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An 8768-year Yamal Tree-ring Chronology as a Tool for Paleoecological Reconstructions

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Abstract—In recent years, the supra-long Yamal tree-ring chronology has been significantly extended and became much more reliable. This article characterizes the sample wood used to build the longest absolutely dated Siberian Larch tree-ring chronology of the Subarctic area, i.e. from 6748 BC to 2019 AD, for a total continuous period of 8768 years. The ecological value of the temporal and spatial distribution of the dated trees are presented, and their potential use for application in various field of natural sciences and humanities are discussed.

Keywords: tree rings, supra-long tree-ring chronologies, Yamal, subfossil wood, tree line

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Tree-ring chronologies are widely used to reconstruct various parameters of natural environment. The significance of these time series is determined, among other things, by their extension. Chronologies spanning thousands of years are of the highest value. To date, very few tree-ring series spanning several millennia have been built throughout the world. Some of them (e.g., the formally longest 12 460-year chronology for Central Europe [1] and some other European and North American chronologies [2–4]) have limited application and are hardly used for reconstructing past environmental conditions. Chronologies with a strong climate signal (e.g., a temperature signal) are most important in this context.

There are currently only nine such tree-ring series extending more than 2 thousand years throughout the world: two series in the Southern Hemisphere (the south of Chile [5] and Tasmania [6]), three series in the Northern Hemisphere outside Russia (Quebec [7], Scandinavia [8, 9], and Alps [10, 11]), and four series in Russia (Altai [12], northern Yakutia [13], Taimyr [14], and Yamal [15]). The temporal coverage of three of the above-mentioned chronologies exceeds 7 thousand years: Alpine (about 10050 years), Scandinavian (7536 years), and Yamal chronologies.

The purpose of this research is to present an 8768-year tree-ring chronology for Yamal, characterize the material used for its construction, demonstrate examples of its use for paleoecological reconstructions, and show the prospects for its application in other fields of natural and human sciences.

MATERIAL AND METHODS

The Yamal Peninsula is one of the few areas in the world with large amounts of well-preserved subfossil trees that died thousands of years ago. S.G. Shiyatov was the first to assess the possibility of using this material for constructing a long-term tree-ring chronology [16]. In 1964, he collected the first subfossil wood samples. The systematic work on creating the collection of ancient wood samples from Yamal started in 1982. Since then, 20 expeditions have been carried out and cut samples were taken from 4800 dead trees. Subfossil wood samples were collected in the southern half of the Yamal Peninsula (Fig. 1). Most of this area is currently devoid of forests. Forest vegetation wedges deep into tundra to about 67°30′ N only in the southern part of the peninsula, along the valleys of some rivers, where sparse larch and spruce–larch forests are widespread in the middle reaches.

Alluvial deposits are the most important source of subfossil wood. Under the conditions of intensive lateral erosion of sandy shores, living trees growing along the river terraces are washed away, fall into water

