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Holocene Treeline History and Climate Change Across Northern Eurasia

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Radiocarbon-dated macrofossils are used to document Holocene treeline history across northern Russia (including Siberia). Boreal forest development in this region commenced by 10,000 yr B.P. Over most of Russia, forest advanced to or near the current arctic coastline between 9000 and 7000 yr B.P. and retreated to its present position by between 4000 and 3000 yr B.P. Forest establishment and retreat was roughly synchronous across most of northern Russia. Treeline advance on the Kola Peninsula, however, appears to have occurred later than in other regions. During the period of maximum forest extension, the mean July temperatures along the northern coastline of Russia may have been 2.5° to 7.0°C warmer than modern. The development of forest and expansion of treeline likely reflects a number of complimentary environmental conditions, including heightened summer insolation, the demise of Eurasian ice sheets, reduced sea-ice cover, greater continentality with eustatically lower sea level, and extreme Arctic penetration of warm North Atlantic waters. The late Holocene retreat of Eurasian treeline coincides with declining summer insolation, cooling arctic waters, and neoglaciation. © 2000 University of Washington.

Key Words: **treeline; climate change; Holocene; arctic; Russia; Siberia; macrofossils.**

INTRODUCTION

The establishment of forests in northern Eurasia contributed to Holocene warming and climate change by lowering high-latitude albedo and influencing the summer position of the arctic front (Foley *et al.*, 1994; TEMPO, 1996; Pielke and Vidale, 1995; Texier *et al.*, 1998). The northern treeline in

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Eurasia is associated with the 10° to 12°C July isotherm and should be sensitive to changes in summer temperature. Holocene temperature changes at the treeline zone might be influenced by a number of factors, including variations in insolation due to Milankovitch orbital forcing, paleogeographic changes associated with deglaciation and sea-level rise, inflow of warm North Atlantic waters into the Arctic, strengthened atmospheric westerlies, and decreased summer sea-ice in the adjacent Arctic Ocean. Climate model experiments suggest northern Eurasia is particularly sensitive to changes in glacial ice extent and sea-surface temperatures in the North Atlantic region (Overpeck *et al.,* 1996; Mikolajewicz *et al.,* 1997). Documenting the timing of establishment of high-latitude forest in northern Eurasia and subsequent changes in treeline is important for understanding the development of Holocene climate and the relative importance of different forcing factors affecting climate at high latitudes and beyond.

Pollen records from the Russian treeline are sparse (Khotinsky, 1984; Peterson, 1993; Texier *et al.,* 1998). However, the occurrence of large numbers of ancient tree stumps on the tundra of northern Siberia has been known since the reports of A.F. Middendorf in the 1860s. Radiocarbon dating of *in situ* macrofossils can provide a means of reconstructing forest development and treeline movement during the late Quaternary (Eronen and Huttunen, 1993; Kullman, 1995; Lavoie and Payette, 1996; Kremenetski *et al.,* 1998). Scientists of the former Soviet Union have reported numerous radiocarbon dates from tree macrofossils from the treeline. These macrofossils are from scattered locales, and the dates from individual sites usually consist of a limited number of specimens (Kremenetski *et al.,* 1998).

In this paper, we present new radiocarbon dates for tree macrofossils from north of the modern Russian treeline. Most of the samples were obtained by systematic sampling at four sites located along a longitudinal transect extending from the Kola Peninsula eastward to the Lena River Delta. We combine these new dates with previously published Russian data to reconstruct the Holocene establishment of northern boreal forest and the subsequent history of the Eurasian treeline. We then examine the climatic forcing factors that may have controlled the timing of forest establishment and treeline movement.

METHODS

Kremenetski *et al.* (1998) provided a compilation of published radiocarbon dates from 249 macrofossils of *Larix* spp. (larch), *Picea obovata* (Ledeb.) (spruce), and tree *Betula* spp. (birch) found north of the modern Russian treeline. To supplement and assess the Russian data, we collected, identified, and radiocarbon dated 57 macrofossils of *Larix* spp., *Picea obovata,* and *Betula* spp. from sites located from the lower Pechora River eastward to the lower Lena River (Fig. 1; Table 1). Most of the samples are wood which was identified to genus by comparing thin sections to modern reference material. We also include radiocarbon dates for an additional 21 samples of *Pinus sylvestris* L. (Scots pine) wood found north of the modern treeline on the Kola Peninsula (MacDonald *et al.,* 2000).

