Reconstruction and prediction of climate and vegetation change in the Holocene in the Altai–Sayan mountains, Central Asia

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Abstract

Two quantitative methods were used to reconstruct paleoenvironments and vegetation in the Altai–Sayan mountains, Central Asia, during the Holocene. The ‘biomization’ method of Prentice \textit{et al} (1996 \textit{Clim. Dyn.} \textbf{12} 185–96), applied to the surface pollen record, worked fairly well in the reconstructions of current vegetation. Applying this method to fossil pollen data, we reconstructed site paleovegetation. Our montane bioclimatic model, MontBioCliM, was used inversely to convert site paleovegetation into site paleoclimates. The differences between site paleo and current climates served as past climate change scenarios. The climatic anomalies for 2020, 2050, and 2080 derived from HadCM3 A1FI and B1 of the Hadley Centre, UK, served as climate change scenarios in the 21st century. MontBioCliM was applied directly to all climate scenarios through the Holocene to map past and future mountain vegetation over the Altai–Sayan mountains.

Our results suggest that the early Holocene ca 10 000 BP was cold and dry; the period between 8000 and 5300 BP was warm and moist; and the time slice ca 3200 BP was cooler and drier than the present. Using kappa statistics, we showed that the vegetation at 8000 BP and 5300 BP was similar, as was the vegetation at 10 000 BP and 3200 BP, while future vegetation was predicted to be dissimilar to any of the paleovegetation reconstructions. The mid-Holocene is frequently hypothesized to be an analog of future climate warming; however, being known as warm and moist in Siberia, the mid-Holocene climate would likely impact terrestrial ecosystems differently from the projected warm and dry mid-century climate.

Keywords: climate change, recent and fossil pollen spectra, Holocene vegetation, Altai–Sayan mountains, Central Asia

1. Introduction

The vulnerability of mountain ecosystems to climate change makes them the best areas to identify climate change impacts on the biota. Along altitudinal gradients, a wide range of different vegetation structure and functions can be found, and altitudinal gradients are in many ways complementary to latitudinal gradients (Koch \textit{et al} 1995, Korner \textit{et al} 1991). Altitudinal gradients facilitate the examination of relations between environmental variability and biotic patterns that can be used to design conceptual and analytical models to predict the distribution of the biota (IGBP Report 43).

Over mountains, due to the complex topography (combinations of elevations and slopes) and to the labor-

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intensive character of collecting and analyzing pollen data, they are usually not sufficient for detailed vegetation and climate reconstructions. Yet, pollen ‘deposits’ in mountain areas represent many different ecosystems. It is difficult, if not impossible, to interpret vegetation change from fossil pollen which originated from locations distant from sample sites. Instead, a reliable paleoecological interpretation should be based on pollen of local origin (Solomon and Silkworth 1986).

Due to the complex topography, many flora and fauna species are able to survive unfavorable times in some habitats called refugia. For instance, some species of tertiary flora (Tilia cordata, Azarum europium, Brumera sibirica, etc) are still found over the Altai–Sayan Mountains, in lowland warm and moist Pinus sibirica–Abies sibirica–Populus tremula forests, called ‘chern’ (black) in Russian, which are rich in flora biodiversity and ferns in particular (Pologii and Krapivkina 1985). Thus, mountain areas may serve as a good model for reconstructions of both paleovegetation and climates. These reconstructions can be translated into detailed maps only by using simulation approaches.

This study’s objectives were (1) to reconstruct paleoclimate and vegetation during the Holocene (from 10 000 before present, BP, to the present) across the Altai–Sayan mountains, embracing about one million square kilometers over both the Russian and foreign parts; (2) to predict a future vegetation pattern by the end of the 21st century; and (3) to compare all Russian and foreign parts; (2) to predict a future vegetation embracing about one million square kilometers over both the

2. Material and methods

The study area is the Altai–Sayan mountains (figure 1) located in Central Asia, mainly in Russia (the northern half) and Mongolia (the southern part), with a small area in Kazakhstan (in the west) and China (in the southwest). The elevation is generally about 1000–2200 m, with the highest point being Mount Belukha (4506 m) in the central Altai. The current climate is of a continental type with cold winters and warm summers. Westerlies are the dominant factor of the atmosphere circulation, resulting in high annual precipitation: up to 1500–2000 mm on the northwestern windward slopes and as little as 200–300 mm of precipitation on the foothills of leeward slopes and the inner intermountain depressions of Tuva and Mongolia. Most of the precipitation (up to 90% in Mongolia) falls in the summer.

In interior Central Asia, with a continental climate, ecosystems vary from steppes in lowlands, with warm and dry climates, to forests at middle elevations to tundra and nival communities in cold/wet highlands. The current vegetation in the Altai–Sayan mountains varies on the leeward and windward macroslopes. The sequence of vegetation types along a south to north direction are as follows. From desert and steppe in the dry climate of Mongolia, north to light-needled (pine) and birch subtaiga; and again steppe in the northern foothills (Smagin et al 1980).