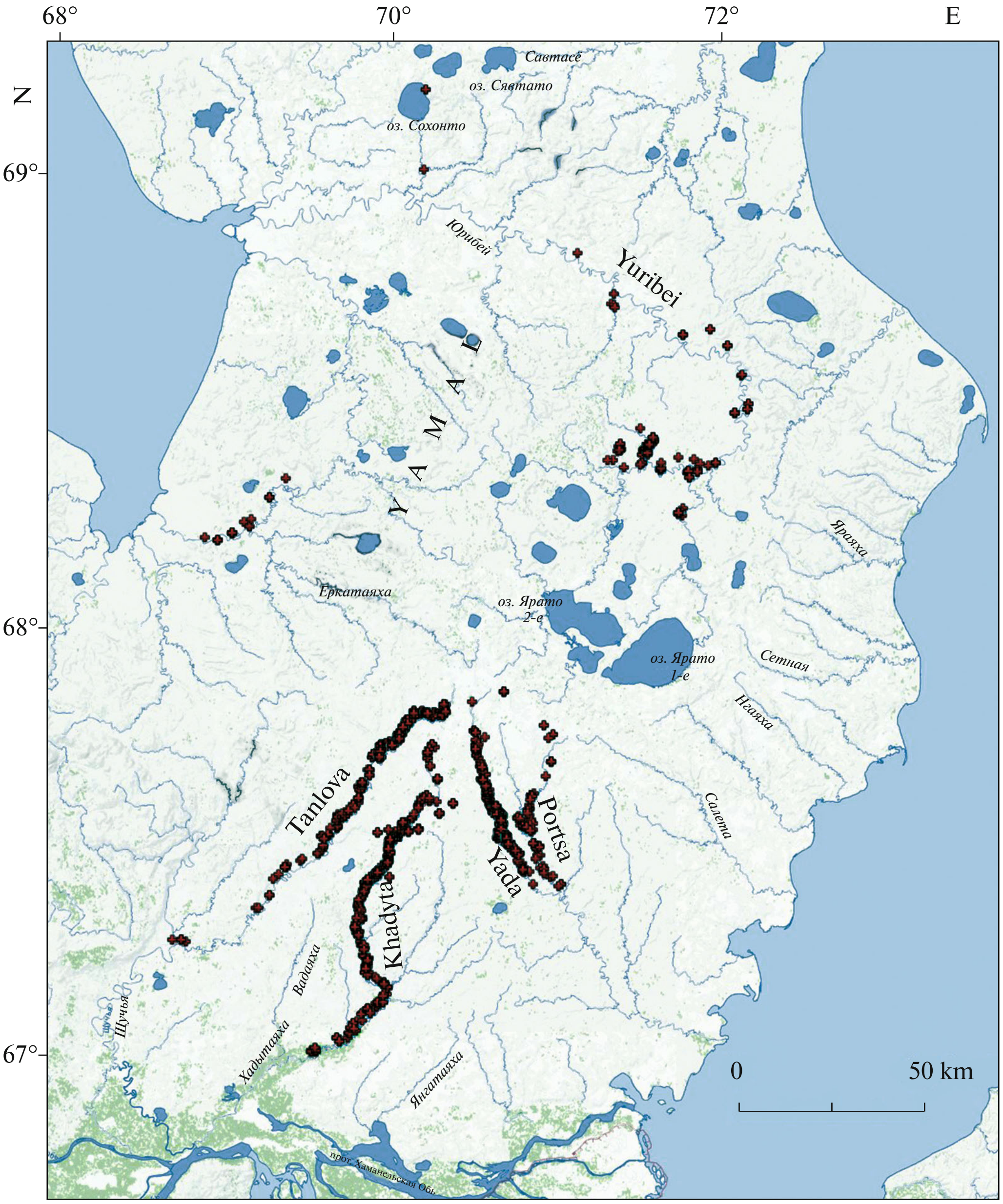

Fig. 1. Sites of collection of subfossil wood on the Yamal Peninsula.

streams, and are covered with sand and silt. The river channel changes and the washed-out trees are soon far from the river locked in permafrost layers. They can be exposed by the same river when its channel returns back to this place, reaching, on a deeper level. Peatlands eroded by rivers or lakes are another source of subfossil wood. Several samples were collected far from river valleys, from trunks extracted from permafrost. They were probably also buried in peatlands. In addition, dead tree remains can be found in Yamal on the land surface in situ.

The most widespread tree species in the collections of subfossil wood samples is Siberian larch (*Larix sibirica* Ledeb.): 91% of all samples; 6.2% of samples were identified as remains of Siberian spruce (*Picea obovata* Ledeb.), 2.7% as remains of mountain birch (*Betula pubescens* ssp. *tortuosa* (Ledeb) Nyman), and 0.1% as remains of alder (*Alnus alnobetula* subsp. *fruticosa* (Rupr). Raus).

The tree-ring width of subfossil wood collected before 1993 was measured under a binocular microscope at an accuracy of 0.025 to 0.015 mm; it was then measured on semi-automatic devices for determining the dimensional characteristics of tree rings at an accuracy of 0.01 mm. In total, the annual ring width of 3800 samples, which were collected mainly from the trunks of subfossil trees and occasionally from root collars, have been measured to date.

The chronology was constructed using the cross-dating method [17]. At the first stage, individual time series were cross-dated based on subfossil wood with the master chronology of living trees, covering the period of about 300 years. As a result, a longer generalized chronology combining the data on living trees and dead wood was obtained. The cross-dating procedure was then sequentially repeated with all remaining samples, each time using the new extended chronology. During the construction of "floating" chronologies, individual chronologies of unknown age, which had a large number of rings and the minimum probability of missing rings, were selected. Chronologies based on these samples were used as temporal master chronologies. The floating chronologies were roughly bound to the calendar time using radiocarbon dating. A total of 166 subfossil wood samples from Yamal were dated at different times by the radiocarbon method: 53 of them at the Institute of Plant and Animal Ecology, Ural Branch, Russian Academy of Sciences, and at the University of Bern [18], and 113 at the Laboratory of Ion Beam Physics, ETH Zurich (13 samples by the AMS method and 100 samples by the speed dating method [19]).

