Volume 30, Number 3
May–June 1999

ISSN: 1067-4136
CODEN: RJOEEW

275 years RUSSIAN ACADEMY OF SCIENCES

RUSSIAN JOURNAL OF ECOLOGY

Official English Translation of *Ekologiya*

Editor-in-Chief
Vladimir N. Bolshakov

http://www.maik.rssi.ru

A Journal of Original Papers and Reviews on Theoretical and Applied Ecology

Translated and Published by
МАИК "НАУКА/INTERPERIODICA" PUBLISHING

Distributed worldwide by KLUWER ACADEMIC/PLENUM PUBLISHERS

Russian Journal of Ecology, Vol. 30, No. 3, 1999, pp. 141–147. Translated from Ekologiya, No. 3, 1999, pp. 163–169.

Main Stages of Woody Vegetation Development in the Yamal Peninsula in the Holocene

R. M. Hantemirov and S. G. Shiyatov

Institute of Plant and Animal Ecology, Ural Division, Russian Academy of Sciences, ul. Vos'mogo Marta 202, Ekaterinburg, 620144 Russia

Received November 12, 1998

Abstract—Radiocarbon dating of 53 subfossil specimens of Siberian larch and Siberian spruce wood collected in alluvial and peaty deposits of the southern Yamal Peninsula provided the basis for distinguishing three long periods of the Holocene, which differed in the location of the polar boundary of the open woodland zone and the amount of forests on the territory. The highest amount of forests and the northernmost position of their boundary were characteristic of the early Holocene (10500–7400 years ago); over the past 3700 years, the amount of forests was minimal, and the open woodland boundary remained in the southernmost position.

Holocene deposits (alluvial, peaty and lakustrine) in the southern Yamal Peninsula contain a large amount of subfossil remains of tree trunks, roots, and branches. Their occurrence in the present-day tundra zone of the Yamal Peninsula was described for the first time by B.M. Zhitkov (1913). Later, subfossil wood was found in other regions of western Siberia (Zubkov, 1931; Andreev *et al.*, 1935; Tikhomirov, 1941; Vasil'chuk *et al.*, 1983). These findings indicate that there was a post-glacial warm period in the north of western Siberia, when trees expanded 200–400 km northward of the current forest boundary. In Yamal, they reached a latitude of about 71°30′ N.

The weakest point in paleoecological and paleoclimatic reconstructions based on the analysis of subfossil wood is that the absolute radiocarbon dates were determined for a relatively small number of samples. The most complete list of radiocarbon dates for subfossil wood from the Yamal Peninsula, compiled by Vasil'chuk *et al.* (1983), includes 15 samples of trees and large shrubs. Recently, the amount of such data has considerably increased (Shiyatov and Erokhin, 1990; Shiyatov *et al.*, 1996; Hantemirov and Shiyatov, 1999). According to our estimates, radiocarbon dating of about 70 subfossil wood samples has been performed to date for the Yamal territory.

In this work, we analyzed these data (mainly the results of our own studies) in order to reconstruct in more detail the dynamics of the polar boundary of the forest zone and the amount of forests in the Holocene.

THE AREA AND OBJECTS OF RESEARCH

Wood samples were taken in the valleys and interfluves of small rivers (Tanlovayakha, Khadytayakha, and Yadayakhodyyakha) in southern Yamal in the region located between 67°00′ and 67°50′ N and 68°30′ and 71°00′ E (Fig. 1). These rivers flow from the north to the south; hence, no driftwood can be brought from the adjacent southern territories. At the present time, the upper reaches of these rivers are woodless; larch and spruce–birch–larch thin forests are located mainly in valley beds in the middle and lower reaches. We obtained more than 2100 wood samples sawed from trunks and, partially, roots of subfossil larch (*Larix sibirica* Ldb.) and spruce trees (*Picea obovata* Ldb). The major part of the subfossil wood was collected from alluvial deposits in the upper and middle reaches of these rivers.

Many samples were taken from under the bottom of relict peat bogs located in the upper reaches of the rivers.

