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Effect of varying oceanicity on early- to mid-Holocene palaeohydrology, Kola Peninsula, Russia: isotopic evidence from treeline lakes

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Abstract: The stable-isotope stratigraphy of sedimentary organic matter and algal cellulose in cores from two lakes near treeline on the Kola Peninsula indicate changes in water and nutrient balance that correlate with inferred expansion of *Pinus sylvestris* during the early to mid-Holocene. Trends in cellulose-inferred lakewater $\delta^{18}O$ values for both lakes suggest that moist conditions after deglaciation were followed by progressive drying from about 9500 to between 8000 and 7500 ^{14}C yr BP. Although pine appeared in the area by 8000 ^{14}C yr BP, the maximum density of trees locally, as suggested by stomate evidence, occurred during subsequent moistening between 7500 and 6000 ^{14}C yr BP. This is *c.* 1000 years later than in other regions of northern Russia and is possibly attributable to limitations on seedling establishment and survival due to root desiccation during dry winters. Changes in nutrient balance and productivity in the lakes, as inferred from variations in sediment carbon and nitrogen elemental abundances and their respective stable-isotope signatures, are also consistent with expected changes in hydrological and edaphic conditions. Development of moister conditions at about 7000 ^{14}C yr BP on the Kola Peninsula is in harmony with evidence for increased oceanicity at this time in central Siberia, which is thought to reflect enhanced propagation of warm, moist air masses across northern Eurasia due to increased sea-surface temperatures and reduced sea-ice cover in the Nordic Seas.

Key words: Isotope palaeohydrology, sedimentary organic matter, lacustrine sediments, carbon and nitrogen cycling, palaeoclimate, algal cellulose, treeline, Russia, Holocene.

Introduction

Integrated records of terrestrial, limnological and hydrological variations along boreal treeline in response to past climatic change are needed to improve predictions of the potential impacts of future climatic change on this sensitive circumpolar ecotone. The Kola Peninsula, Russia, is an especially important region to study because its climate is strongly controlled by North Atlantic thermohaline circulation, which plays a key role in redistributing global energy. A multiproxy approach to the analysis of lake sediments provides an effective method for reconstructing past climatic change and its impact on aquatic and terrestrial environments. Stable-isotope tracers of lakewater and dissolved nutrients within organic components of lake sediments in particular have proven to be sensitive recorders of past changes in water and nutrient balance in response to past hydrological and climatic change at the boreal treeline (MacDonald *et al.*, 1993; Edwards *et al.*, 1996; Wolfe *et al.*, 1996; 1999; 2000).

Recent studies have indicated that *Pinus sylvestris*, the dominant species at the boreal conifer treeline on the Kola Peninsula, advanced to 20 km north of the mapped modern limits between 6680 and 3830 ^{14}C yr BP (MacDonald *et al.*, 2000a; 2000b). This vegetation change has generally been attributed to warmer con-

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ditions caused by several factors, including increased summer insolation, deglaciation and increased sea-surface temperatures and reduced sea-ice cover in the Nordic Seas. Delayed forest expansion on the Kola Peninsula compared to other sectors of northern Russia, however, has led to speculation about the role of changing moisture regimes during the early to mid-Holocene (MacDonald *et al.*, 2000a; 2000b; Snyder *et al.*, 2000). In northern Fennoscandia, early-Holocene summer climate was notably moist, and the late increase of *Pinus sylvestris* may be a result of its adaptation to drier conditions (Seppä and Hammarlund, 2000). On the other hand, reduced winter insolation during the early Holocene and susceptibility of *Pinus sylvestris* to desiccation and root damage during relatively dry winters has been invoked to explain delayed northward expansion of boreal pine on the Kola Peninsula (MacDonald *et al.*, 2000a).

As part of continuing efforts to reconstruct circumpolar treeline palaeohydrology and palaeoclimate, we examined carbon, nitrogen and oxygen stable-isotope records from bulk organic matter and algal cellulose from two lakes on the northern part of the Kola Peninsula (Figure 1). Results indicate that shifts in water and nutrient balance are associated with the pine expansion during the early to mid-Holocene, ultimately reflecting changes in hydroclimatology. Notably, these data contribute to mounting support for the hypothesis that increased oceanicity during the early to mid-Holocene related to greater penetration of North Atlantic waters into the Nordic Seas played an especially significant role in the postglacial climate history of northern Eurasia.

Study area

The present climate of the Kola Peninsula is strongly influenced by the Murman Coast current, a branch of North Atlantic surface water, resulting in anomalously warm conditions for this high latitude. Ice-free coastal waters in particular have a moderating effect on the winter climate of coastal regions, although a steep landward climatic gradient is characterized by strongly increasing rates of evaporation and enhanced continentality. Mean July and January temperatures for Murmansk are 12.8 and –9.9°C respectively, and mean annual precipitation is 376 mm (Lydolph, 1977).

Isotopic records were obtained on sediment cores from Lake Yarnyshnoe-3 and Poteryanny Zub Lake on the Kola Peninsula (Figure 1). Lake Yarnyshnoe-3 (69°04′N, 36°04′E; 54 m a.s.l.) is located in the tundra of the central Murman coast. This region is characterized by abundant lakes situated in glacier-scoured basins in Precambrian metamorphic and intrusive igneous rocks of the Baltic Shield (Murmansk Atlas, 1971). The lake is surrounded by steep hills rising to approximately 250 m a.s.l. The lake basin has emerged from the sea since deglaciation as a result of glacio-isostatic rebound. During its marine phase, the basin was connected to the sea by a shallow (<10 m), narrow (<200 m) arm of Yarnyshnoe Bay. The modern vegetation surrounding the lake is tundra dominated by ericoids with sedges, diverse tundra herbs and mosses in poorly drained sites. Scattered stands of *Betula pubescens* occur in low-elevation and protected areas. Lake Yarnyshnoe-3 is 33.9 ha in area and contains two subbasins each about 20 m deep. The lake has one inflow stream that drains a

