Botanica Pacifica. A journal of plant science and conservation. 2019. 8(1): 19–30
DOI: 10.17581/bp.2019.08107

RESEARCH PAPER

Changes of the *Pinus koraiensis* distribution in the south of the Russian Far East in the postglacial time

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Manuscript received: 22.10.2018
Review completed: 20.01.2019
Accepted for publication: 02.02.2019
Published online: 11.02.2019

A B S T R A C T

The newly obtained palynological and chronostratigraphic data allowed a definite conclusion on the time of the first appearance of the Korean pine (*Pinus koraiensis* Siebold et Zucc.) in the southern Far East of Russia. Its further evolution has been traced through the postglacial interval. As follows from our studies, after the last stage of the Pleistocene cryochron had come to its end, the Korean pine expanded its range and gained in importance in the continental ecosystems of the Russian Far East. The species boundary shifts to the north were synchronous with episodes of climate changes. Soon enough the Korean pine occupied a prominent place in the vegetation: it became one of the leading components in spruce-fir forests with oak and elm in the Early Holocene. Intervals noted for an increase in its proportion in the vegetation coincided mostly with periods of greater heat supply. According to the obtained palynological data supported by radiocarbon dating results, it fell on the middle intervals of the Early and Middle Holocene, and also on the 2nd part of the Late Holocene. At that, the most diversified plant formations with the Korean pine were most typical of the Holocene optimum. The species importance was somewhat reduced at the time of a lower heat supply at the end of the Early Holocene, as well as at initial stages of the Middle and Late Holocene – the intervals marked by a reduced participation of the broadleaf species, while dark coniferous and small-leaved trees became more important.

K e y w o r d s : southern Far East of Russia, Korean pine, vegetation evolution, plant migrations in time and space, Holocene, environmental components

Р Е З Ю М Е

Белянин П.С., Белянина Н.И. Изменения распространения *Pinus koraiensis* на юге российского Дальнего Востока в послеледниковое время. В статье приводятся новые палинологические и хроностратиграфические данные, позволившие датировать появление и описать пространственно-временную динамику сосны корейской (*Pinus koraiensis* Siebold et Zucc.) на юге Дальнего Востока России в послеледниковое время. Нами показано, что после завершения последней стадии плейстоценового криохрона, в континентальных экосистемах юга Дальнего Востока России началась экспансия сосны корейской. Ее ареал смещался к северу синхронно с улучшением климатических условий. Сосна корейская достаточно быстро заняла ведущую роль в растительности, став уже в раннем голоцене одним из основных компонентов елово-пихтовых лесов с дубом и ильмом. Расширение ее участия в растительности соответствует периодам с лучшей теплообеспеченностью, что согласно полученным нами палинологическим данным, подкрепленных результатами радиоуглеродного датирования, приходится на середину раннего и среднего, а также на вторую половину позднего голоцена. При этом, наиболее флористически разнообразные растительные формации с сосной корейской получали развитие в оптимум голоцена. Сокращение ее роли в растительности фиксируется при снижении теплообеспеченности в конце раннего, а также на начальных стадиях среднего и позднего голоцена, когда снижалось участие широколиственных растений, но возрастала роль темнохвойных и мелколиственных пород.

Ключевые слова: юг Дальнего Востока, сосна корейская, эволюция растительности, пространственно-временные миграции растений, голоцен, ландшафтные компоненты

The Korean pine (*Pinus koraiensis* Siebold et Zucc.) belongs to the pine family (Pinaceae Lindl.), genus *Pinus* L. It is one of the chief forest-forming species in the south of the Far East of Russia – the region is among those, quite few in number, with barely disturbed primary forests still occurring (Krestov 2003). The species is included into the Red List of Threatened Species developed by the International Union for Conservation of Nature (Thomas & Farjon 2013).

It is not quite clear when the Korean pine first appeared in the continental ecosystems of the southern Far East of Russia in the postglacial time; nor its dynamics has been completely understood in the Holocene plant formations. According to the present views, the Last Pleistocene cryochrone (corresponding to Marine Isotope Stage 2) was marked by a major restructuring of the vegetation all over the Earth including the Sea of Japan basin. Under deteriorating climate conditions the south of Russian Far East was dominated by forests of spruce and fir, birch and larch with shrub birch (Korotky et al. 2005, Anderson et al. 2017), and a negligible presence of the Korean pine. The latter species was confined to the south of the Korean Peninsula and extended to the islands of Japan joined with the continent by a land bridge due to the lower sea level stand (Khershberg et al. 2013, Tsukada 1984, Igarashi 1993, Nakamura & Krestov 2005).

The abundant pollen records recovered from sequences dated to the Late Pleistocene cryochrons lend support to the view that the Korean pine disappeared almost completely from the southern Far East of Russia. Nevertheless, it is quite possible that pollen grains of *Pinus* subgenus *Haploxylon* recovered from interstadial deposits in the southern Far East are attributable to *Pinus koraiensis*. That is suggested by the taxonomic composition of pollen spectra indicative of a wide occurrence of dark coniferous (spruce and fir) forests highly diversified in structure. The presence of the Japanese stone pine (*Pinus pumila* (Pall.) Regel) (similar to *Pinus koraiensis* in the pollen grain morphology) may be practically excluded as the species is light-demanding and poorly competitive; it can hardly compete with other trees and shrubs and does not form compact communities under a close canopy of trees (Kabanov 1977).

The biostratigraphic data have been obtained from studies of fluvial-lacustrine deposits (borehole 579, depth. 5.2 m) dated by radiocarbon at 21 402±453 cal BP (Ki-2166); the proportion of *Pinus koraiensis* pollen in the spectra amounts to 6.2 % (Belyanin & Belyanina 2012). Individual pollen grains of *Pinus koraiensis* (Anderson et al. 2017) were recovered from the Lake Karasye sediments chronologically close to the above mentioned (20 599±83 cal BP, CAMS # 73291). Pollen assemblages recovered from valley deposits in the middle reaches of the Bikin River dated at 17 290±170 cal BP (LU-7559) show the proportion of *Pinus koraiensis* pollen up to 17 % (Razzhigaeva et al. 2017). The deposits sampled downstream the same valley (observation points 6204 and 6205) and dated by the radiocarbon to 21 673±448 cal BP (Ki-3293), 18 138±288 cal BP (Ki-3294), and 13 173±112 cal BP (Ki-3343) yielded only rare grains of the Korean pine pollen.

