

# Monitoring of high-altitude terrestrial ecosystems in the Altai Mountains

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**Abstract.** The Aktru mountain glacier basin (the North-Chuya Ridge, Altai Mountains) is a region of highly important ecosystems. We have been performing a monitoring of the autotrophic component of the basin ecosystems for the last 16 years. The primary indicator species with the most clearly defined response to climatic changes are Siberian stone pine and Siberian larch with their individuals and populations. The ecosystem level of the monitoring includes that of old forests, ecotone ecosystems, and ecosystems on the new moraines. The old forests have remained stable for about 1000 years. The reasons for this stability are the long lifespan and the long generative stage of stone pine and larch, their ability to produce several growth forms, optimal ecological conditions of the basin for these species and high  $\alpha$ -diversity of the old forests. The treeline has moved up by 100–200 m for the last 150 years and by 40–90 m for the last 40 years, mostly because of an invasion of stone pine to the ecotone. The primary successions on the moraines are also relatively stable, although at present only stone pine has been involved in the successions. No regeneration of larch has been observed for the last 16 years in the entire basin.

## 1. Introduction

The modern scientific community shows great interest in the studies of mountains under modern global climate changes. The reasons for this interest are numerous. These include: the assumption of early response of mountain ecosystems to climatic changes, high biodiversity of ecosystems and species in mountain regions caused by the existence of altitudinal belts, the importance of mountains as sources of water, mineral, and biological resources necessary for the population wellbeing, and many other reasons, such as the high cultural value of mountains [1,2].

Monitoring of different components of mountain environments as a whole system is one of the most important goals of modern science [3]. The efforts of some networks (GLOCHAMORE; GLORIA, MIREN) and numerous independent observatories are focused on various kinds of the monitoring. The research program of the GLOCHAMORE network is the widest and most diverse in comparison with the other networks. However, the monitoring of wildlife within the framework of the program is limited. An “optimal” level of monitoring, which is the widest of the three suggested levels of monitoring, includes only 7 indices used for the wildlife monitoring, namely: species composition, cover/abundance, vegetation type, moss layer cover, the presence and the quantity of dung (for indirect assessment of the abundance of grazing animals), the presence of some local species of invertebrates and the treeline altitude measured through satellite imagery deciphering [3]. The GLORIA and MIREN networks were designed for biospheric monitoring, but the only indices directly related to wildlife are the species composition and the abundance of species [4].

Our investigations are based on an assumption of a key role of the autotrophic component of ecosystems, an integrated approach, and an idea of multiple levels of wildlife organization. We select the autotrophic component of ecosystems (plant communities) as the main object of monitoring. The autotrophic component is directly affected by the climate and, at the same time, it affects the soil and animal population dynamics. The stability of the autotrophic component is necessary for the ecosystem's stability as a whole, and its change automatically changes the ecosystem as a whole. The



essence of the applied integrated approach is simultaneous monitoring of a number of indices with the purpose of a comprehensive estimation of the changes in our object. The integrated approach allows us to obtain information that cannot be obtained by monitoring of individual parameters.

## 2. Study area

We have been monitoring high-altitude areas of the Altai Mountains for 16 years. We have a group of observatories for the monitoring of terrestrial ecosystems in 5 mountain areas. There are two observatories at the North-Chuya Ridge (Aktru, Korumdu): two at the South-Chuya Ridge (Akkol, Jazator) and one at the Katun Ridge (Akkem).

Our primary observatory is the Aktru mountain glacier basin. In this basin we perform regular annual studies of the ecosystems. The basin was selected because of its highly representative climatic, glaciological [5], and floristic peculiarities [6]. The basin has been used for glaciological (since 1952) and climatic (since 1956) monitoring by Tomsk State University scientists, and was chosen by the UNESCO Executive Committee as one of 8 glaciological and meteorological representative areas of the former USSR during the International Geophysical Year (1957–1958). We have been performing monitoring of the ecosystem in the basin since 1999.

The basin (50°05' N, 87°45' E, 2150–5040 m a.s.l.) is situated in the highest part of the North-Chuya Ridge, at the mountain junction Bish-Iirdu. The current relief of the basin is complex, deeply disjointed and typical for high mountains [7]. The slopes of the Aktru River valley are steep and asymmetrical. The valley glaciers of Maly Aktru, Levy Aktru, and Pravy Aktru and their moraines are located at the upper sources of the Aktru River. The new moraines have been deglaciated since the mid-19th century up to the present day.