RADIOCARBON DATING OF SUBFOSSIL WOOD

The table presents the data on 55 radiocarbon dates determined for 53 remains of subfossil trees (51 samples of Siberian larch and 2 of Siberian spruce). Radiocarbon analysis and data calibration were performed in the Laboratory of Population and Historical Ecology of the Institute of Plant and Animal Ecology (IPAE), the Ural Division of the Russian Academy of Sciences, Yekaterinburg (11 dates), and the Radiocarbon Laboratory of the Physical Institute of the Bern University, Switzerland (44 dates). For two samples (nos. 2 and 5), dating was repeated in both laboratories. Samples selected for dating usually contained a small number of annual rings (5–30) to reduce the error resulting from differences in the age of wood in the sample.

Figure 2 presents the results of radiocarbon dating in the form of time intervals equal to the life span of individual trees (samples) and oriented in time and space. Ordinate shows the distance from the sample location to the northernmost clump of larch trees growing near each river, measured along meridionally oriented river valleys. These data provide the possibility of

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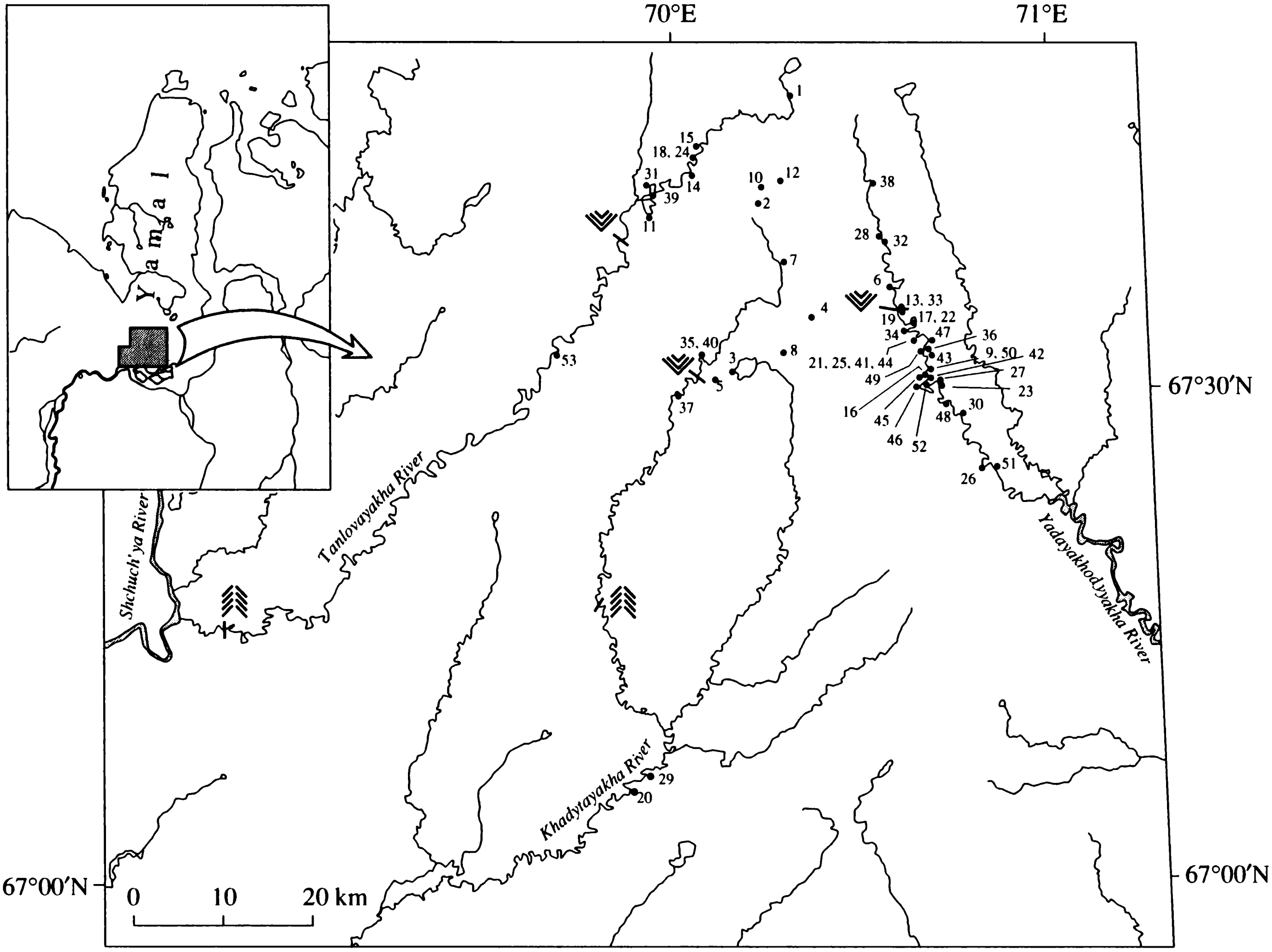