In our paleo studies, to construct retrospective pollen diagrams, nine long sediment cores were extracted with a square-rod piston sampler (Wright 1991) from the deepest parts of small mountain lakes or with a peat corer from peat deposits down to the underlying rocks in the intermountain hollows across the study area. The upper-most sediments from lakes were taken with a transparent plastic tube fitted with a piston and subsampled in the field while vertical. The length of collected sediment cores ranged from 230 to 450 cm. Samples for pollen analyses were collected with intervals of 6–9 cm and prepared according to the method of Grichuk and Zaklinskaya (1948) using HCL, KOH, HF, and acetolysis. The pollen analysis was carried out under 400× magnification. Pollen types were identified with the help of reference books of Kupriyanova (1965), Kupriyanova and Aleshina (1972, 1978), Bobrov et al (1983), Moore et al (1997). In each sample, 300–500 pollen grains of tree taxa plus other types of pollen and spores were counted. The percentage of all taxa was calculated as a sum of all pollen and spore taxa without aquatic and wetland plants and redeposited pollen. Pollen diagrams were constructed with the program TILIA (Grimm 1991). Radiocarbon ages were determined by accelerator mass spectrometry (AMS) at the University of Colorado (USA) and by a bulk method at the Geological Institute of Novosibirsk (Russia). Terrestrial macrofossils were used for radiocarbon dating (5–15 dates for a core) when applicable. If macrofossils were absent, then the humic acid fractions of gyttja were dated. The series of pollen diagrams used in this study were published by Blyakharchuk et al (2004, 2008).

Our pollen spectra were examined for five time slices of the Holocene: 10 000, 8000, 5300 3200 years BP and
the present. These time slices characterize relatively steady periods in the paleovegetation development when it was in equilibrium with the climates of the time. For these time slices we took pollen spectra dated with the use of depth-age models on the base of neighboring radiocarbon dates from each of nine pollen diagrams. We used an uncalibrated radiocarbon age, so that our results could be easily compared with other pollen data for Siberia. 

Montane paleovegetation across the Altai–Sayans during the Holocene was reconstructed based on nine pollen diagrams using the qualitative method of ‘the principle of actualism’ (Markov and Velichko 1967), is similar to the ‘analog’ method developed and used by Davis (1963) and McAndrews (1966), quantified by numerous paleoecologists (Prentice 1980, Overpack et al 1985, Giuot 1990) a couple of decades later. 

In order to simulate paleovegetation from pollen data at the biome level, this study used the method of Prentice et al (1996), the ‘biomization’ of pollen data successfully applied in many studies (e.g. Tarasov et al (1998), Herzschuh et al (2004)). Pollen taxa are assigned to plant functional types from which biomes are constructed. We omitted this step and assigned the dominant taxa directly to orobiomes. Russian vegetation classifications are based on vegetation types much like the broad classes Prentice et al (1992) defined: tree versus shrub, broadleaved versus needle leaved, evergreen versus deciduous, steppe forb, desert forb, grass, sedge, etc. Thus, Boreal zonal/altitudinal vegetation classes (biomes/subbiomes): tundra, forest tundra, light conifer and dark conifer taiga, broadleaved, mixed, forest steppe, steppe, and desert constructed from plant species indicators are similar to those of Prentice et al (1992): tundra, cold deciduous, taiga, mixed, cool conifer, steppe, and desert constructed from plant functional types.

As Prentice et al (1996) did, we designed a ‘biome × taxon’ matrix indicating which pollen taxa may occur in each biome: ‘1’ was assigned to an orobiome if the taxon could occur and ‘0’ was assigned if it could not. Our ‘biome × taxon’ matrix included 15 orobiomes and 39 dominant taxa identified in surface spectra. To evaluate the work of the matrix, it was applied to 22 pollen surface samples each of which was averaged from 2 to 5 samples located closely to each other, counting in total 132 samples. Modern oribiomes at these sites were identified in situ from plant indicators and were presumed not to be much disturbed over the mountains. An affinity score was calculated for all pollen samples according to the formula of Prentice et al (1996), and each pollen sample was ‘biomized’ according to its maximal affinity, determined by an affinity score. If several biomes had the same score then the ‘1’ was assigned to a sample which had a smaller number of taxa (table 1). 