Though the evolution of the Russian Far East through the Late Pleistocene and Holocene has been investigated in considerable detail (Anderson et al. 2017, Alekseyev & Golubeva 1980, Golubeva & Karaulova 1983, Korotky 2002, Korotky et al. 2005, Mikishin et al. 2008, Pavlyutkin & Belyanina 2002, Razjigaeva et al. 2018), the spatial-temporal migrations of vegetation constituents in the region are still insufficiently understood. That is true in particular for the time of the Korean pine appearance and its dynamics trough the post-glacial time. Most likely, it may be attributed to some gaps in biostratigraphic records not yet adequately investigated. Slight changes in the ranges of plants resulting from small-amplitude and short-term climatic fluctuations are hard to record. Besides, finding and opening the Early Holocene and Late Pleistocene sequences presents certain problems. All the above interferes considerably with reconstructing paleoenvironments and forecasting development of continental ecosystems in the Pacific landscape zone.

Most of earlier works tend to assign the Korean pine appearance in the southern Far East to the Late Holocene. According to Shumova and Klimanov (1989), its expansion started about 900 cal yr BP, while Urusov (1999) considers the beginning of the Korean pine dispersal over the region to occur after 4000 cal. yr BP. In the opinion of Neustadt (1952) based on studies of pollen assemblages recovered from peat sequences, the Korean pine first appeared in the southern Sikhote-Alin foothills and in the East Manchuria Mountains as early as the Early Holocene 12 000–9500 BP, or about 13 800–10 800 cal BP. This opinion, however, could not be properly substantiated as the studied sections were too few in number and had not been dated by radiocarbon. It was much later that the first evidence of the Korean pine expansion onto the southern Far East of Russia in the Early Holocene were obtained (Pavlyutkin & Belyanina 2002, Mikishin et al. 2008, Anderson et al. 2017, Belyanin 2017). However, no investigation aimed specially at the stated problem has been performed.

The present paper presents the first high-resolution record of the Korean pine evolution in the south of the Far East in the Holocene. The purpose of the present study is to date the Korean pine appearance and to reconstruct its participation in the regional vegetation through the post-glacial time.

OBJECT, MATERIAL AND METHODS

When viewed in the context of the East Asian continental ecosystems, the Korean pine is a typical element of landscapes in mountain systems of the Sikhote-Alin, Manchurian-Korean Mountains, Changbai Plateau, Wanda mountains, and the Lesser Khingan Ridge (Kolesnikov 1954, 1956, Nakamura & Krestov 2005). On the Islands of Japan it is found occasionally in the Central and Southern Japanese Alpes (Honshu Isl.), as well as on Shikoku Isl. (Ohwi 1965) (Fig. 1).

Range and ecology

The Korean pine range coincides closely with the boundaries of the Manchurian floristic province notable for the pine forests being a typical constituent of the ridge-and-valley landscapes (Komarov 1949). In the south of the Russian Far East forests of Korean pine are mostly confined to the altitudes between 200 and 900 m a.s.l. In the Northeastern China they grow at altitudes from 500 to 1300 m, while on the Korean Peninsula (Chun 1994), on Honshu and Shikoku (Ohwi 1965) islands the Korean pine occurs at elevations up to 2500 m a.s.l.

There are three ecological zones recognizable within the Korean pine range in the south of the Russian Far East. In the southern zone (the Manchurian-Korean Mountains, southern Sikhote-Alin offspurs) it appears as a codominant in the formations most diversified floristically

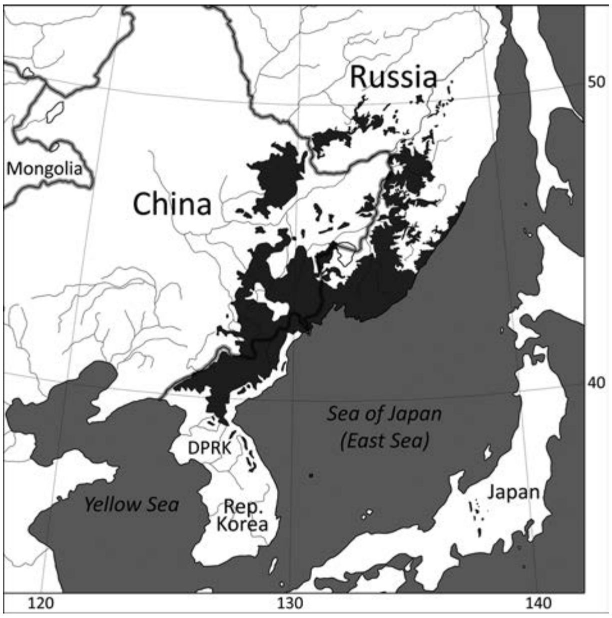


Figure 1 Distribution of forests with *Pinus koraiensis* (modified from Krestov et al. 2006)

and composed primarily of *Carpinus cordata* Blume, *Abies holophylla* Maxim., *Pinus densiflora* Siebold et Zucc. and others. In the middle zone (the northeast of China, southern and middle Sikhote-Alin) the Korean pine is distinct for the best growth and technical characteristics. Here it is a constituent of mixed and dark coniferous forests. In the northern zone (the Northern Sikhote-Alin and Lesser Khingan mountains) the Korean pine proportion in the dark coniferous forests with larch is reduced and it does not occur above 250 m a.s.l. That may be attributed to the lower annual temperatures and an increased competition with plants of the boreal taiga flora (Kolesnikov 1954).

Although the Korean pine is distributed over a large enough area, the most favorable climatic conditions for its growth exist between 41° and 49°N in North Korea and northeastern China (Kolesnikov 1954, Urusov et al. 2007). In the southern Far East of Russia the greatest part of its range belongs to the Amur River drainage basin and a smaller part – to the coast of the Sea of Japan.

The Korean pine occurrence mostly depends on the climate (Soloviev 1958) (Table 1). In the Sea of Japan coasts the regional climate is under control of the southern monsoon, the continental climate influence increasing from the coast inland. The leading factors that determine the composition and structure of the mixed forest with *Pinus koraiensis* are as follows: the maximum temperature of the warmest month; the mean temperature of the warmest quarter of a year; total precipitation of the wettest month (Zhang et al. 2014).