RESULTS

Absolute and Floating Chronology

The current absolute chronology covers the period from 6748 BC to 2019 AD, with at least three or more samples from 6671 BC. The chronology in Fig. 2 only includes the individual series of Siberian larch. The construction of the chronology did not include root collar samples, as well as damaged samples, which could lead to the distortion of the variability of the annual ring width, and samples with long-term periods of growth suppression, which made it difficult to accurately date some of the rings. Individual series were indexed using a 50-year cubic spline in ARSTANL [20]. It is important to emphasize that this method does not make it possible to reveal secular and supersecular growth fluctuations; therefore, the use of the presented chronology is limited for dating purposes.

In addition, a floating chronology from 14 trees with a duration of 337 years was built. Radiocarbon dating of two samples included in this chronology makes it possible to approximately (with an uncertainty of about 70 years) estimate its calendar dates from 7080 to 6744 BC. Three or more samples are available for the period of 216 years (from about 6996 to 6781 BC) (see Fig. 2). It is possible that the floating chronology overlaps with the absolute one; however, the duration of this overlap is not yet sufficient for the cross-dating of these chronologies.

Characteristics of Measured and Dated Samples

On average, each measured sample has 125 rings; however, the distribution is biased towards fewer rings (Fig. 3), the median accounts for 110 rings, and 44% of samples have 100 rings or less. A total of 2071 subfossil wood samples were dated using absolute chronology. If we include 14 samples from floating chronology, this will account for about 55% of trees for which the growth ring width was measured. Most of the remaining 45% of samples were not dated due to a small number of rings. The proportion of dated samples increases among samples with a greater number of rings.

The proportion of spruce and birch is slightly lower among the dated samples than in the total collection of samples (3.9 and 0.6%, respectively). This is probably due to the fact that the absolute chronology is based on information about larch, which may have some features of radial growth even under the effect of a common limiting factor for all tree species, namely, the temperature of the growing season.

The sample coverage of the chronology varies among the river valleys (Fig. 4). Samples collected in the Yada River valley completely and relatively evenly cover the entire period of chronology. The proportion of trees that grew in the last 1.5–2 millennia is high in the Khadyta River valley. The valley of the Tanlova River is dominated by trees that grew 4–7 thousand years ago; there are no findings for the last 4400 years north of 68° N.

Most of the dated samples (2023 samples) are from alluvial deposits. These samples cover the entire interval of absolute and floating chronology (Fig. 5b). Thirty-four samples were dated from peat deposits. They cover most of the floating chronology and discretely cover part of the absolute chronology from 6209 to 3872 BC. Other five dated samples were collected far from the river valleys, from trunks extracted from permafrost (presumably from peatlands); their life intervals are distributed from 5135 to 4734 BC. Twenty-three samples were dated among the samples that were collected in situ on the daylight surface; most of them have died in the last 300 years, while the oldest remain died about 700 years ago (i.e. 1307 AD).

The geographical coordinates of subfossil wood findings allowed us to present the life spans of each tree along the latitudinal gradient (Fig. 5a).

DISCUSSION

Dynamics of the Polar Forest Boundary in Yamal

To interpret Fig. 5a it has to be considered that the locations of the subfossil wood in alluvial deposits may slightly differ from the original place of growth. This is due to the transfer of the washed-out trunk by the water flow down the river before its burial or due to the redeposition of buried remains. According to our observations, the distance of this transfer does not