We intensively sampled three sites (Fig. 1) for tree macrofossils to supplement the existing Russian data set and to determine if the general history of forest development inferred from the Russian dates is supported when reconstructed from carefully and intensively sampled individual sites. At the Pechora River (67°58′N, 51°35′E), Taymyr Peninsula (70°22′N, 87°33′E), and Lena River (71°52′N, 127°04′E) we conducted a series of radial transects ($<$5 km in length) and collected stumps from the tundra surface, the littoral zones of small lakes, and surface deposits and sections along streams. The Taymyr site lies about 60 km northwest of the mapped treeline (based upon 1:500,000 Russian topographic maps and U.S. Tactical Pilotage Charts). One living krummholz, *Larix sibirica* (Ledeb.), was encountered in the transects. The Lena site lies just beyond the mapped treeline, and a number of small *Larix dahurica* (Trautv.) trees and krummholz were encountered at low elevations near the main channel of the river. The uplands, where collection efforts were concentrated, were completely devoid of living trees. No living trees were encountered in the Pechora study area, which lies approximately 75 km north of the mapped treeline. Samples have also been obtained from the Kola Peninsula, where searches were conducted in the shallow waters of small lakes. Two lakes in the birch forest–tundra zone (68°43′N, 35°19′E) provided a series of *Pinus sylvestris* samples from approximately 25 km north of the mapped limits of the species (MacDonald *et al.,* 2000).

We avoided sites which may have contained macrofossils transported from more southerly regions. Many of the specimens were found in rooted position. We therefore conclude that radiocarbon dates from the macrofossils provide reliable evidence of the past presence of living trees. As a first approximation, we assume that the numbers of radiocarbon-dated tree macrofossils within 1000-yr age-classes are positively related to the relative density of trees during each 1000-yr period. Each date represents a sample of wood from a different tree and not multiple dates from an individual specimen. The samples for each local area come from a number of collecting sites. Many of our samples are surface finds on the tundra or from shallow lakes although some samples were found in peat exposures or lake-sediment cores. Thus, our sampling strategy should not be biased toward overrepresentation of a given time period.

RESULTS

The radiocarbon dates from the Kola, Pechora, Taymyr, and Lena sites (Table 1; Fig. 1) fall between 9000 and 3000 yr B.P. (All ages are reported as ^{14}C years before A.D. 1950). The samples from the Pechora and Taymyr sites contained both *Larix* and *Picea.* Only *Larix* wood was identified from the Lena River site. Only *Pinus* was reported from the Kola

TABLE 1
Radiocarbon Dated Macrofossils of Trees from the Northern Treeline Zone of the Russian Federation

Location (N latitude; E longitude)	Material	Age yr B.P.	Age CAL	Lab no.
Betula (tree)				
70°59′, 66°33′	wood	8780 ± 150	9709	GX-21799
69°43′, 66°50′	bark	8610 ± 150	9524	GX-21801
	wood	8020 ± 80	8954	IGAN-368
69°13′, 86°33′	bark	4010 ± 70	4492	WAT-2754
	bark	3980 ± 70	4417	WAT-2753
Larix				
67°58′, 51°35′	wood	5280 ± 70	6079	Beta-84942
	wood	4815 ± 83	5584	IGAS-1600
70°22′, 87°33′	wood	8430 ± 80	9436	WAT-2726
	wood	8260 ± 70	9242	WAT-2716
	wood	8260 ± 80	9242	WAT-2727
	wood	8240 ± 90	9214	WAT-2718
	wood	7880 ± 80	8578	WAT-2723
	wood	7680 ± 80	8412	WAT-2719
	wood	7050 ± 70	7860	WAT-2725
	wood	6100 ± 80	6942	WAT-2720
	wood	6030 ± 80	6878	WAT-2729
	wood	4610 ± 70	5309	WAT-2722
	wood	3750 ± 70	4089	WAT-2721
	wood	3530 ± 70	3774	WAT-2724
71°52′, 127°04′	wood	7840 ± 90	8556	WAT-2850
	wood	7014 ± 65	7799	IGAS-1525
	wood	6554 ± 81	7393	IGAS-1520
	wood	6517 ± 88	7387	IGAS-1522
	wood	6101 ± 71	6943	IGAS-1515
	wood	6030 ± 80	6878	WAT-2852
	wood	5722 ± 53	6490	IGAS-1506
	wood	5220 ± 80	5943	WAT-2849
	wood	4880 ± 80	5605	WAT-2846
	wood	4614 ± 59	5310	IGAS-1519
	wood	4570 ± 80	5295	WAT-2851
	wood	4549 ± 69	5288	IGAS-1524
	wood	4239 ± 56	4830	IGAS-1518
	wood	4220 ± 70	4740	WAT-2853
	wood	4210 ± 80	4743	WAT-2854
	wood	4200 ± 70	4729	WAT-2855
71°30′, 128°58′	wood	7744 ± 62	8468	IGAS-1517
Picea				
67°58′, 51°34′	wood	8460 ± 70	9445	Beta-84944
	wood	8380 ± 80	9414	Beta-84941
	wood	8080 ± 70	8948	Beta-84940
	wood	7820 ± 70	8550	Beta-84945
	wood	6740 ± 70	7544	Beta-84947
	wood	6500 ± 90	7384	Beta-84946
	wood	6050 ± 80	6887	Beta-84948
	wood	5200 ± 60	5935	Beta-84937
	wood	4130 ± 70	4609	Beta-84936
	wood	4092 ± 49	4561	IGAS-1604
	wood	4080 ± 70	4535	Beta-84935
	wood	3920 ± 70	4361	Beta-84939
	wood	3880 ± 70	4335	Beta-84943
	wood	3710 ± 80	4029	Beta-84938

