Potential influence of the late Holocene climate on settled farming versus nomadic cattle herding in the Minusinsk Hollow, south-central Siberia

T A Blyakharchuk$^{1,4}$, N M Tchebakova$^2$, E I Parfenova$^2$ and A J Soja$^3$

$^1$ Institute for Monitoring Climatic and Ecological Systems, Siberian Branch, Russian Academy of Sciences, Akademichesky Prospekt 10/3, 643055 Tomsk, Russia
$^2$ V.N. Sukachev Institute of Forests, Siberian Branch, Russian Academy of Sciences, Academgorodok, 50/28 660036 Krasnoyarsk, Russia
$^3$ National Institute of Aerospace (NIA), NASA Langley Research Center, Climate Sciences, 21 Langley Boulevard, Mail Stop 420, Hampton, VA 23681-2199, USA
$^4$ Tomsk State University, Lenina 36, 634050 Tomsk, Russia

E-mail: tarun5@rambler.ru, ncheby@ksc.krasn.ru, lyeti@ksc.krasn.ru and Amber.J.Soja@nasa.gov

Received 5 August 2013, revised 10 April 2014
Accepted for publication 21 May 2014
Published 13 June 2014

Abstract

Prehistoric and early historic human cultures are known to be closely connected to and dependent on their natural environments. We test the hypothesis that climate change influenced the means of subsistence of ancient tribes and favored agricultural or cattle herding economic strategies. Our study area is the Khakass–Minusinsk Hollow, located in the foothills of the Sayan Mountains, south-central Siberia, which was, for a few millennia, a buffer zone for human migrations across the Great Eurasian Steppe. Three different methods (the Montane BioClimatic Model, MontBCliM; the biomization method; and the actualizm method) are employed to reconstruct vegetation taken from the fossil pollen of sediment cores in two mountain lakes at eleven time slices related to successive human cultures back to the mid-Holocene. MontBCliM model is used inversely to convert site paleo-vegetation into site paleo-climates. Climate-based regression models are developed and applied to reconstructed climates to evaluate possible pasture and grain crops for these time slices. Pollen-based reconstructions of the climate fluctuations uncovered several dry periods with steppe and forest-steppe and wetter periods with forests since 6000 BP. Grasslands increased by an order of magnitude during the dry periods and provided extensive open space suitable for pastoralism; however, both grain and pasture yields decreased during these dry periods. During wetter climates, both grain and pasture yields increased twofold and supported more fixed human settlements centered around farming and cattle herding. Thus, the dry periods favored pastoralist rather than farming activities. Conversely, tribes that practiced agriculture had some advantage in the wet periods.

Online supplementary data available from stacks.iop.org/ERL/9/065004/mmedia

Keywords: Holocene, human culture, economic strategies, Siberia
1. Introduction

Gumilev (2002), a Russian historian, geographer, and ethnologist, developed a theory relating the rise, development and decline of ethnoses (human cultures) to the changing environment. This theory was the first to connect an increase in human population in prehistoric Eurasia with increased productivity in the ‘Great Steppe Belt’ during humid climatic periods, which expands our understanding of human history as a natural interaction between the biosphere and sociosphere. Gumilev defined the ethnos as a phenomenon of the biosphere and an entity exerting itself using the biogeochemical energy of living matter in the correspondence with the second law of thermodynamics that is confirmed by a diachronous sequence of historic events’. Peoples and landscapes coexisted and interacted uniquely through the establishment and progressions of the human history. Throughout history, people’s expansion and advance have been related to changes in the environment, and this is found in a variety of diverse human epochs across natural landscapes. Historic security and food accessibility for ancient peoples, given limited technical advances and knowledge, likely controlled human development and migration towards natural resources (Chugunov 2012, Kozintsev 2008, Chernukh 2008, Frachetti 2011). Since prehistoric times, the extensive Eurasian Steppe (6000 km in the west-east span) is known to have been settled and cultivated by both farmers and nomads with pastoralism dominating by the 18th century (Slavnin and Sherstova 1999).

From the viewpoint of dependence on specific environmental conditions, Siberian human cultures have not been sufficiently explored (Okladnikov 1968). Our study area, the Minusinsk Hollow, is an intermountain hollow, located in the foothills of the Sayan Mountains in south-central Siberia (figure 1). The Minusinsk Hollow is currently shared by two administrative units of the Russian Federation: the Republic of Khakassia and the southern Krasnoyarsk territory. The paleo-botany, paleo-climates, and archeology of the Minusinsk Hollow have been separately examined for half a century (Yamskikh 1981). Recent studies analyzing available direct historic and archeological data and paleo-proxies from natural archives (pollen data, macrofossil peat data, radiocarbon dating) attempted to relate human migrations to climate change (Yasuda 2004, van Geel et al 2004a, 2004b, 2004c, Blyakharchuk and Chernova 2013). The authors found that the development of different human cultures across the Minusinsk Hollow was related to climatic moisture and dryness. To support a growing population and to promote the

Figure 1. The Minusink Hollow in the background of the Altai-Sayan Mountains. Study sites (two big red dots): Dikoe Lake (left) and Kutuzhekove Lake (right) located at a distance of ~100 km. White dots show locations of 28 pollen surface sample sites on the background of actual vegetation cover (Samoylova 2001). Vegetation key: 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.
development and expansion of various ancient tribes, their economies would have had to concur with harsh Siberian climates that limit many crops in this risky agricultural zone in the Central Asian interior.

Archeological findings in the Minusinsk Hollow showed that ancient people practiced either predominantly a settled and semi-nomadic agricultural and cattle herding economy or a nomadic cattle herding economy (Slavnin and Sherstova 1999).

Numerous signs of ancient human cultures are found across landscapes in the Minusinsk Hollow. Three main findings are the following: first, all ancient cultures that thrived in this area originated from migrations of human tribes from either the west and southwest or from the south and southeast (Vadetskaya 1979, Bokovenko 1996, Slavnin and Sherstova 1999, Chernukh 2008, Frachetti 2011, Korolkova 2012, Ryabkova 2012, Chugunov 2012); second, our recent research found that a given lifestyle (settled agricultural-cattle-herding or nomadic cattle herding) might to a great degree be related to fluctuations between dry and wet periods in the great Eurasian steppe belt (Blyakharchuk and Chernova 2013); and third, the diversity of landscapes (forested mountains, alpine meadows, intermountain steppe, and flood-plain meadows) allowed for the coexistence of human tribes with different types of lifestyles (Slavnin and Sherstova 1999).

**Archeological background**

Khakassia within the Minusinsk Hollow is a unique and important area. It was recognized as ‘the heart of the ethno-genesis, where various cultures and ethnogenic groups of people that migrated from the southwest and the southeast interacted over a long period of time’ (Slavnin and Sherstova 1999, page 12).

**Neolithic time**

Archeological evidence showed that in the Neolithic time, the plains of the Hollow were not colonized by people until 6000 BP (Before Present) (van Geel et al. 2004a). Only sparse findings in temporal camps of hunters and fishers dated by this time frame have been found by archeologists in Khakassia.

**Afanasievo culture**

Formed after the Neolithic period, in the 6th to 5rd millennium BP by tribes of Indo-Europeans that migrated from southwestern areas of Eurasia to Khakassia. They had a complex economy (Slavnin and Sherstova 1999), which included hunting and fishing, primitive agriculture and cattle herding. The main cultivated plant was barley (*Hordeum*) and domestic animals included dogs, cows, and horses. The people could weave cloth from the fiber of nettle (*Urtica*) and hemp (*Cannabis*). They also mined copper. Archeologists (Kiselev 1968) have related the first burial mounds in Khakassia to this culture (figure 2).

**Figure 2.** Burial mounds in Khakassia. The Afanasievo culture (4th to 3rd millennium B.C.) was known to be the first to build burial mounds in southern Siberia. The graves were designed so they could be modified and used repeatedly (Kiselev 1968). Photo courtesy of A Soja.