Materials and methods

The suggested reconstruction of the Korean pine migration in space and time in based on the concept of climate-controlled migrations developed by Troitskiy (1979). The palynological and chronostratigraphic data have been obtained from observation points and sequences penetrated by boreholes and described in valleys and forelands of the Manchurian-Korean Mountains, southern and middle Sikhote-Alin (Fig. 2). The data were correlated using the stratigraphic scheme of the Quaternary suggested by the Subcomission on the Quaternary Stratigraphy and by the INTIMATE Working Group (Walker et al. 2012).

Pollen analysis

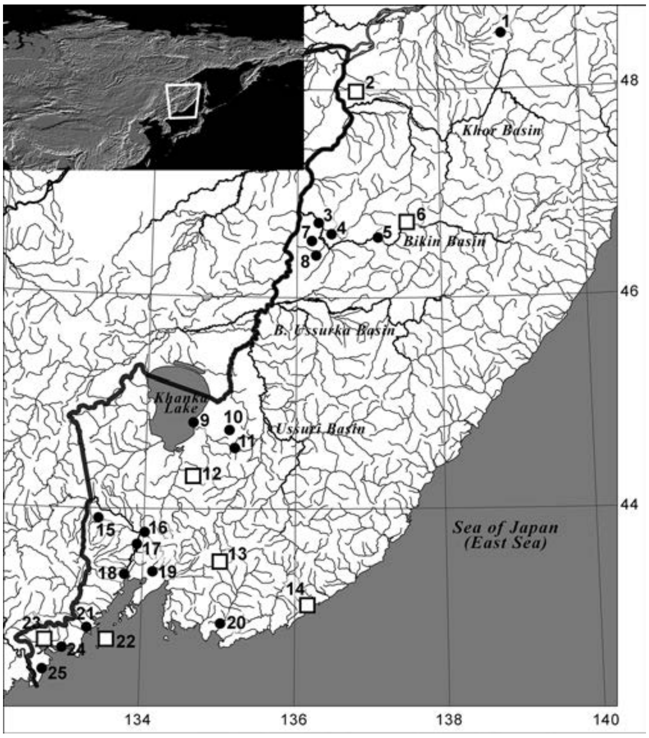
Pollen assemblages obtained by Belyanina from 132 samples permitted to trace changes in the Korean pine significance in the regional vegetation. The samples were prepared using the technique suggested by von Post (Pokrovskaya 1950). The specimens were viewed and photographically documented under the optical microscope Axio Scope A1 (Carl Zeiss). The pollen and spores were identified, when possible, to a level of species. In case of microfossils poorly identifiable by their micromorphology their genera or families were determined. The percentage of individual taxa was estimated separately for groups: arboreal pollen (trees and bushes – AP); herb and grass pollen together with dwarf shrubs (NAP); and spores. Proportion of aquatic plant pollen was calculated with reference to sum of land plant pollen.

Chronology

The chronology of changes in the Korean pine pollen proportion is based on radiocarbon dates and in their absence – on the stratigraphic correlation of palynological sequences. Tree and plant remains were dated by radiocarbon

Table 1. Extreme and optimum values of the most important climatic parameters that determine the range of Korean pine in the south of the Russian Far East (after Kolesnikov 1954)

Parameter of climate	Physical characteristics		
	minimum	maximum	optimum
Mean annual temperature, °C	0	+6	–
Extreme values of daily temperatures, °C	-50	+40	–
Number of months in a year with mean temperature above 0°C	6	8	7
Growing period, days	150	200	170–180
Duration of frost-free period, days	100	170	120–150
Degree day temperatures, °C	2600	>3200	–
Mean annual precipitation, mm	500	1000	600–700
Extreme values of mean annual rainfall in individual years, mm	320	>1200	–
Mean annual relative air humidity as recorded at 13 p.m., ‰	60	72	<70
Mean relative air humidity as recorded at 13 p.m. of the most rainy month (July or August), ‰	68	91	75
Mean relative air humidity as recorded at 13 p.m. of the most dry month in the growing period (April or May), ‰	41	45	–



in the Lawrence Livermore Center of Accelerated Mass-Spectrometry of the National Laboratory, Department of Energy, the University of California (T.A. Brown), and also in the Laboratory of Geochronology, St.-Petersburg State University (Kh.A. Arslanov, F.B. Maksimov), and in Institute of Geology, Academy of Sciences of the USSR (N.N. Kovalyukh). The radiocarbon dates were calibrated into calendar ones using the «CalPal» program (Weninger et al. 2012) (Table 2).

RESULTS

The reconstructions of Korean pine first appearance and subsequent occurrence in the south of the Russian Far East are based on the pollen assemblages recovered from a series of sections dated by ^{14}C (see Fig. 2 for the location of the sections).

Early Holocene

The first evidence of the Korean pine presence was recorded in the sequence of the Sorochevka River floodplain (borehole 508, in the vicinities of Chkalovka Settlement). The sandy loam layer dated to 11 003±186 cal BP

Figure 2 Locations of the boreholes and observation points studied by authors (dots) and other researchers (squares): **Khor River Basin:** 1 – o.p. Stream Bolotisty; **Kiya River Basin:** 2 – o.p. Kiya; **Bikin River Basin:** 3 – o.p. 6022, 4 – o.p. 6010, 5 – o.p. 08/20-2008, 6 – o.p. 314, 7 – 6056, 8 – o.p. 6205; **Upper Ussuri River and Khanka Lake Basin:** 9 – bor. 579, 10 – bor. 508, 11 – o.p. 4074, 12 – o.p. 1438; **South Primorye Region:** 13 – bor. 613, 14 – o.p. Kit, 15 – o.p. Kazachka, 16 – o.p. 9119, 17 – o.p. 4005, 18 – bor. Utinoye Lake, 19 – o.p. 1706-17, 20 – bor. 9, o.p. 9031a, 21 – bor. 24-1, 22 – o.p. Stenina Isl., 23 – bor. 272, 24 –bor. Karasie Lake, 25 – o.p. 1508-1