TABLE 1—*Continued*

Location (N latitude; E longitude)	Material	Age yr B.P.	Age CAL	Lab no.
68°15′, 68°10′	needles	3770 ± 70	4109	TO-4744
69°13′, 86°33′	cone	6070 ± 130	6895	WAT-2756
	cone	6000 ± 130	6821	WAT-2755
69°25′, 86°39′	cone	8790 ± 110	9704	WAT-2770
	cone	8750 ± 130	9761	WAT-2764
	cone	8210 ± 140	9123	WAT-2771
70°22′, 87°33′	wood	6520 ± 70	7387	WAT-2728
	wood	6230 ± 70	7105	WAT-2717
		Pinus		
68°43′, 35°19′	wood	6680 ± 70	7530	Beta-112747
	wood	6600 ± 60	7430	Beta-112753
	wood	6450 ± 70	7355	Beta-112743
	wood	6440 ± 80	7295	Beta-112751
	wood	6340 ± 90	7219	Beta-112763
	wood	6330 ± 80	7215	Beta-112762
	wood	6220 ± 70	7165	Beta-112744
	wood	6150 ± 70	7013	Beta-112748
	wood	6090 ± 80	6915	Beta-112754
	wood	6050 ± 60	6887	Beta-112746
	wood	6010 ± 60	6865	Beta-112745
	wood	5800 ± 70	6635	Beta-112761
	wood	5770 ± 70	6740	Beta-112765
	wood	5530 ± 90	6303	Beta-112766
	wood	5520 ± 70	6300	Beta-112764
	wood	5070 ± 80	5815	Beta-112768
	wood	4820 ± 90	5590	Beta-112759
	wood	4640 ± 90	5319	Beta-112749
	wood	4570 ± 70	5295	Beta-112757
	wood	4500 ± 80	5165	Beta-112758
	wood	3830 ± 70	4230	Beta-112750

Note. Radiocarbon dates (yr B.P.) and calibrated (Stuiver and Reimer, 1993) dates (CAL) before present for identified tree wood, bark, needles, and cones from sites at and beyond the modern northern treeline zone of the Russian Federation.

(MacDonald *et al.*, 2000), and the oldest samples are relatively young (<7000 yr B.P.) as compared to sites from the other regions.

The span of 9000 to 3000 yr B.P. obtained from our sampling of *Larix* is less than the total time span of the previously published Russian dates, which range from 16,000 to 600 yr B.P. However, the 9000 to 3000 yr B.P. interval corresponds with the period in which the vast majority of the Russian dates fall (Fig. 2). The previously published samples that are older than the ones described here may represent the occurrence of scattered trees captured in the larger and more geographically dispersed Russian data network. The most recent dates from the Russian data set come from sites that are at or just south of the present limits of *Larix* (Kremenetski *et al.*, 1998).

The dates we obtained from *Picea* macrofossils correspond with the interval of 9000 to 4000 yr B.P. reported from the Russian data set (Fig. 2). The dates from *Pinus sylvestris* span a shorter range (~6680 to 3830 yr B.P.) than any of the other tree taxa. However, the ages obtained from Kola *Pinus* correspond closely with the range of ages obtained from radiocarbon-dated *Pinus* samples from northern Fennoscandia (Eronen and Huttunen, 1993). Although we have recovered and dated fossils of *Betula* trees from peat sections (Table 1), we did not recover any during our systematic sampling of the four local sites. The Russian *Betula* samples are all found in peat and colluvial deposits (Kremenetski *et al.*, 1998), and the wood is likely not preserved on the tundra surface or in the shallow lake sediments from which most of our samples come.

The new samples from the Kola, Pechora, and Taymyr regions provide a geographic extension of the published Russian data set (Kremenetski *et al.*, 1998). The samples of *Larix* and *Picea* from the Pechora are the westernmost dated macrofossils of these genera. The samples of *Picea* from the Taymyr are the easternmost dated macrofossils available for that genus. No previously obtained dates are available from the Russian literature for *Pinus* wood on the Kola Peninsula.