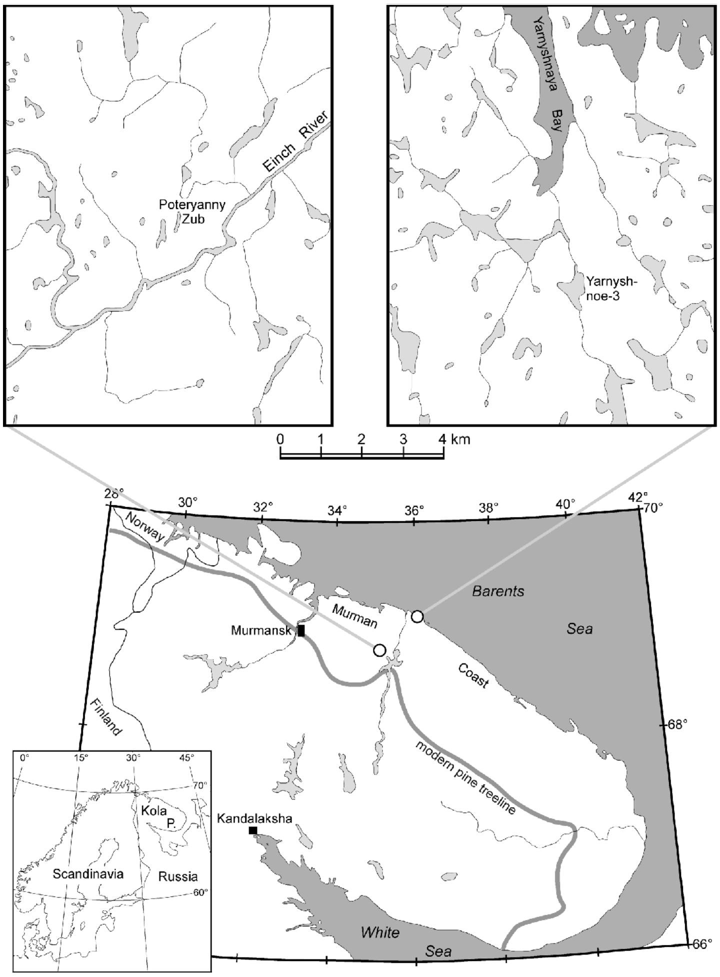

Figure 1 Location of lake-study sites on the Kola Peninsula.

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system of lakes to the south spanning a catchment area of approximately 83 km^2. A bedrock threshold controls the lake outflow to the north.

Poteryanny Zub Lake (68°49′N, 35°19′E; 131 m a.s.l.) lies approximately 50 km south of the Murman coast and 25 km north of the *Pinus sylvestris* limit. The surrounding vegetation is birch forest-tundra dominated by *Betula* spp., including *Betula pubescens* ssp. *tortuosa*, *Betula nana* and *Betula pendula*, interspersed with patches of *Juniperus communis* and ericoids. *Salix* spp. grow at the moistest sites on the lake shore. Ground lichens, primarily *Cladonia*, are ubiquitous. Poteryanny Zub Lake is 3.2 ha in area and has a maximum depth of 5.5 m. The lake drains a small catchment area of 0.2 km^2, and outflow occurs via seepage through organic terrain.

Methods

Cores were taken from Poteryanny Zub Lake using a modified Livingstone corer (Wright *et al.*, 1984) and from Lake Yarnyshnoe-3 with a percussion-driven piston-core system (Nesje, 1992). Subsequent laboratory sample preparation and analysis for bulk organic carbon and nitrogen elemental and stable-isotope composition and cellulose oxygen-isotope composition followed methods detailed in Wolfe *et al.* (2001b). Briefly, samples were treated with 1 M HCl to remove carbonate material, rinsed repeatedly with distilled water, freeze-dried, and then passed through a 500 µm sieve to remove coarse debris. Carbon and nitrogen content and stable-isotope composition were determined on the fine-grained acid-washed residue by an elemental analyser interfaced to a continuous-flow isotope-ratio mass spectrometer. Additional sample treatment to concentrate cellulose involved solvent extraction, bleaching and alkaline hydrolysis to remove non-cellulose organic constituents plus hydroxylamine leaching to remove iron and manganese oxyhydroxides. Cellulose oxygen-isotope composition for Lake Yarnyshnoe-3 was determined with off-line nickel-tube pyrolysis to generate CO_2 for dual-inlet isotope-ratio mass spectrometry (Edwards *et al.*, 1994; Wolfe *et al.*, 2001b), whereas for Poteryanny Zub Lake cellulose oxygen-isotope composition was determined by high temperature (1250 °C) pyrolysis using a Micromass Isoprime continuous-flow isotope-ratio mass spectrometer. All elemental and isotopic analyses were conducted at the University of Waterloo - Environmental Isotope Laboratory (UW-EIL), Canada. Isotope results are expressed as 'δ' values, representing deviations in per mil (‰) from the VPDB, AIR and VSMOW standards for carbon, nitrogen and oxygen, respectively, such that $\delta_{sample} = [(R_{sample}/R_{standard}) - 1] * 10^3$ where R is the $^{13}C/^{12}C$, $^{15}N/^{14}N$ or $^{18}O/^{16}O$ ratio in the sample and standard. Oxygen-isotope results are normalized to $\delta^{18}O_{SLAP} = -55.5$ ‰ (Coplen, 1996). Based on repeated analyses of samples, analytical uncertainty for bulk organic carbon and nitrogen-isotope analyses is ±0.1‰; cellulose $\delta^{18}O$ values have an uncertainty of ±0.4‰ for Lake Yarnyshnoe-3 and ±0.6 ‰ for Poteryanny Zub Lake.

Radiocarbon ages were measured by accelerator mass spectrometry on organic matter extracted from the core sediments, as reported in Gervais *et al.* (2002) and Snyder *et al.* (2000) and shown in Table 1.