Fig.1. The region of subfossil wood sampling. Dots show the location of wood remains used for radiocarbon dating. Figures show the number of tree sample (see the table). Signs show the present-day polar boundary of (larch sign) larch and (spruce sign) spruce growth in river valleys.

estimating the time when woody vegetation appeared in Yamal and the dynamics of its northern boundary and amount of forests.

The data concerning the southern forest boundary in these river valleys are also of some paleogeographic interest, as they can be used for determining the dates of sea transgressions during which the lower reaches of rivers were flooded and, hence, no wood remains were buried here. According to the data presented in Fig. 2, the sea level rise and inundation of river mouths could take place in this region from the eighth to the fifth millenniums B.C., as well as during the last two millenniums B.C. (hereinafter, we use only calibrated dates). However, these conclusions should be interpreted cautiously, as we cannot exclude that some fallen trees were transported by floods from the north to the south and then buried or, in some cases, were buried more than once. Note also that the number of available radiocarbon dates is not sufficient. In our opinion, the site of growth was determined precisely only for trees whose remains were found outside river valleys, in particular, in peat bogs.

DATING THE APPEARANCE OF FOREST VEGETATION IN YAMAL

According to the results of radiocarbon dating performed by other researchers, trees appeared in Yamal not later than 10500 years ago (Vasil'chuk *et al.*, 1983). There are some indications that trees grew in the middle Yamal Peninsula 12–15 thousand years ago (Trofimova and Korona, 1996). Our data cited in the table and Fig. 2 show that larch and spruce appeared in southern Yamal not later than 9400 and 7500 years ago, respectively. Since that time, larch and spruce always grew there, surviving cold periods in the areas with the most favorable microclimatic and soil conditions (refugia), in particular, in river valleys composed of fresh alluvium. Valley habitats are better protected from strong winds and, on the other hand, accumulate a fairly thick (1–2 m)

Results of radiocarbon dating of subfossil *Picea obovata* (nos. 12 and 28) and *Larix sibirica* wood samples collected in Yamal