| No | Latitude °N | Longitude °E | Elevation (m) | From plant indicator | From pollen |
|----|--------------|--------------|---------------|---------------------|-------------|
| 1  | 50°16'       | 89°36'       | 2208          | Cryosubsteppe       | Cryosubsteppe |
| 2  | 51°20'       | 94°50'       | 700           | Steppe              | Steppe      |
| 3  | 50°13'       | 89°20'       | 2748          | Subalpine           | Subalpine   |
| 4  | 50°12'       | 87°44'       | 1753          | Subalpine meadow    | Subalpine   |
| 5  | 50°06'       | 88°26'       | 2054          | Forest steppe       | Forest steppe |
| 6  | 50°28'       | 87°40'       | 2114          | Forest steppe       | Forest steppe |
| 7  | 54°32'       | 90°08'       | 390           | Light taiga         | Light taiga |
| 8  | 52°58'       | 84°59'       | 289           | Subalpine           | Subalpine   |
| 9  | 55°15'       | 89°45'       | 475           | Dark taiga          | Light taiga |
| 10 | 51°45'       | 85°43'       | 324           | Subalpine           | Subalpine   |
| 11 | 54°07'       | 90°22'       | 813           | Light taiga         | Light taiga |
| 12 | 51°18'       | 85°40'       | 568           | Subalpine           | Subalpine   |
| 13 | 51°          | 95°10'       | 720           | Dark taiga          | Subalpine   |
| 14 | 50°27'       | 87°37'       | 1940          | Subalpine           | Subalpine   |
| 15 | 51°46'       | 85°46'       | 351           | Subalpine           | Subalpine   |
| 16 | 51°02'       | 85°36'       | 1721          | Subalpine           | Subalpine   |
| 17 | 51°42'       | 87°35'       | 500           | Subtaiga            | Subtaiga    |
| 18 | 53°16'       | 87°14'       | 373           | Subalpine           | Subalpine   |
| 19 | 54°01'       | 89°51'       | 1257          | Chern                | Forest steppe |
| 20 | 53°21'       | 87°21'       | 439           | Subalpine           | Subalpine   |
| 21 | 52°50'       | 93°15'       | 1300          | Subalpine           | Subalpine   |
| 22 | 52°35'       | 93°30'       | 865           | Light taiga         | Light taiga |
these pairs of orobiomes are located next to each other and pollen can easily intermix (table 1).

Using the constructed ‘biome × taxon’ matrix, each paleo orobiome was then simulated from a pollen spectrum for 3200, 5300, 8000, and 10 000 BP in nine sites across the Russian part of the Altai–Sayans. Simulated reconstructions corresponded well to our expert reconstructions. Only those Russian part of the Altai–Sayans. Simulated reconstructions 3200, 5300, 8000, and 10 000 BP in nine sites across the orobiome was then simulated from a pollen spectrum for altitudinal vegetation belt (an orobiome, Walter 1985). Three MontBioCliM is a set of climate envelopes limiting each requirements for warmth; negative degree days below 0 ◦C and available water (Dokuchaev 1948). Since then, various to correspond well to specific values of ratios between heat and water stress. Our choice to use a ratio between heat and water growing degree days above 5 ◦C, GDD5 characterizing plant (Budyko 1974). We avoided this problem by only using variables that are direct functions of observed temperature and precipitation, thus arriving at a straightforward annual moisture index.

Climate limits of each orobiome (table 2) were derived from the ordinations of approximately one hundred Altai–Sayan weather stations (with assigned orobiomes) in two pairs of climatic indices: GDD3–AMI and GDD3–DD0.

MontBioCliM is based on the montane vegetation classification of Smagin et al (1980) for the Altai–Sayan mountains: (1) mountain tundra, (2) subalpine dark coniferous open taiga (Abies sibirica, Pinus sibirica, with Picea obovata), (3) subalpine light coniferous open taiga (Larix sibirica), (4) dark and (5) light coniferous stocked middle elevation taiga, (6) subtaiga (Larix sibirica, Pinus sylvestris, and Betula pendula) and forest steppe, (7) dark coniferous lowland ‘chern’ (Abies sibirica, Pinus sibirica, and Populus tremula) taiga, (8) steppe, (9) dry steppe, (10) semidesert/desert, (11) tundra steppe (or cryosteppe), a specific mountain biome occurring in cold and dry highlands that comprises both steppe and tundra flora. Additionally, three temperate biomes were included in MontBioCliM to predict biomes in a warming climate: temperate broadleaved forests, forest steppe and steppe.

A validation of MontBioCliM was done by comparing predicted vegetation with mapped actual vegetation (Samoylova 2001) using kappa statistics (Monserud 1990, Monserud and Leemans 1992). The overall kappa was 0.4 and varied between 0.2 (e.g. light conifer, subalpine, steppe) and 0.6 (e.g. tundra, ‘chern’, semidesert) for individual orobiomes, which showed a fair match of the model with actual vegetation (figure 2). The worst match was found for the Mongolian part of the mountains, poorly represented by climatic data and thus poorly interpolated climatic surfaces. Additional disagreement was caused by the fact that the model was designed based on the Russian part of the mountains, and was also applied to Mongolia, representing the other half of the mountains.

MontBioCliM was inversely used to predict average climatic indices (growing degree days above 5 ◦C and an