The Aktru basin has severe high-mountain climate. The basin has a high solar radiation level (975–1045 W/ m<sup>2</sup>), low temperatures (the mean annual temperature is –5,2°C, and the mean summer temperature is +8,7°C), significant precipitation (the mean annual precipitation is 563 mm), and high relative air humidity (about 67%) [8, 9]. The winds are usually south or south-west throughout the year, and the highest wind speed is in winter (up to 20–24 m/s). The precipitation is inhomogeneous, with the greatest precipitation amount in summer. The winter winds greatly affect the snow cover. Our winter observations indicate that some parts of the valley slopes (especially in the treeless areas) may lack snow, which is probably removed to the lower parts of the slope by the wind and due to gravity.

## 3. Materials and methods

The monitoring has been made at levels of the organism, population, and ecosystem. The main objects of the monitoring are old forests (2100–2300 m a.s.l.), phytocenoses of forest-tundra ecotone (2200–2500 m a.s.l.) and new moraines of the Maly Aktru glacier (2200–2300 m a.s.l.) at the ecosystem level, and indicator species of Siberian stone pine (*Pinus sibirica* Du Tour) and Siberian larch (*Larix sibirica* Ledeb.) at the organism and population levels. These species are of high importance for the ecosystem. Since they are dominant in the vegetation communities, they have a very long lifespan (up to 800 years) and clearly distinguishable generations. They are also responsive and sensitive to climate changes at the organism (radial increment and growth form) and population (tree age structure) levels.

These objects were studied on ecological and cenotic transects along the elevation gradient from 2100 to 2500 m a.s.l. from old forests on slopes of various orientations and steepness to high-altitude tundra and from these forests through the new moraines of the Maly Aktru glacier to its terminus. We studied 70 sample areas. We measured all trees, seedlings, and saplings (diameters and heights) and took cores from 500 sample trees. The cores were the basis of the age structure and ring width chronologies. The ring widths were measured by LINTAB with the software TSAP [10] with an accuracy of 0.01 mm. Individual ring series were dated using a combination of cross-correlation analysis [11] and graphic dating [12] in the TSAP [10] and COFECHA programs [11]. Then the series were generalized into chronologies by the standardization routine (minimization of the age trend and the autocorrelation component in the chronology) by the CRONOL program [11]. To find the correlation between the tree ring width chronologies and the climate variables, the monthly

temperature and precipitation values of the Aktru weather station were used. Siberian stone pine and Siberian larch growth forms were identified by I. Serebryakova [13] and A. Chistyakova [14]. In all the sample areas, comprehensive phytosociological descriptions were made in Russia using a standard method [15]. The seedlings and saplings less than 50 years old of the Siberian stone pine and Siberian larch were called young individuals.