We combined our data with the broader Russian data set to determine if there were longitudinal trends or differences in

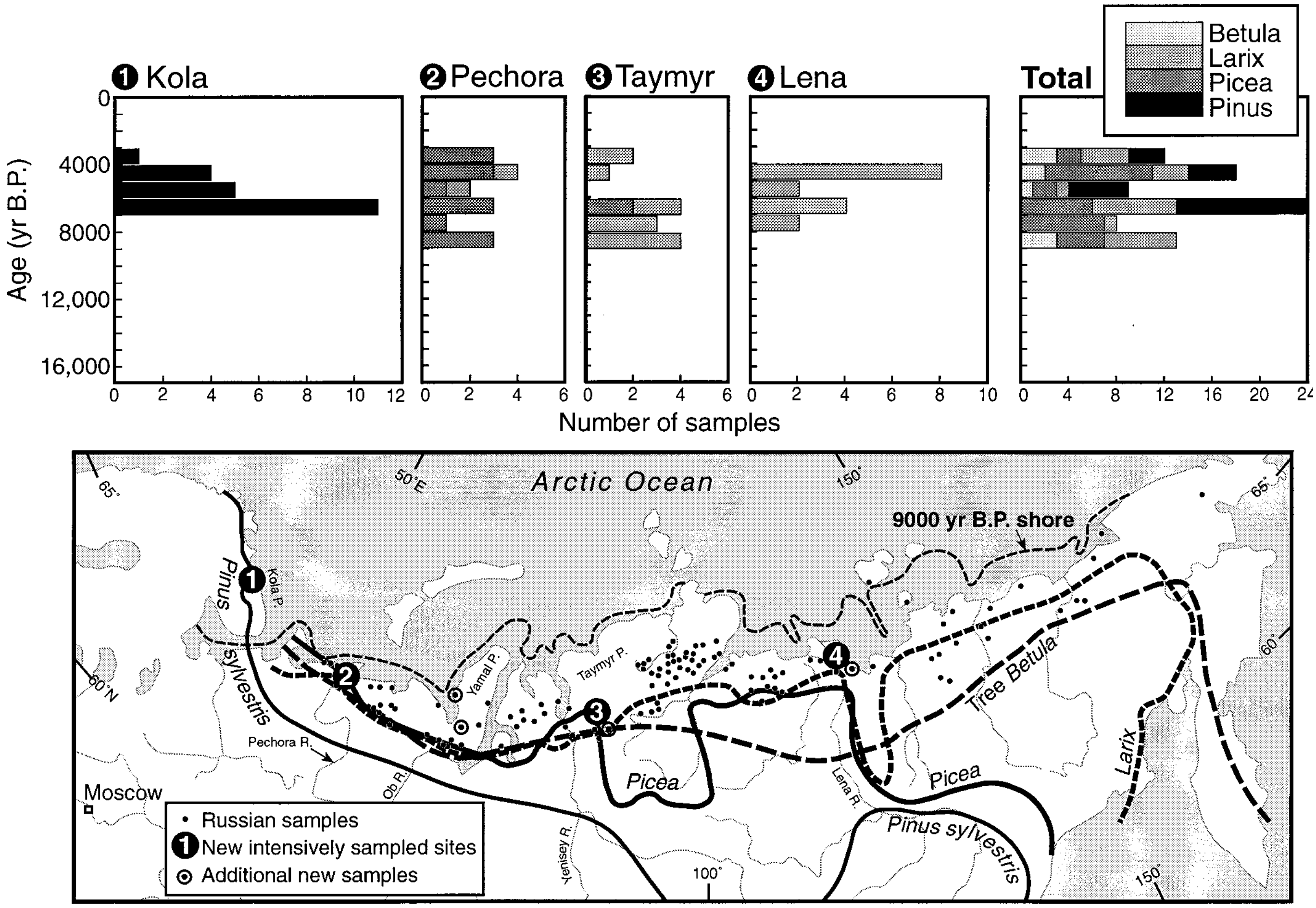


FIG. 1. The locations of the Kola Peninsula, Pechora River, Yamal Peninsula, Taymyr Peninsula, and Lena River regions where intensive local collecting of samples was conducted. The modern range limits of arboreal *Betula, Larix, Picea,* and *Pinus* are illustrated ("Tree and Shrub Distribution in the USSR," 1991). The present *Larix* treeline corresponds roughly with the 10° to 12°C July isotherms ("Arctic Atlas," 1985). The histograms present the distribution of uncalibrated radiocarbon ages for *Larix, Picea,* and *Pinus* macrofossil wood recovered at the four sites (see Table 1).

treeline establishment and retreat (Fig. 3). We plotted the longitudinal distribution of the earliest late glacial and Holocene dates (>8000 yr B.P.) and the most recent late Holocene dates (<5000 yr B.P.) in the combined data set. With the exception of the late expansion of *Pinus* on the northern Kola and an early expansion and possible retreat of tree *Betula* in far eastern Siberia, evidence for major longitudinal trends in far northern forest establishment or subsequent retreat appears to be absent. The combined data set (Fig. 3) indicates that the greatest number of dates for trees from north of the modern treeline falls between 9000 and 3000 yr B.P.

