coincides approximately with the establishment of *Pinus*, *Populus*, and *Betula* trees in the Valdai Highlands and of *Betula*, *Pinus* and *Picea* trees on the Karelian Isthmus. Similar vegetation and climate changes have been reconstructed for southern Finland (Bondestam et al., 1994), where tundra vegetation dominated by *Betula* shrubs was succeeded by open boreal forest composed of *Betula*, *Populus*, and *Pinus* trees as late as 10.6 cal ka BP. The delayed response of limnic and terrestrial environments in these regions could be explained by the presence of permafrost and stagnant ice, cold surface waters of the Baltic Sea and by strengthened easterlies along the eastern and south-eastern margins of the ice sheet. Final drainage of the Baltic Ice Lake at ~11.5 cal ka BP (Björck et al., 1996; Andrén et al., 2002), the rapid disintegration of the ice sheet and the disappearance of stagnant ice and/or permafrost in addition to warmer air masses reaching the region from the North Atlantic would have gradually resulted in warmer climatic conditions in the early Holocene. These in turn would have led to more stable soils and less run-off, which facilitated tree establishment and raised lake organic production.

The palaeoenvironmental development on the Karelian Isthmus and in the Valdai Highlands contrasts with that in Russian Karelia, where a remarkably stable and low productivity lake phase at Lake Pichozero follows the initial rise in organic productivity at 11.5 cal ka BP (Fig. 4A). Here, local conditions, possibly influenced by the inflow of cold water from melting of dead ice and permafrost, must have played an important role in modulating the response of the limnic environment (Wohlfarth et al., 2004). Herb pollen increase shortly before 11 cal ka BP (Wohlfarth et al., 2004), which coincides in time approximately with the Preboreal Oscillation (Björck et al., 1996, 1997). Increases in herbaceous pollen could have been caused by a change in climatic conditions and/or by an expansion of wetlands around the lakes, due to lake level lowering and/or a gradual infilling of the basin. A second phase of herb community expansion and/or a reduction in plant cover is observed around 10 cal ka BP in records from both the Karelian Isthmus and eastern Russian Karelia. The coincidence of these phases may indicate a response of the vegetation to climatic oscillations observed around 10 cal ka BP (e.g., Björck et al., 2001; Nesje et al., 2001).

4.3. Climate and environment after 10,000 cal yr BP (early Holocene)

Palaeoclimatic reconstructions and simulations suggest that with the final disintegration of the SIS and reduction in the associated cold easterlies, humidity and summer temperatures increased in the early Holocene as a result of deeper penetration of warm North Atlantic air masses into western Russia (e.g., Kutzbach et al., 1993; Harrison et al., 1996). Also, incoming solar radiation was higher in summer and lower in winter than at present, resulting in amplified seasonality (Kutzbach and Webb, 1993; Peterson, 1993; COHMAP members, 1988). Minimum mean summer temperature estimates based on plant macrofossils were $>12\,^{\circ}$C throughout northwestern Russia (Fig. 4C).

High lake organic productivity, low run-off and stable catchment soils are marked features for this time interval. Most remnant ice and permafrost had melted. By about 10 cal ka BP, lakes on the Karelian Isthmus and in eastern Russian Karelia were productive and stable, while productivity continued to increase at Lake Terebenskoye in the Valdai Highlands, stabilising after 9 cal ka BP (Figs. 3 and 4A). The degradation of permafrost and stagnant ice due to warmer air temperatures likely led to subsurface drainage of lakes Chashnitsy and Zaozer'e in the Rostov-Jaroslavl' region as is the case with thaw lakes (e.g., Burn, 1997; Smith et al., 2005). Forests in northwestern Russia likely became denser, which led to a stabilisation of soils and favoured the immigration and establishment of new tree species. After 10 cal ka BP, forests throughout northwestern Russia were dominated by *Betula pubescens* and *Pinus sylvestris* with variable amounts of *Picea abies*, *Populus tremula*, and *Corylus*. Other plant taxa such as *Alnus*, *Ulmus*, *Juniperus communis*, and *Andromeda polifolia* as well as sedges and grasses were also locally important.

4.4. Tree migration

Determining precise tree arrival times and migration routes for northwestern Russia proved somewhat difficult using the available data since some sediment sequences did not contain macrofossils of the major tree species. Moreover, although macrofossils confirm the local presence of a species, their first occurrence in a sediment sequence does not necessarily record initial immigration and establishment. Our best estimations of Lateglacial immigration of the principal tree species into northwestern Russia are summarised in Fig. 4B. While Lateglacial vegetation was dominated by *Betula nana* and *Salix* shrubs and various herbs, pollen and plant macrofossils suggest that *Betula* trees became established as early as 14–13 cal ka BP in the Rostov-Jaroslavl' region (Wohlfarth et al., 2006). Plant macrofossils and pollen assemblages suggest that trees migrated from the southeast (region A–Rostov-Jaroslavl') to the west (region B–Valdai Highlands) and then spread later to the northeast (region C–Eastern Russian Karelia) and northwest (region D–Karelian Isthmus) (Fig. 4B). This pattern parallels the principal direction of deglaciation in northwestern Russia (Fig. 2B), and is in agreement with reconstructions for *Picea abies* by Giesecke and Bennett (2004) and Latałowa and van der Knaap (2006). In general, it appears that the first trees to immigrate were *Betula pubescens*, followed by *Pinus sylvestris* and *Picea abies*.