Table 1 Radiocarbon data for Poteryanny Zub Lake (Gervais *et al.*, 2002) and Lake Yarnyshnoe-3 (Snyder *et al.*, 2000). Samples denoted with an asterisk were not used to develop the chronologies. For Poteryanny Zub Lake, sample OS-21516 was considered reworked and all but one sample for geochemical and stable-isotope analyses were obtained at depths above 220 cm. Similarly, for Lake Yarnyshnoe-3, samples for geochemical and stable-isotope analyses were obtained at depths above 275.5 cm. Note also misprint in Table 1 of Snyder *et al.* (2000); sample data for NSRL-10275 and AA-15620 are correctly displayed below

Lab. number	Material	Core depth (cm)	Reported age (^{14}C yr BP)
Poteryanny Zub Lake			
OS-18861	twig	28	1800 ± 60
OS-21522	decalcified sediment	60	4630 ± 50
OS-18862	wood fragment	82	5180 ± 50
OS-18863	aquatic moss	112	5720 ± 50
OS-21516*	twig	180	8860 ± 65
OS-18864	leaf fragment	190	8890 ± 55
OS-21517*	bark fragment	220	9500 ± 65
OS-18865*	aquatic moss	230	9410 ± 70
Lake Yarnyshnoe-3			
GX-20142-AMS	aquatic moss	1.5	1110 ± 60
NSRL-10272	aquatic moss	35.5	2310 ± 55
NSRL-10273	woody twig	76.5	3610 ± 95
AA-15621*	woody twig	107.0	4770 ± 60
AA-15622	aquatic moss	108.0	4860 ± 60
NSRL-10274	aquatic moss	137.5	5870 ± 65
NSRL-10590	aquatic moss	167.5	7620 ± 55
NSRL-10275	woody twig	202.5	8450 ± 190
AA-15620	woody twig	225.5	9260 ± 80
AA-20501	aquatic moss	275.5	10440 ± 100
GX-20139-AMS*	marine algae	303.5	10950 ± 120
GX-20140-AMS*	marine algae	366.5	11350 ± 100

AA: NSF Facility for Radioisotope Analysis at the University of Arizona.
GX: Geochron Laboratories.
NSRL: NOSAMS facility at Woods Hole Oceanographic Institute/ INSTAAR AMS Radiocarbon Preparation and Research at the University of Colorado.

Results and discussion

Treeline history during the Holocene

Detailed vegetation reconstructions for Poteryanny Zub Lake and Lake Yarnyshnoe-3 have been reported by Gervais *et al.* (2002) and Snyder *et al.* (2000), respectively. At Poteryanny Zub Lake, pine pollen, stomate and macrofossil evidence indicates the presence of pine at this site between about 8000 and 3000 ^{14}C yr BP with maximum pine density between 7000 and 6000 ^{14}C yr BP (Gervais *et al.*, 2002). A lag of more than 1000 years occurs in the maximum density of pine trees compared to its initial appearance in the lake-sediment stomate record. Pine forest was replaced by birch forest-tundra between 3500 and 2500 ^{14}C yr BP (Gervais *et al.*, 2002).

At Lake Yarnyshnoe-3, *Pinus* stomates recovered between 8000 and 6000 ^{14}C yr BP, in addition to elevated values of pine pollen, indicate that *Pinus sylvestris* grew near the Arctic coastline of the central Kola Peninsula during this time, although the small number of stomates suggests that pines were not locally extensive (Snyder *et al.*, 2000). The tundra and sparse *Betula* forest-tundra vegetation that characterizes the area today became established after 4000 ^{14}C yr BP (Snyder *et al.*, 2000).

Isotope palaeohydrology

Lakewater $\delta^{18}O$ ($\delta^{18}O_{lw}$) records for Lake Yarnyshnoe-3 and Poteryanny Zub Lake were reconstructed from cellulose $\delta^{18}O$ using a cellulose-water oxygen-isotope fractionation factor of 1.028 (Figure 2; Sternberg, 1989; Yakir, 1992; Wolfe *et al.*, 2001b). Overall, $\delta^{18}O_{lw}$ values are lower at Lake Yarnyshnoe-3 than Poteryanny Zub Lake, although similar trends (smoothed by a three-point running mean) are evident, particularly in the lower parts of the records. At Lake Yarnyshnoe-3, $\delta^{18}O_{lw}$ values increase from 9500 to 8000 ^{14}C yr BP and then decline until 6000 ^{14}C yr BP. This is then followed by a brief increase in $\delta^{18}O_{lw}$ values to

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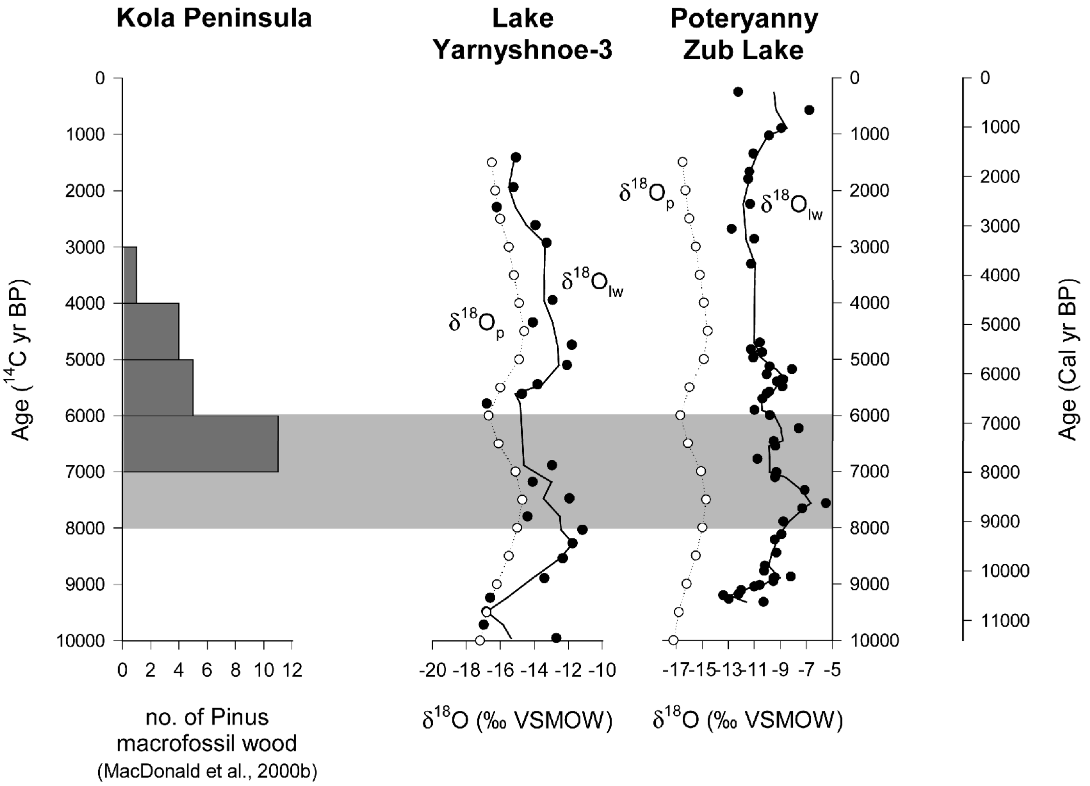