**Okunevo culture**

Dated to the Early Bronze Age, the end of the 5th to the beginning of the 4th millennium BP, the Okunevo developed in Khakassia. These peoples had features that were similar to the Afanasievo culture, although these people had some Mongoloid features (Bokovenko 1996). The material cultures of both groups were similar.

**Andronovo culture**

Dated to the middle Bronze Age, 4th millennium BP. According to Slavnin and Sherstova (1999) this archeological culture was formed by martial tribes of Indoians (Arians), who migrated to Khakassia from the west-southwest. This, possibly more humid period, resulted in a population bloom in steppe tribes across the ‘great steppe belt of Eurasia’ and excessive numbers of the population were forced to migrate to the east in Khakassia (Bokovenko 1992, 1996, Slavnin and Sherstova 1999, Chernykh 2008, Blyakharchuk and Chernova 2013).

Cattle herding became increasingly important, as did horse breeding. In the Minusinsk Hollow, they practiced a sedentary lifestyle, developing agriculture and cattle herding around their settlements on the rivers valleys. They also hunted and fished. Barley (*Hordeum* sp.), millet (*Panicum* sp.) and big-spike wheat (*Triticum* sp.) were grown in small fields near settlements (Slavnin and Sherstova 1999). As an innovation, spoke-wheeled chariots were used, especially in wars that became necessary during migrations to new areas.

**Karasuk culture**

Dated to the late Bronze Age, the end of 4th millennium BP. Human tribes from Ordos migrated with herds of sheep from China, to Khakassia along steppe valleys. The decreased role of agriculture during the Karasuk cultural period can be
inferred from only occasional findings of the anthropogenic pollen indicator Cannabis (Blyakharchuk and Chernova 2013). Karasuk people were nomadic tribes of sheep herders. Their main occupation was cattle breeding with seasonal transhumance. Their innovations included using horses for riding and casting bronze. Farming played an ancillary role in this culture. They hunted periodically, but did not fish.

Tagar culture

Dinlin tribes are part of the Scythians, in Khakassia, dated to the early Iron Age, 8th to the 3rd century of the 3rd millennium BP. The economy of Tagar tribes was complex and the lifestyle sedentary (Slavnin and Sherstova 1999, Kozintsev 2008, Mandryka 2008). Both cattle breeding and agriculture were employed, with a slight predominance of agriculture. Barley, millet, wheat, and dry-land rice were grown on irrigated fields. At this time, light iron plows were used for the first time in Siberia. A stratum of craftsman produced fluxed bronze, gold and iron.

Tashtyk culture and Yenisey–Kirgiz culture

Dated to the late Iron Age, the end of the 3rd and beginning of the 2nd millennium BP. New tribes with the Kirgiz ancestry penetrated Khakassia in the beginning of a new dry period (Slavnin and Sherstova 1999). Originally they formed the Tashtyk culture, which developed parallel with the Tagar culture. Initially, the Kirgiz peoples penetration on the Dinlin (Tagar) tribe territory in Khakassia was peaceful, however later, military conquests resulted in the extermination of most of the Dinlins (Slavnin and Sherstova 1999). Similar conflicts have been described in northern Khakassia, at the boundary of steppe and forest-steppe and in the south at the forest boundary (Mandryka 2008). Eventually, the Tashtyk culture evolved into the Yenisey–Kirgiz culture in the second millennium BP. Lifestyles of the Yenisey–Kirgiz culture basically followed the Tagar and Tashtyk traditions, which were based on a settled and semi-nomadic agricultural and cattle breeding economy. They grew millet, wheat, and himalayan barley, using irrigation and the plough. Additionally, they practiced sheep and horse breeding and to a lesser degree, cattle breeding.

Tatar–Mongolian invasion

During the 13th–14th century AD. (After the Death of Christ), anthropogenic pollen indicators and charcoal were almost absent in the peat layer of this timeframe in the pollen diagram of the upland Lugovoe mire located 100 km upslope of Dikoe Lake (Blyakharchuk and Chernova 2013). All these indicators, including Hordeum pollen, appeared again later. These indicators were interpreted as signs of an interruption in economic development during the Mongolian invasion.

Russian colonization

At the boundary between 17th and 18th centuries AD until the present, settlements and populations increased, and the steppe became increasingly ploughed.

In this study, we test the hypothesis: climate change altered the means of subsistence of ancient tribes and forced them to migrate and conquer new lands. Specifically, using a combination of paleo-ecological modeling approaches, we reconstruct climates and predict climate-based potential pasture and grain crop distributions to argue that nomadic migrations and the development of transhumant pastoralism are related to dry climates and steppe expansions and settled farming is related to moist climates, while the Minusinsk Hollow was slowly being populated by humans during the second half of the Holocene.

2. Methods

Study area

The Minusinsk Hollow is an intermountain hollow of the Sayans Mountains (Mts) in interior central Asia, framed by the leeward macroslope of the Kuznetsky Alatau Mts in the west, by the windward macroslope of the highest range of the West Sayan Mts in the south and by the windward macroslope of the East Sayan Mts in the east (figure 1). The climate is continental, characterized by short warm summers and long cold winters, with a thin snow cover (5–10 cm) in the west and central portions of the Hollow under the rain shadow of the Kuznetsky Alatau Mts. and a deep snow cover (up to 1 m) on the windward slopes of the West Sayan Mts. Air masses bearing water from the Atlantic are transported to the Siberian interior, driven by the westerlies that are the dominant atmospheric circulation pattern, which results in high annual precipitation in the mountains (up to 1500–2000 mm on northwestern windward slopes) and as little as 250 mm of precipitation on leeward slopes and the inner Hollow. Most of the annual precipitation (75–90%) falls in the summer. The Hollow is protected by montane ridges and thus occurs in a particularly warm and sufficiently moist climate on fertile Siberian chernozem soils. It is presently known to be a famous local granary, where farmers have cultivated a variety of crops.

Ecosystems across and surrounding the Minusinsk Hollow are very diverse: from steppe in the lowlands with warm dry climates to forests at middle elevations to tundra and nival communities in cold wet highlands. Current vegetation over the Sayan Mountains varies on leeward and windward macroslopes. Along the northern macroslope, the sequence of vegetation types is as follows upslope: steppe in the northern foothills followed by light-needled (Pinus sylvestris) and birch (Betula pendula) subtaiga; then by lush dark-needled ‘chern’ (which means ‘black’ in Russian) forests (Pinus sibirica and Abies sibirica with Populus tremula), productive and rich in flora and ferns with some nemoral (temperate) tall herbs in lowlands succeeding to dark-needled (P. sibirica and...
A. sibirica with some Picea obovata) taiga upslope; then to subalpine, alpine and tundra in the highlands. Beyond the Minusinsk Hollow, along the southern macroslope, the sequence of vegetation types follows downslope along an abrupt moisture gradient from tundra to light-needled (Larix sibirica) taiga to steppe, dry steppe and semidesert at the border with Mongolia.

### Data

Blyakharchuk (2012) collected fossil pollen sediments from Dikoe Lake (54° 07’N and 90° 22’E, elevation 800 m) on the Batenevsky Ridge in the rain shadow of the Kuznetsky Alatau Mts, sheltering the Hollow from the west, and also data are used from the van Geel et al (2004a) Kutuzhekovo Lake pollen diagram (53° 36’ N and 91° 56’ E, elevation 460 m) in the interior of the Minusinsk Hollow (figure 1). Dikoe Lake is located in the lowland subtaiga (P. pendula and P. sylvestris); Kutuzhekovo Lake is located in steppe. The Dikoe Lake pollen diagram was dated by five calibrated AMS (accelerator mass spectrometry) dates (Blyakharchuk 2012) (table 1). The lake’s sediment core is 410 cm long (dark brown gyttja) and was extracted from the middle of Dikoe Lake, where the depth of water is 3 m. A Wright system piston corer (Wright 1991) was used to extract the undisturbed lake sediment. Later in laboratory, 1 cm³ samples by volume were extracted from each 5–8 cm intervals from gyttja cores for pollen and LOI (loss-on-ignition) analyses. On the whole, 500–600 pollen grains of each tree species in excess of grains of other pollen and spores in a pollen sample were employed in the analyses as recommended by Moore et al. (1997).