TREELINE RECONSTRUCTION

We can reconstruct the following general history of the northern Eurasian treeline based upon our new data and the previously published Russian data (Fig. 3). *Betula* trees were established in the far northeast by 11,000 to 10,000 yr B.P. and were widely distributed beyond modern northern limits across Eurasia by 9000 to 8000 yr B.P. Given the modern distributions, *Betula pubescens* Ehrh. and *Betula pendula* (Roth.) were likely present at sites west of the Lena River. Sites east of the Lena River were probably occupied by *Betula pendula.* Based on macrofossil numbers, the greatest density of tree *Betula* perhaps occurred between 10,000 and 7000 yr B.P. *Betula*-dominated forest may have slightly preceded *Larix*- and *Picea*-dominated forest in the early Holocene, and tree *Betula* density appears to have decreased following the increase in the conifers. The final decline of arboreal *Betula* north of the modern treeline occurred between 4000 and 3000 yr B.P.

Larix perhaps was present in low numbers in the far north as early as 16,000 yr B.P. (Fig. 3). The widespread expansion of *Larix* beyond the modern treeline occurred between 9000 and 8000 yr B.P. Based on the modern ranges, areas west of the

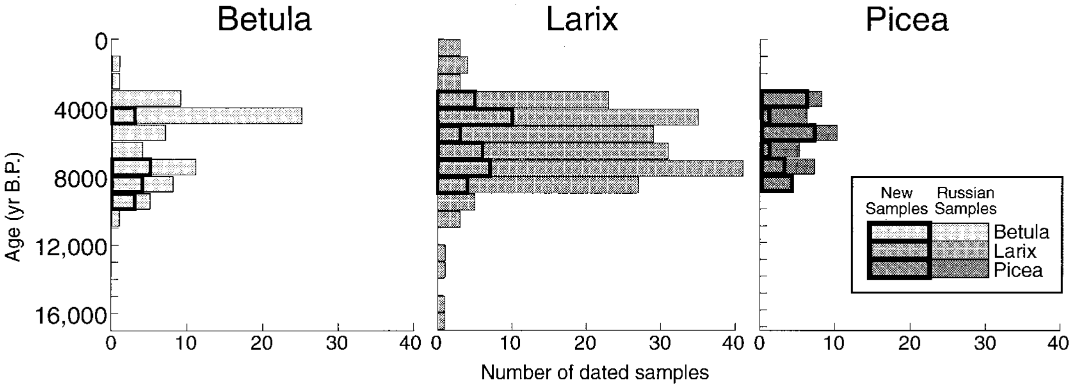


FIG. 2. Comparisons between the radiocarbon ages of macrofossils of *Larix, Picea,* and tree *Betula* from this study with previously published materials (Kremenetski *et al.,* 1998).

Yenisey River were likely occupied by *Larix sibirica,* while sites to the east supported *Larix dahurica.* The density of *Larix* tree-cover north of the modern treeline was at a maximum between 8000 and 4000 yr B.P. (Fig. 3). *Larix* declined to its modern limits between 4000 and 3000 yr B.P.

Picea obovata is the only *Picea* species growing near the treeline in our study area. Consequently, *Picea* macrofossils recovered in this study are likely from this species. The expansion of *Picea* to sites north of the modern treeline occurred between 9000 and 8000 yr B.P. (Fig. 3). The retreat of *Picea* to its current limit and density at treeline occurred between 4000 and 3000 yr B.P.