#### 4. Results and discussion

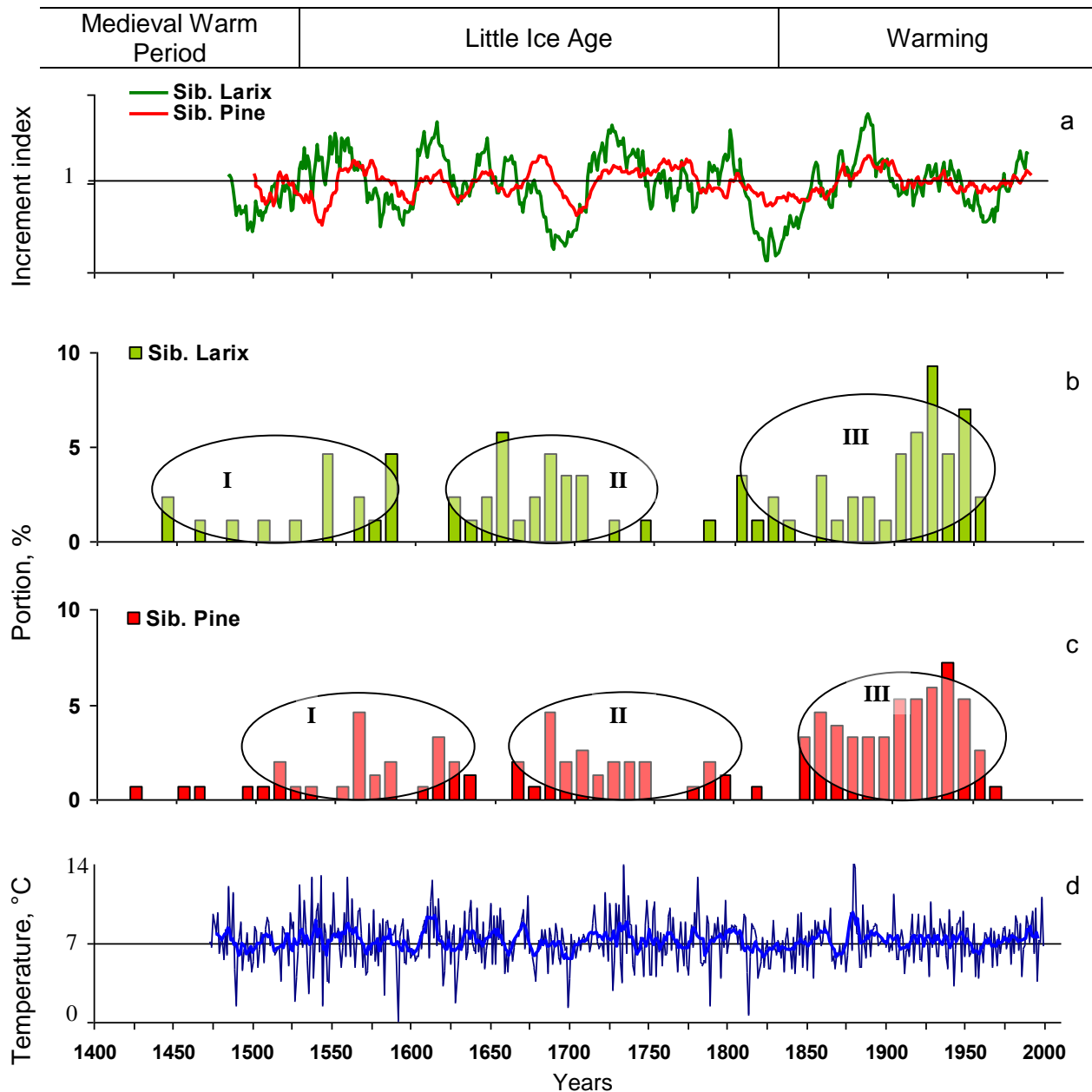
The most interesting object of monitoring are the *old forests*, which are usually dominated (up to 80–90% of all the forest trees) by Siberian stone pine. These forests provide the best data on the contemporary and retrospective states of high-altitude forest ecosystems at the organism, population, and ecosystem levels.

Long-term changes in tree ring widths indicate general trends of increasing growth in the mid-18th and late 19th centuries. A general decrease in the growth of Siberian stone pine and Siberian larch was found for the late 17th and early 18th centuries, in the middle of the first half of the 19th century, and the mid-20th century. Major peaks of growth depression of Siberian stone pine were in 1544, 1599, 1630, 1662, 1706, 1798, and 1829, and of Siberian larch, in 1497, 1580, 1688, 1822, and 1961. The most prominent and long periods of increasing growth indexes took place in 1544–1575, 1704–1776, 1828–1902, and the last decade of the 20th century for Siberian stone pine and in 1499–1562, 1580–1616, 1689–1726, and 1824–1888 for Siberian larch. Major periods of decreasing growth of Siberian stone pine were identified in 1576–1600, 1683–1700, 1776–1826, and less significant ones, in 1902–1913. As for Siberian larch, the same periods occurred in 1562–1594, 1616–1689, 1800–1824, and 1890–1963. The amplitude of radial growth fluctuations (Figure 1a) in Siberian larch (which prefers arid habitats and deciduous) is higher than those in Siberian stone pine (which prefers humid habitats and evergreen), i.e. the curve of the radial growth is smoother for Siberian stone pine. The behavior of the radial growth curves is generally similar for both species.

The highest correlation between the radial growth and the climatic variables (according to the Aktru weather station data) was found for Siberian larch (the correlation coefficient with the May temperature is +0.55; with the June and July temperatures, +0.50, and with the June precipitation, 0.34). This significant correlation between the spring and summer temperatures and the radial growth in the Siberian larch allowed us to reconstruct these temperatures for the entire mountain glacier basin (Figure 1d). The variability of mean annual spring and summer temperatures varied from 4.7 to 9.7°C. Major periods of temperature increase were in the mid-16th, early 17th, mid-18th, and late 19th centuries. Major periods of temperature decrease were in the late 16th, late 17th, and early 19th centuries.