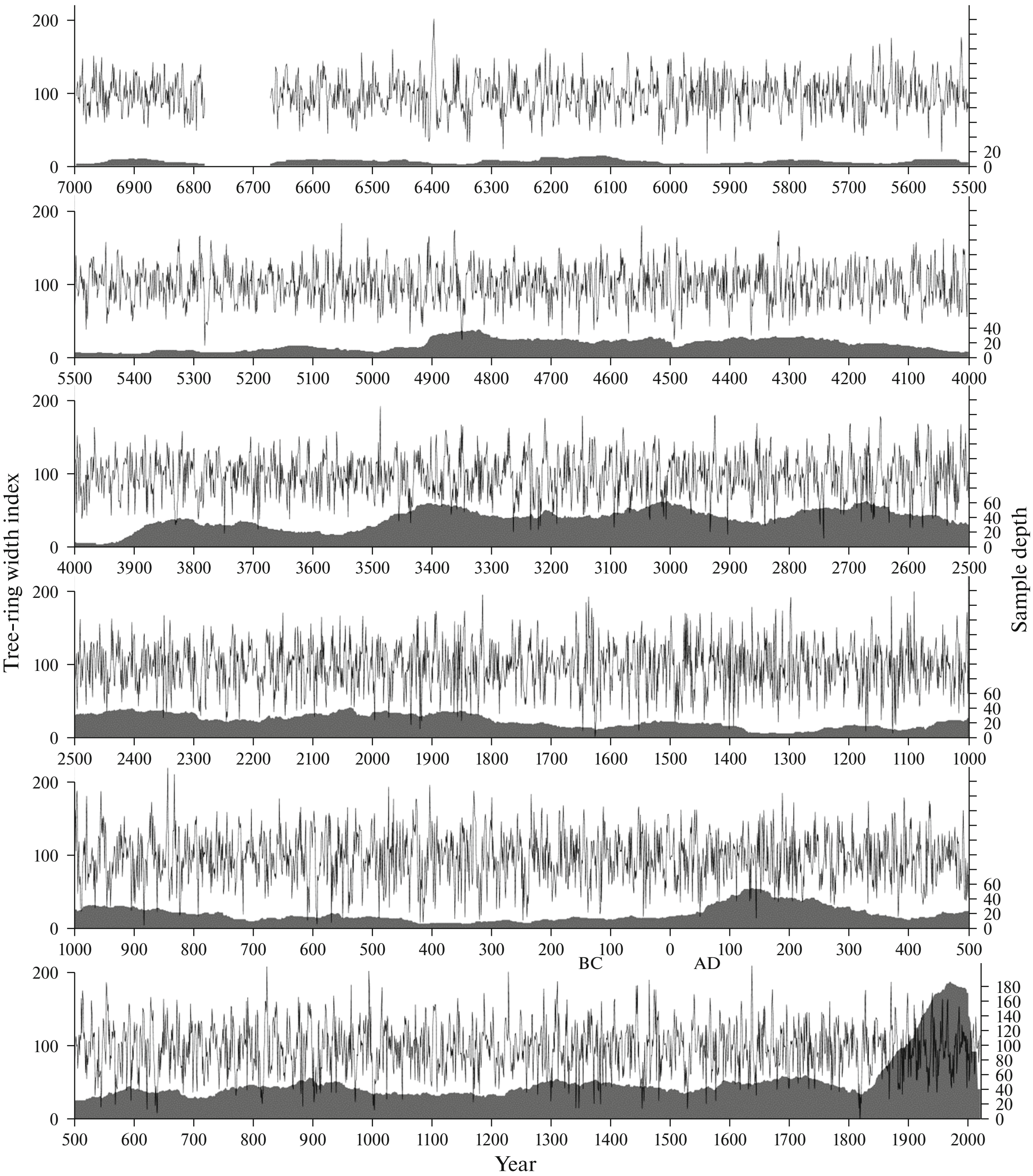

Fig. 2. Indexed Yamal chronology with only high-frequency variations (black line) and its sample depth (grey surface).

exceed several tens or the first hundreds of meters; a tree can be transferred down the river over several kilometers only in rare cases. The transport of trees by the river flow can introduce an error in determining the position of the northern forest boundary. However, this is true only for the area north of 68° N in our case. The Yamal rivers to the south of this latitude flow from north to south (see Fig. 1); therefore, the transfer of driftwood from south to north is completely excluded.