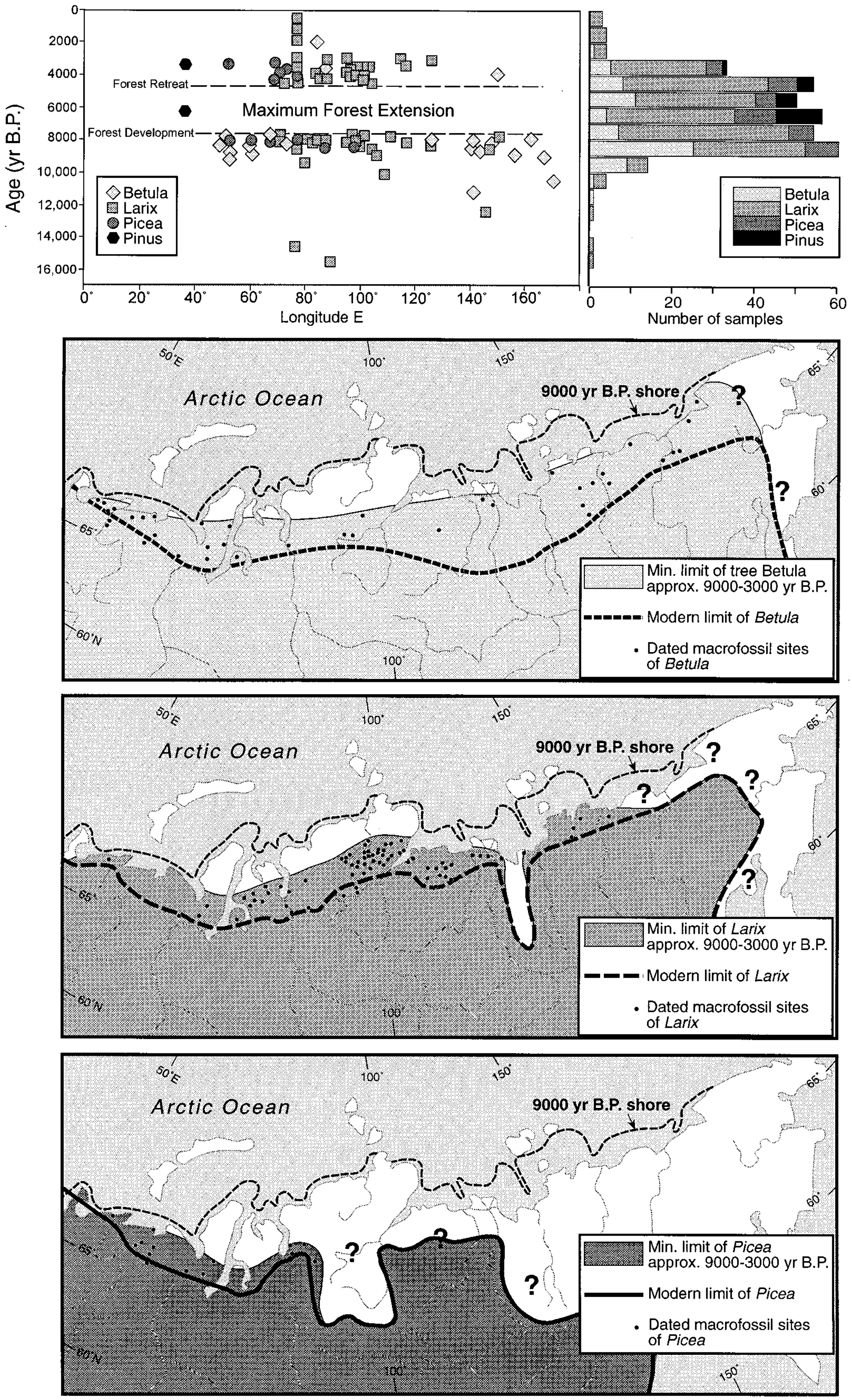
The record from the Kola Peninsula indicates that *Pinus sylvestris* was present beyond its modern northern limits by 6680 yr B.P. and persisted there until 3830 yr B.P. The timing of the advance and retreat of treeline here is consistent with evidence from radiocarbon-dated wood found in adjacent northern Fennoscandinia. The advance of treeline in these northern regions appears to have occurred later than in more southern and central portions of Fennoscandia, where *Pinus sylvestris* wood has produced dates as old as 9000 yr B.P. (Eronen and Huttunen, 1993; Kullman, 1995). The scarcity of dated *Pinus* remains suggests that the genus was never important north of the modern treeline in areas east of the Kola Peninsula.

Most of far northern Eurasia was forested by 9000 to 8000 yr B.P. (Fig. 3). The longitudinal distribution of tree genera at the treeline appears to have been roughly similar to today. However, macrofossils indicate that the early Holocene range of *Larix sibirica* south of the treeline extended as far west as the Scandes Mountains in Sweden (Kullman, 1998). The large number and size (some >20 cm in diameter and >2 m in length) of specimens recovered from northern Russia suggest that forest, or relatively well-treed forest–tundra, was present, rather than scattered krummholz. The decline of dated macrofossils from 4000 to 3000 yr B.P. indicates that the present tundra vegetation was established during this time.

DISCUSSION

The modern conifer treeline of Eurasia (Fig. 3) corresponds roughly with the 10° to 12°C July isotherms, while the tundra, where many of the stumps have been recovered, lies between this and the 7.5° to 5.0°C July isotherms ("Arctic Atlas," 1985). This implies that over much of northern Eurasia summers may have been 2.5° to 7.0°C warmer than today during the period ~9000 to 4000 yr B.P. However, many other climatic factors may influence treeline (Stevens and Fox, 1991; Prentice *et al.,* 1992). For example, adequate snow depth to protect young trees during the winter may play an important role in determining the northern limits of *Picea* in Scandinavia (Kullman and Engelmark, 1997).