Radiocarbon dates were calibrated using the Radiocarbon Calibration program CALIB6.0.0 (http://radiocarbon.pa.qub.ac.uk/calob/calib/html). The Dikoe Lake depth-age model (figure 4) demonstrated a slow rate of gyttja accumulation from 8000 to 4220 cal. yr BP (calibrated years before present) and a sharp increase in the accumulation rate from 4220 cal. yr BP to the present time. The accuracy of calibrated dates was enhanced by calculating each date as an average of all calibrated dates based on CALIB6.0.0.

The composition of the Dikoe Lake pollen diagram (Blyakharchuk 2012, p. 79; see supplementary table 1) and Kutuzhekovo pollen diagram (van Geel et al 2004a, p. 1738) are examined for eleven (including contemporary) time slices to reconstruct vegetation and climates to relate to archeological human cultures that existed from the mid-Holocene to the present in Khakassia. We choose these time slices summarizing archeological data from: Kiselev (1968), Bokovenko (1996), Slavnin and Sherstova (1999), van Geel et al (2004a, 2004b), Chernyk (2008) and Blyakharchuk and Chernova (2013). Eleven time slices and corresponding human cultures resulted in: 6350 and 6150 cal. yr BP during the temporal settlement of hunters and fishes; 5240 cal. yr BP during the Afanasievo culture; 4220 cal. yr BP during the Okunevo; 3730 cal. yr BP during the Andronovo; 3190 cal. yr BP during the Karasuk; 2620 cal. yr BP during the Tagar or Siberian Scythians; 1620 cal. yr BP during the Tashlyk; 1240 cal. yr BP during the Yenisey–Kurgiz; 700 yr. BP during the Mongolian invasion; and from 400 yr. BP to the present Russian colonization. Time slice depths are marked with red stars in the Dikoe Lake depth-age model (figure 4).

### Models for pollen-based reconstruction of paleo-vegetation and climate

Three methods are used to reconstruct paleo-biomes and climates for various time slices in the Minusinsk Hollow: the Russian qualitative method (‘the principle of actualization’ of Markov and Velichko 1967) and the quantitative method of Prentice et al (1996) to predict biomes directly from pollen; and a two-step method to first predict climates from pollen using stepwise regression models and then to predict biomes coupling these climates to our montane bioclimatic model, MontBCliM (Tchebakova et al 2009). MontBCliM is an envelope-type model that limits montane biomes using three climatic indices characterizing plant requirements for warmth, plant resistance to cold, and plant tolerance to water stress. MontBCliM may be run in two directions: directly to predict orbiomes from given climatic indices; and inversely to predict average climatic indices from given biomes. Finally, we selected the most probable biome reconstructed by these three methods for each time slice and ran MontBCliM inversely to reconstruct climates from those biomes. The sequence of vegetation and climate reconstruction is shown in figure 3.

The Russian principle of actualization is to a large extent subjective. Here, expert-constructed pollen-climate relationships are similar to the ‘analog’ method developed and used by Davis (1963) and McAndrews (1966), which was later quantified by numerous paleo-ecologists (Prentice 1980, Overpack et al 1985, Giuot 1990) decades later.

The Prentice et al (1996) quantitative method simulates paleo-vegetation from pollen data at the biome level; this is the pollen ‘biomization’ approach. Tchebakova et al (2009) used the biomization method successfully in the Altai-Sayan Mts, Herzschuh et al (2004)—in near west-northern China, and Tarasov et al (2009)—in the Lake Baikal and Mongolia.
regions. Please see Tchebakova et al (2009) for additional details.

In this paper, we employed the third approach: we constructed and applied our pollen-based multiple regression models to predict climates directly from the pollen in theMinusinsk Hollow. Bukreyeva (1991) and Konovalov and Ivanov (2007) developed regression models for the West Siberia plains, which produced satisfactory results. However, their models cannot be applied to montane regions or to regions beyond West Siberia.

Our models relate surface pollen specters to contemporary climates, namely to growing-degree days that are greater than 5 °C (GDD), which characterize available heat, and to an annual moisture index (AMI), which is the ratio of GDD to annual precipitation that characterizes available moisture. These two climatic indices are basic in the MontBCliM, which has been successfully used to predict montane vegetation in the Altai-Sayan Mts (Tchebakova et al 2009) and crop and pasture yields in the Minusinsk Hollow (Tchebakova et al 2011, Parfenova et al 2005). These indices GDD and AMI are easily converted to values typically used in paleo-studies, July temperature and annual precipitation. Using data from 38 weather stations in the Minusink Hollow, July temperature is found to be linearly related to GDD (R² = 0.91, p = 0.0000). Annual precipitation is calculated as a ratio of GDD to AMI.

Surface pollen is collected from each of 28 sites at which 2–5 samples located in close proximity are acquired, totaling 80 samples from 11 montane biomes across the Altai-Sayan Mts where the Minusinsk Hollow is located (figure 1). These 80 samples represent all biomes found across the Altai-Sayan Mts: tundra—3 samples; subalpine—5; dark-needled taiga—4; lowland ‘chern’ taiga—7; light-needled taiga—7; subtaiga—9; forest-steppe—5; steppe—11; and semidesert—4.

Because pollen sample sites did not necessarily correspond to weather station locations, current climate data for these sites are derived from climatic maps of GDD and AMI according to their latitude and longitude. The maps are drawn using the Hutchinson interpolation procedure (Hutchinson 2000) based on data from about 100 weather stations across the Altai-Sayan Mts (Tchebakova et al 2009).

A linear step-wise regression procedure that is used to relate surface pollen to climatic indices, adds one variable at a time (Statistica v.6.). Because the program automatically entered the variable with the highest F statistic, the most significant pollen taxa are selected out of 18, comprising >90% of the pollen in the sample, which provided the best statistical parameters for these models. We related surface

Figure 3. Flow chart of vegetation and climate reconstruction in the Minusinsk Hollow during the late Holocene.
pollen to climatic indices that selected the most significant out of 18 pollen taxa and species in the sample. The value of a climatic parameter for each time slice is calculated:

\[ \text{Climatic parameter} = a + a_1 p_1 + a_2 p_2 + \ldots + a_n p_n, \]

where \( a_1, \ldots, a_n \) are empirical coefficients, \( p_1, \ldots, p_n \) are taxa pollen (%).

Thus, to calculate GDD\(_5\), pollen of \( P. sibirica, Alnus, Betula nana, P. sylvestris, Salix, \) and \( Artemisia \) are determined to be the best predictors (\( r = 0.57, n = 80, \text{ st. er.} 400, p < 0.0001 \)). To calculate AMI, \( Poaceae, B. nana, P. sibirica, Alnus, Chenopodiaceae, \) and \( P. obovata \) are found to be the best predictors (\( r = 0.57; n = 80; \text{ st. er.} = 0.90, p < 0.0001 \)).

Regression model statistics confirm their high reliability, however they also show large standard error due to the large range in deviations from the mean. Given the high confidence in the pollen-based equations, we are able to demonstrate the equations work well for two weather stations that are located in close proximity to the study sites. Other pollen sample sites are not located near weather stations. Station data are corrected to account for site elevation using temperature and precipitation lapse rates. The comparison of predicted climatic indices, GDD\(_5\) and AMI, as well as July temperature and annual precipitation converted from these indices both show a relative error of ±0–15% in comparison to the station-calculated data (table 2). To validate our pollen-based climate reconstructions for the paleo-time slices, the MontBCliM model is applied to predict paleo-vegetation (montane biomes) from the reconstructed climate for two sites Dikoe Lake and Kutuzhekovo Lake.

