Late Quaternary environmental changes in Yakutia (NE Siberia, Russia) - inferred from pollen and testate amoebae records

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"The more closely one gets to know the Polar Regions,
the more their uniformity disappears from view
and the more the separate individual regions stand out
in their characteristics."

Otto Nordenskjøld, 1928, Swedish explorer

Abstract

An increase of the global mean temperature during the last decades can already be recognised and will further continue over the future decades. It is stated that high latitudes warm more than the global mean, especially in winter. Here, effects of the current warming can obviously be seen from the present destruction of terrestrial and marine permafrost as well as the reduction of sea–ice. Increasing temperatures in winter and changing precipitation patterns will significantly affect the vegetation zonation, particularly the treeline and northern limit of boreal forests, which is expected to move northwards.

There has been an increase of studies dealing with the climate change reconstruction of the late Quaternary based on multi-proxy studies from sedimentary records of high latitude regions over the last decades. However, for most of the previous studies definite age control or detailed palaeoclimatic implications are lacking. Sedimentary studies from permafrost archives of NE Siberia allow obtaining essential data on the palaeoenvironmental history of this region. In this study the region of Yakutia is of particular interest. Central Yakutia represents the most continental region of the northern hemisphere.

The thesis presented here follows two main different approaches. The first approach utilises qualitative and quantitative palaeoenvironmental analysis, while the second approach evaluates ecological investigations of recent material. It is aspired to refine and improve the indicator ability of testate amoebae (hereafter TA) from Holocene and late glacial deposits in northern Yakutia. An attempt was made to use TA from permafrost regions of NE Siberia (Mamontov Klyk, Laptev Sea coast) as indicators of palaeoenvironmental changes at local and regional scales. A total of 59 fossil and 10 modern samples were used for the TA analysis. Results of this attempt show that soil-living taxa dominate the TA assemblages at the study site during the last 45 kyr. Until ca. 25 kyr BP environmental conditions were most favourable (relatively warm and humid). From ca. 25 to 15 kyr BP an opposite environmental situation was reconstructed. Much colder and drier environments prevailed during this time interval reflecting the maximum phase of the last glacial. The onset of the Holocene is indicated by increasing species diversity. Especially the broad representation of obligate hydrophilic TA taxa suggests wet and relatively warm conditions. By comparison with other environmental indicators from this and adjacent arctic regions it is suggested that TA analysis can provide valuable information for a better understanding of late Quaternary environmental developments and climate fluctuations in arctic Siberia.

A total of 200 fossil pollen samples from two sediment cores from Lake Billyakh, situated in the western foreland of the Verkhoyansk Mountains in central Yakutia, were analysed. They have provided detailed information about palaeoenvironmental conditions during the last 50 cal. kyr. A set of 53 surface pollen samples from Yakutia representing tundra, cold-deciduous forest and taiga vegetation was used to validate the quantitative approach of the biome reconstruction and attribution of pollen taxa to the regional biomes. The thereupon adjusted approach was applied to the fossil pollen records from Lake Billyakh to gain an objective reconstruction of the regional vegetation and environments since about 50 cal. kyr BP.

The pollen record and the pollen based biome reconstruction of both cores indicate that open cool steppe and herbaceous tundra communities dominated the area between 50 and 13.5 cal. kyr BP. Low pollen concentrations and high percentages of herbaceous pollen, suggesting scarce vegetation cover and dominance of steppe-like plant communities during the last glacial maximum (ca. 21 cal. kyr BP), representing the driest and coldest interval in the entire record. A major spread of shrubby tundra communities is dated to 13.5-12.7 cal. kyr BP, indicating favourable climatic conditions during this period, the Bølling-Allerød interstadial. The pollen spectrum between 12.7 and 11.4 cal. kyr BP suggest strengthening of the steppe communities associated with relatively cold and dry conditions during the Younger Dryas stadial. At about 11.4 cal. kyr BP warmer and wetter climatic conditions set in, which is marked by highest values of shrub and lowest values of herbaceous pollen taxa. After 7 cal. kyr BP increasing tree taxa percentages reflect the spread of boreal cold deciduous trees and taiga forests in the region. An interval between 7 and 2 cal. kyr BP is noticeable for the highest tree pollen percentages (pine, spruce, and fir), indicating the mid-Holocene optimum of climate amelioration and increasing permafrost degradation. The pollen records presented here indicate the absence of continuous forest cover at Lake Billyakh during the late Pleistocene (last 50 cal. kyr BP). However, a key finding of this study is the almost constant presence of larch pollen in the two analysed sediment cores, suggesting that larch could survive the last 50 cal. kyr BP in locally favourable environments. Noticeable variations in larch pollen abundances and reconstructed biome scores point to multiple short-term warming episodes synchronous to the Dansgaard-Oeschger events found in the North Atlantic records.