### Table 2. Montane bioclimatic model, MontBioCliM (climate envelopes), of the Altai–Sayan mountains.

| Ororbiome                  | Growing degree days, 5 °C | Climatic limits | Negative degree days, 0 °C |
|---------------------------|---------------------------|-----------------|---------------------------|
|                           | Lower | Upper | Lower | Upper | Lower | Upper |
| Boreal: Montane tundra    | —     | <300  | 0.3   | 1.8   | —     | —     |
| Subalpine dark open taiga | 300   | 550   | 0.3   | 1.0   | —     | —     |
| Subalpine light open taiga| 300   | 550   | 1.0   | 1.8   | —     | —     |
| Montane stocked dark taiga| 550   | 1150  | 0.3   | 1.8   | —     | —     |
| Montane stocked light taiga| 550  | 1150  | 1.8   | 3.3   | —     | —     |
| Subtaiga and forest steppe| 1150  | 1600  | 1.8   | 3.3   | —     | —     |
| ‘Chern’ taiga             | 1150  | 1600  | 0.5   | 1.8   | —     | —     |
| Steppe                    | 300   | 1600  | 3.3   | 5.0   | —     | —     |
| Dry steppe                | 300   | 1600  | 5.0   | 8.0   | —     | —     |
| Semidesert                | 300   | 1600  | >8.0  | —     | —     | —     |
| Cryosteppe                | —     | <300  | >3.3  | —     | —     | —     |
| Temperate:                | —     | —     | —     | —     | —     | —     |
| Broadleaved               | >1600 | —     | 0.3   | 1.8   | —     | —     |
| Forest steppe             | >1600 | —     | 1.8   | 3.3   | —     | —     |
| Steppe                    | >1600 | —     | >3.3  | —     | —     | —     |
Figure 2. Mountain vegetation of the Altai–Sayans region: actual mapped vegetation (top, Samoylova 2001) and predicted from MontBioCliM in the current climate (bottom). Kappa statistics showed a fair (kappa 0.40) agreement between these maps. White dots show locations of 22 pollen surface sample sites (narrow circles) and 9 coring sites (wide circles) on the background of actual vegetation.

Vegetation key. BOREAL: 1—tundra, 2—subalpine dark conifer and meadow, 3—subalpine light conifer, 4—montane dark conifer, 5—montane light conifer, 6—subtaiga and forest steppe, 7—dark-conifer 'chern', 8—steppe, 9—dry steppe, 10—semidesert/desert, 11—cryosteppe; TEMPERATE: 12—temperate mixed conifer broadleaved, 13—forest steppe, 14—steppe.

We calculated climate indices (annual moisture index) for each simulated paleo orobiome in each time slice of the Holocene as Monserud et al. (1998) did. We converted these climatic indices correspondingly to average July temperatures and precipitation. The July temperature was derived from growing degree days, base 5 °C, which are strongly correlated ($R^2 = 0.9$). Annual precipitation was derived from the ratio between the growing degree days and the annual moisture index. Climate change (anomalies) in each Holocene time slice was evaluated as the differences between the July temperature and annual precipitation between contemporary and paleoclimates (3200, 5300, 8000, and 10 000 BP).

On average over the mountains, July temperature anomalies with respect to the contemporary climate were negative $-2$ to $-3$ °C 3200 BP and especially greatly negative $-2$ to $-5$ °C 10 000 BP. July anomalies were positive (2–4°C) both 8000 and 5300 BP. For comparison, in the Minusinsk depression located in the north of our study area, Koshkarova (2004) reconstructed the July temperature as being 3 °C higher in 7000–5800 BP than today and 1 °C lower in 3000–2400 BP than today based on the macrofossil analysis. Zubareva (1987) used palynology to reconstruct July temperature anomalies at approximately $-2$ °C about 3000 BP.

Next, our differences were scaled down to 1 km grid cells using the Surfer software (www.ssg-surfer.com) and were added to the current July temperature and annual precipitation surfaces which were mapped using Hutchinson’s (2000) thin plate smoothing splines on our base map at a resolution of 1 km. Thus, detailed paleo July temperature and annual precipitation maps were obtained based on which paleoclimatic indices. Coupling paleoclimatic indices were calculated with MontBioCliM, we reconstructed and mapped vegetation over the Altai–Sayan mountains for the major Holocene time slices: the present, SubBoreal, Late Atlantic, the end of Boreal, and PreBoreal.

MontBioCliM was also used to predict future mountain vegetation in the 21st century. The future bioclimatic indices were calculated using climatic anomalies for 2020, 2050, and 2080, derived from two climate change scenarios, the HadCM3 A1FI and B1, of the Hadley Centre in the UK based on the SRES Emission Scenarios (IPCC 2000). These scenarios reflect opposite ends of the SRES range, the largest
temperature increase from the A1FI scenario and the smallest temperature increase from the B1 scenario.

Similarities/dissimilarities in mountain vegetation during the Holocene starting from 10 000 BP through the present to 2080 were found using kappa statistics (Monserud 1990, Monserud and Leemans 1992) in order to identify possible analogs in vegetation which are commonly used in paleoecological reconstructions (Budyko 1986, Overpack et al 1985, Giouft 1990, Jackson and Williams 2004). The qualitative descriptors of Monserud and Leemans (1992) were used to evaluate the agreement between paired maps: ‘excellent’ and ‘very good’ for a kappa $>0.7$, ‘good’ for a kappa $0.55–0.7$, ‘fair’ for a kappa $0.4–0.55$, and poor for a kappa $<0.4$.

3. Results

Our pollen-based expert reconstructions of vegetation patterns during the Holocene across the Russian part (where pollen samples were collected) in the Altai–Sayan mountains included the following: before 10 000 BP—most of the Altai–Sayan mountains (see figure 1 for geography) were covered by treeless steppe and tundra vegetation. Only in the Kuznetzky Alatau mountains were there islands of spruce and larch forests spread along river valleys and around lakes.