Figure 5a clearly shows a shift of the forest boundary to the south in the 3rd millennium BC. The last of the trees that we found north of 68° N died in 2419 BC. This retreat was accompanied by a decrease in the number of trees, which started in about 2550 BC and

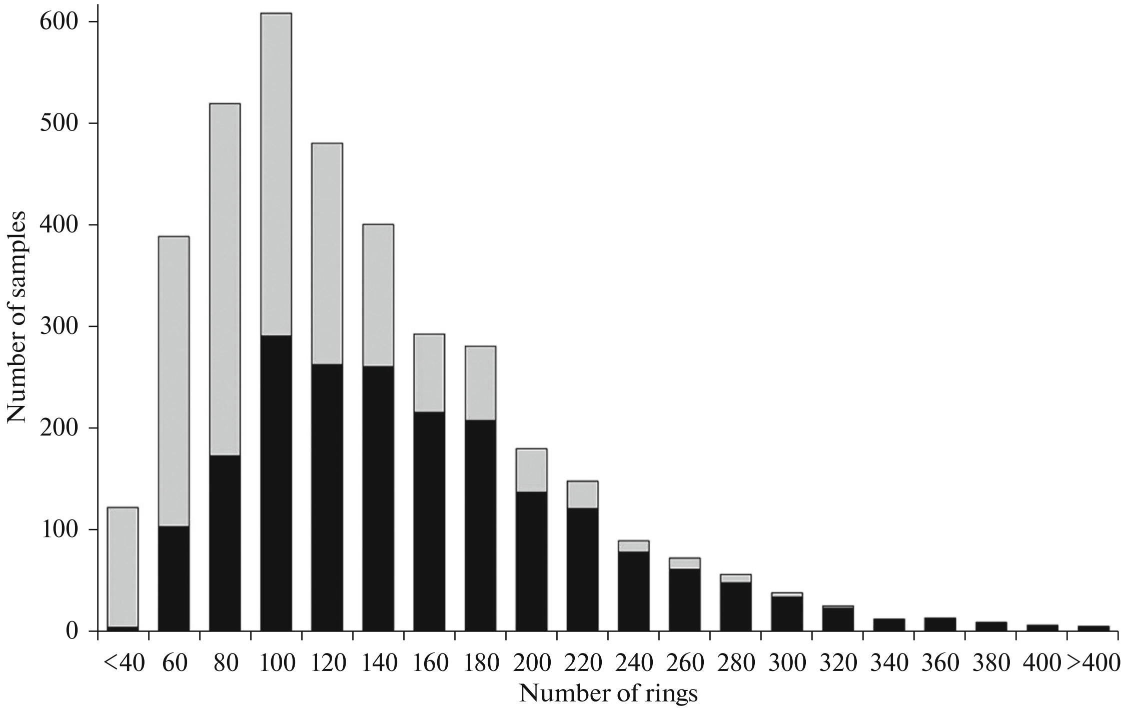

Fig. 3. Distribution of samples by tree age. The black colored part of the bars indicate the amount of dated samples.