The Holocene expansion of treeline likely reflects a number of environmental factors. The delay in development of extensive forest until 9000 yr B.P. suggests a lag between increased summer insolation produced by Milankovitch orbital forcing and initiation of sustained warming of the treeline zone (Fig. 4). Assuming that factors such as seed dispersal, population growth rates, and soil conditions are not critical at the 1000-yr time-steps being considered here, this lag suggests that changes in boundary conditions due to Eurasian deglaciation, sea-level rise, and subsequent increase in advective heat transport from warm lower latitudes may have been additional factors influencing northern Eurasian climate and treeline. Scandinavian deglaciation enhanced the northward penetration of thermohaline circulation with sustained warming of the Norwegian, Greenland, and Barents seas starting at ~9500 yr B.P. (Salvigsen *et al.,* 1992; Koç *et al.,* 1993; Sarnthein *et al.,* 1995; Bjorck *et al.,* 1996; Jones, 1994). Deglaciation and sustained sea-surface warming in the Norwegian and Barents seas would have enhanced heat transport into the Arctic. Evidence from marine diatoms, marine bivalve distributions, and lake sediment cores all indicate substantial warming of the North Atlantic and Norwegian/Greenland seas between 9000 and 4000 yr B.P. (Fig. 4). Cyclonic activity would have increased with


Age (yr B.P.)
0
2000
4000
6000
8000
10,000
12,000
14,000
16,000
Forest Retreat
Maximum Forest Extension
Forest Development
◇ Betula
▨ Larix
● Picea
⬢ Pinus
0°
20°
40°
60°
80°
100°
120°
140°
160°
Longitude E
0
20
40
60
Number of samples
Betula
Larix
Picea
Pinus
50°E
100°
150°
Arctic Ocean
9000 yr B.P. shore
?
65°
60°
60°N
Min. limit of tree Betula approx. 9000-3000 yr B.P.
Modern limit of Betula
• Dated macrofossil sites of Betula
Min. limit of Larix approx. 9000-3000 yr B.P.
Modern limit of Larix
• Dated macrofossil sites of Larix
Min. limit of Picea approx. 9000-3000 yr B.P.
Modern limit of Picea
• Dated macrofossil sites of Picea

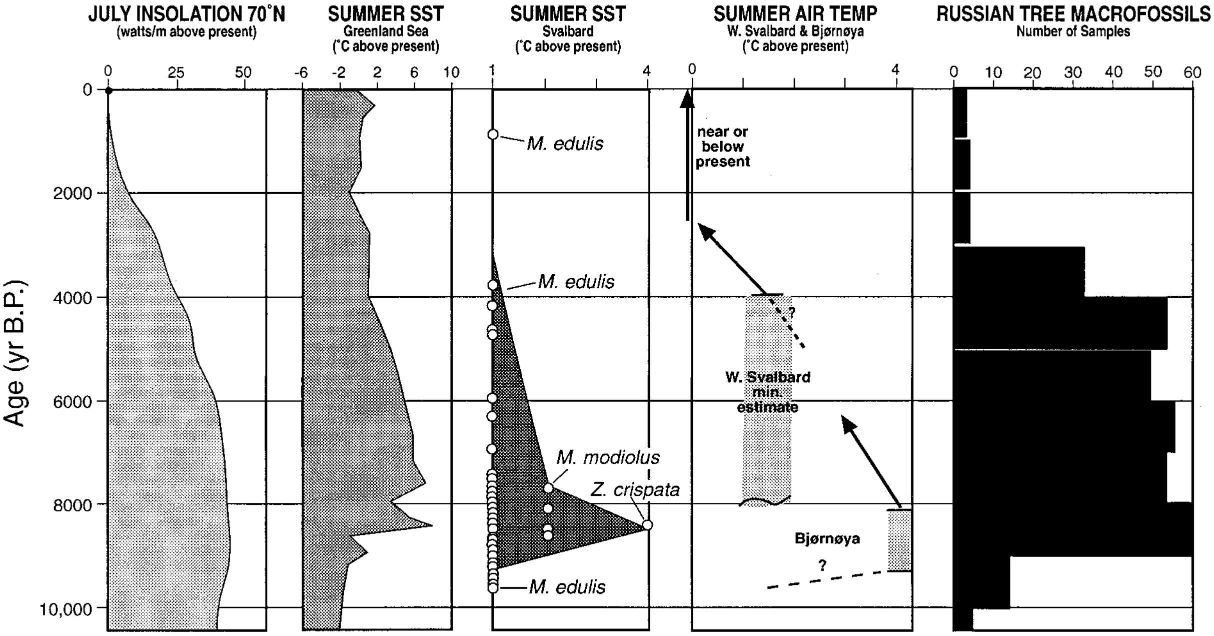


FIG. 4. July insolation at 70° N (Berger, 1978). Summer sea surface temperatures (SSTs) in the Greenland Sea reconstructed on the basis of diatoms (Koç *et al.,* 1993). SSTs near Svalbard inferred from the occurrence of *Mytilus edulis, M. modiolus,* and *Zirphaea* shells (Salvigsen *et al.,* 1992). Summer air temperatures for Svalbard and Bjørnøya reconstructed from plant macrofossil and paleolimnological records (Birks, 1991; Wolfarth *et al.,* 1995). The chronological distribution of all tree macrofossils from the Russian treeline. All records are presented in uncalibrated radiocarbon years before present, and this imparts an uneven profile to the insolation curve due to variations in the relationship between radiocarbon years and calendar years (Stuiver and Riemer, 1993).

expansion of the Icelandic low into the Barents Sea, increasing the flow of warm and moist air into arctic Siberia (Rogers and Mosely-Thompson, 1995; Thompson and Wallace, 1998). Change in the Icelandic low would have its strongest impact on winter conditions in Eurasia. However, recent analyses of Arctic synoptic activity indicate that both winter and summer cyclone activity for the period A.D. 1952–1989 generally exhibit similar trends (Serreze *et al.,* 1993). In addition, warmer winters leading to decreased sea-ice thickness, and earlier spring melting of ice and snow would have produced decreased albedo, increased growing season length, and enhanced early season sensible heat (Overpeck *et al.,* 1996).