One notable exception to this pattern is the record from Lake Terebenskoye in the Valdai Highlands, where the order of arrival based on macrofossils of these species is reversed (Figs. 3 and 4B). *Picea abies* was the first recorded tree species at ~12 cal ka BP, and was followed by *Pinus sylvestris* and *Populus tremula* at ~11.4 cal ka BP and *Betula pubescens* at ~11.2 cal ka BP. Fossil pollen assemblages from the same sediment core (T. Sapelko, unpublished data) are consistent with this order of arrival. *Picea abies* is able to colonise recently deglaciated terrain and it is likely that small stands or scattered individuals were present in cold shrub tundra or taiga-like communities ca 12 cal ka BP. There is also macrofossil evidence for *Picea abies* in the Usa River basin in northeastern European Russia at ~12 cal ka BP (Väliranta et al., 2006) and abundant *Picea abies* pollen in the central Russian Plain and the Baltic States during GI-1 and GS-1 (Alleröd and Younger Dryas) (Khotinsky and Klimanov, 1997; Latałowa and van der Knaap, 2006).

5. Conclusions

Multi-proxy palaeoenvironmental studies of nine sediment sequences from four areas in northwestern Russia (Wohlfarth et al., 1999, 2002, 2004, 2006; Wastegård et al., 2000; Subetto et al., 2002; Subetto, 2003) reveal significant changes in regional and local climate, lake productivity, and vegetation. Our studies demonstrate that the nature, timing, and extent of the palaeoenvironmental response in north-western Russia show some correlation with climatic variation reconstructed from sites throughout the North Atlantic region. At Lake Nero in the Rostov-Jaroslavl' area, which is outside the maximum limit of the SIS, sedimentation recommenced shortly after 15 cal ka BP in response to increases in temperature and humidity during Greenland Interstadial 1 (GI-1; Bølling-Allerød) (Wohlfarth et al., 2006). However, in general, the studied sediment sequences indicate that much of north-western Russia was characterised by low lake productivity, unstable soils, and shrub and herb tundra until the end of Greenland Stadial 1 (GS-1; Younger Dryas). A cold and relatively dry Lateglacial climate was eventually replaced by warmer and more humid conditions; with retreat and disintegration of the SIS and the increasing influence of warm air masses from the North Atlantic, summer temperatures and lake organic productivity increased and *Betula pubescens*, *Pinus sylvestris*, and *Picea abies* formed mixed forest communities. Distinct changes in lake organic productivity, catchment soils and vegetation occurred across northwestern Russia at the GS-1/Holocene transition. For example, the immigration of *Betula* and *Populus* trees and increases in lake productivity in eastern Russian Karelia around 11.5 cal ka BP (Wohlfarth et al., 2002, 2004) coincide with rapid warming at the start of the Holocene and similar changes elsewhere in the North Atlantic region. Indeed, plant macrofossil-based estimates of mean summer temperatures indicate warming at most sites in northwestern Russia at the end of GS-1.

However, these studies also underscore the importance of local conditions in shaping postglacial landscapes and their development in this region. Warmer temperatures during GI-1 were slow to increase lake organic productivity or trigger large-scale vegetation changes in most areas, leaving environmental conditions characterised by long-lasting lake-ice cover, erosion from unstable soils, and tundra vegetation dominated by *Betula* shrubs and various herbs until after the end of GS-1. On the Karelian Isthmus, increases in lake productivity at the beginning of the Holocene were followed by more pronounced increases around 11 cal ka BP coincident with the establishment of *Betula*, *Pinus* and *Picea* trees (Subetto et al., 2002). The delayed response of these limnic and terrestrial environments to warming could be explained by the cold surface waters of the Baltic Sea, the proximity of the SIS, strengthened easterlies along the eastern and southeastern margins of the ice sheet, and/or extensive permafrost.

In the Rostov-Jaroslavl'region, palaeoenvironmental reconstructions (Wohlfarth et al., 2006) are limited due to asynchronous sedimentary hiatuses in the lakes and the nature of local conditions. In the case of lakes Chashnitsy and Zaozer'e, it appears that permafrost degradation related to warmer air temperatures may have led to subsurface drainage of the lakes. Stagnant ice and permafrost were widespread in north-western Russia during the Lateglacial and early Holocene, particularly in areas formerly covered by the SIS (Demidov et al., 2006; Morozova and Nechaev, 2002; Velichko et al., 2002). The large temporal lag between the likely retreat of the ice margin (i.e., <18 cal ka BP) (Demidov et al., 2006; Lunkka et al., 2001; Saarnisto and Saarinen, 2001) and the beginning of lake sedimentation suggests that stagnant ice and/or permafrost remained in some areas for as much as a few thousand years following deglaciation. Influx of cold meltwater from disintegrating stagnant ice or permafrost and rapid sedimentation may have kept lake organic productivity low in Lake Pichozero in eastern Russian Karelia until well into the early Holocene (Wohlfarth et al., 2004), delaying the response of the limnic environment to increases in summer temperatures. Similarly, tree immigration was delayed on the Karelian Isthmus, with shrub and herb communities dominating until *Betula*, *Pinus* and *Picea* trees appeared ca 11 cal ka BP (Subetto et al., 2002).

The progression of climate change is consistent within the four regions of northwestern Russia, but not between all regions, as would be expected if the environmental response at these sites were closely linked to large-scale features affecting the entire Northern Hemisphere. Plant macrofossils of indicator species suggest that summer temperatures increased earlier and more rapidly in the Valdai Highlands. Lateglacial vegetation change in northwestern Russia was time-transgressive, and therefore may not be the most reliable proxy for climate change. Independent measures of Lateglacial and early Holocene climate (e.g., chironomid-based palaeotemperature estimates) are needed for accurate palaeoclimatic reconstructions for northwestern Russia.

Acknowledgements

The Swedish Institute through the Visby Programme, the Swedish Royal Academy of Sciences and the Swedish Research Council funded fieldwork in Russia, scholarships to Russian scientists, and analytical work.

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