10 000 BP—In the Kuznetzky Alatau mountains, mountain tundra dominated. Intermountain depressions were covered by cold steppe with islands of spruce forests. In central Altai and south-western Tuva, vast areas were occupied by grass Artemisia steppe with subalpine shrubs upslope. Small islands of forests started to spread. Steppes in the southern part in the mountains were drier compared to those in the northern part.

8000 BP—The Kuznetzky Alatau was covered by thick dark conifer forests with Abies sibirica and with tall herbs and ferns in the ground layer. The lower Batenev Ridge of the Kuznetzky Alatau was covered by forests with Pinus sibirica and Picea obovata which stretched to lower elevations along river valleys. In the drier central Altai, larch forests with an admixture of Pinus sibirica and Abies sibirica covered a large area. On the western ridges of Altai, the portion of Pinus sibirica increased in the forests. At the upper elevations, mountain tundra and meadows developed. Lower than 1800 m, real steppe occurred. Forests of Larix sibirica mixed with Picea obovata were spread further to the dry south-eastern Altai and south-western Tuva. In those forests Pinus sibirica was also found.

5300 BP—Vegetation of the Kuznetzky Alatau did not change much compared to 8000 BP, but in the forests of the Batenev Ridge, Picea obovata disappeared. Also from the forests of the central Altai, Abies sibirica disappeared. The steppe vegetation of intermountain depressions became more xerophytic with a greater role played by Artemisia.

3200 BP—Dark conifer ‘chern’ forests retreated from central areas of Kuznetzky Alatau to its western macroslope. In the central Altai, vegetation cover was similar to that which occurred in 5300 BP. In the lower mountains, adjacent to Altai and West Sayan, the role of Betula pendula increased.

The above picture of vegetation change across the Altai–Sayan mountains reflects a relatively rapid change of climate from dry and, possibly, cold in the early Holocene to wet and warm from 8000 BP to 5300 BP. Then, a gradual change to a more continental and less humid climate took place in the second half of the Holocene. A more pronounced climate and vegetation change occurred in the leeward south-eastern and eastern parts over the Altai–Sayan mountains and a less pronounced change on windward western macroslopes. Such changes can be explained by the weakened Atlantic cyclone activities in the SubBoreal (Blyakharchuk et al 2004).

Our simulated vegetation distribution for eight time slices (10 000 BP, 8000, 5300, 3200, the present, 2020 AD, 2050, 2080) and orobiome area change are shown in figure 3 and in table 3.

At 10 000 BP and 3200 BP, the climate was both cooler and drier, especially in the early Holocene, than the present, favoring cold tundra and subalpine (open light conifer taiga) to expand in highlands and semidesert to expand in lowlands (table 3). Kappa statistics show (table 4) that the vegetation distribution 10 000 BP and 3200 BP was similar ($\kappa = 0.62$).

The 8000 BP and 5300 BP climates were predicted to be warmer and wetter, respectively to the present, that were favorable for dark conifer taiga including ‘chern’ taiga and subtaiga (table 4). At these times, cold orobiomomes like tundra disappeared, and subalpine open forests substantially decreased. Boreal steppe shrank; wetter climates were more suitable for temperate broadleaved forests, forest steppe and steppe. In total, Boreal and temperate steppes dominated a quarter of the mountain area in both the mid-Holocene and present. Holocene vegetation at 8000 BP and 5300 BP was predicted to be very similar ($\kappa = 0.80$). Khotinsky (1977) interpreted the maximal occurrence of spruce in the south of West Siberia during the Boreal and Late Atlantic with a warm period in the Holocene. He associated 4500 BP with the start of cooling. Khotinsky (1977), in the south of West Siberia, and Tarasov et al (1998), in western Mongolia, both believed that the boundary between forest and steppe did not shift substantially in the mid-Holocene; thus they concluded that in the south, the past climate was as dry as it is today. However, a vast current area of steppe, rather than contemporary semidesert/desert, is mapped in the mid-Holocene in the south of Mongolia that suggests a wetter climate of the mid-Holocene (figure 3).

The climate in the 21st century, as predicted from GCMs, will be warm and dry, which will cause a decrease in forests, a disappearance of tundra, and a considerable increase of grasslands (forest steppe, steppe and semidesert, table 3). Habitats for temperate vegetation would expand from none, in the current climate, to 15% by 2080, which is comparable to its area in the mid-Holocene (table 3). Current refugia for broadleaved forests, like the 5000 ha Tilia ‘island’ in the foothills of Kuznetzky Alatau (Polikarpov et al 1986), may expand somewhat by the end of the century, but will likely not be as large as in the Late Atlantic because future climates are predicted to be drier than the past climates reconstructed for the mid-Holocene. Both B1 and A1FI climate change scenarios yield similar results regarding the
Table 3. Orobiome area change (%) in the Altai–Sayan mountains during the Holocene. (Note that bold marks an area increase, italic—an area decrease, blank—no change.)