The age structure of the tree storey of old forests consists of three stone pine and larch age generations. The forests also contain single stone pine and larch trees from the previous generations; they are 550–600 or even 730 and 830 years old, they settled in 1150–1460 and have survived since the Medieval Warming, which ended in the 90s of the 15th century in the Altai Mountains [16]. The first generation of Siberian stone pine is the oldest one; it was formed in 1490–1630. The first generation of larch was formed in 1440–1580. The second generations of stone pine and larch were formed in 1660–1790 and 1620–1740, respectively, the third generations, in 1840–1960 and 1900–1950, respectively (Figure 1). The range between the oldest and youngest trees is 140 years for the first generation in both species, 120 years for the second generation in stone pine and 130 years in larch, and 120 years for the third generation in stone pine and 150 years in larch. The third generation is the youngest. It began to form at the end of the Little Ice Age (Figure 1c). The least number of larch trees that settled down between the generations was detected in the late 16th–early 17th centuries and in the late 18th century (1750–1780). The worst colonization of stone pine occurred in the mid-17th century and in the first half of the 19th century. These decreases in regeneration are clearly connected with intra-century coolings (Figure 1d) which occurred during a long-term decrease in the temperatures, i.e. in the Little Ice Age [16]. The times of formation of the stone pine and larch

generations are different and separated by 40–50 years (Figure 1b,c) due to different reactions of these species to decreases in air temperature during the coolings (Figure 1d).

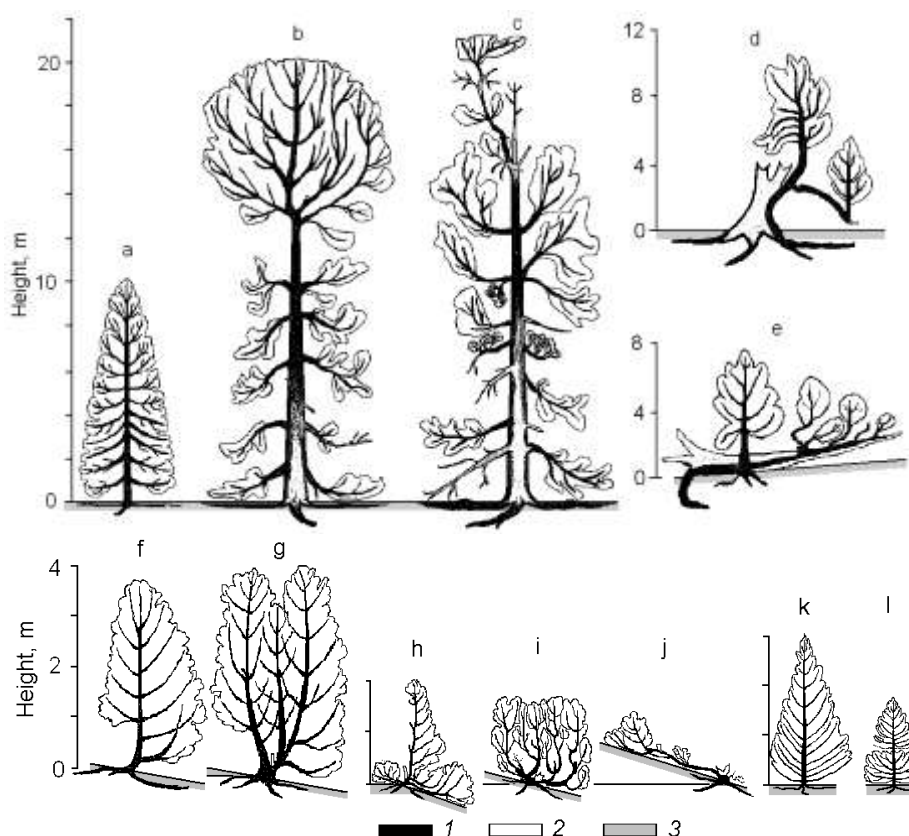


**Figure 1.** Radial increment with 7-year smoothing in Siberian larch and Siberian stone pine (a), age structure of the tree storey of old forests (b, c), and reconstructed annual and smoothed (7-year) mean spring-summer temperature (d) in Aktru mountain glacier basin (North-Chuya Ridge, Altai Mountains).