Figure 2 Number of *Pinus* macrofossils recovered from beyond the conifer treeline on the Kola Peninsula (MacDonald *et al.*, 2000b) and cellulose-inferred lakewater $\delta^{18}O$ ($\delta^{18}O_{lw}$) records for Lake Yarnyshnoe-3 and Poteryanny Zub Lake. Both raw $\delta^{18}O_{lw}$ data and three-point running mean curves are shown. Note that gaps in the $\delta^{18}O_{lw}$ reconstructions at Lake Yarnyshnoe-3 (≈7000 to 6000 ^{14}C yr BP interval) and Poteryanny Zub Lake (≈4500 to 3500 ^{14}C yr BP interval) are due to insufficient cellulose in these sediment samples. The precipitation $\delta^{18}O$ ($\delta^{18}O_p$) profile is estimated at 500-year intervals, linking the most ^{18}O-depleted data points from the Lake Yarnyshnoe-3 record. Data are plotted versus radiocarbon-age scale based on linear interpolation using data from Table 1. Calendar yr age scale is also shown for reference, based on the Intcal98 calibration curve (Stuiver *et al.*, 1998) and the OxCal Program v3.3 (Bronk Ramsey, 2000). Shaded zone between 8000 and 6000 ^{14}C yr BP represents main interval of pine expansion.

5000 ^{14}C yr BP and a subsequent trend to lower $\delta^{18}O_{lw}$ values towards the top of the core. At Poteryanny Zub Lake, $\delta^{18}O_{lw}$ values also increase from about 9500 ^{14}C yr BP with a subsequent shift to lower values from 7500 to 6000 ^{14}C yr BP. Poteryanny Zub Lake $\delta^{18}O_{lw}$ values then remain relatively constant through the mid- and late Holocene, followed by a rise at the top of the core.

Interpretation of $\delta^{18}O_{lw}$ records generally requires separating changes related to the isotopic composition of source water, reflecting the integrated signature of surface and subsurface inflow and precipitation, from changing hydrological factors (often primarily evaporative enrichment) that may subsequently modify the isotopic content of the lakewater. To deconvolute the $\delta^{18}O_{lw}$ records, we have constrained precipitation $\delta^{18}O$ ($\delta^{18}O_p$) at 500-year intervals by fitting a curve through the most negative $\delta^{18}O$ data points from the more variable and ^{18}O-depleted Lake Yarnyshnoe-3 record, which are interpreted to represent intervals of minimal lakewater evaporative ^{18}O-enrichment and values that may most closely reflect unmodified $\delta^{18}O_p$ (Figure 2). While the $\delta^{18}O_p$ reconstruction is speculative given the few number of data points that can be used from the Lake Yarnyshnoe-3 $\delta^{18}O_{lw}$ record for anchoring, it does provide a first-order conservative approximation that is required for interpretation of $\delta^{18}O_{lw}$ reconstructions. Indeed, this is an approach that we have advocated elsewhere (Edwards *et al.*, 1996; Wolfe *et al.*, 2000) in the absence of independent records of $\delta^{18}O_p$ (Wolfe *et al.*, 2001a). We have also tentatively paired this $\delta^{18}O_p$ reconstruction to the less variable, more ^{18}O-enriched Poteryanny Zub Lake record. The larger offset between the preliminary $\delta^{18}O_p$ reconstruction and the Poteryanny Zub Lake $\delta^{18}O_{lw}$ record may reflect greater evaporative ^{18}O-enrichment at this much smaller and shallower lake.

Inferred $\delta^{18}O_p$ records are commonly interpreted to vary in positive relation to mean annual temperature (MAT) based on the modern spatial $\delta^{18}O_p$-MAT relation, which is typically about 0.6–0.7 ‰/°C at mid- to high latitudes (Dansgaard, 1964; Rozanski *et al.*, 1993). However, our tentative $\delta^{18}O_p$ reconstruction for the coastal region of the Kola Peninsula shows a general decline between 7500 and 6000 ^{14}C yr BP during the interval of pine expansion when temperatures are thought to have been increasing. As elaborated below in relation to inferred changes in lake hydrology, we suggest that important factors contributing to the history of $\delta^{18}O_p$ in this region may be changes in the ratio of winter:summer precipitation driven by changes in winter sea-ice cover.