Sample number	Laboratory number	Part of the tree	Type of deposits	Total number of tree rings	^{14}C date, years ago	Calibrated date, year B.C.	Geographic coordinates, degree : min	
							lat. N	long. E
1	B-6072	Trunk, outer rings	Alluvium	28	8220 ± 40	7200	67:48	70:19
2	B-6031	Root, all rings	Peat	79	8180 ± 40	7140	67:42	70:14
	IPAE-77	"			8400 ± 240	7400		
3	IPAE-79	Root	Peat	59	8180 ± 230	7130	67:31	70:10
4	IPAE-78	"	The same	127	8000 ± 200	6900	67:35	70:22
5	B-6032	Trunk, inner rings	"	111	8000 ± 50	6900	67:31	70:07
	IPAE-80	Trunk, all rings			7730 ± 220	6500		
6	B-6060	Trunk, outer rings	Alluvium	189	7920 ± 40	6730	67:37	70:35
7	IPAE-74	Root	Peat	75	7820 ± 200	6640	67:38	70:16
8	IPAE-73	"	"	48	7800 ± 170	6620	67:33	70:18
9	B-6038	Trunk, outer rings	Alluvium	382	7780 ± 40	6590	67:32	70:40
10	IPAE-76	Root	Peat	64	7640 ± 220	6430	67:41	70:14
11	B-6077	Trunk, outer rings	Alluvium	124	7260 ± 40	6080	67:41	69:56
12	IPAE-75	Trunk	Peat	118	6550 ± 170	5400	67:43	70:17
13	B-6411	Trunk, outer rings	Alluvium	149	6252 ± 30	5223	67:35	70:36
14	B-6074	Trunk, inner rings	The same	254	6200 ± 40	5150	67:44	70:03
15	B-6416	Trunk, outer rings	"	217	6140 ± 33	5059	67:46	70:04
16	B-6039	The same	"	243	5740 ± 40	4620	67:31	70:39
17	B-6062	"	"	354	5730 ± 40	4550	67:34	70:38
18	B-6073	"	"	127	5723 ± 34	4542	67:45	70:04
19	B-6410	Trunk, inner rings	"	317	5717 ± 32	4539	67:35	70:36
20	B-6409	Trunk, outer rings	Peat	169	5535 ± 29	4356	67:05	69:55
21	B-6413	The same	Alluvium	239	5404 ± 32	4290	67:33	70:38
22	B-6412	"	The same	134	5329 ± 29	4190	67:33	70:41
23	B-6042	Trunk, inner rings	"	301	5030 ± 30	3860	67:30	70:42
24	B-6417	Trunk, outer rings	"	317	4746 ± 31	3580	67:45	70:04
25	B-6035	Trunk, inner rings	"	243	4590 ± 40	3330	67:33	70:38
26	B-6070	Trunk, outer rings	"	145	4520 ± 40	3200	67:25	70:48
27	B-6069	The same	"	216	4370 ± 40	2920	67:31	70:41
28	B-6059	"	"	133	4290 ± 40	2900	67:40	70:33
29	B-6408	"	"	138	4242 ± 27	2882	67:06	69:56
30	B-6044	Trunk, inner rings	"	296	4210 ± 40	2800	67:29	70:46
31	B-6075	"	"	234	4120 ± 40	2700	67:43	69:56
32	B-6034	Trunk, outer rings	"	350	3970 ± 30	2510	67:40	70:34
33	B-6061	The same	"	243	3890 ± 40	2370	67:35	70:36
34	B-6063	"	"	226	3800 ± 30	2200	67:34	70:37
35	IPAE-157	Trunk	"	127	3630 ± 190	2020	67:33	70:04
36	B-6037	Trunk, outer rings	"	243	3620 ± 40	2010	67:32	70:41
37	IPAE-154	Trunk	"	169	3600 ± 150	1970	67:30	70:01
38	B-6033	Root, outer rings	"	148	3590 ± 30	1960	67:43	70:32
39	B-6076	Trunk, outer rings	"	185	3580 ± 30	1920	67:42	69:57
40	IPAE-156	Trunk	"	129	3540 ± 280	1870	67:33	70:04
41	B-6036	Trunk, outer rings	"	127	3530 ± 30	1860	67:33	70:38
42	B-6067	The same	"	151	3390 ± 30	1680	67:31	70:39
43	B-6415	"	"	178	3083 ± 26	1350	67:33	70:40
44	B-6064	"	"	59	2850 ± 40	1000	67:33	70:38
45	B-6040	"	"	269	2750 ± 30	900	67:31	70:39
46	B-6041	Trunk, inner rings	"	161	2010 ± 30	30	67:30	70:39
47	B-6065	Trunk, outer rings	"	176	1960 ± 30	65 A. D.	67:33	70:40
48	B-6043	Trunk, inner rings	"	207	1910 ± 30	90 A. D.	67:29	70:43
49	B-6414	Trunk, outer rings	"	102	1675 ± 24	401 A. D.	67:33	70:40
50	B-6066	The same	"	143	1230 ± 30	790 A. D.	67:32	70:40
51	B-6071	"	"	244	920 ± 30	1100 A. D.	67:25	70:50
52	B-6068	"	"	109	890 ± 30	1170 A. D.	67:30	70:40
53	B-6078	"	Ground surface	25	680 ± 22	1298 A. D.	67:33	69:41

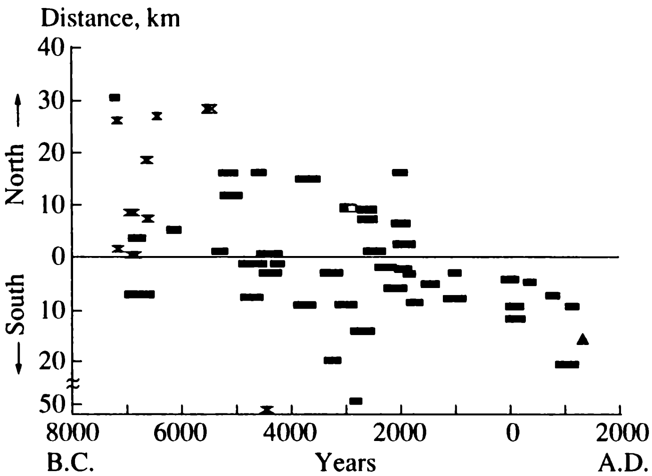

Fig. 2. The intervals of lifetime of trees determined by the radiocarbon method (calibrated data) and location of trees relative to the present-day boundary of Siberian larch growth in river valleys. Signs show wood remains from (—) alluvial deposits, (×) peat deposits, and (Δ) ground surface. Black marks refer to Siberian larch, and black-and-white marks to Siberian spruce.