Thus, three methods are utilized to estimate paleo-biomes: MontBCliM predictions; the ‘biomization’; and actualization methods. The comparison of paleo-biomes reconstructed by the above three methods showed a good match (table 3). The most probable biome is selected for each time slice if the match is 3 out of 3, or 2 out of 3 if agreement is not consistent.

Consequently, a list of resultant paleo-biomes are obtained for each time slice at both sites, Kutuzhekovo and Dikoe Lakes, which are used to reconstruct paleo-climates from the mid-Holocene. Then, MontBCliM is simulated in a reverse mode and explicitly ascribed a range of GDD\(_5\) and AMI corresponding to a given biome (table 4). Monserud et al. (1998) first used a similar climate-driven model in reverse to infer the range of climates (e.g., GDD\(_5\) and AMI) corresponding to each observed pollen-based vegetation zone located across Siberia in the mid-Holocene. For a biome to change into a neighboring biome in our study, we allowed it to reach the mean of a climatic range from its closest border.

Finally, climate change anomalies in each latter Holocene time slice are evaluated as the differences between the reconstructed contemporary and paleo GDD\(_5\) and AMI. These anomalies are averaged for the two sites and summed with contemporary climatic layers (0.1 degree latitude by 0.1 degree longitude) across the Minusinsk Hollow to calculate climatic layers for eleven time slices back to the mid-Holocene. When coupled with these climatic layers, MontBCliM produced a vegetation distribution (steppe, forest-steppe and forest) across the Minusinsk Hollow (table 5).

**Climate-based models to predict crop and pasture yields**

Based on archeological studies in this region, ancient peoples have been found to cultivate barley, millet and later wheat. All three crops are known to be resistant to the drought that often occurs in interior Siberia. Barley and millet are tolerant to saline soils, which are also characteristic of dry climates (steppe and forest-steppe soils). Barley is a productive and fast-ripening crop. Millet produces grain and thatch that is comparative to hay by its forage quality and may be used for cattle. So, the first humans seemed to exploit these crops because of their natural traits.

We constructed two climate-based regression models that predicted the annual grain and pasture yields from AMI, assuming that moisture controls the vegetation productivity rather than heat, which is not the limiting factor in the forest-steppe and steppe zones. Model statistics demonstrated the high significance of our models (supplementary table 2). Given sufficient heat in the steppe and forest-steppe, GDD\(_5\) only explained an additional 7% in grain yield and only 1% in pasture yield. Thus, for consistency, we applied the models where crop and pasture yield estimates are only a function of AMI. The pasture crop is better approximated by a logarithmic function and the grain crop by a linear function (supplementary figure 1).

Climate and grain yield data used to construct the models are collected from 1966–2009 from 30 farming regions located in forest-steppe or steppe within the Minusinsk Hollow (Tchebakova et al. 2011). The grain yield (\( G, 100 \text{ kg ha}^{-1} \)) is calculated:

\[ G = 20.2 \times 3.22^* \text{AMI} \times (r = 0.62, n = 29, \text{ st. er.} = 2.83, p = 0.0003) \]

Pasture climate and yield data are collected from Climatic Reference books (1967–1970) and Kuminova (1960), Kuminova et al. (1976) correspondingly. The pasture yield (\( R, \))
Both grain and pasture yields are calculated within the steppe and forest-steppe zones that are modeled from MontBCliM by the AMI value of 1.8. A yield value for each pixel in each time slice of the latter Holocene is calculated by coupling both equations with AMI maps. The 1 km resolution AMI maps for each time slice are constructed by adding the AMI departures to the contemporary AMI map for the study area. The AMI departures for each time slice are approximated as residues of a reconstructed contemporary biome value from a reconstructed past biome value for both sites and then the departures are averaged to get one value for each period.

To avoid the influence of modern cultivation means and genetically selected seed on the grain productivity in prehistoric times, relative yield is calculated at each time slice as the ratio of past yield to the contemporary yield. Thus, only climate impacts on potential crops during the latter Holocene are analyzed. For consistency, the ratio of past pasture yield to the contemporary yield is used to quantify relative pasture yield. The distribution of the steppe and forest-steppe zones and both grain and pasture yields (%) are mapped across the Minusink Hollow for eleven time slices during the late Holocene when various human cultures with unique economies were settled (table 5).

3. Results

Past biomes are reconstructed using three different methods (MontBCliM, biomization, and the actualization methods) for eleven time slices, and these time slices match well at both sites. Reconstructed biomes match completely in 36% of all cases (3 out of 3 cases); they match 2 times out of 3 times in 59% of all cases; and they did not match in one case (4.5%, table 3). Climates are reconstructed for each time slice using these biomes and by applying MontBCliM in the reverse mode. Climate change is then evaluated by comparing successive climates (table 4). Using these data, historic steppe and forest-steppe lands that are suitable for pasture and farming are mapped, and then potential grain yields for farming and pasture crops for pastoralism are evaluated (table 5). In this section, we intentionally provide model results on vegetation and climate reconstructions in parallel with archeology-based evidence on the means of subsistence in ancient tribes in order to

$$P = 22.2 - 10.2 \ln \text{AMI} \times (r = 0.83, n = 19, \text{st. er.} = 3.34, p = 0.0000)$$

| Period, cal. yr BP, ancient culture | DIKOE LAKE | KUTUZHEKOVO LAKE |
|-----------------------------------|------------|-------------------|
| Contemporary                      | Light conifer | Forest-steppe |
| 700, Russian colonization          | Light conifer | Forest-steppe |
| agriculture                       | Light conifer | Forest-steppe |
| 1240, The Kirgiz settled          | Dark conifer | Forest-steppe |
| farming, semi-nomadic             | Dark conifer | Forest-steppe |
| 1620, The Tashtyk                  | Dark conifer | Forest-steppe |
| predominantly nomadic             | Forest-steppe | Forest-steppe |
| 2620, The Tagar                    | Dark conifer | Forest-steppe |
| (Scythians) predominantly          | Forest-steppe | Forest-steppe |
| farming, semi-nomadic             | Forest-steppe | Forest-steppe |
| 3190, The Karasuk                  | Forest-steppe | Forest-steppe |
| culture herding                   | Light conifer | Light conifer |
| 3730, The Andronovo               | Light conifer | Light conifer |
| primitive agriculture             | Light conifer | Light conifer |
| cattle herding                    | Light conifer | Light conifer |
| 4220 The Okunevo                   | Light conifer | Forest-steppe |
| Cattle herding                    | Forest-steppe | Forest-steppe |
| 5240, The Afanasievo              | Dark conifer | Steppe |
| a complex economy (hunting,       | Dark conifer | Steppe |
| fishing, primitive agriculture    | Dark conifer | Steppe |
| and cattle herding                | Dark conifer | Steppe |
| 6150, The Afanasievo              | Light conifer | Steppe |
| Primitive agriculture             | Dark conifer | Steppe |
| of hunters and fishers            | Dark conifer | Steppe |
| 6350 Temporal settlements          | Dark conifer | Steppe |
| of hunters and fishers            | Dark conifer | Steppe |

Table 3. Reconstructed vegetation at Dikoe Lake and Kutuzhekovo Lake at periods of ancient human cultures in the Minusink hollow.
demonstrate the similarity in the patterns of model predicted climate change and alterations in farming and pastoral areas. We argue these alterations in climate resulted in or heightened the sequential replacement of human cultures: settled farming versus nomadic cattle herding.

Dry periods

Fluctuations of forest and steppe/forest-steppe lands, which are directly related to climate change in the latter Holocene, revealed at least four dryer periods with extensive open space, likely suitable for pastoralism. Grasslands increased by an order of magnitude during the dry periods and together with forest-steppe covered 70–85% of the Minusink Hollow (table 5). All four periods are characterized by intensive nomadic rather than farming activities. Both predicted grain and pasture crops decreased to 70–80% during these periods: 4220, 3730, 3190 and 1620 cal yr BP, but it is probable these lands remained sufficiently productive for pastoralist practices.