To predict future changes in climate and ecosystems, especially in response to global warming, palaeoenvironmental studies are essential. The observed environmental changes, inferred from TA and pollen analysis from Yakutian sediment archives, underline the important role of arctic habitats for the reconstruction of past climate changes. For the broad understanding of the driving mechanisms behind palaeoenvironmental changes during the late Quaternary further research efforts are needed.

Zusammenfassung

Während der letzten Jahrzehnte ist bereits ein Anstieg der globalen Durchschnittstemperatur festgestellt worden, welcher sich in den zukünftigen Jahrzehnten fortsetzen wird. Für die Region der höheren Breiten wird dabei ein stärkerer Temperaturanstieg angegeben als im globalen Durchschnitt, besonders in den Wintermonaten. Hier sind Effekte aktueller Erwärmung offensichtlich, wie das Schmelzen terrestrischen und marinen Permafrosts sowie der Rückgang der Meereisbedeckung. Ansteigende Wintertemperaturen und veränderte Niederschlagsmengen werden die Vegetationszonen stark beeinflussen, insbesondere die Lage der Baumgrenzen und das nördliche Verbreitungslimit borealer Wälder, welches sich vermutlich nach Norden verlagert.

Die Zahl der Untersuchungen, die sich mit der Klimarekonstruktion des Spätquartärs auf der Grundlage von „multi-proxy“-Studien sedimentärer Ablagerungen aus den hohen Breiten beschäftigen, ist innerhalb der letzten Jahrzehnte angestiegen. Allerdings fehlen für die meisten dieser Untersuchungen verlässliche Datierungsergebnisse oder aber daraus abgeleitete paläoklimatische Aussagen. Untersuchungen von Permafrostarchiven erlauben es essentielle Informationen über die Paläoumweltgeschichte NO-Sibiriens zu gewinnen. In den hier vorgestellten Untersuchungen steht die Region Jakutiens im Mittelpunkt. Zentral-Jakutien stellt die kontinentalste Region der nördlichen Hemisphäre dar.

Die vorliegende Dissertation folgt im Wesentlichen zwei Ansätzen. Im ersten Ansatz findet die qualitative und quantitative Paläoumweltrekonstruktion Anwendung, während im zweiten Ansatz ökologische Studien anhand von rezentem Material durchgeführt werden. Dies hat zum Ziel den Indikatorwert beschalter Amöben aus holozänen und spätglazialen Ablagerungen aus Nord-Jakutien zu verfeinern und zu verbessern. Es wurde der Versuch unternommen beschalte Amöben aus Permafrostregionen NO-Sibiriens (Mamontov Klyk, Laptev-See Küste) als Indikatoren für Paläoumweltveränderungen auf lokaler und regionaler Ebene zu nutzen. Insgesamt wurden 59 fossile und 10 moderne Proben für die Analyse beschalter Amöben genutzt. Die Resultate dieser Untersuchung zeigen, dass im Boden lebende Taxa die lokalen Amöbengemeinschaften während der letzten 45.000 Jahre dominierten. Bis ca. 25.000 Jahre v.h. herrschten mit relativ warmen und feuchten klimatischen Verhältnissen günstige Umweltbedingungen vor. Für den Zeitraum von ca. 25 bis 15.000 Jahren v.h. wurden gegenteilige Umweltbedingungen rekonstruiert. Während dieses