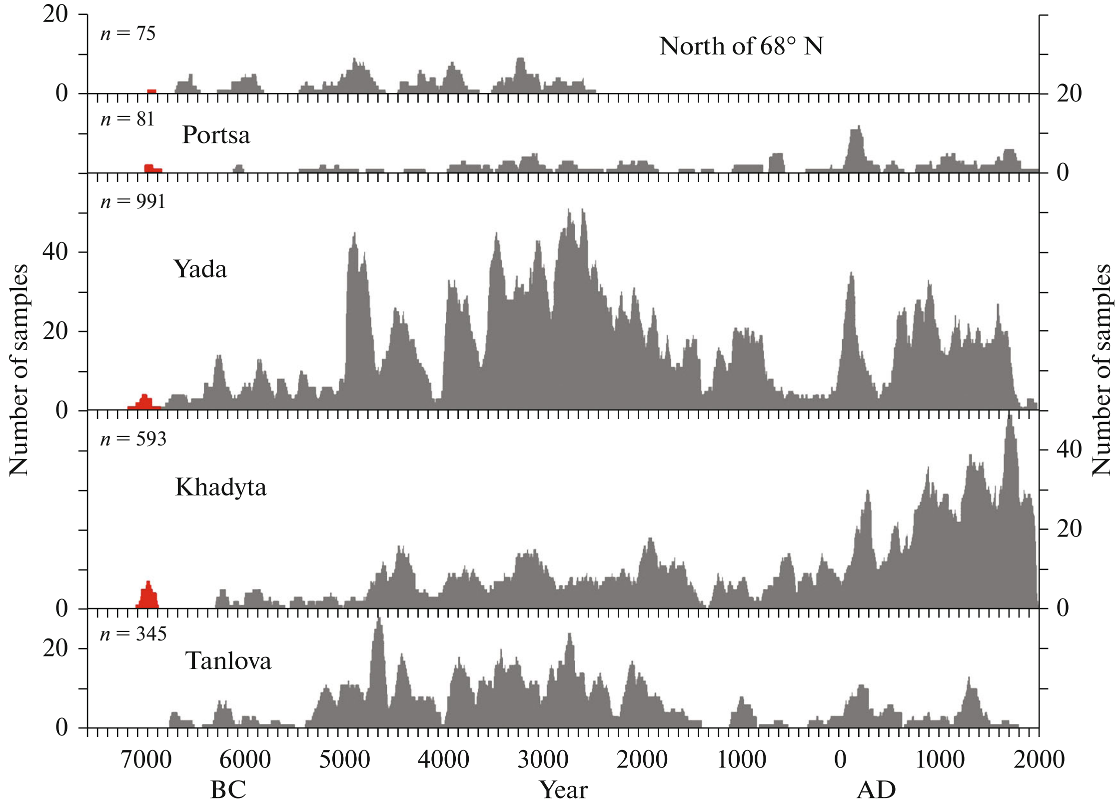

Fig. 4. Temporal coverage of samples collected in the different rivers in the southern part of the Yamal Peninsula (including the nearby lakes outside the valleys). "Floating" chronology samples are highlighted in red.