snow cover in winter. These factors, along with the warming effect of flowing waters and a weak growth of mosses and lichens, determine the summer thermal regime of soils that is the most favorable for tree growth in river valleys, especially in floodplains.

The absence of radiocarbon dates for intervals of 6100–5400 and 900–100 B.C. can be explained by the fact that subfossil wood of this age is difficult to find, rather than by its absence from southern Yamal. Thus, we collected and dated dendrochronologically the remains of trees that lived throughout the first millennium B.C., which was one of the most unfavorable for tree growth (Shiyatov *et al.*, 1996; Hantemirov, 1999).

In all periods of the Holocene, Siberian larch dominated in normal and thinned forest stands, especially in interfluvial habitats, its polar boundary lying northward of that of spruce. This is confirmed by the fact that the major part (95%) of samples was larch rather than spruce (5%), although they were mainly taken from alluvial deposits of river valleys, which are the most favorable for spruce growth. At present, relatively small areas of closed and open forests with the prevalence of spruce are found only in the middle reaches of the Khadytayakha River. In the valleys of other rivers in southern Yamal, the proportion of spruce is very small. The present-day polar boundary of larch distribution in the Yamal Peninsula lies 30–50 km northward of the spruce boundary.

THE DYNAMICS OF THE POLAR BOUNDARY OF CONIFEROUS SPECIES DISTRIBUTION

Figure 3a shows changes in the northernmost location of wood samples with respect to the present-day polar boundary of the larch range, which reflect long-term trends in the dynamics of the polar boundary of conifer distribution over the past 9400 years. It is seen that trees maximally expanded to the north in the early Holocene (9400–7400 years ago). At that time, they grew far north of the river basins under consideration; many tree remains of this age were found outside the river valleys. These remains were taken from under the bottom of relict peat bogs formed on elevations (50–60 m a.s.l.), i.e., in interfluvial habitats, which are less favorable for tree growth than river valleys. For example, the present-day polar boundary of coniferous forest zone outside river valleys lies 50–70 km south of that in river valleys. Published data (Vasil'chuk *et al.*, 1983) also show that the northernmost wood remains, which were found 400 km north of the current thin forest boundary and radiocarbon-dated from about 7200 and 5450 B.C., belong to the same period. Therefore, we can derive a conclusion that this period of the Holocene was the most favorable for tree growth in the Yamal Peninsula.

Thereafter, the polar boundary of open coniferous forests moved southward and had been shifting insignificantly during a fairly long period of time (7400–3700 years ago), remaining several dozens of kilometers, on average, to the north from the present-day boundary. The northernmost location of wood remains is the upper reaches of the Yuribei River (about 68°20′ N), 50–70 km north of the current boundary (Vasil'chuk *et al.*, 1983).

In the early second millennium B.C., the polar boundary of coniferous forest zone shifted to the south rapidly and significantly. During the past 3700 years, the polar boundary of thin forest occupied the southernmost position. Larch and spruce–larch thin forests grew mainly in the river valley habitats, in the middle and lower reaches of the rivers under consideration.

Thus, the available data on the location of radiocarbon-dated tree remains in Yamal allowed us to characterize latitudinal changes in the location of the polar boundary of forest–tundra open forests and suggested that the Holocene may be divided in this respect into three chronological intervals: the early Holocene (10500–7400 years ago), the middle Holocene (7400–3700 years ago), and the late Holocene (the past 3700 years).

DYNAMICS OF THE AMOUNT OF FORESTS

To assess the adequacy of conditions for tree growth and discuss the dynamics of the amount of forests, it is possible to use the data on the number of tree remains dated from a certain time interval (Fig. 3b). We used the dates determined for the first 43 samples because the latter were chosen randomly (the remaining ten samples were collected with the purpose of estimating the age of trees that grew during relatively unfavorable periods).