Table 2. Radiocarbon dates

Boreholes (bor.), observation points (o. p.)	No on the Fig. 2	Depth, m	Dated material	Laboratory number	^{14}C age, BP	^{14}C-calibrated age, cal BP
o. p. 6205	8	6.9	wood	Ki-3293	17 990±200	21 673±448
bor. 579	9	5.2	humified loam	Ki-2166	17 840±200	21 402±453
bor. Lake Karasye	24	3.24–3.23	seeds, wood, tree moss	CAMS # 73291	17 160±40	20 599±83
o. p. 6205	8	5.7	wood	Ki-3294	14 800±100	18 138±288
o. p. 6205	8	3.6	wood	Ki-3298	12 300±100	14 459±361
bor. 508	10	4.5	wood	Ki-2171	9680±130	11 003±186
o. p. 4074	11	2.0	buried soil	Ki-2140	9600±110	10 944±171
o. p. 6205	8	1.8	wood	Ki-3293	9270±60	10 440±99
o. p. 9119	16	2.1	wood	–	9250±70	10 421±103
o. p. 9119	16	1.6	wood	–	8960±80	10 079±112
bor. 9	20	6.5	plant detritus	Ki-3688	8900±60	10 030±112
o. p. Bolotisty Stream	1	3.2	peat	LU-8138	8620±90	9644±99
bor. Lake Karasye	24	1.40–1.37	seeds, wood, charcoal	CAMS # 73290	7550±40	8374±23
o. p. 4005	17	2.4	plant detritus	Ki-2365	7240±120	8077±111
o. p. 6010	4	1.7	plant detritus	Ki-3269	6660±70	7537±52
o. p. 4005	17	2.2	plant detritus	Ki-2159	6530±75	7434±74
o. p. 6056	7	2.9	plant detritus	Ki-3256	6090±70	6988±116
o. p. 6205	8	0.8	peat	Ki-3372	5120±80	5859±94
bor. Lake Karasye	24	1.04–1.03	seeds, charcoal	CAMS # 71814	5050±40	5813±63
bor. Lake оз. Utinoye	18	4.71–4.68	wood, charcoal	CAMS # 73295	5000±80	5763±98
bor. Lake Karasye	24	0.77–0.74	seeds	CAMS # 74346	4890±40	5632±26
o. p. 1706-17	19	1.86–1.89	buried soil	LU-8780	4650±110	5350±160
o. p. Kazachka	15	1.2	wood	DVGU-TIG-29	4472±75	5119±134
bor. Lake Karasye	24	0.67–0.60	seeds	CAMS # 73288	4300±40	4894±44
o. p. 9031a	20	2.4	wood	Ki-3686	4210±60	4736±92
bor. Lake Utinoye	18	3.47–3.45	wood	CAMS # 76800	3920±40	4329±64
bor. Lake Karasye	24	0.45–0.43	seeds	CAMS #74344	3870±40	4311±71
o. p. 1706-17	19	0.73–0.7	buried soil	LU-8779	3020±100	3190±130
bor. Lake Utinoye	18	2.23–2.21	plant detritus	CAMS #76799	2510±60	2589±109
o. p. 1508-1	25	2.88–2.73	buried soil	LU-7961	2460±100	2543±138
o. p. 6022	3	1.6	plant detritus	Ki-3270	2350±40	2398±49
o. p. 4005	17	1.8	wood	Ki-3678	1930±40	1883±43
o. p. 1508-1	25	1.52–1.44	buried soil	LU-7960	1930±100	1880±130
bor. Lake Utinoye	18	1.30–1.27	wood, leaves	CAMS #76798	1810±60	1736±80
o. p. 1508-1	25	0.65–0.57	buried soil	LU-7959	1360±60	1280±60

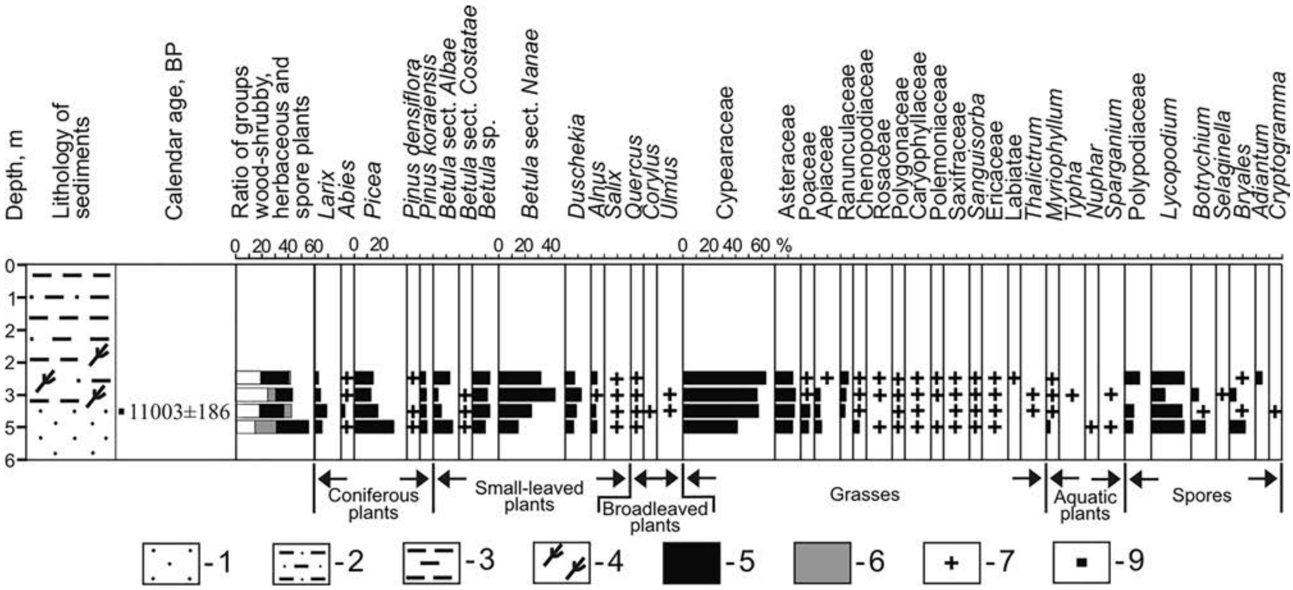


Figure 3 Pollen diagram from borehole 508. 1 – sand, 2 – sandy loam, 3 – loam, 4 – plant detritus. Relationship between plant groups: 5 – trees and shrubs, 6 – herbs and dwarf shrubs, 7 – spores, 8 – the taxa present in the assemblage in amounts less than 3 %. 9 – samples for ^{14}C analysis.

(Ki-2171) (see Table 2) yielded a pollen assemblage that indicates a subdominant position of the Korean pine (5 %) in the coniferous group including also *Picea* sp., *Larix* sp., and *Abies* sp. In the of small-leaved species group dominant are pollen of *Betula* sect. *Nanae*, *Betula* sp., as well as *Duschekia* sp. Some other trees – *Salix* sp., *Alnus* sp., *Betula* sect. *Albae* and *Betula* sect. *Costatae* – are present as accompanying species. The broadleaved trees are represented by *Quercus* sp., *Corylus* sp. and *Ulmus* sp. Typically, *Sphagnum* sp. spores are found in abundance (Fig. 3). The origin of those deposits is unquestionably indicated by the presence of the diatom assemblage characteristic of floodplains in the sample taken from 5 m depths.