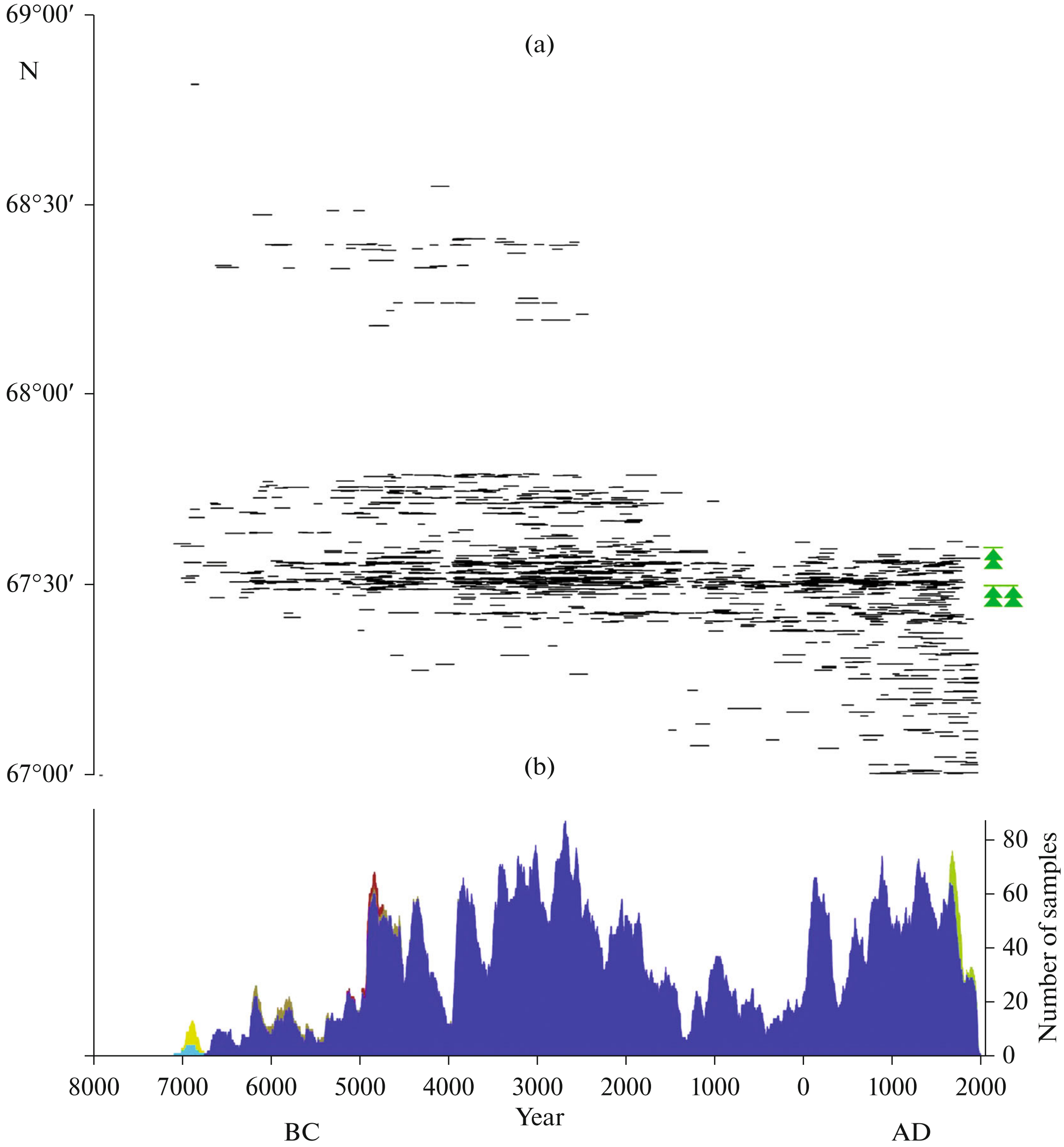

Fig. 5. Overview of lifespans of individual trees (a) and temporal coverage of the samples (b) along latitude. The green symbols in (a) indicate the latitude of the current position of the northernmost open (upper symbol) and northernmost open forests (lower symbol) in the river valleys. In (b), trees from alluvial deposits are in blue, those from peatlands are in brown, and those on the surface are in green.

lasted until 2250 BC (see Fig. 5b). The last date coincides with the transition from the Northgrippian Holocene period to the Meghalayan period (about 4200 years ago) (about 2250 BC) [21]. However, the shift of the forest boundary to the south did not stop at this point and continued for several more centuries. Between 1650 and 1500 BC, the polar forest boundary additionally retreated by approximately 20 km, to about its current position.

However, during the retreat to the south, small groups of trees in some (presumably, particularly favorable) habitats might be preserved 10–15 km north of the polar boundary of distribution of open forests along river valleys for 200–500 years. Finds of single trees (five individuals; all the individuals in the Tanlova River valley) at a distance of over 10 km to the north of the main set of samples dated for this time indicate the presence of small refugia of forest vegetation. The presence of these places to survive under unfavorable climatic conditions can explain a very rapid displacement of the boundary of open forests to the north in the 20th century after its significant shift at the beginning of the 19th century. Thus, larch that appeared at the beginning of the 19th century was recorded on the Yada River in the group of the northernmost currently growing trees; i.e., the boundary of distribution of single trees has changed very little during the last two centuries, while the boundary of open forests in the 19th century AD was much farther to the south than its current position [22].

Along with the high number of recorded samples, the favorable conditions for tree growth during a certain period can be indicated by tree remains extracted from peatlands. This is evidence that, at that time, trees occupied not only river valleys but also upland habitats (50–60 m a.s.l.), which are less favorable for the growth of woody vegetation than valley areas. These periods include the interval covered by floating chronology, which is built mainly on the basis of data on trees from peatlands, as well as the periods from 6200 to 5300 and from 5150 to 4500 BC.

If we continue the comparison with the formal division of the Holocene into periods, the transition from the Greenlandian to the Northgrippian period about 8200 years ago (about 6250 BC) is not marked by any remarkable event according to our data. Possibly, this period marks the first significant shift of the forest boundary to the south, which, according to the views based on the data of radiocarbon dating of subfossil wood [18], occurred in Yamal about 7400 years ago. The more accurate dating of this shift requires large-scale collections of subfossil wood north of 69°.

Data on the "southern" boundary of tree distribution along the valleys of the rivers under consideration are of certain paleogeographic interest. This boundary is obviously determined by the degree of flooding of the mouth and lower reaches of the Khadyta River, where the southernmost samples were collected (see Fig. 1). After a decrease in the river level, trees began to grow in this area (mainly in the last 1500 years). It is possible that the water level decreased due to the shallowing and drying of lakes in the upper reaches of the river and its tributaries. This process has also been noticeable in recent decades (personal observations). It is quite possible that the change in the river level is determined by marine transgressions. If we accept this assumption, the sea level was higher than the current one 7–9 thousand years ago and gradually decreased. The difference in the elevation of the river level between the latitude where the "southern" boundary of tree distribution passed approximately until 1500 BC and latitude where the southernmost remains of dead trees were found at a later time is about 10 m.