When analyzing these data, one should take into account that the most ancient wood remains are more difficult to find, especially in alluvial deposits, because they could be repeatedly exposed to daylight, which often leads to mechanical destruction and decay.

Figure 3b shows that the first (the most ancient) peak corresponds to the period between 7200 and 6000 B.C., which can be regarded as the most favorable for woody vegetation in Yamal, as trees grew not only in river valleys, but also in interfluves. Hence, it may be concluded that amount of forests at that time also reached the highest value for the Holocene.

In the middle Holocene, the most favorable periods were 5200–4500 and 3900–1700 B.C., especially the latter.

In the late Holocene, characterized by a low abundance of trees, three relatively favorable periods are distinguished: 1200–900 B.C., 100 B.C.–200 A.D., and 800–1400 A.D. The latter period is coeval with climate warming in the Middle Ages, which was observed in Europe, Iceland, Greenland, and other regions of the world.

According to the data shown in Fig. 3, unfavorable periods were the following: 6000–5500, 4500–3900, 1600–1200, 800–200 B.C., and 200–700 A.D. Radiocarbon dates for the past 700 years are absent because the wood of this age was identified as young (by color, resin content, and weight), and its dating was not performed.

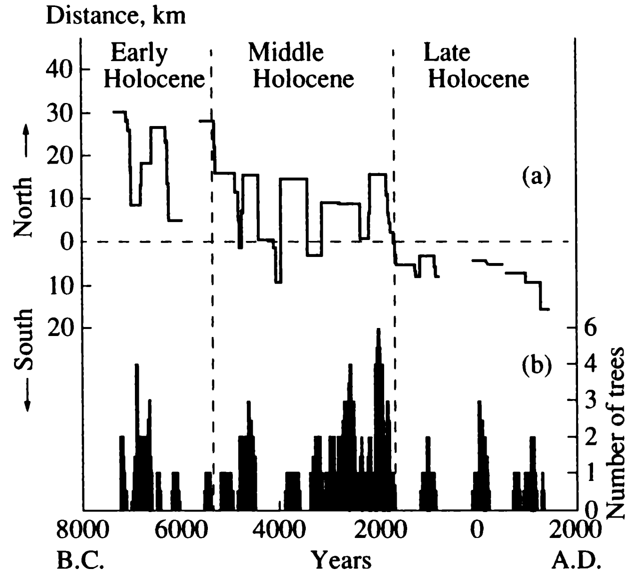

Fig. 3. Fluctuations in the polar boundary of coniferous tree distribution with respect to the current location of the northernmost clumps of larch trees in river valleys (a), time distribution of trees dated by the radiocarbon method (b), and a proposed periodization of the Holocene in Yamal reflecting the main stages of woody vegetation development.

PERIODIZATION OF THE HOLOCENE IN YAMAL

Changes in trees abundance and shifts in the polar boundary of the forest zone were usually synchronous and apparently depended on long-term changes in thermal conditions during growing periods. The dynamics of these two characteristics are not completely the same, and we explain this fact by a greater time lag in shifts of the forest boundary than in changes of stocking density in the existing forests. When climatic conditions became more favorable, there was also a delay in forest expansion to the north and interfluves because of the lack of high-quality larch and spruce seeds in the tundra territories (Shiyatov, 1966). A delay in the southward regression of forest boundary during unfavorable periods can be accounted for by the fact that a certain amount of trees could be preserved in refugia, so that rapid shifts occurred only after considerable climatic changes.

Based on radiocarbon dating of subfossil wood, we can derive the following conclusions concerning the dynamics of woody vegetation in the Yamal Peninsula.

The available data are insufficient for precisely estimating the time when trees appeared in Yamal. However, there is no doubt that open larch forests have already been growing in Yamal in the early Holocene, i.e., 9–10.5 thousand years ago. The most favorable period for tree growth lasted from 7200 to 6000 B.C. Then, until 5600 B.C., climatic conditions were slightly worse; however, this did not result in any significant shift of the polar boundary to the south. Such a shift occurred later, about 5400 B.C. By that time, the overall amount of woodland in Yamal also decreased considerably, which allows us to regard this stage as a transition to the next period of the Holocene. From 5400 to 1700 B.C., the polar boundary was located at approximately 69° N. Trees survived in river valleys during unfavorable periods (4500–3900 and 3600–3400 B.C.) and expanded to interfluvial habitats in favorable periods (5200–4500, 3900–3600, and 3400–1800 B.C.). Although the last period was probably one of the most favorable in the Holocene, trees failed to return to the boundary of 5400 B.C.