The above data are complemented with the results of biostratigraphic studies of bluish-gray sandy loam exposed in the river bank scarp north of Kronshtadka settl. (observation point 4074) upstream of the above-described site (borehole 508) The proportion of *Pinus koraiensis* pollen in the assemblage amounts to 2.3 %, the age of enclosing deposits is 10 994±171 cal BP (Ki-2140) (see Table 2).

In the north of the Primorye region, in the lower reaches of the Bikin River (o.p. 6205), a layer of bluish-gray loam dated to 10 440±99 cal BP yielded a pollen assemblage distinct for a pronounced dominance of coniferous and small-leaved plants. *Pinus koraiensis* prevails in the coniferous group (29.4 %). It is accompanied with a few broad-leaved, such as *Ulmus*, *Picea*, *Quercus*, *Corylus* and *Tilia* sp. Small-leaved plant microfossils are present in a considerable proportion – *Betula* sp. (12.5 %), *Betula* sect. *Nanae* (30.9 %), *Betula* sect. *Albae* (up to 13.1 %), *Duschekia* (up to 9.2 %) and *Alnus* (up to 13.8 %)

The Korean pine presence has been documented also in the early Holocene deposits in the lower reaches of the Razdolnaya River, at the Popovka River mouth (o.p. 9119). A sample taken at a depth 2.1 m from blue-gray sandy loam with wood remains dated by ^{14}C to 10 421±103 cal BP contains the Korean pine in proportion of 2 %; its amount rises steeply upwards up to 65 % at a depth of 1.6 m (10 079±112 cal BP) (Fig. 4).

Similar biostratigraphic materials were obtained in studies of blue-gray loam with plant remains at the mouth of the Partizanskaya River near Golubovka village (borehole 9); there the *Pinus koraiensis* proportion amounted to 23.6 %. The age of the enclosing sediments is indicated by the ^{14}C date 9672±87 cal BP, Ki-3688) (Pavlyutkin & Belyanina 2002). A similar pollen assemblage with *Pinus koraiensis* proportion of 26.7 % has been obtained from a depth of 6 m at the Tumannaya Rover mouth (borehole 103).

In the Middle Sikhote Alin, at an altitude of 650 m a.s.l. there were dated and sampled loose deposits of the Bolotisty Creek (the upper part of the Khor River drainage basin). A sample of a heavily decomposed brown peat from a depth of 3.2 m was dated by radiocarbon to 9644±99 cal BP (LU-8138). The pollen assemblage recovered from the peat is dominated by *Picea*, with pollen grains of *Abies* and *Larix* also present, and the proportion of *Pinus koraiensis* is 2.3 % only. In the group of small-leaved species shrubs *Duschekia* and *Betula* sect. *Nanae* are dominant, along with some tree species – *Betula* sect. *Costatae*, *Betula* sect. *Albae*, and *Alnus*. Pollen of broadleaf trees – *Quercus*, *Ulmus* and *Tilia* – is rather scarce (Belyanin et al. 2018).

Previously, when studying dark-gray silts with wood fragments in the section of the Chernigovka River terrace (o.p. 1438), Korotky found a proportion of the Korean pine in the total assemblage to be high – up to 15 % ; the sample was dated by radiocarbon to 9160±108 cal BP (Korotky et al. 1980). At the mouth of the Vinogradnaya River at its entering the Expedition Bay (borehole 272) Mikishin identified a pollen complex distinct for a high percentage of *Pinus koraiensis* (59–64 %), accompanied by an assortment of broad-leaved and small-leaved plants. The enclosing sediments are dated to 8871±93 cal BP (Mikishin et al. 2008). In

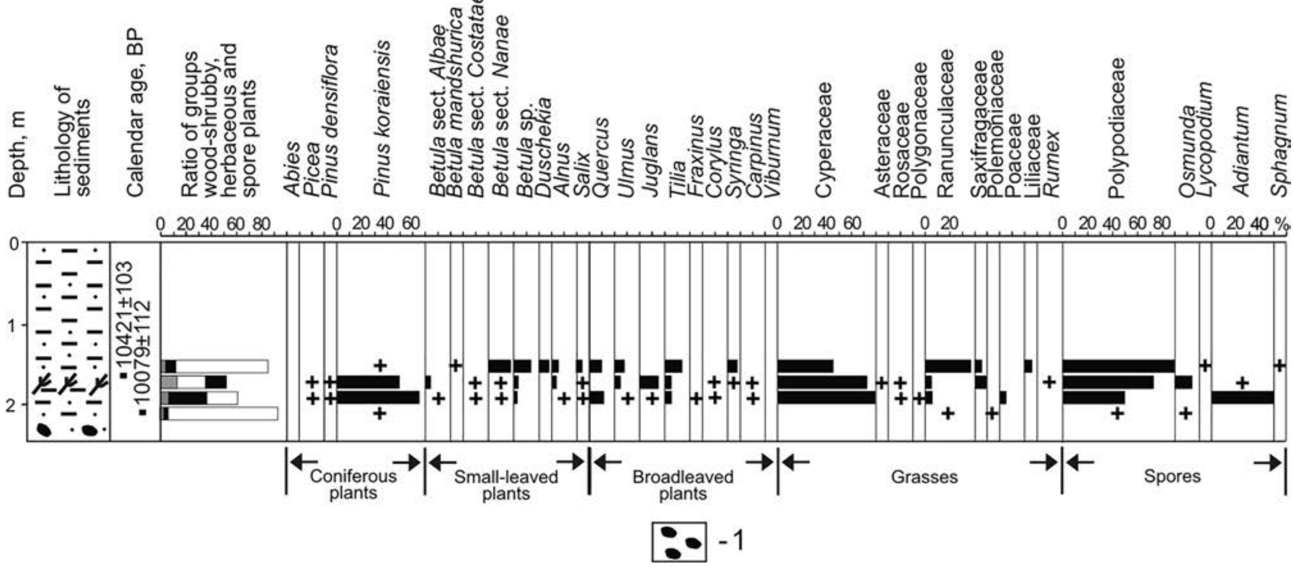


Figure 4 Pollen diagram from the sequence in o.p. 9119. For explanation see Fig. 3. 1 – pebbles

the extreme south of the Russian Far East there were single grains of the Korean pine pollen recovered from bottom sediments of Karasye Lake dated by ^{14}C to 8374±23 cal BP (CAMS # 73290) (Anderson et al. 2017).