| Time slices | –10000 | –8000 | –5300 | –3200 | 1960–1990 | A1FI 2020 | B1 2020 | A1FI 2050 | B1 2050 | A1FI 2080 | B1 2080 |
|-------------|--------|-------|-------|-------|-----------|-----------|--------|-----------|--------|-----------|--------|
| Boreal:     |        |       |       |       |           |           |        |           |        |           |        |
| Tundra      | 23.2   | 0.5   | 0.5   | 18.5  | 7.3       | 2.2       | 2.3    | 0.1       | 0.5    | 0         | 0.2    |
| Subalpine (dark conifers) | 4.6   | 2.6   | 2.3   | 3.8   | 6.8       | 4.3       | 3.9    | 0.9       | 2.2    | 0         | 1.3    |
| Subalpine (light conifers) | 10.0  | 0     | 0     | 6.3   | 4.3       | 2.0       | 2.2    | 0.1       | 0.6    | 0         | 0      |
| Montane dark conifers | 8.8   | 20.5  | 19.3  | 11.2  | 12.4      | 9.9       | 8.7    | 7.3       | 9.3    | 1.8       | 8.4    |
| Montane light conifers | 10.5  | 1.1   | 0.5   | 9.4   | 16.6      | 14.7      | 14.1   | 8.1       | 11.4   | 1.7       | 9.4    |
| Subtaiga/forest steppe | 0.1   | 16.4  | 14.8  | 0.3   | 9.9       | 13.0      | 11.5   | 8.7       | 9.8    | 9.3       | 8.8    |
| ‘Chern’ dark conifers | 0.2   | 18.2  | 20.6  | 0.1   | 5.6       | 5.7       | 4.8    | 4.1       | 5.4    | 2.5       | 4.7    |
| Steppe      | 6.1    | 1.0   | 0.5   | 5.5   | 7.2       | 10.0      | 11.7   | 9.7       | 10.2   | 6.3       | 10.1   |
| Dry steppe  | 4.9    | 7.2   | 11.4  | 5.7   | 6.7       | 6.9       | 7.9    | 10.6      | 8.6    | 14.5      | 9.4    |
| Semidesert/desert | 31.4  | 3.6   | 0.2   | 38.4  | 23.2      | 28.9      | 30.3   | 32.2      | 29.9   | 34.0      | 31.2   |
| Cryosteppe  | 0.3    | 0     | 0     | 0.6   | 0         | 0         | 0      | 0         | 0      | 0         | 0      |
| Temperate:  |        |       |       |       |           |           |        |           |        |           |        |
| Mixed conifer broadleaved | 0    | 4.8   | 6.1   | 0     | 0         | 0         | 0      | 0         | 0.5    | 0.1       | 0.5    |
| Forest steppe | 0    | 11.4  | 12.0  | 0     | 0         | 1.1       | 0.9    | 10.3      | 6.5    | 14.5      | 9.2    |
| Steppe      | 0     | 12.5  | 11.8  | 0.1   | 0.1       | 1.5       | 1.8    | 7.4       | 5.5    | 14.7      | 6.8    |
| Total       | 100   | 100   | 100   | 100   | 100       | 100       | 100    | 100       | 100    | 100       | 100    |

Table 4. Kappa statistics showing agreement between montane vegetation over the Altai–Sayan mountains predicted in various time slices during the Holocene. (Note that bold marks fair good–very good agreements between pairs of maps.)

| Time slice | 2080 B1 | 2080 A1FI | 2050 B1 | 2050 A1FI | 2020 B1 | 2020 A1FI | 2010 B1 | 2010 A1FI | 3200 BP | 3200 BP | 5300 BP | 5300 BP | 8000 BP | 8000 BP | 10000 BP | 10000 BP |
|------------|---------|-----------|---------|-----------|---------|-----------|---------|-----------|---------|---------|---------|---------|---------|---------|----------|----------|
| 2080 B1    | 1.0     | 1.0       |         |           |         |           |         |           |         |         |         |         |         |         | 1.0      | 1.0      |
| 2080 A1FI  | 0.4     | 1.0       | 0.77    | 0.29      |         |           |         |           |         |         |         |         |         |         | 1.0      | 1.0      |
| 2050 B1    | 0.86    | 0.47      | 0.65    | 1.0       |         |           |         |           |         |         |         |         |         |         | 1.0      | 1.0      |
| 2050 A1FI  | 0.48    | 0.23      | 0.62    | 0.4       | 1.0     |           |         |           |         |         |         |         |         |         | 1.0      | 1.0      |
| 2020 B1    | 0.41    | 0.19      | 0.56    | 0.32      | 0.85    | 1.0       |         |           |         |         |         |         |         |         | 1.0      | 1.0      |
| 2020 A1FI  | 0.13    | 0.13      | 0.17    | 0.13      | 0.29    | 0.35      | 1.0     |           |         |         |         |         |         |         | 1.0      | 1.0      |
| 3200 BP    | 0.24    | 0.26      | 0.22    | 0.28      | 0.25    | 0.22      | 0.22    | 1.0       |         |         |         |         |         |         | 1.0      | 1.0      |
| 5300 BP    | –0.08   | –0.08     | 0.13    | 0.04      | 0.06    | 0.08      | 0.04    | –0.03     |         |         |         |         |         |         | 1.0      | 1.0      |
| 8000 BP    | –0.05   | –0.05     | 0.17    | 0.07      | 0.12    | 0.1       | 0.1     | –0.01     |         |         |         |         |         |         | 0.8      | 1.0      |
| 10000 BP   | 0.21    | 0.22      | 0.22    | 0.21      | 0.24    | 0.24      | 0.27    | 0.62      | –0.02   | 0.0     |         |         |         |         | 1.0      | 1.0      |

impact on vegetation distribution in 2020 and 2050, while they are quite dissimilar in 2080 (table 4).