The modern, fourth, generation of Siberian stone pine in the old forests is represented by rare young individuals from 1–3 to 50 years of age. The same generation of Siberian larch consists of single individuals about 40–50 years of age.

Modern warming has been registered in the Altai region since the 1980s. During this warming, we observe an increase only in the Siberian stone pine regeneration, but no regeneration of the Siberian larch.

In the old forests studied, six growth forms (single-stemmed tree, several-stemmed tree, grove-forming tree, tree with a multi-storey root system, “living” windfallen tree, and “living” stump) were identified in Siberian stone pine. The single- and multi-top single-stemmed trees prevail (over 90% of the total) in the tree storey. Such Siberian stone pine trees can be more than 450–600 years old (Figure 2a–c) and can bear cones during 500 years [17]. Trees with a multi-storey root system are formed when the tree butts are periodically buried down by rock debris, “living” stumps (Figure 2d) are formed when the trunks of old trees break, a grove-forming tree is formed when lower branches establish, and a “living” windfallen tree (Figure 2e) appears when the trunks of old trees fall down and several living adventitious roots remain in the soil [18]. Individuals of the growth forms can live for 300–700 years and produce cones during many recent decades. High solar radiation, sufficient precipitation, and a relatively low wind speed are the factors contributing to these growth forms. Grove-forming trees, “living” windfallen trees, and “living” stumps are found only in old forests. Single-stemmed trees and several-stemmed trees are identified only in Siberian larch.



**Figure 2.** Growth forms of Siberian stone pine in old forests (a–i), forest-tundra ecotone (f–j) and on new moraines of Maly Aktru glacier (k–l) in Aktru mountain glacier basin (North-Chuya Ridge, Altai Mountains). The ages of individuals: a – 100–200, b – 250–350, c – 450–600, d – 450–700, e – 300–700, f, g – 50–125, h, i, j – 40–100, k – 50–100, l – 40–60 years. 1 – living and 2 – dead sections of trunks and branches; 3 – substrate surface.

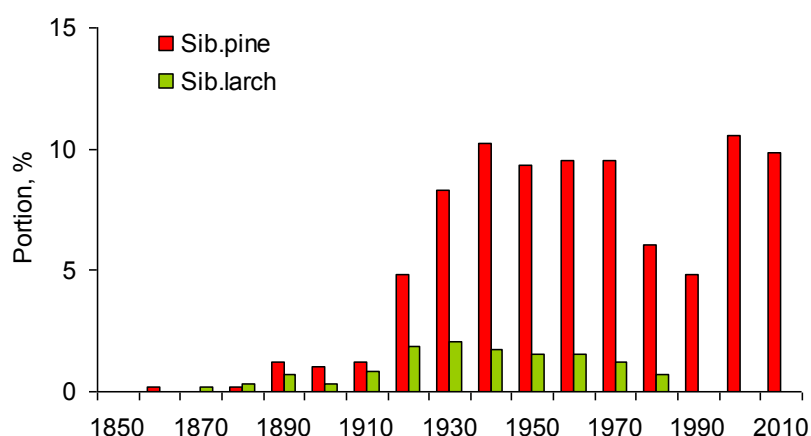
Investigation of the shrub and herb storeys of old forests allowed us to determine high  $\alpha$ -diversity of vessel plants: the density of species measured on sampling areas of 100 m<sup>2</sup> and consists of 36 species on average; the general species richness of old forests is 104 species, which is equal to 50% of

the entire vessel plant flora of the stone pine forest of the entire Altai Mountains, thoroughly investigated by A.V. Kuminova [19]. Our long-time (16-year) monitoring of these storeys shows their significant stability under the impact of modern global changes.

The high stability of the old forests under the climate change impacts is mostly due to the stability of larch and stone pine populations. The ecological conditions of the North-Chuya Ridge are optimal for both species in precipitation, dampening, and richness of the soils [20], which contributes to diversity of growth forms of primary trees and high  $\alpha$ -diversity of vessel plants of the shrub and herb storeys of these forests.