Time of the Appearance of Woody Vegetation in Yamal and Possibility of Extending the Chronology

Radiocarbon dating of subfossil wood from northern Yamal regions indicates that the peninsula was almost completely covered with forest back in the early Holocene, no later than 10 thousand years ago [18, 23]. However, according to the data on the possible [24] and real [22] rate of the expansion of coniferous trees to the north, Yamal afforestation could not occur in a relatively short period (1–2 millennia) at the beginning of the Holocene. Presumably, open forests or single trees also survived on the peninsula in the Late Pleistocene. This is evidenced by the data of radiocarbon speed dating of one of the subfossil samples that we found in the upper reaches of the Tanlova River, which has an age close to the limit of detection by the dating method, i.e., more than 40 thousand years (ETH-103244). Woody remains that were found on the Bely Island, at the northernmost edge of the Yamal Peninsula, were approximately of the same age, according to [25]. On the Gydan Peninsula to the east of Yamal, north of 72°N, larch branches were found in the stomach of a mammoth that lived about 18 thousand years [26]. The dating of these branches by the AMC method at the Laboratory of Ion Beam Physics, ETH Zurich, showed an even earlier radiocarbon age: 46098 ± 924 years (ETH-102854).

As a result, there is reason to believe that single trees might grow on the Yamal Peninsula in the Late Pleistocene. Since the average annual temperatures were much lower in that period than at the present time [27], it can be assumed that the climate was much more continental and the low average annual temperatures were mainly due to severe winter, rather than summer, conditions.

The presence of wood at the age of several tens of thousands of years on the Yamal Peninsula does not mean that it is possible to build a continuous chronology of this duration. Finds of Pleistocene wood are extremely rare. It is currently real to additionally extend the absolute chronology by 300–400 years, i.e., to 7050–7150 BC, by connecting it with the nearest floating chronology. The further extension of the chronology back through the centuries is problematic.

The calibrated age of six of the 166 samples dated by the radiocarbon method proved to be higher than 9000 years (not taking into account the Pleistocene samples): in the range of 7535 to 7060 BC. Four of them are possibly covered by the floating chronology; however, they are not yet dated with this chronology, primarily due to the small number of rings. It is difficult to construct new floating chronologies based on two older samples (7535 ± 180 BC (ETH-103209) and 7430 ± 350 BC (ETH-103145) (calibrated dates)), since they also have a small number of rings: 67 and 57, respectively. Therefore, we expect to extend the current chronology to 9500 years only in the long term. A further extension is questionable.

Prospects for Using the Yamal Supra-long Chronology

The Yamal tree-ring chronology is an excellent tool for reconstructing various parameters of the natural environment in the past. First of all, the chronology based on the width of tree rings has a strong climate signal [28]: it helps to reconstruct various air temperature indicators in summer seasons at annual resolution. Reconstruction requires the use of a particular approach to selecting samples and methods of indexing the primary data. The homogeneity of chronology requires one to use only one tree species and a relatively small area from which the samples were collected, i.e., use the data on larch collected in the range from 67° to 68° N. To preserve data on supersecular climatic fluctuations, one should apply indexing methods using regional curves, which, in turn, requires a large number of samples (not less than 10–15 samples for each reconstruction year). To date, only part of the period covered by the chronology meets these conditions.

Analysis of anomalous anatomical structures, such as frost rings, false rings, and light rings, makes it possible to reconstruct extreme temperature events, some of which are indicators of large volcanic eruptions [29].

A promising approach is the analysis of the cellular structure of tree rings, which makes it possible to reconstruct the climatic parameters that can hardly or cannot be determined using the tree ring width.

As shown above, chronology makes it possible to carry out large-scale and very accurate dating of the life span of trees, the remains of which have been preserved in alluvial and peat deposits and on the surface. This dating method makes it possible to reconstruct the dynamics of various parameters of woody vegetation: position of the northern boundary of open forests, ratio of tree species, density and age structure of stands, etc. [15, 30]. None of the currently known methods can make the dating of wood remains at large-scale and accurate as this one.

The wood of precisely dated rings can be used in constructing calibration radiocarbon curves. Serious initiatives to build a calibration curve with annual resolution using materials from different regions of the globe have been planned and begun to be implemented in recent years [31].

Finally, chronology makes it possible to date archaeological Yamal settlement (where wood remains with an undisturbed tree-ring structure have been preserved) almost throughout the Holocene period [32, 33].

Thus, the 8768-year chronology, which was built using ring width data of subfossil trees in Yamal (the longest chronology for the circumpolar regions of the Earth), is a unique tool for reconstructing various parameters of the natural environment in the Holocene.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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