Middle Holocene

The beginning of the next (Middle Holocene) stage in the Korean pine evolution in the region has been documented in the lower reaches of the Razdolnaya River (o.p. 4005). There a sand layer with plant remains (dated by ^{14}C to 8077±111 cal BP, Ki-2365) yielded a pollen assemblage dominated by *Pinus koraiensis* (30 %) and *Quercus* (35–42 %). A practically identical pollen assemblage was obtained from the same sequence slightly higher; it is distinct for the prevalence of moderately thermophilic plants – *Quercus*, *Ulmus*, *Juglans mandshrica* Maxim., and *Tilia*, while the *Pinus koraiensis* proportion is reduced to 14 % (its ^{14}C age is 7290±88 cal BP, Ki-2159). Such an assortment of taxa suggests polydominant forests with the Korean pine to be widely distributed in the surrounding landscapes (Pavlyutkin & Belyanina 2002).

The Korean pine occurred also in the landscapes of near-shore islands in the Sea of Japan. That is suggested by the pollen assemblage from the marine mud with mollusk shells sampled on Stenin Island (^{14}C age – 7252±46 cal BP); the amount of the Korean pine in it was 8 % (Lyashchevskaya 2016).

A similar pollen assemblage with amount of *Pinus koraiensis* varying between 19.7 % and 38.6 % was described in the lower reaches of the Poyma River, in the section of a steep bank (borehole 24-1), between 3.8 and 2.0 m from the top. The age of the sediments may be inferred from the assemblage of fluvio-marine diatoms that inhabited the near-shore water there at the time of high stand of the sea level (the Holocene optimum). The leading position in the studied assemblage belonged to the pollen of broadleaved trees, including *Quercus*, *Ulmus*, *Juglans* and *Carpinus* sp. They are accompanied by grains of *Syringa* sp., *Corylus*, *Acer* sp., *Tilia* sp., *Weigela* sp. and *Fraxinus*, as well as by some representative of Araliaceae Juss. and Rosaceae Juss. families (Belyanin 2017).

As follows from the palynological studies of the sediments in the lower reaches of the Bikin R., the Korean pine presence in the pollen assemblages was much lower. To take but a few examples, its proportion amounts to 2.1 % in the sample taken from the high floodplain of the Alchan River (o.p. 6010, ^{14}C age is 7537±52 cal BP, Ki-3269); in the sample taken from the high floodplain of the Burlitovka River (o.p. 6056, 6988±116 cal BP, Ki-3256) it is 2.3 %; deposits of the Kontrovod River terrace (o.p. 6205, ^{14}C 5859±94 cal BP, Ki-3372) yielded a slightly higher value – 3.6 %. The pollen assemblages are dominated by *Quercus* and *Ulmus* with accompanying dark coniferous, small-leaved, and broad-leaved plants (Belyanina 2005).

Similarly small amount of *Pinus koraiensis* pollen (2.3 %) was recovered from the Karasye Lake bottom sediments (silt) ^{14}C-dated at 5813±63 cal r BP, CAMS # 71814, and 5632±26 cal BP, CAMS # 74346. In the Utinoye Lake sediments of approximately same age (^{14}C 5763±98 cal BP, CAMS # 73295) it is as high as 9.8 % (Anderson et al. 2017).

Earlier, in the course of the biostratigraphic works in the Kit Bay, a peat layer yielded a pollen spectrum indicative of widely distributed forests of oak and Korean pine. The *Pinus koraiensis* pollen makes up to 65 % of the total. The enclosing deposits are dated at 5760±90 cal BP (Razjigaeva et al. 2018).

A high proportion of *Pinus koraiensis* pollen (33.7 %) was recorded in a sample taken from a terrace of the Knevichanka River (o.p. 1706-17) and dated at 5360±160 cal BP (LU-8780).

A pollen assemblage recovered from deposits of a high floodplain of the Bolshaya Kazachka River (Kazachka o.p.) displayed the Korean pine presence in a reduced quantity – 1.8 %. The sample taken from a depth of 1.2 m from the surface is composed of brownish-gray sandy loam. Its ^{14}C age is 5119±134 cal BP, DVGU-TIG-29). The bulk of the pollen consists of *Betula* sect. *Albae*, *Betula* sect. *Costatae*, *Betula* sp. and *Duschekia* sp. (Pavlyutkin et al. 1984).

A sandy silt member with plant detritus exposed in the Partizanskaya River bank (o.p. 9031a) was palynologically studied and dated by ^{14}C to 4736±92 cal BP (Ki-3686). The pollen assemblage is noted for an increased proportion of the Korean pine pollen (up to 57 %) (Pavlyutkin & Belyanina 2002). Similar pollen spectra were found in the bottom sediments of Utinoye Lake, the proportion of *Pinus koraiensis* pollen rising to 11.9 % (14C 4356±59 cal BP, CAMS # 75544) (Anderson et al. 2017).

Late Holocene

We can gain some idea of the Korean pine presence in plant formations at the beginning of Late Holocene from the pollen assemblage recovered from bottom deposits of Karasye Lake (an algal mud member dated by ^{14}C to 4311±71 cal BP, CAMS # 73288). The Korean pine pollen comes in it to 14.8 % of the total (Anderson et al. 2017).

In the north of the considered region the Korean pine pollen was recorded, though in smaller quantities (7.3 %, according to Belyanin 2013) in the floodplain deposits of the Bikin River (the middle reaches, o.p. 08/20-2008). Similar pollen spectra have been obtained from the floodplain sequences on the interfluve of the Khor and Kiya rivers (^{14}C 4089±145 cal BP) (Bazarova et al. 2008).

A high proportion of the Korean pine pollen (up to 28 %) was recorded in the Larchenkov swamp sediments (Shkotovo Plateau). About 3840±140 cal BP the pine was the dominant species in mixed forests with the participation of birch (Razjigaevaa et al. 2016).

Similar palynological data were inferred from an analyzed sample from the Knevichanka River terrace (o.p. 1706-17). The Korean pine pollen occurs there in abundance (up to 38.4 %), and the enclosing deposits were dated by radiocarbon at 3190±130 cal BP (LU-8779).