The basin also contains pronounced early response areas which are *forest-tundra ecotones* (2200–2500 m a.s.l.) where the reaction of terrestrial ecosystems to global and regional climate changes is maximal. An invasion of stone pine and larch into the forest-tundra ecotones began after the start of a warming in the 60s of the 19th century. This warming was followed by the strongest cooling in the last millennium, which occurred in the first half of the 19th century. This cooling greatly destroyed a previous generation of trees which existed earlier in the ecotone. The dead adult trees were found by M.V. Tronov [21] in 1936.

At present, the most abundant tree species of the ecotone is stone pine (60–80% of all trees), while the presence of larch is significantly lower (20–20%). Here the age structures of the tree populations are totally different from those of the old forest below the ecotone. There is only one adult generation of Siberian stone pine and Siberian larch in the ecotone. The age of the trees is 50–130 years (Figure 3). The generation began to form in the 60s of the 19th century and continued during the subsequent warming [16]. The trees of the second generation of stone pine are young and numerous, and the age of individuals is 4–50 years. The second larch generation is represented by individuals 36–49 years old. An invasion of stone pine to the lower and higher sections of the ecotone was simultaneous and occurred in 1860–1960. An invasion of larch to the lower section of the ecotone occurred in 1870–1960, and to the upper section, 20 years later (since 1900). A fast and effective invasion of stone pine began in 1920s and continues up to the present day. An invasion of larch was insignificant during the 20th century and stopped in the 1980s (Figure 3).



**Figure 3.** Age structure of the tree storey in forest-tundra ecotone of the Aktru mountain glacier basin (North-Chuiya Ridge, Altai Mountains).

The treeline moved up by 60–210 meters since the beginning of the warming in the 60s of the 19th century. It moved up by 40–120 meters (up to 2390 m a.s.l.) from the 1960s to mid-1970s and by 20–90 m more (the stone pine line to 2480 m, and the larch line to 2420 m a.s.l.) for the last 40 years. Our monitoring data indicate that the invasion of stone pine to the ecotone is continuing.

In the forest-tundra ecotone, six growth forms (single-stemmed tree, several-stemmed tree, multi-stemmed tree, skirted tree, shrub-like tree, and elfin wood) were identified in Siberian stone pine. Single- and multi-top single-stemmed and multi-stemmed trees prevail (70–80% of the total) in the tree storey. Their age is rarely more than 125 years. Such trees have often an asymmetric crown (Figure 2f–g). The skirted tree, the shrub-like tree, and the elfin wood (Figure 2h–j) are found only in the ecotone rather than in the old forest, they are 40–100 years old and do not produce cones. These forms are found throughout the ecotone, and the elfin wood is formed only in the upper section of the ecotone. They are formed when the tree crown and the trunk are damaged mechanically. Climatic (strong winter winds and thin snow covers) and geomorphological (rockfalls and avalanches) factors contribute to these growth forms, as in the other high-altitude areas [22, 23]. Three growth forms (single-stemmed tree, several-stemmed tree, and “living” stump) were identified in Siberian larch. The Siberian stone pine and Siberian larch individuals keep steadily their growth forms at least for 15 years, according to our monitoring data.

The monitoring of the shrub and herb–low shrub storeys of the ecotone plant communities allowed us to find high  $\alpha$ -diversity of the vessel plants: the species density in the ecotone is about 41 species per 100 m<sup>2</sup>, and the general species richness is 222 species. The species include about 36% of all periglacial flora of the Altai–Sayan mountain area [24]. Our 16-year long observations show high stability of the species composition and the structure of these storeys during the entire observation period.

Some *new moraines* of the valley Maly Aktru Glacier (2200–2300 m a.s.l.) are of special interest, since the developing ecosystems there may also provide valuable data on the early response of ecosystems to regional and global climate changes. The moraines are located in the upper forest belt of the North-Chuya Ridge, and a colonization of the moraines began in 60s of the 19th century.

A primary succession on the moraines has been continuing for the last 160 years. They include the formation of pioneer communities on a terrain aged 5–30 years, willow-moss communities on a terrain aged 30–90 years, and a young larch forest with a *Betula rotundifolia*-dominated shrub storey on a terrain aged more than 100 years. The tree storey of this forest is dominated by larch (more than 90%). There is only one adult generation of Siberian larch here. The age of this generation is 60–97 years. The stone pine trees are less numerous (less than 10% of all trees), the age of the trees of an individual adult generation is 50–70 years. A second generation is represented by stone pine trees aged 3–50 years and larch individuals 30–50 years old. Individuals of the second generation may be found even on younger terrains (the terrain age is 30–90 years). Individuals of stone pine may be found on a very young terrain deglaciated less than 30 years ago. These individuals are usually 5 years old and do not survive for a longer time. There are no young larch trees on the moraines: we found only stone pine trees.