4. Discussion

Mountains are useful areas of study for monitoring and modeling vegetation changes in both past and future climates because diverse ecosystems are characteristic of a rather small area. In mountains, mapping environments and related vegetation patterns is a difficult exercise due to complex topography and a lack of proper data. The task becomes more difficult for the past because acquiring paleodata necessitates even more time and labor. Paleoenvironmental studies must therefore rely on comprehensive modeling approaches based on sufficient and available data.

The method of modern analogs and a similar method, ‘the principle of actualism’ (as described in Russia), which have been employed in studying quaternary vegetation and climates, follow the logic that modern and fossil pollen or macrofossil assemblages match and the relationships between modern vegetation and related pollen assemblages and paleovegetation and fossil pollen assemblages match as well. How well they match, paleoecologists judged subjectively in earlier studies (Davis 1963, McAndrews 1966, Savina and Khotinsky 1984) or, in studies following a couple decades later, assessed objectively using numerical tools (Andrews et al 1980, Bartlein et al 1984, Giuot 1990, Solomon and Bartlein 1992). It is known in paleoecology that fossil pollen assemblages may lack modern analogs, e.g. for the late glacial period in eastern
Figure 3. MontBioCliM-based mountain vegetation of the Altai–Sayans region in the Holocene: reconstructed from pollen-based climate change scenarios (left), and predicted from climate change scenarios of the Hadley Centre B1 (center) and A1FI (right) in the 21 century. Vegetation key is as in figure 2.

North America and other regions (Jackson and Williams 2004) or for the early Holocene (Savina and Khotinsky 1984) in the former Soviet Union. However, since the Boreal period, and completely since the Atlantic when the vegetation zones became established in Siberia (Khotinsky 1977), past pollen and vegetation assemblages have modern analogs. This fact allowed us to apply this method in the present study.

Pollen-based studies of reconstructed vegetation and climates in Central Asia during the Holocene are still limited. Our pollen-reconstructed paleovegetation and paleoclimates of the Holocene in general agreed with previous findings of other paleoecologists for the Altai–Sayan mountains, although our studies revealed some contradictory conclusions as well (table 5). Our reconstructions of paleovegetation and climates of all time slices (10,000, 8000, 5300, and 3200 BP) corresponded well with those of Blyakharchuk et al. (2004, 2007). We reconstructed the 5300 BP climate to be wetter and warmer, as other authors did within the study area at 5000–6000 BP (Wu and Lin 1988), at 5400 BP (Herzschuh et al. 2004), at 5300 BP (Yamshikh et al. 1981), and at 5200 BP (Savina and Koshkarova 1981). However, Grunert et al. (2000) found from archeological evidence that the climate about 5000 BP near Lake Uvs Nuur, Mongolia, was drier (table 3). The 3200 BP climate we reconstructed as cooler and drier corresponded well to the reconstructions of Herzschuh et al. (2004) at 3100 BP and Savina and Koshkarova (1981) at 3200 BP, although, Wu and Lin (1988) reconstructed the 3000 BP climate as cooler and wetter.

The Holocene vegetation distribution across the Altai–Sayan region was different from the current vegetation distribution: kappa statistics varied between 0 and up to 0.27. The vegetation distribution predicted for the 21st century is also dissimilar to that under the contemporary climate, resulting in kappa statistics less than 0.4. Just as Monserud
et al (1993) concluded that the vegetation of the mid-Holocene and the future vegetation in Siberia would be dissimilar, no analogous patterns in the vegetation distribution were found over the Altai–Sayan mountains in the past (the Holocene) and the future (the 21st century), because all kappa statistics paired between the Holocene time slices and 2020, 2050 and the future (the 21st century), no analogous patterns in the vegetation distribution were found over the Altai–Sayan mountains in the past (the Holocene).