Zeitintervalls herrschten kältere und trockenere Umweltbedingungen vor, welche den Höhepunkt des letzen Glazials widerspiegeln. Der Beginn des Holozäns wird angezeigt durch ansteigende Diversität. Insbesondere das breite Spektrum an ausschließlich aquatisch lebenden Organismen lässt auf feuchte und relativ warme Umweltbedingungen schließen. Der Vergleich mit anderen Umweltindikatoren aus diesen und angrenzenden arktischen Gebieten lässt die Aussage zu, dass die Analyse beschalter Amöben wichtige Informationen für ein besseres Verständnis spätquartärer Umweltveränderungen und Klimafluktuationen liefern kann.

Insgesamt 200 fossile Proben zweier Sedimentkerne aus dem Billjach-See, welcher sich im westlichen Vorland des Werchojansker Gebirges in Zentral-Jakutien befindet, wurden pollenanalytisch untersucht. Sie enthielten detaillierte Informationen über die Paläoumweltbedingungen der letzten 50.000 Jahre. Für den quantitativen Ansatz der Biomrekonstruktion und der Zuordnung der Pollentaxa zu den entsprechenden regionalen Biomen wurden 53 Oberflächenproben aus verschiedenen Teilen Jakutiens untersucht, welche Tundra-, boreale Nadelwald-, sowie Taigavegetation repräsentieren. Der daraufhin angepasste Ansatz wurde auf die fossilen Pollendatensätze vom Billjach-See angewendet um eine objektive Rekonstruktion der regionalen Vegetation und der allgemeinen Umweltbedingungen seit ca. 50.000 Jahren zu gewährleisten.

Der Pollendatensatz und die darauf basierende Biomrekonstruktion beider Kerne deuten darauf hin, dass offene Steppen und krautige Tundrengesellschaften das Gebiet zwischen 50.000 und 13.500 Jahren dominierten. Geringe Pollenkonzentrationen und hohe Pollenprozentwerte krautiger Pflanzen deuten auf eine spärliche Vegetationsbedeckung und die Dominanz steppenähnlicher Pflanzengemeinschaften während des letzten glazialen Maximums (vor ca. 21.000 Jahre v.h.) hin. Dies kann als die trockenste und kälteste Phase der letzten 50.000 Jahre bezeichnet werden. Eine verstärkte Ausbreitung strauchiger Tundrengesellschaften wurde zwischen 13.500 und 12.700 Jahren v.h. rekonstruiert und deutet auf günstige klimatische Bedingungen während dieser Phase, des Bølling-Allerøds, hin. Das Pollenspektrum zwischen 12.700 und 11.400 Jahren v.h. lässt auf relativ kalte und trockenere Bedingungen während der Jüngeren Dryas schließen, da Steppengesellschaften hier vermehrt auftreten. Etwa um 11.400 Jahre v.h. setzen warme und feuchte Klimabedingungen ein, welche sich innerhalb des Pollenspektrums durch die höchsten

Pollenprozentwerte von Sträuchern und die niedrigsten von Kräutern manifestieren. Ansteigende Baumpollenprozentwerte nach 7.000 Jahren v.h. lassen auf die Ausbreitung boreal/sommergüner Bäume und Taigawälder in der Region schließen. Charakteristisch für das folgende Intervall zwischen 7.000 und 2.000 Jahren v.h. sind die höchsten Baumpollenprozentwerte (Kiefer, Fichte, und Tanne), welche das mittlere holozäne Optimum einer generellen Klimaverbesserung und die erhöhte Permafrostdegradation in der Region anzeigen. Die hier dargestellten Pollenspektren weisen auf das Fehlen geschlossener Waldgebiete im Untersuchungsgebiet während des Spätpleistozäns (der letzten 50.000 Jahre v.h.) hin, jedoch konnte anhand steter Vorkommen von Lärchenpollen in den analysierten Sedimentkernen nachgewiesen werden, dass Lärchenbestände in lokalen Rückzugsgebieten die letzten 50.000 Jahre überdauerten. Mehrfach auftretende kurzzeitige Wärmeperioden, welche sich zeitlich mit den aus dem nordatlantischen Raum berichteten Dansgaard-Oeschger-Ereignissen decken, konnten aufgrund der fluktuierenden Lärchenpollenabundanzen und der Biomwerte rekonstruiert werden.