At Lake Yarnyshnoe-3, the immediate postglacial interval between 10 000 and 9500 ^{14}C yr BP was likely moist given the low $\delta^{18}O_{lw}$ values at this time which are inferred to closely correspond to $\delta^{18}O_p$. This interpretation correlates with changes in the pollen record, including a rise in *Betula*, appearance of *Sphagnum*, and maxima in Ericaceae, fern taxa and *Lycopodium annotinum*, indicating that there was sufficient moisture for the development of peatlands at this time (Snyder *et al.*, 2000). Subsequent drying is suggested by the large increase in $\delta^{18}O_{lw}$ from 9500 to about 8000 ^{14}C yr BP, which may have been coupled with increasing mean annual temperature and/or decreasing winter precipitation based on the inferred increase $\delta^{18}O_p$ over this same time interval (Figure 2). This interpretation supports the hypothesis that dry winters during this interval may have delayed pine expansion on the Kola Peninsula, in spite of increasing temperature (MacDonald *et al.*, 2000a). Indeed, comparison with the *Pinus* macrofossil wood record, representing samples recovered from beyond the conifer treeline (MacDonald *et al.*, 2000b), shows that

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the main interval of pine expansion at about 7000 ^{14}C yr BP corresponds to a decrease in $\delta^{18}O_{lw}$ probably reflecting, in part, reduced evaporative ^{18}O-enrichment (Figure 2). In addition, *Sphagnum* correspondingly declines to near 0 % between 9000 and 8000 ^{14}C yr BP in conjunction with lakewater ^{18}O-enrichment, and then does not rise again until after 7000 ^{14}C yr BP subsequent to lakewater ^{18}O-depletion (Snyder *et al.*, 2000). This inferred change in moisture conditions may have been associated with reduced winter sea-ice cover, enhanced winter:summer precipitation ratio, and increased input of ^{18}O-depleted snowmelt based on the shift to lower $\delta^{18}O_p$ values after 8000 ^{14}C yr BP which, as noted above, is in the opposite direction expected for continued warming.

Following the main interval of pine expansion (after 6000 ^{14}C yr BP), $\delta^{18}O_{lw}$ increases at Lake Yarnyshnoe-3, possibly in response to drier conditions developing near the coast of the Kola Peninsula. The $\delta^{18}O_{lw}$ increase may have also been due to an increase in $\delta^{18}O_p$, reflecting greater winter sea-ice cover and a reduced winter:summer precipitation ratio in response to a cooler climate. A trend towards lower $\delta^{18}O_{lw}$ values after 5000 ^{14}C yr BP may be partly due to a gradual shift to wetter conditions, in addition to lower $\delta^{18}O_p$.

Changes in the Poteryanny Zub Lake $\delta^{18}O_{lw}$ record appear to largely support the inferred early to mid-Holocene palaeohydrological reconstruction from the Lake Yarnyshnoe-3 $\delta^{18}O_{lw}$ record. Moist conditions in the immediate postglacial are also suggested at this site by relatively low $\delta^{18}O_{lw}$ values, consistent with high amounts of Ericaceae pollen between 10 000 and 9000 ^{14}C yr BP (Gervais *et al.*, 2002). The substantial increase in $\delta^{18}O_{lw}$ of about 7 ‰ from 9000 to 7500 ^{14}C yr BP followed by a decrease of about 4 ‰ to 6000 ^{14}C yr BP may also be largely in response to dry conditions followed by a shift to a moister climate during the main interval of pine expansion. Such large changes in $\delta^{18}O_{lw}$ are more likely to be in response to changing hydrological conditions at this small, shallow lake, compared to shifting $\delta^{18}O_p$, and corresponding changes in the carbon and nitrogen stable-isotope records support this interpretation as described below. In addition, decreasing Ericaceae and increasing *Lycopodium* between 9000 and 8000 ^{14}C yr BP may also suggest drying, whereas increases in *Alnus*, Ericaceae, *Sphagnum* and various aquatic taxa just before 7000 ^{14}C yr BP may be in part related to increasing moisture (Gervais *et al.*, 2002). Between 6000 and 2000 ^{14}C yr BP, minor fluctuations in the $\delta^{18}O_{lw}$ record suggest relatively stable hydrological conditions. A shift to higher $\delta^{18}O_{lw}$ values after 2000 ^{14}C yr BP may be due in part to an increase in $\delta^{18}O_p$, similar to late-Holocene $\delta^{18}O_p$ reconstructions for the lower Yenisey River and Lena River Delta regions in northern Russia to the east (Wolfe *et al.*, 2000; see also Figure 4 below).

Carbon and nitrogen cycling

Systematic trends are evident in the organic carbon and nitrogen content and stable-isotope compositions for Poteryanny Zub Lake and Lake Yarnyshnoe-3 (Figure 3). At Poteryanny Zub Lake, carbon and nitrogen contents rapidly increase at the base of the core, marking establishment of postglacial conditions, and remain relatively high until 7000 ^{14}C yr BP. Organic content decreases slightly at 7000 ^{14}C yr BP and then remains constant to the top of the core. Bulk organic $\delta^{13}C$ ($\delta^{13}C_{org}$) values show a brief increase at 9500 ^{14}C yr BP, a decline at 7000 ^{14}C yr BP and a subsequent gradual trend to higher values towards the top of the core. Bulk organic $\delta^{15}N$ ($\delta^{15}N_{org}$) values also briefly increase at the base of the record and then decrease to about 7000 ^{14}C yr BP. A rapid increase in $\delta^{15}N_{org}$ values occurs at 7000 ^{14}C yr BP, followed by a gradual decline to lower values to about 4000 ^{14}C yr BP, and then $\delta^{15}N_{org}$ values gradually increase to the present.

At Lake Yarnyshnoe-3, C (%) and N (%) increase to about 8500 ^{14}C yr BP and remain high until about 6000 ^{14}C yr BP. Organic content declines slightly after 6000 ^{14}C yr BP, and then values remain relatively constant before increasing at the top of the core. $\delta^{13}C_{org}$ values decrease sharply at 9000 ^{14}C yr BP and show a gradual trend to lower values until 6000 ^{14}C yr BP. $\delta^{13}C_{org}$ values then abruptly increase, followed by another gradual trend to lower values. $\delta^{15}N_{org}$ values are relatively high and constant until 8000 ^{14}C yr BP, which is then followed by a distinct shift to lower and more variable values between 8000 and 5000 ^{14}C yr BP. $\delta^{15}N_{org}$ values then increase and become less variable.