The climate at 4220 cal. yr BP likely worsened the living environment for the Okunevo people. The formation of idiomatic cosmogenic religious practices designed to protect them from severe natural phenomena was reflected in the semantic monuments (Blyakharchuk and Chernova 2013). This local dry period matched well with lower lake levels in west-central Europe (Magny 2013). An expansive dryer climate possibly motivated human masses to migrate, with mobile martial tribes having an advantage over others.

Van Geel et al (2004a, 2004b) highlighted a long arid period from 4630 to 3200 cal. yr BP, when the Tyva area located south and south-east of the Minusinsk Hollow was depopulated. This desertification might have forced people to migrate from Ordos Inner Mongolia to northern Khakassia in search of improved living conditions. They migrated with herds of sheep, developed bronze casting craft, introduced innovative horse riding to Khakassia, and conquered the agricultural tribes of the Andronovo culture.

| Periods, BP | Vegetation | AMI Mean | GDD5 Mean | Climate change to the previous period | Vegetation | AMI Mean | GDD5 Mean | Climate change to the previous period |
|------------|------------|----------|-----------|--------------------------------------|------------|----------|-----------|--------------------------------------|
| Contemporary | Light conifer | 2.5 | 800 | No change | Forest-steppe | 2.5 | 1300 | No change |
| 700, Russian colonization, agriculture | Light conifer | 2.5 | 800 | Dryer | Forest-steppe | 2.5 | 1300 | No change |
| 1240, Kirgiz settled farming, semi-nomadic | Dark conifer | 1.0 | 800 | Wetter/Cooler | Forest-steppe | 2.5 | 1300 | Wetter |
| 1620, Tashtyk predominantly nomadic | Forest-steppe | 2.5 | 1300 | Dryer/Warmer | Steppe | 4.6 | 1300 | Dryer |
| 2620, Tagar (Scythians) predominantly farming, semi-nomadic | Dark conifer | 1.0 | 800 | Wetter | Forest-steppe | 2.5 | 1300 | Wetter |
| 3190, Karasuk cattle herding, decreased farming | Light conifer | 2.5 | 800 | No change | Dry/Steppe | 7.0 | 1300 | Dryer |
| 3730, Andronovo primitive agriculture, cattle herding | Light conifer | 2.5 | 800 | Cooler | Steppe | 4.6 | 1300 | No change |
| 4220, Okunevo cattle herding | Forest-steppe | 2.5 | 1300 | Dryer/Warmer | Steppe | 4.6 | 1300 | No change |
| 5240, Afanasievo a complex economy (hunting, fishing, primitive agriculture, cattle herding) | Dark conifer | 1.0 | 800 | No change | Steppe | 4.6 | 1300 | No change |
| 6150, Afanasievo primitive agriculture | Dark conifer | 1.0 | 800 | No change | Steppe | 4.6 | 1300 | No change |
| 6350 temporal settlements of hunters and fishers | Dark conifer | 1.0 | 800 | — | Steppe | 4.6 | 1300 | — |

* van Geel et al (2004a)
During the dry period around 3730 cal yr BP, the Andronovo people had a complex economy that included primitive agriculture and cattle breeding near settlements (Slavnin and Sherstova 1999). The Andronovo culture arose somewhere in the steppe between the southern Ural Mts and the mouth of the Volga River. From this area, they increased their range to the east and to the south, using chariots for the first time in Siberia and exercising a war-like lifestyle (Slavnin and Sherstova 1999). They came to the area of modern Khakassia and overcame the tribes of the Okunevo culture, who were weakened by the previous dry climate phase.

In another phase of dry climate in 3190 cal. yr BP, a new wave of human migrations emerged, this time from the south-

| Periods, cal. yr BP | Ancient culture | Vegetation* (gray—steppe; green—forest-steppe; white—forest) | Area of Steppe/Forest-steppe, % to total area | Potential grain yield, % to current | Potential pasture yield, % to current |
|--------------------|----------------|---------------------------------------------------------------|---------------------------------------------|----------------------------------|-------------------------------------|
| Contemporary       |                |                                                               | 4/50                                        | 100                             | 100                                 |
| 700, Russian colonization | Farming      |                                                               | 4/50                                        | 100                             | 100                                 |
| 1240, The Kirgiz settled farming, semi-nomadic |               |                                                               | 2/40                                        | 110–120                          | 120–130                             |
| 1620, The Tashyk predominantly nomadic |               |                                                               | 22/63                                       | 70–90                           | 70–80                               |
| 2620, The Tagar (Scythians) predominantly farming, semi-nomadic |               |                                                               | 2/40                                        | 110–120                          | 120–130                             |
| 3190, The Karasuk Cattle herding, decreased farming |               |                                                               | 22/50                                       | 70–90                           | 70–80                               |
| 3730 The Andronovo primitive agriculture, cattle herding |               |                                                               | 22/50                                       | 70–90                           | 70–80                               |
| 4220 The Okunevo Cattle herding |               |                                                               | 22/63                                       | 70–90                           | 70–80                               |
| 5240 The Afanasievo a complex economy (hunting, fishing, primitive agriculture and cattle herding) |               |                                                               | 10/57                                       | 80–100                          | 80–90                               |
| 6150 The Afanasievo Primitive agriculture |               |                                                               | 10/57                                       | 80–100                          | 80–90                               |
| 6350 Temporal settlements of hunters and fishers |               |                                                               | 10/57                                       | 80–100                          | 80–90                               |
east rather than from the west. A Mongoloid people migrated from the territory of modern China. They were nomadic herders who arrived in Khakassia, with herds of sheep and horses, and they formed the new Karasuk culture (Slavnin and Sherstova 1999). At this time, the diverse landscapes that existed in southern central Siberia included intermountain hollows covered by steppe vegetation with meadows in flood plains, forests on the mountain slopes, and with alpine meadows reaching to the mountain tops. This diverse landscape provided for unique economies including pastoralism. The diverse, large herds of domestic animals were supplied forage in any season of the year, despite the dry climate. The decreased role of agriculture during the Karasuk cultural period (Slavnin and Sherstova 1999, Kozintsev 2008, Hemphill and Mallory 2004) has been supported by only occasional findings of the anthropogenic pollen indicator Cannabis (Blyakharchuk and Chernova 2013).

Panyushkina (2012) used dendrochronological methods to show the territories south and east of the Russian Altai were rapidly warming between 2480–2360 cal. yr BP. Northern steppe likely expanded northward and provided newly available grazing areas that could have attracted Scythian pastoralists of the Pazyryk culture in the Central Altai Mts. They increased mobility and intensified interactions with the outside world in warm periods.

At 1620 cal. yr BP, the climate of Khakassia is dry (figure 4). A new wave of nomadic tribes migrated from the southeast (from Ordos Inner Mongolia) to north of Khakassia and formed the Tashtyk culture (Slavnin and Sherstova 1999). Nomadic tribes settled and accepted the experience of agricultural tribes through contacts, the exchange of products, and inter-marriage (Kozintsev 2008, Keyser et al. 2009). Thus, the peoples inherited the anthropological features and genomes of both the Europeoid and Mongoloid races. The contemporary population of Khakass has been formed by and has experienced both nomadic and agricultural economies in the diverse landscapes of Khakassia. The last rather dry stage is at 620–500 cal BP, which is known as the Little Ice Age (LIA) in western Europe. By this time, the Russian Empire had begun establishing its settlements in the Altai-Sayan Mts, so this stage is not considered a migratory stage.