A high content of the Korean pine pollen, 22.1 %, was recorded in the bottom sediments of Utinoye Lake (^{14}C 2589±109 cal BP, CAMS # 76799) (Anderson et al. 2017). Marine sediments studied in a beach ridge at the Tumannaya River mouth (o.p. 1508-1) are composed of fine sand with plant detritus; they appeared to be close in age to the above-mentioned (^{14}C 2540±130 cal BP, LU-7961) and revealed a higher proportion (up to 24 %) of the Korean pine pollen.

A pollen assemblage absolutely dominated by *Pinus koraiensis* (up to 51.1 %) has been obtained in the lower reaches of the Bikin (o.p. 6022) with *Picea*, *Betula* sect. *Albae*, *Ulmus*, *Quercus* and *Juglans* present as accompanying species. The sediments were dated at 2398±49 cal BP (Ki-3270).

The analysis of peat from the Razdolnaya River floodplain (o.p. 4005) dated at 1883±43 cal BP (Ki -3678) also revealed a high percentage of *Pinus koraiensis* pollen (22.4 %) (Pavlyutkin & Belyanina 2002). The paleobotanical investigations performed on the Utinoye Lake bottom sediments (^{14}C 1736±80 cal BP, CAMS # 76798) revealed the Korean pine proportion as high as 18.3 %; that result is similar to the above cited, as well as to those obtained on the Shkotovo Plateau (Razjigaeva et al. 2016).

In the north of the region pollen assemblage recovered from a high floodplain sequence on the Bikin River is distinct for an exceedingly high proportion of *Pinus koraiensis* – 72.5 % (Belyanin 2013). Its high values (27 %) have been also documented by Razjigaeva et al. (2017) in the Larchenkovo swamp deposits dated at 240±160 cal BP.

DISCUSSION

The obtained pollen records dated on organic remains to 11 000–10 500 cal BP contain grains of *Pinus koraiensis* pollen (Fig. 5). The fact agrees well with evidence on the global climate and environment amelioration at that time (Korotky et al. 2005, Bezrukova et al. 2005, Anderson et al. 2017, Belyanin et al. 2018) which led to essential changes in the plant formation structure due to the beginning of the plant migrations northward. At that time the environments were favorable for a wide distribution of the Korean pine under the forest canopy. The ecosystems began to acquire gradually their modern appearance.

In the early Holocene the Korean pine presence in forest formations in the Middle Sikhote-Alin foothills was still insignificant. Farther south, however, in the southern Sikhote-Alin ridges and in the East Manchuria Mountains it became one of codominants in dark coniferous-small-leaved forests with Mongolian oak and elm. That is strongly suggested by the pollen records where the proportion of the Korean pine pollen is notably greater than in valley deposits of the Middle Sikhote Alin. The data are in good agreement with those on the Baikal vicinities where an expansion of another pine species – Siberian stone pine (*Pinus sibirica* Du Tour) began ~11 000 cal BP (Bezrukova et al. 2005).

A greater proportion of the Korean pine pollen in the Early Holocene pollen assemblages documented in the Southern Primorye (Maritime) regions suggests the species came to the Sikhote-Alin and Manchuria-Korean mountains from the Korean Peninsula where environment were favorable for the vegetation even at MIS 2 time (Tsukada 1984, Nakamura & Krestov 2005).

The transition from the Early to Middle Holocene was marked by a short-term cooling that resulted in the Korean pine being replaced in part by more cold-tolerant conifers. In the mountain ecosystems, in particular on north-facing slopes, the Korean pine (in common with broadleaved species) gave largely way to fir and spruce. Its presence was more considerable still in the Southern Primorye plant formations.

The heat supply continued to rise through the Middle Holocene which led to the shift of natural zones northward by 200–400 km (Khotinsky 1977). According to the data published by A.A. Velichko (2012), the global temperatures at the Holocene optimum were 0.7–1ºC above those of today. In all probability, the rise in temperature could be as great as 3–5º C in Primorye (Maritime territory) (Korotky et al. 1999), and 2–3 ºC in the south of the Korean Peninsula (Sohn 1984).

As a result of a rise of mean annual temperatures the Korean pine increased notably its presence in the south of the Russian Far East. Plant formations were more diversified in species composition as compared with that of the present days. Quite probably, they included species inhabi-