A number of factors control the carbon and nitrogen-stable isotope signatures of organic matter in lake sediments. For example, the carbon-isotope composition of aquatic organic matter, which is primarily determined by the $\delta^{13}C$ of dissolved inorganic carbon (DIC) in lakewater, may be controlled by isotopic exchange with atmospheric CO_2 and ^{13}C-enrichment derived from preferential uptake of ^{12}C by phytoplankton during photosynthesis (Brenner *et al.*, 1999). Both of these processes tend to raise DIC $\delta^{13}C$, while recycling of ^{13}C-depleted carbon from the decay of organic matter in the water column and bottom sediments generally leads to lower DIC $\delta^{13}C$. Variations in isotopic fractionation between the carbon source and aquatic organic matter, commonly caused by fluctuating dissolved CO_2 concentration, may also play an important role (Street-Perrott *et al.*, 1997; Hollander and Smith, 2001). Several variables can also influence the nitrogen-isotope composition of aquatic organic matter, including the isotopic signature of available nitrogen reservoirs used by phytoplankton, nitrogen isotope fractionation, and transformation in the water column and sediments, such as denitrification and ammonia volatilization, which lead to ^{15}N-enrichment of the residual dissolved inorganic nitrogen (DIN) pool (Teranes and Bernasconi, 2000). Strong kinetic effects can occur during nitrate and ammonium assimilation, although isotopic fractionation may not be significant in environments where DIN is limiting or during fixation of atmospheric N_2 by cyanobacteria (François *et al.*, 1996).

Previous studies on lakes near the northern treeline have suggested that watershed vegetation changes, delivery of dissolved byproducts from soil decomposition (principally CO_2 and NO_3^-) and hydrological conditions are the major controls of $\delta^{13}C_{org}$ and $\delta^{15}N_{org}$ values recorded in lake sediments (Wolfe *et al.*, 1996; 1999). Similar conclusions have been drawn from other mid- and high-latitude lake records whose catchments underwent significant changes in vegetation and soil maturation following deglaciation (Hammarlund, 1993; Hammarlund *et al.*, 1997). Similar factors seem to control the carbon and nitrogen stable-isotope records from Poteryanny Zub Lake because abrupt changes occur concurrently with pine expansion and inferred changes in the hydrological regime at 7000 ^{14}C yr BP (Figure 3). As has been suggested in the above-mentioned studies, the decrease in $\delta^{13}C_{org}$ at this horizon is probably a reflection of increased influx of ^{13}C-depleted dissolved CO_2 from soil decomposition in company with rapid hydrological flushing. Subsequent ^{13}C-enrichment post-6000 ^{14}C yr BP likely records declining soil decomposition in relation to pine retreat and establishment of the modern birch forest-tundra vegetation.

Additional insight to changing limnological conditions is evident in the Poteryanny Zub Lake $\delta^{15}N_{org}$ record. Between 9000 and 7000 ^{14}C yr BP, high organic content and $\delta^{15}N_{org}$ values close to 0‰ suggests high lake productivity, possibly accompanied by N-limitation and algal fixation of atmospheric N_2. Abrupt ^{15}N-enrichment at 7000 ^{14}C yr BP may be due to elevated leaching and supply of ^{15}N-enriched soil-derived nitrate under more moist conditions (cf. Wolfe *et al.*, 1999). Reduced soil decomposition and production of soil nitrate probably explains the slight ^{15}N-depletion after 6000 ^{14}C yr BP, while internal DIN uptake within the water column may explain the subdued ^{15}N-enrichment after 4000 ^{14}C yr BP.

The overall narrower ranges of carbon and nitrogen elemental

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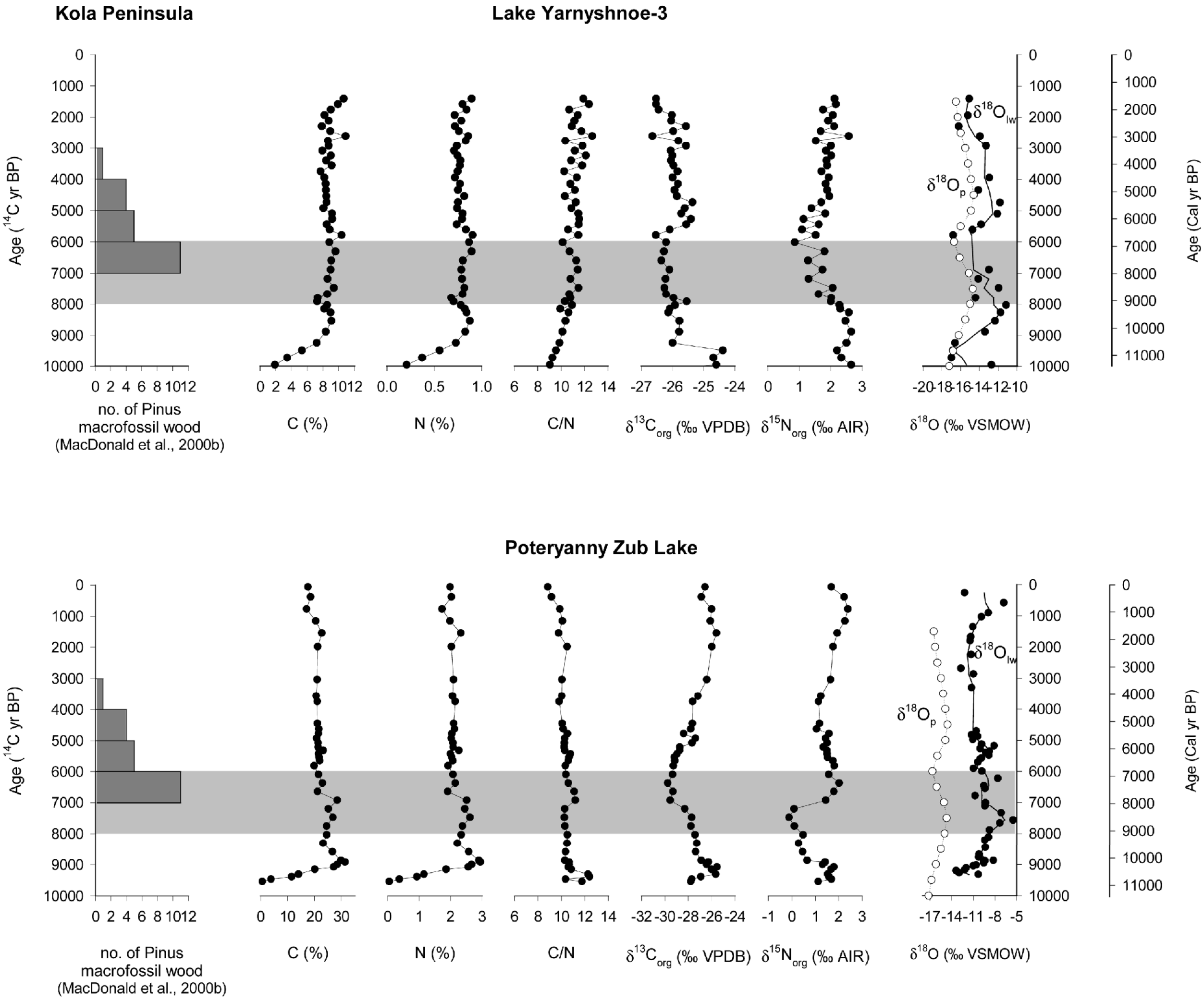