Wetter periods

Before the Russian colonization, these are five wetter periods: from 6350, 6150, 5240, 2620 and 1240 cal. yr BP with prevailing forest lands (figure 4). Reconstructions resulted in 45–60% forest cover in the Minusinsk Hollow in 2620 and 1240 cal. yr BP wet climates (table 5). During this period, the dominant human economic activity was farming. Both grain and pasture yields increased about twofold compared to those in dry climates (120–130% compared to 70–80%). Two time slices (6350 and 6150 cal. yr BP) during of Late Atlantic showed this period to be sufficiently wet and warm across the Minusinsk Hollow, which favored thriving forest.
conifer taiga advanced to lower elevations to 800 m at Dikoe Lake (table 4). Although the climate favored farming activities, only sporadic hunters and fishers visited the Minusinsk Hollow and did not built permanent settlements in 6000 BP (van Geel et al 2004a, 2004b). Not until later (5240 cal. yr BP), tribes of the Afanasievo culture (the first Indo-European peoples) migrated to Khakassia through the Altai Mts and settled this territory (Slavnin and Sherstova 1999). They practiced primitive agriculture and cattle grazing around the settlements. Later these people developed a complex economy.

At 2620 cal. yr BP the climate became moist, which again favored farming activities. An additional proxy to support this finding was a sharp increase in the organic content in Dikoe Lake sediments (Blyakharchuk 2012). Additionally, van Geel et al (2004a, 2004b) pointed to a strong decrease in the xerophytic taxa at Kutuzhekovo Lake at 2800 BP. Moreover, lake levels in Mongolia were found to have increased from 2000–3000 BP, after the lowest level in 3000 BP (Tarasov et al 1996, Dorofeyuk and Tarasov 1998). The Tagar culture of the Siberian Scythians thrived in Khatassia during this wet phase. According to the archeological data and China’s scripts, a Europoeid Dinlin tribe migrated to Tyva and Khakassia from the south and south-east (Slavnin and Sherstova 1999). This was the second wave of this ethnos to migrate north. The first was ancestors of the Afanasievo culture that migrated about three thousands years earlier. The husbandry of the Dinlins was complex and included agriculture (planting of barley, wheat, dry-land rice) and cattle breeding near the permanent settlements. The humid climate allowed for harvesting a rich supply of crops. Food surpluses stimulated the growth of the human populations and the development of the social structure in the Tagar culture.

Southwest of Khakassia, in the Altai Mountains, climate was cold and highly variable during 2700–2480 cal. yr BP (Panyushkina 2012). Panyushkina (2012) speculated the growth of the Pazyryk culture of Siberian Scythians attested to their successful behavioral adaptations to the cold climate. Additionally, we found precipitation increased during this period, which supports the notion of increases in agriculture, pasture and Pazyryk productivity.

4. Discussion

The last wetter stage occurred at 1240 cal. yr BP. This was the period of the formation and development of the Yenisey—Kirgiz culture. These ethnic peoples were formed by descendants of the people that settled earlier and lived in Khakassia. The diversity of landscapes across the mountains promoted the development of complex, productive households within the Yenisey—Kirgiz people, which included cattle breeding and agriculture. In their households, they inherited the experience of their diverse ancestors.

Khakassia, due to its geographically central location in Eurasia and its diverse montane landscapes, was a buffer zone during several millennia of humans searching for a better place to live during climatic and ecological crises in Eurasia, and these lands can truly be considered a ‘melting pot of ethnogenesis’ (Slavnin and Sherstova 1999). This work highlights the significance and control of weather and climate on culture and in changes in the dynamics of human populations, from favoring one culture over another. This example could serve as a present day warning of the impact of weather and climate on peoples.

The models developed and applied in this study are site-specific and should be restricted to the Minusinsk Hollow and adjacent regions, although the ideas and model development could be portable depending on the underlying data available. This modeling approach has been used to quantitatively support existent empirical archeological knowledge, to provide possible motivations for ancient migrations in response to changing environments. To enhance the reliability of the pollen-based paleo-biome and climate reconstruction, three supporting methods are simultaneously employed. We relied on reconstructed climate change, defined as the difference between current and historic times, because climate departures are more spatially stable and reliable for mapping climates and vegetation at higher resolution for each time slice. It is not possible to map paleo-climates having only one pollen diagram for a terrain as topographically complex as the Minusinsk Hollow.

New high resolution well-dated pollen sites for study areas will certainly improve future model reconstructions. Generally, the match between the biomes reconstructed by these three methods is very good and suggest likely paleo-climates from the two lakes for our eleven paleo-time slices during the Late Holocene. There is overall model agreement (2 out of 3 cases) in all but one case (table 3 italic). In some cases, only 2 models agreed; for example, in 1620 cal. yr BP, the MontBCliM pollen-constructed climate reconstruction suggested the climate is wet and suitable for water-loving dark-needled taiga. However, the other two model reconstructions suggested the vegetation is mesophytic, forest-steppe, thus the resulting biome is reclassified as forest-steppe. This study suggests that our step-wise regression models reliably predict a pollen-based climate range at the biome scale, but it is not likely reliable at a small site scale, even though our weather station reconstruction compared well. Nonetheless, we believe using the 3 models provides the best possible result.

In the Russian paleo-geographic literature, there are two hypotheses on the steppe and forest boundary, which is a critical matter in this study. The earlier hypothesis, based on pollen data from steppe and forest-steppe mires, suggest a stable boundary between forest and steppe during the Late Holocene (Neishtadt 1957, Khotinsky 1977). However, numerous facts from soil and archeological investigations contradict this statement. For example, at the present time, signs of steppe pedogenesis can be found in the forest zone (Gadzhiev 1982, Ivanov and Chernyavskiy 1996). Archeological evidence of the migrations of ancient tribes in Siberia also contradicts this statement (Ivanov and Lukovskaya 1998). In our opinion, the hypothesis asserting a stable boundary between the steppe and forest in the second half of Holocene is not correct, because it is based on pollen data.
from steppe mires where the local mire vegetation pollen dominates the pollen of the zonal steppe vegetation, due to the low pollen productivity of steppe landscapes in general. In this respect, we support the hypothesis that states there was permanent fluctuation at the boundary between steppe and forest during the Holocene (Khazina et al. 2006, Blyakharchuk et al. 2007, 2012, Ryabogina 2010). These studies demonstrate that pollen data taken from lake sediments was less distorted by local mire pollen and clearly marked fluctuations of precipitation in southern Siberia, which influenced the expansion and retreat of forest and steppe vegetation. In this study, the reconstructions based on pollen data from two lakes located in steppe and forest-steppe reveal fluctuations of the forest-steppe boundary in Khakassia in southern Siberia and confirmed the climatic sensitivity of lake sediments to minor climatic and landscape changes.

Paleo-ecological interpretations of fossil pollen are reliable if the pollen is of local origin while pollen from distant sites is more difficult to interpret basing on one pollen diagram (Solomon and Silkworth 1986). Therefore, we built our vegetation and climate reconstructions on two sites located in relative close proximity (~100 km) to each other in the steppe and forest-steppe subtaiga, which are the vegetation zones of interest.

Pollen from anthropogenic indicators like Cannabis, Urtica and Hordeum is consistently found when farming flourishes. These were scarce or absent in the Lugovoe pollen diagram south of Minusinsk Hollow in periods when cattle breeding dominated the economy of human cultures, which provides support for our hypotheses. Additionally, maxima charcoal in peat deposits marked both natural and artificial fires related to developed human development (Blyakharchuk and Chernova 2013). Ruderal pollen of Cannabis and Urtica were also found in the Dikoe Lake pollen diagram. Ivanov and Ryabogina (2010) divided the pollen of ruderal plants (anthropogenic indicators) in two groups: segetal plants (growing as weeds on arable fields) and ruderal plants (growing near settlements and pathways). In their research, the pollen of Cannabis was classified both as segetal and ruderal, but the pollen of Urtica was classified only as ruderal. Ivanov and Ryabogina (2010) conclude that even a small amount of these ruderal pollens distinguish anthropogenic impact on the landscape. In the Dikoe Lake pollen diagram, we found a synchronous maxima of Cannabis and Urtica pollen attributed to the Tagar (agricultural) archeological culture. During the time when the nomadic Okunevo and Karasuk cultures were dominant, we find maximums of only Urtica pollen without Cannabis, which confirms the dominant economy of the Tagar, Okunevo and Karasuk cultures.