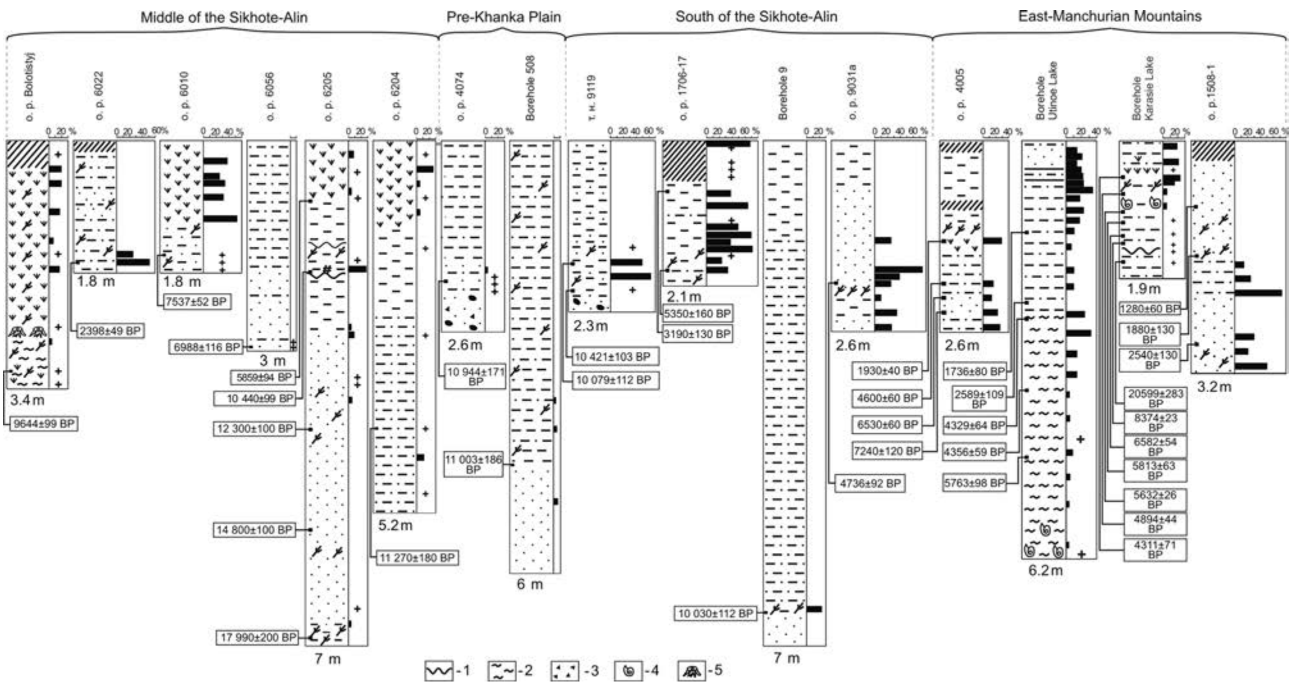


Figure 5 The presence of the Korean pine pollen in assemblages studied in the Holocene sequences (boreholes and observation points) in the southern Far East of Russia. For explanation see Fig. 3. 1 – gap in sedimentation, 2 – mud, 3 – gravel, 4 – marine shells, 5 – stump horizon

ting at present North Korea (north of 40ºN) and eastern regions of Mongolia; some of the genera were noted for a considerable species diversity.

It should be noted, that in a drier climate in the mountains in northeastern China, near Lake Sihaylongwan, the Korean pine began to spread ~ 6600 cal BP., and became one of the main forest-forming species ~ 5200 cal BP (Stebich et al. 2015). In the mountains of Changbaishan, the Korean pine expansion occurred ~ 5000 ^{14}C BP, 5800 cal. BP, and about Lake Qingbohu (Jingbo) ~ 5400 cal. BP (Li et al. 2011).

Similar processes are known to take place in the Near-Baikal region where the Siberian stone pine was one of the main forest-forming species ~6800 cal yr BP (Danko et al. 2009). The spatial migrations of plants were recorded also in the Middle Holocene on the Isles of Japan. For example, about 7800 cal BP *Larix cajanderi* disappeared from the flora of Hokkaido Island, and dark coniferous forests were replaced by oak forests with *Quercus crispula* Blume between 7800 and 5900 (Igarashi 1996), while warm temperate evergreen forests spread considerably over the archipelago from south to north (Tsukada 1984).

The cooling that started at the end of the middle Holocene aggravated the competition between the Korean pine and more cold-tolerant species like spruce and fir, which again resulted in a shrinking areas under pine forests.

Fluctuations of the Korean pine range occurred in the Late Holocene against the background of an unstable climate and gradually lowering heat supply (Wanner et al. 2008). The newly obtained palynological data suggest some wave-like fluctuations of the pine proportion in the plant formations.

A cooling at the beginning of the Late Holocene induced a wide expansion of dark coniferous and small-leaved plants along with a decrease of the Korean pine presence in the vegetation. The general trend towards cooling was interrupted once by a short-term warming. It was marked by a rising importance of the Korean pine in the mountain landscapes. In all probability, it was a co-dominant species in the plant formations with *Pinus densiflora*, *Quercus mongolica* Fisch. ex Ledeb., *Abies holophylla*, *Abies neprolepsis* (Trautv.) Maxim. and other trees. Similar processes took place in the Fore-Baikal region 2600–1800 cal BP, when forests of the Siberian stone pine gained essentially in area (Bezrukova 2009).

Later on, the subsequent decline in the heat supply led to a transformation of pine-broadleaved forests into pine-dark coniferous and small-leaved ones as the Korean pine had been replaced by spruce and fir, along with a lowering of its altitudinal boundary (tree line).

Another short-term warming (Wanner et al. 2008) correlatable with a Medieval Climate Anomaly and long-known in mid-latitudes took place in the second part of the Late Holocene. It resulted in an expansion of polydominant forests (with a notable proportion of the Korean pine) in ecosystems of the Sikhote Alin and East Manchuria Mountains. It may be safely suggested that *Pinus densiflora*, *Betula* sect. *Albae*, *Betula* sect. *Costata*, *Betula davurica* Pall., *Abies holophylla*, *Carpinus cordata* and some other plants were present as co-dominants.

In the Late Holocene the Korean pine position in the vegetation of the southern Far East of Russia was increasingly stabilized. It became the main forest-forming species in the polydominant forests of the southern Sikhote-Alin and East Manchuria Mountains; in the middle Sikhote-Alin (and above 700–900 m in the southern mountains) it is among forest-forming trees in forests of fir and spruce with a limited presence of other broad-leaved and small-leaved species.

CONCLUSIONS

The palynological and chronostratigraphic data obtained in the course of our works gave grounds for dating the Korean pine appearance in the south of the Russian Far East to 11 000–10 500 cal BP and for reconstructing changes in its proportion in the continental ecosystems of the region through the postglacial time. Fluctuations in the proportion of the Korean pine pollen in the studied pollen assemblages suggest its fast response to climate changes.

There is strong evidence that the range of the Korean pine expanded northwards as far as the south of the Russian Far East at the transition from MIS 2 cryochron to the thermochron (the Holocene beginning). The continental ecosystems of the Pacific landscape zone began to acquire their modern outlook, with the Korean pine becoming their principal constituent in the southern Sikhote-Alin and East Manchuria Mountains. That interval (MIS 2 to MIS 1 transition) corresponds to the time of coniferous-broadleaved forest recovery after the cold epoch had come to its end.

The Korean pine continued strengthening its position in the regional vegetation through the Middle Holocene, the process being occasionally interrupted with short-term coolings. In the southern Sikhote Alin and East Manchuria Mountains the species became the main element of the coenoses in polydominant forests of complex structure, while in the middle Sikhote Alin it formed a component of mixed forests in association with small-leaved trees, Yezo spruce, Khingan fir and a few broad-leaved species.

In the Late Holocene the less stable climatic conditions account for differently directed (mostly from north to south and vice versa) migrations of the Korean pine in the south of the Far East. The range of the species increased in area at the end of the Late Holocene due to an amelioration of natural conditions, its outlines being close to those of today. The natural ecosystems acquired their modern appearance. The species composition of the vegetation, however, was still poorer than that of the Holocene optimum.

ACKNOWLEDGEMENTS

The author is grateful to Khikmatulla A. Arslanov (Saint Petersburg State University) for radiocarbon dates and Anatoly V. Lozhkin (Northeastern Integrated Scientific-Research Institute) for field assistance.

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