Figure 3 Number of *Pinus* macrofossils recovered from beyond the conifer treeline on the Kola Peninsula (MacDonald *et al.*, 2000b) and C (%), N (%), C/N ratio, bulk organic $\delta^{13}C$ and bulk organic $\delta^{15}N$ records for Poteryanny Zub Lake and Lake Yarnyshnoe-3. Also shown are $\delta^{18}O_{lw}$ and $\delta^{18}O_p$ reconstructions from Figure 2. Data are plotted versus radiocarbon-age scale based on linear interpolation using data from Table 1. Calendar yr age scale is also shown for reference, based on the Intcal98 calibration curve (Stuiver *et al.*, 1998) and the OxCal Program v3.3 (Bronk Ramsey, 2000). Low C/N ratios indicate an aquatic source for the organic matter (Meyers and Lallier-Vergès, 1999). Shaded zone between 8000 and 6000 ^{14}C yr BP represents interval of pine expansion.

and isotopic values at Lake Yarnyshnoe-3 likely reflects the larger size of the lake and catchment and less significant terrestrial changes at this more northerly site, which is suggested by the comparatively lower inferred density of local pine during the early to mid-Holocene (Snyder *et al.*, 2000). Trends of $\delta^{13}C_{org}$ and organic content at Lake Yarnyshnoe-3, however, can largely be explained by similar mechanisms as those proposed for the Poteryanny Zub Lake record. For instance, the abrupt decline to lower $\delta^{13}C_{org}$ values at about 9000 ^{14}C yr BP is also most likely related to contribution of dissolved soil CO_2 to the lakewater DIC pool. This change appears to have occurred much more rapidly than at Poteryanny Zub Lake, although it may instead be related to overcoming a nutrient balance threshold rather than a reflection of the rate of soil CO_2 production and supply to the lake. Base cation leaching from early soil development has also been cited as an explanation for the change from alkaliphilous to oligotrophic diatom assemblages at this same horizon (Snyder *et al.*, 2000). Availability of nutrients derived from the catchment probably favoured primary productivity, contributing to the increase in organic content of the sediments. An increase in $\delta^{13}C_{org}$ values and a slight decrease in organic content after 6000 ^{14}C yr BP following the interval of pine expansion are changes most likely related to decreased supply of soil CO_2, and drier conditions, as suggested by the increase in $\delta^{18}O_{lw}$ values and which may also be related to a subsequent change in diatom flora between 5000 and 4000 ^{14}C yr BP thought to reflect a decrease in nutrient availability (Snyder *et al.*, 2000). Decline in $\delta^{13}C_{org}$ and $\delta^{18}O_{lw}$ values after about 5000 ^{14}C yr BP suggest a gradual shift to wetter conditions during the late Holocene.

Changes in the Lake Yarnyshnoe-3 $\delta^{15}N_{org}$ profile appear to be more closely tied with changes in the hydrological regime. Relatively low and more variable $\delta^{15}N_{org}$ values during the interval of pine expansion are associated with low $\delta^{18}O_{lw}$ values, possibly indicating that rapid hydrological flushing diluted the ^{15}N concentration in the lakewater DIN. Following this interval, an abrupt change to higher and less variable $\delta^{15}N_{org}$ values occurred at 4500 ^{14}C yr BP which may reflect reduced hydrological through-flow.