We compared our vegetation and climate reconstructions in the Minusinsk Hollow (tables 4 and 5) with three major episodes of glacial advances that were larger than those in the Aktru valley of the central Altai during the second half of Holocene epoch. We found these advances took place at the end of three wet intervals (figure 4). This comparison provides additional confirmation of the vegetation and climate reconstructions. For example, advances of the Altai glaciers took place during the following time periods: 4900–4200 cal. yr BP (the Akkem stage); at 2300–1700 cal. yr BP (the historical stage); and in the 13–19th centuries (Little Ice Age, or the Aktru Stage) (Agatova et al. 2012). These advances of mountain glaciers are known to take place during synchronous temperature minima and humidity maxima. Thus, we assume that at the end of each humid period, the climate was cool enough for the glaciers to advance. However, in the next arid period, the advance ceased. When the climate was warm and arid, the glaciers quickly retreated leaving Akkem and the Aktru moraines in the Aktru valley (Agatova et al. 2012). This scenario coincides very well with our reconstructions (figure 4). The information on the structure of the last Aktru (Little Ice Age) moraines in the Aktru valley is especially impressive. The thermal minimum in the middle of the 19th century, the greatest in the last millennium, did not positively influence the mass balance of this glacier due to the dryer climate.

Mayewski et al. (2004) analyzed 50 global paleo-climate records, and they emphasized ‘the complexity of the Holocene climate and highlighted the importance of using widely distributed, site-specific, paleo-climatic data to avoid the risk of using a data series from one area to extrapolate to another’. This research will be another important contribution to understanding the complex mechanism of local climate-landscape-human interactions.

5. Conclusions

We produced paleo-biome vegetation and climate reconstructions in parallel with archeology-based subsistence evidence to demonstrate the similarity in the patterns of model-predicted climate change and historic alterations in farming and pastoral practices. The three pollen-based reconstructions established fluctuations in forest and non-forest vegetation and climate in the Minusinsk Hollow during the latter Holocene.

At least four dry periods, where steppe and forest-steppe dominate up to 85% of the area are described, and five wet periods, where forests dominate up to 60% of the area are defined. Grasslands increased by an order of magnitude during the dry periods and provided extensive open space suitable for pastoralism. The dry periods favored nomadic rather than farming activities. Agriculture became less productive in dry climates even with the application of irrigation (e.g. at the end of the Tagar culture), and agricultural tribes gradually weakened. New mobile, nomadic tribes migrated from other regions and easily conquered or assimilated local tribes living in Khakassia within the Minusinsk Hollow, which caused a shift in the archeological human cultures. During wet climates, both grain and pasture yields increased by about twofold and supported human farming and cattle herding settlements. Thus, during the times of wetter climates, human tribes that practiced agriculture had some advantage over tribes who practiced pastoralism. Conversely, grasslands decreased during wet climatic phases, and nomadic migrants could be assimilated by agricultural tribes.
We argue these alternations in climate resulted in or heightened the sequential replacement of human cultures: settled farming versus nomadic cattle herding. This work highlights the significance and control of weather and climate on culture and in changes in the dynamics of human populations, by favoring one culture over another. This example could serve as a present day warning of the impact of weather and climate on peoples.

Acknowledgements

This study was supported by the Russian integration project #53, the NASA Interdisciplinary Science NNH09ZDA001N-IDS program, a grant from the Russian Foundation of Basic Research № 13-04-00984а, as well as a research grant carried out in accordance with the Resolution of the Government of the Russian Federation № 220 dated 09 April 2010, under Agreement № 14.B25.31.0001 with the Ministry of Education and Science of the Russian Federation dated 24 June 2013 (BIO-GEO-CLIM). The authors are grateful to Robert Monserud, Jerry Rehfeldt, Jane Bradford and Natalia Vygodskaya for invaluable help and to useful comments by three anonymous reviewers in preparation of this manuscript.

References

Agatova A R, Nazarov A N, Nepop R K and Orlova L A 2012 Radiocarbon chronology of Holocene glacial and climatic events in southern Altai (Central Asia) Russ. Geol. Geophys. 53 546–65

Blyakharchuk T A 2012 New Palaeo pollen Data About Dynamics of Vegetation Cover and Climate of Western Siberia and Adjacent Areas in Holocene (Novosibirsk: GEO) p 139 (in Russian)

Blyakharchuk T A, Wright H E, Borodavko P S, van der Knaap W O and Ammann B 2007 Late glacial and Holocene vegetational history of the Altai Mountains (Southern Tuva Republic, Siberia) Palaeoecog. Palaeoecol. 245 518–34

Blyakharchuk T A and Chernova N A 2013 Vegetation and climate in the Western Sayan Mountains according to pollen data from Lugovoe Mire as a background for prehistoric cultural change in southern Middle Siberia Quat. Sci. Rev. 75 22–42

Bokovenko N A 1992 The problem of the origin of the horse-raider burial ceremony of South Siberia The Second History Lectures in the Memory of M G Gryzovna (Omsk: Omsk University) pp 99–100 (in Russian)

Bokovenko N A 1996 Asian influence on European Scythia International Journal of Comparative Studies in History and Archaeology 3 97–122 (in Russian)

Bukreyeva G F 1991 Pattern recognition many-dimensional analysis for paleo-geographical [sic] reconstruction of the Holocene Acta Palaeobotanica 31 289–94 (in Russian)

Chernykh E N 2008 Formation of the Eurasian ‘steppe belt’ of stockbreeding cultures: viewed through the prism of archeometallurgy and radiocarbon dating Archaeology, Ethnology and Anthropology of Eurasia 35 36–53 (in Russian)

Chugunov K V 2012 Early nomads of central Asia and southern Siberia in the 1st millennium B.C. Nomads of Eurasia on the Way to the Empire ed M B Piotrovski (Sankt-Petersburg: Slavia) pp 19–49 (in Russian)

Davis M B 1963 On the theory of pollen analysis Am. J. Sci. 261 897–912

Dorofeyuk N I and Tarasov P E 1998 Vegetation and lake levels in northern Mongolia in the last 12 500 years as indicated by data of pollen and diatom analyses Stratigraphy and Geological Correlation 6 70–83 (in Russian)

Frachetti M D 2011 Migration concepts in central eurasian archaeology Annu. Rev. Anthropol. 40 195–212

Gadzhiev I M 1982 Evolution of Soils of Southern Taiga of Western Siberia (Novosibirsk: Nauka) p 279 (in Russian)

Gius J 1990 Methodology of the last climatic cycle reconstruction from pollen data Palaeogeog. Palaeoclim. Palaeoecol. 80 49–69

Gumilev L N 2002 Ethnogenesis and Biosphere of the Earth (Moscow: Rolf)) p 557 (in Russian)

Hempfl B E and Mallory J P Horse-mounted invaders from the Russo–Kazakh steppe or agricultural colonists from western central Asia? A craniometric investigation of the Bronze Age settlement of Xinjiang 2004 Am. J. Phys. Anthropol. 124 199–222

Herzschuh U, Tarasov P, Wummemann B and Hartmann K 2004 Holocene vegetation and climate of the Alashan Plateau, NW China, reconstructed from pollen data Palaeogeog., Palaeoclim. Palaeoecol. 211 1–17

Hutchinson M F 2000 ANUSPLIN Version 4.1 User’s Guide (Canberra: Australian National University, Centre for Resource and Environmental Studies) ACT 0200

Ivanov I V and Chernyavskiy S S 1996 General peculiarities of development of humus soils of Eurasia and evolution of humus soils of the Urals Eurasian Soil Sci. 9 1045–55