In the past, with slow climate change, the time interval for the vegetation change could have been as long as hundreds to thousands of years. In the 21st century, with rapid climate change caused by unprecedented rates of increasing CO₂ concentration, the time interval might be as little as decades, as predicted from global circulation models (GCM) runs. Recent experiments suggest that high CO₂ levels can spur faster photosynthesis and growth (Tangley 2001), increase the total net primary production (DeLucia et al 1999), increase the fecundity of forest trees, and change dispersal and recruitment patterns (LaDeau and Clark 2001) which may facilitate quick adaptation to a changing environment, although GCM runs also suggest unprecedented rates of warming and decreased moisture in the near future greenhouse world with doubled or tripled CO₂ concentrations. Global vegetation model runs suggest significant shifts in vegetation distribution (Smith and Shugart 1984, Cramer et al 2001, Brovkin et al 2006, Tchebakova et al 2009) with chances that some plant assemblages and species will become extinct in a rapidly changing climate. Still, plants may adapt in this changing world by migration and adaptation. Although migration rates of Boreal tree species, as estimated from paleoecological evidence, were only as 300–500 m yr⁻¹ (King and Herstrom 1997), species with broad climatic niches could adjust to a

### Table 5. Pollen-based reconstructions of vegetation and climate over the Altai–Sayan mountains and adjacent areas cited in literature.

| Site, LON, LAT, Elev (if available) | PreBoreal | Boreal | Atlantic | SubBoreal | Present | Reference |
|---|---|---|---|---|---|---|
| Lake Kotokel, Transbaikalia 108.1°E, 52.5°N, 458 m | 10800–7300 BP Coniferous forests, expansion of birch Warmer and wetter | 7000–6500 BP Coniferous forests, expansion of pine Warmer and drier | 8000–5500 BP dark conifers. A tree-line was 300 m higher Warmer and wetter | 5000 BP Steppe. Dark conifers declined. Cooler and drier | Light conifer taiga | Tarasov et al (2009) |
| Grusha Lake, Tuva, Central Asia 89°25'E, 50°23'N, 2413 m | 11000–10000 BP Tundra steppes Cooler and drier | 8000–5500 BP dark conifers. A tree-line was 300 m higher Warmer and wetter | 5000 BP Steppe. Dark conifers declined. Cooler and drier | | Steppe | Blyakharchuk et al (2007) |
| Juyan Lake, China 101.8°E, 41.9°N 892 m | 10700–5400 BP Deserts Dry | 5400 BP Steppes dominate Wetter | 3100 BP Deserts dominate Drier | | Grassland | Herzschuh et al (2004) |
| Lake Uvs Nuur, Northern Mongolia 93°E, 50°N | 5000 BP Archaeological evidence shows Drier | 3000–2500 BP A rise of lake levels. Transition from steppe to forest. Wetter | | | Grassland | van Geel et al (2004) |
| Tibetan Plateau | 6000–5000 BP coniferous forests Warmer and wetter | 3000 BP Glacier advance. Cooler and wetter | | | Grassland | Wu and Lin (1988) |
| Kansk-Achinsk basin, north of the Minusinsk basin | 5200 BP Forests dominate versus steppes Warmer and wetter | 3200 BP Steppes dominate. Birch versus dark conifers Cooler and drier | | | Forest steppe | Savina and Koshkarova (1981) |
| River Kemchug, Kansk-Achinsk basin | 5300 BP dark conifer forests Wetter | | | | Dark conifer taiga | Yamskikh et al (1981) |
| Altai–Sayan mountains | 10000 BP Cooler and drier | 8000 BP Warmer and wetter | 5300 BP Warmer and wetter | 3200 BP Cooler and drier | | Tchebakova et al (2009), this study |
Figure 4. MontBioCliM-based mountain vegetation of the Altai–Sayans region: reconstructed from pollen-based climate change scenario in the mid-Holocene (top) and predicted from the Hadley Centre B1 2050 climate change scenario in the current mid-century (bottom). Vegetation key is as in figure 2.

rapidly warming climate while species with a restricted range of suitable habitats and limited dispersal are likely to disappear first (Solomon and Leemans 1990). Man’s role in transporting seed throughout the world using contemporary technical means substantially increase migration rates. Environmental changes can also alter the behavior of long-distance dispersal: warming can promote wind-driven movements of plant genotypes and populations in Boreal forests (Kuparinen et al. 2004). While extirpation and immigration are the main processes at the margins of the forest distribution, within the forest zone, natural selection and gene flow are primary processes favoring tree adaptation to climate change (Davis and Shaw 2001, Rehfeldt et al. 2004). Evolutionary processes of adjusting to predicted climate change would take a time at least one order of magnitude greater than the time it takes for the climate itself to change. Estimates for Pinus sylvestris in Siberia suggest that 5–10 generations (about 150 years) are required for the evolutionary process to follow a predicted warming. Genotypes would be reorganized within tree distributions, and tree boundaries would follow a changing climate. The forest adjustment to climate change would occur, but it would require a long time due to the large amount of change predicted by the end of the current century (Rehfeldt et al. 2004).

Our predictions of climate and past vegetation are subject to many potential sources of error: sparse fossil pollen sites and their complete absence in some parts of the study area such as eastern Tuva and Mongolia, which therefore necessitates data extrapolation; sparse climate data (especially in Mongolia) and related poor interpolation of climate surfaces; erroneous or inadequate pollen analysis (including radiocarbon sample dating) and related ‘biomization’ of the pollen; and inaccurate climatic limits of orobiomes in the bioclimatic model and a related degree of disagreement between modeled and actual vegetation. Nevertheless, for the study area, the main conclusions regarding pollen-reconstructed vegetation and the climate of the major time slices during the Holocene showed agreement with many previously held interpretations by other paleoecologists.

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