Early- to mid-Holocene palaeohydrology and palaeoclimate at northern treeline, Russia

Previous studies have suggested that boreal forest expansion and warming along the northern Eurasian coast during the early Holocene was driven mainly by oceanic forcing, which spawned increased cyclonic activity and the eastward flow of warm and moist air (Salvigsen *et al.*, 1992; Koç *et al.*, 1993; Lubinski *et al.*,

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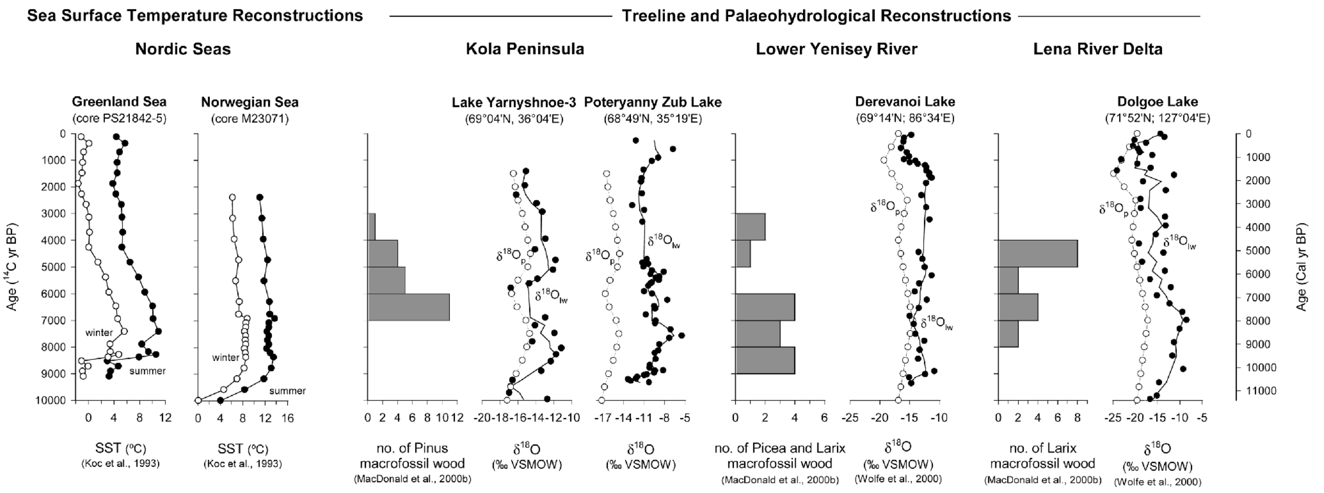

Figure 4 Sea-surface temperature reconstructions for the Nordic Seas (Koç *et al.*, 1993) and west–east transect of cellulose-inferred lakewater $\delta^{18}O$ and reconstructed $\delta^{18}O_P$ records, including Poteryanny Zub Lake and Lake Yarnyshnoe-3 on the Kola Peninsula (from Figure 2), Derevanoi Lake in the lower Yenisey River region (Wolfe *et al.*, 2000) and Dolgoe Lake on the Lena River Delta, Russia (Wolfe *et al.*, 2000). See Wolfe *et al.* (2000) for constraints on the development of precipitation $\delta^{18}O$ profiles for Derevanoi Lake and Dolgoe Lake. Also shown are tree macrofossil records for each area, representing the number of samples found beyond conifer treeline (MacDonald *et al.*, 2000b). Data are plotted versus radiocarbon-age scale based on linear interpolation using data from Table 1. Calendar yr age scale is also shown for reference, based on the Intcal98 calibration curve (Stuiver *et al.*, 1998) and the OxCal Program v3.3 (Bronk Ramsey, 2000).

1999; Kerwin *et al.*, 1999; MacDonald *et al.*, 2000b). According to Koç *et al.* (1993), maximum influence of warm Atlantic waters in the central and eastern portions of the Greenland, Iceland and Norwegian Seas developed at 7000 ^{14}C yr BP. Warm sea-surface temperatures for the southeastern Barents Sea between about 7500 and 4500 ^{14}C yr BP have also recently been inferred from dinoflagellate cyst assemblages in marine sediment cores (Voronina *et al.*, 2001), with the earliest part of this interval marked by maximum influx of North Atlantic water into the northern margin of the Barents Sea (Duplessy *et al.*, 2001; Lubinski *et al.*, 2001). Enhanced supply of moisture-laden air masses to the Kola Peninsula at 7000 ^{14}C yr BP is consistent with reduced lakewater evaporative ^{18}O-enrichment at Poteryanny Zub Lake and Lake Yarnyshnoe-3, possibly associated with increased snowmelt contributions to the lakewater balances driven by reduced winter sea-ice cover (Figure 4).

The shift in moisture regime also correlates with treeline advancement on the Kola Peninsula, both of which were delayed in comparison to other sectors of northern Russia. For example, boreal forest expansion had already begun by 9000 ^{14}C yr BP and was accompanied by increasingly moist conditions to 7000 ^{14}C yr BP in the lower Yenisey River region of central Siberia (Figure 4; Wolfe *et al.*, 2000). Although changes in nutrient balance at Poteryanny Zub Lake and Lake Yarnyshnoe-3 suggest that productive and presumably warm conditions were established by 9000 ^{14}C yr BP, sufficient winter snowcover may have been a key determinant in the expansion of *Pinus sylvestris* on the Kola Peninsula. In contrast, sufficient snowcover may not have been as critical a factor in altitudinal pine expansion in the Scandes Mountains of northern Fennoscandia. Indeed, attenuation of strong westerly flow and declining precipitation appears to have triggered the expansion of pine by 5500 ^{14}C yr BP in the Abisko area (Barnekow, 1999; Seppä and Hammarlund, 2000; Seppä and Birks, 2001; Hammarlund *et al.*, 2002), perhaps suggesting important differences in the response of pine to climatic change in Arctic alpine versus maritime settings. Elevated summer moisture and temperature may have alternatively played a more significant role in the northward spread of *Larix* and *Picea*, the dominant treeline species in western Siberia. Farther east on the Lena River Delta, large areas of continental shelf exposed by glacial sea-level draw-down during the early Holocene may have suppressed maritime climatic influence in what are now coastal areas (Figure 4; Wolfe *et al.*, 2000).

Reduced North Atlantic influence in the Nordic Seas after 6000 ^{14}C yr BP contributed to drier (and cooler) conditions on the Kola Peninsula and eastward along the northern Siberian coast to at least the lower Yenisey River valley, while a cool maritime climate was established on the Lena River Delta mainly as a result of rising sea level (Figure 4; Wolfe *et al.*, 2000). Treeline correspondingly retreated in all sectors reaching the present-day configuration by about 3000 ^{14}C yr BP (MacDonald *et al.*, 2000b).

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