Ivanov I V and Lukovskaya T C 1998 Dynamic of natural conditions, soil formation and teleconnections of nature and human societies in steppes of Eurasia, some questions of palaeogeography of the Holocene Ecology and Soils Selected lectures of the VII School 1991–1997 vol 1 (Pushino: Russian Academy of Sciences Press) pp 283–302

Ivanov S N and Ryabogina N E 2010 Natural and anthropogenic change of ecosystems of Tobol river area in Holocene (from spore-pollen data) Ecosystems Dynamics in the Holocene (Ekaterinburg: Rifei) pp 86–90

Keyser C, Bouakaze C, Crubezy E, Nikolaev V G, Montagnon D, Reis T and Ludes B 2009 Ancient DNA provides new insights into the history of South Siberian Kurgan people Hum. Genetics 126 395–410

Khazina I V, Volkova V S, Krivonogov S K and Takahara H 2006 Vegetation and climate changes in the south of west Siberia, Novosibirsk region since the Holocene (proxies of pollen data) Promoting Environmental Research in Pan-Japan Sea Area (Kanazawa: Kanazawa University) pp 21–2

Khotsinsky N A 1977 Holocene of the Northern Eurasia (Moscow: Nauka) p 200 (in Russian)

Kiselev S V 1968 History of Siberia from the Ancient Times to Present Days vol 1 (Leningrad: USSR Academy of Sciences Press) (in Russian)

Konovalov A A and Ivanov S N 2007 Climate. Phytosproductivity and Paleo-Spectra: Relationships, Distribution and Methods of Paleo-Reconstructions in West Siberia (Novosibirsk: GEO) p 130

Korolkova E F 2012 Nomads in the eastern European steppe in the Medieval period Nomads of Eurasia on the Way to the Empire ed M B Piotrovski (Sankt-Petersburg: Slavia) pp 224–33 (in Russian)

Kozintsev A G 2008 The ‘Mediterraneans’ of Southern Siberia and Kazakhstan, Indo-European migrations, and the origin of the Scythians: a multivariate craniometric analysis Archaeol. Anthropol. Eurasia 36 140–4 (in Russian)

Kuminova A V 1960 Way to the Empire (Sankt-Petersburg: Slavia) pp 19–49 (in Russian)

Kuminova A V, Zvereva G A, Maskaev Y M, Pavlova G G, Sedinikov V P, Koroleva A S, Neifeld E Y, Tanzybaev M G,
Chizhikova N M and Lamanova T G 1976 Vegetation Cover of Khakassia (Novosibirsk: Nauka) p 422 (in Russian)

Magny M 2013 Orbital, ice-sheet, and possible solar forcing of Holocene lake-level fluctuations in west-central Europe: a comment on Bleicher Holocene 23 1202–12

Mandryka P V 2008 Early iron age archaeology in middle Siberia: the relations between inhabitants of the taiga and the steppe Humanit. Soc. Sci. 1 260–8

Markov K K and Velichko A A 1967 Quaternary Period (Glacial Period-Anthropogenic Period) (Moscow: Nedra) vol 3 (in Russian)

Mayewski P A et al 2004 Holocene climate variability Quat. Res. 62 243–55

McAndrews J H 1966 History of prairie, savanna, and forest in Minnesota Memoirs of the Torrey Bot. Club Met. 22 1–72

Monserud R A, Tchebakova N M and Denissenko O V 1998 Reconstruction of the mid-Holocene palaeoclimate of Siberia using a bioclimatic vegetation model Palaeoclimat. Palaeoecol. 139 15–36

Moore P D, Webb J A and Collinson M E 1997 Pollen Analysis (Oxford: Blackwell Science)

Neishtadt M I 1957 History of Forests and Palaeogeography of The USSR in the Holocene (Novosibirsk: Nauka) p 279 (in Russian)

Okladnikov A P 1968 History of Siberia (Leningrad: Nauka) p 454 (in Russian)

Overpack J T, Webb T III and Prentice I C 1985 Quantitative interpretation of fossil pollen spectra, dissimilarity coefficients and the method of modern analogs Quat. Res. 23 87–108

Panyushkina I P 2012 Climate-induced changes in population dynamics of Siberian Scythians (700–250 B.C.) Climates, Landscapes, and Civilizations Geophysical Monograph (Series 198) American Geophysical Union

Parfenova E I, Tchekabova N M and Stasova V V 2005 Chlorophyll index in hollows of the Altai-Sayan ecoregion Environmental Conditions, History and Culture of West Mongolia and Adjacent Regions ed V I Lebedev, S O Ondar and Y G Polulyakh (Kyzyl: TuvIKOPR SO RAN) pp 228–31 (in Russian)

Prentice I C 1980 Multidimensional scaling as a research tool in quaternary palynology: a review of theory and methods Rev. Paleo-bot. Palynol. 31 71–104

Prentice I C, Guiot J, Huntley B, Jolly D and Cheddadi R 1996 Reconstructing biomes from palaeocological data: a general method and its application to Europe Clim. Dyn. 12 185–96

Ryabkova T V 2012 Nomads of Eurasia on the way to the empire Nomads of Eurasia on the Way to the Empire ed M B Piotrovski (Sankt-Petersburg: Slavia) pp 4–11 (in Russian)

Ryabogina N E 2010 Spore-pollen data of peat and mineral soils as object for reconstruction of forest-steppe vegetation in Holocene Ecosystems Dynamics in the Holocene (Ekaterinburg: RIPEI) (in Russian) pp 171–6

Slavnin V D and Sherstova L I 1999 Archaeologic-ethnographic Essay of Northern Khakassia in the Area of Geological Polygon of Siberian High School (Tomsk: Tomsk Polytechnical University Press) (in Russian)

Solomon A M and Silkworth A B 1986 Spatial patterns of atmospheric pollen transport in a montane region Quat. Res. 25 150–62

Tarasov P E et al 1996 Lake Status Records From the Former Soviet Union and Mongolia: Documentation of the Second Version of the Data Base. Publications Series Report 5 (Boulder: Colorado USA) p 224

Tarasov P E, Bezrukova E V and Krivonogova S K 2009 Late glacial and Holocene changes in vegetation cover and climate in southern Siberia derived from a 15 kyr long pollen record from lake Kotokel Clim. Past 5 127–51

Tchekabova N M, Blyakharchuk T A and Parfenova E I 2009 Reconstruction and prediction of climate and vegetation change in the Holocene in the Altai–Sayan mountains, central Asia Environ. Res. Lett. 4 045025

Tchekabova M N, Parfenova E I, Lysanova G I and Soja A J 2011 Agroclimatic potential across central Siberia in an altered twenty-first century Environ. Res. Lett. 6 045207

Vadetskaya E B 1979 Hypothesis on the origin of the Afanasievo culture Peculiarities of Natural-Geographical Environment and Historical Processes in West Siberia ed A A Chindina (Tomsk: Tomsk University Press) pp 64–6 (in Russian)

van Geel B et al 2004a Climate change and the expansion of the Scythian culture after 850 BC: a hypothesis J. Archaeol. Sci. 31 1735–42

van Geel B et al 2004b Impact of the Environment on Human Migration in Eurasia ed E M Scott et al (The Netherlands: Kluwer Academic Publishers) pp 151–8

van Geel B, Shinde V and Yasuda Y 2004c Solar forcing of climate change and monsoon-related cultural shift in western India around 800 cal. yrs. BC Monsoon and Civilization ed Y Yasuda and V Shinde (New Delhi: Roli Books Pvt. Ltd) pp 275–9

Wright H E 1991 Coring tips J. Paleo-Limnol. 6 37–49

Yamskikh A F 1981 Natural Conditions of the Minusink Basin (Krasnoyarsk: Krasnoyarsk Pedagogical Institute Press) (in Russian)

Yasuda Y 2004 Monsoon and religions Monsoon and Civilization ed Y Yasuda and V Shinde (New Delhi: Roli Books Pvt. Ltd)) pp 319–38