Recent climate model experiments suggest that Scandinavian deglaciation and warming of northern water masses could have caused the Eurasian treeline zone to warm by 6° to 12°C (Overpeck *et al.,* 1996; Fawcett *et al.,* 1997; Mikolajewicz *et al.,* 1997). However, the model experiments also suggest that the impact of this warming might have been most significant from the Taymyr Peninsula westward. Several factors perhaps influenced the eastward propagation of warming. The establishment of high latitude forests across western Eurasia would have decreased albedo and further enhanced warming to the east. The arctic coastline was located as much as 150 km north of its modern location at 9000 yr B.P. due to globally depressed sea level (Fig. 3). This situation would have promoted warmer continental temperatures at sites which are today strongly influenced by the cold Arctic Ocean. The impact of this phenomenon would have been greatest east of the Taymyr Peninsula and near the lower Ob and Yenisey rivers. Finally, reduced sea-ice could have lowered albedo and increased ocean-atmosphere heat and moisture exchange, thereby enhancing warming and moisture flux (Mitchell *et al.,* 1988; Ganopolski *et al.,* 1998).

The relatively late advance of *Pinus sylvestris* forest on the Kola Peninsula and in northern Fennoscandia remains problematic. Recent work combining stable isotope and palynological analyses of lake sediments suggests that the early Holocene climate of the region may have been con-

FIG. 3. The latitudinal pattern of boreal forest development and retreat across Russian Eurasia based upon the distribution of radiocarbon dated wood >8000 and <5000 yr B.P. from the data of this study combined with previously published dates. The maps provide the northern limits of tree genera between ~8000 and 3000 yr B.P. as evident from the macrofossil data. The inferred location of the arctic coastline of Eurasia at 9000 yr B.P., which approximates the present 25-m bathymetric contours, is also indicated. Placement of the shoreline is based on global records that indicate sea level was approximately 25 m lower than present at 9000 yr B.P. and reached modern levels by 6000 yr B.P. (Fairbanks, 1989). Some indication of changes in the relative density of treeline forest as it developed, occupied its Holocene northern limits, and then retreated is provided by a histogram that combines the radiocarbon ages obtained from this study with previously published data.

siderably more influenced by marine flow and was wetter than the mid-Holocene climate (Seppä and Hammarlund, in press). The late increase of *Pinus* might be explained by its preference for drier conditions (Seppä and Hammarlund, in press). The types of trees growing in the Scandes Mountains of Sweden during the early Holocene suggest that there may be no modern analogue for the climate of Fennoscandia and the adjacent Kola Peninsula (Kullman, 1998). MacDonald *et al.* (2000) pointed out that winter insolation was lower than present during the early Holocene and that the susceptibility of *Pinus sylvestris* to desiccation and root damage due to cold winters may have restricted the northward advance of the species in this region. Colder winters might have also benefited the deciduous conifer genus *Larix,* which had an early Holocene range that included southern Scandinavia (Kullman, 1998).

The retreat of treeline between 4000 and 3000 yr B.P. coincides with decreasing summer insolation, cooling of arctic waters, possible expansion of sea ice, and neoglaciation (Fig. 4). Declining summer insolation would have decreased solar energy and temperatures during the growing season at treeline (Kutzbach *et al.*, 1993). Cooler surface waters in the Norwegian, Greenland, and Barents seas would promote cooler conditions in northern Eurasia. In turn, the summer persistence of sea ice would lead to cooler air temperatures. The southward progression of tundra would result in an increase in albedo and displacement of the arctic front, providing positive feedbacks that enhanced cooling (Foley *et al.*, 1994; TEMPO, 1996; Ganopolski *et al.*, 1998).

The history of treeline development and retreat reflects the sensitivity of the Eurasian Arctic to a variety of changes in boundary conditions from the North Atlantic eastward. Summer insolation was already high when the conclusion of Scandinavian deglaciation and a strengthening of the mean-state of the North Atlantic resulted in increased advective heat transport into the Arctic. A more northerly coastline coupled with decreased albedo due to forest establishment and reduced sea-ice cover may have helped propagate warming east of the Taymyr Peninsula. Although the precise importance of each of these factors remains to be resolved, the end result was the development of boreal forest north of its modern limits across most of Russian Eurasia between 9000 and 8000 yr B.P.

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