On the new moraines, three growth forms (single-stemmed tree, several-stemmed tree, and skirted tree) were identified in Siberian stone pine and Siberian larch. Single-stemmed (Figure 2k) and several-stemmed trees prevail (over 90% of total), their age is less than 100 years. A skirted tree (Figure 2l) is found on the new moraines rather than in the old forest. The reason for its appearance is a combined impact of the winter wind and snow.

The monitoring of the species composition of the primary communities forming on the moraines allowed us to find significant  $\alpha$ -diversity. The species density varies from 17 species per 100 m<sup>2</sup> for the terrain aged 5–30 years to 29 species per 100 m<sup>2</sup> for the moraines more than 100 years old. The general species richness is 146 species of the vessel plants. These species are represented by 25% of the periglacial vessel plant flora of the Altai–Sayan mountain area investigated by N.V. Revyakina [24].

## 5. Conclusions

The monitoring of the modern state of the high-altitude terrestrial ecosystem of the Altai Mountains and supporting retrospective investigations have-been performed at the organism, population, and ecosystem levels of the organization of wildlife for the last 16 years. The primary monitoring areas

were old forests (2100–2300 m a.s.l.), forest-tundra ecotones (2200–2500 m a.s.l.), and new moraines with a recently deglaciated terrain (2200–2300 m a.s.l.). The most sensitive indicators of climate changes are Siberian stone pine and Siberian larch available in all monitoring areas.

A retrospective estimation of the radial growth in the old forest allowed finding the intra-century periods of its significant increases and decreases. It also allowed us to reconstruct the fluctuations of spring and summer temperatures for 500 years. The formation of generations of stone pine and larch in these forests was cyclical, and the formation periods were interrupted by 40–50 years of long cooling.

These forest ecosystems demonstrate high stability. They were formed about 1000 years ago in the periglacial area and survived during 3 prolonged strong cooling periods, including the strongest early 19th century cooling in the last millennium. The cause of this stability is the long lifespan of stone pine and larch trees (up to 800 years old), the long generative stage of their life cycle (almost 500 years), the high diversity of the growth forms, and high biodiversity of the lower (shrub and herb) storeys of the ecosystems.

An invasion of stone pine and larch into the ecotone and the formation of the first generation began at the start of a warming in the 60s of the 19th century following a very strong cooling in the first half of the 19th century. The invasion of stone pine into the upper and lower sections of the ecotone was simultaneous. An invasion of larch began 10 years later in the lower section and 20 years later in the upper section of the ecotone. The later stage of stone pine invasion into the ecotone was considerable and fast. It began in the 1920s and has been continuing up to the present day. The invasion of larch was insignificant during the entire 20th century and stopped in the 1980s. Only stone pine continues its invasion now.

The investigation of the early response of the terrestrial ecosystems to the climate warming and monitoring of the ecosystem changes on the Maly Aktru Glacier moraines allowed us to describe the modern primary succession with the successive formation of pioneer communities, willow-moss communities, and young forests. A colonization of the moraines by Siberian larch began about 100 years ago, and a colonization by Siberian stone pine, 30 years later. An effective colonization of larch occurred only during the first 50 years after the beginning of the glacier recession. The colonization of stone pine was weak during the entire period after the beginning of the glacier recession. Only stone pine is colonizing the moraines now, during the modern fast climate warming, which has been detected in the Altai region since the mid-1970s. Stone pine is successfully colonizing the terrain moraines whose age is more than 30 years, and the young individuals found on the younger terrain quickly die. No larch colonization has been observed on the moraines during the 16-year monitoring.

The monitoring of the high-mountain terrestrial ecosystems and the populations of indicator species was supplemented by dendroclimatic investigations and allowed us to understand their dynamics during the previous climate changes and the climatic response in the past during the Little Ice Age period and at present during the modern warming period.

The Aktru mountain glacier basin is a key area of high value, which can serve as a model for investigations of the reaction of highly stable high-altitude ecosystems to climatic changes. The collected data of monitoring are valuable for preserving the biodiversity of the Altai Mountains.

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