A strong southward shift of the polar boundary of open forests and a significant decrease in the amount of forests occurred for the second time approximately in 1700 B.C. This stage may be regarded as the end of the middle Holocene and the onset of the current stage of woody vegetation development in the Yamal Peninsula. To date, many paleohydrologic, paleoecological, and archeologic data have been accumulated that provide evidence for an abrupt climatic change (cooling and an increase in humidity) that occurred between 1900 and 1500 B.C. in different regions of northern Europe (Anderson *et al.*, 1998).

Over the past 3700 years, forest-and-tundra communities were preserved mainly in river valleys located in the very south of the Yamal Peninsula. The open forest boundary shifted insignificantly, no more than 10 km along river valleys (Hantemirov and Surkov, 1996). Relatively favorable conditions existed in 1200–900 B.C., 100 B.C.–200 A.D., and during "the medieval optimum" (700–1400 A.D.).

This periodization of the Holocene, based on the data on forest–tundra vegetation dynamics, generally agrees with schemes proposed by other authors for territories of different rank (Neishtadt, 1957; Vasil'chuk *et al.*, 1983; Khotinskii, 1977, 1991). However, there are some differences. Thus, according to Khotinskii (1991), an early subboreal coolingspan occurred in the forest and tundra zones of northern Eurasia between 3350 and 2700 B.C. Our data, by contrast, show that climatic conditions in this period were most favorable for tree growth in Yamal. We dated the onset of the late subboreal cold period in Yamal at about 1700 B.C., whereas Khotinskii noted that it began 200 years later. Our and Khotinskii's data also differ in dating the end of the middle Atlantic warm period (4500 and 4900 B.C.) and the end of the early Atlantic warm period (6000 and 5700 B.C., respectively). Our data show that the "afforestation" phase in the Yamal Peninsula ended much later (1700 B.C.) than was determined in 1983 by Vasil'chuk *et al.* (8500–3700 B.C.).

CONCLUSIONS

As the procedure of radiocarbon dating is expensive and labor-consuming, we can hardly expect that the amount of corresponding data will increase significantly in the nearest future. This limits the possibility of performing detailed reconstruction of natural conditions and the dynamics of forest–tundra ecosystems. A more expedient approach to large-scale dating of subfossil trees and large bushes, which is sufficiently accurate and less labor-consuming, is the dendrochronological method based on the analysis of variation in radial increment.

At the Institute of Plant and Animal Ecology, Ural Division of the Russian Academy of Sciences, specialists of the Dendrochronological Laboratory have been collecting subfossil wood of the Holocene age in Yamal for many years in order to create continuous tree-ring chronologies for the past nine to ten thousand years by analyzing samples of larch and spruce (Shiyatov *et al.*, 1996). To date, this work has resulted in creating an absolute 7000-year chronology (from 5000 B.C. to 1996 A.D.) based on the data on larch and several "floating" chronologies for more ancient time, which were related to the calendar scale with the aid of radiocarbon dating. In the nearest future, we hope to connect these "floating" chronologies with each other and the abovementioned absolute chronology and, thus, to obtain an absolute and continuous chronology for nine to ten thousand years. This would allow us to determine absolute dates for more than 2000 samples of subfossil wood (including those from further northern areas of Yamal) with a high resolution (year, season), to reconstruct thermal conditions of summer months, and to estimate in detail the dynamics of woody vegetation in the forest–tundra zone and the polar boundary of open spruce–larch forest throughout the Holocene.

ACKNOWLEDGMENTS

We are grateful to N.G. Erokhin (Institute of Plant and Animal Ecology) and specialists of the Radiocarbon Laboratory of the Institute of Physics (University of Bern, Switzerland) for carrying out radiocarbon dating and calibration of results. This study was supported by the Russian Foundation for Basic Research, projects nos. 99-04-48984 and 96-04-50038.

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