Paläoumweltrekonstruktionen sind für die Vorhersage künftiger Klima- und Ökosystemveränderungen, speziell im Zusammenhang mit der globalen Erwärmung, von großer Bedeutung. Die festgestellten Umweltveränderungen, welche durch Untersuchungen an Pollen und beschalten Amöben aus Jakutien rekonstruiert wurden, unterstreichen die wichtige Rolle arktischer Habitate, wenn es um die Klimarekonstruktion der Vergangenheit geht. Für ein umfassendes Verständnis der treibenden Kräfte bei Paläoumweltveränderungen des Spätquartärs sind weitere wissenschaftliche Anstrengungen unerlässlich.

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List of figures and tables

List of abbreviations

^{14}C - radiocarbon dated
°C - degree Celsius
a.s.l. - above sea level
B-A - Bølling-Allerød
BP - Before Present (before 1950)
ca. - circa
cal. - calibrated
E - east
km - kilometre
kyr - kilo years
LGM - last glacial maximum
m - meter
M - million
MIS - marine isotope stage
N - north
NE - north-east
NO - nord-ost
S - south
T - temperature
T_{I} - mean January temperature
T_{VII} - mean July temperature
TA - testate amoebae
v.h. - vor heute (vor 1950)
W - west
YD - Younger Dryas
yr - year(s)

1. Introduction

Present-day climate changes in NE Siberia are among the largest in the world and probably affect the global climate system. In order to understand them and to interpret the observations and generate projections of the most plausible scenarios of future changes the use of multi-proxy data sources provides great means to reconstruct the climate of different time scales, especially to distinguish between naturally and anthropogenic induced events. In the context of global climate changes, the main attention should be focused on the most vulnerable ecosystems, like forest tundra, forest steppe, and steppe desert.

Testate amoebae (also rhizopods, testaceae etc.) react sensitive to various ecological variables. It is possible to describe local changes in past environments, where the testate amoebae record mostly co-varies with lithology and other proxy results. The pollen assemblages of lake sediments and permafrost deposits reflect the local-regional vegetation composition in palaeoenvironments. Thus palynological and testate amoebae studies provide not only information about fluctuations within the palaeoclimate but also about ecosystem dynamics that might occur in the future.

This thesis overall intends to obtain new insights for the reconstruction of late Quaternary environments from NE Siberia. Reconstruction results were mainly derived from testate amoebae and pollen analysis using quantitative and qualitative approaches. In this study, the usage of different bioindicators within the time range of the last 50 kyr makes it possible to investigate long-term as well as short-term climate fluctuations during this period. It demonstrates the importance of palaeoenvironmental studies in this particular region for getting an idea of general and specific features on climate change. The work presented here is relevant to the understanding of potential effects on the sensitive high-latitude environments due to climate change.

The investigations presented in this thesis are part of the German Research Foundation (DFG) projects “Late Quaternary environmental history of interstadial and interglacial periods in the Arctic reconstructed from bioindicators in permafrost sequences in NE Siberia” (RI 809/17) and “Comparison of climate and carbon cycle dynamics during late Quaternary interglacials using a spectrum of climate system models, ice-core and terrestrial archives” (TA 540/1) and the IPY (International Polar Year) project 106 “Lake Records of Late Quaternary Climate Variability in northeastern Siberia”.

1.1 Late Quaternary palaeoenvironmental studies in NE Siberia

The Quaternary period (the last 2.6 Myr; International Commission on Stratigraphy, 2008) is marked by drastic changes in environments and climates. Increasing debates on climate change over the last two decades intensified scientific research on the late Quaternary sediments and climate archives from the Siberian Arctic through a number of international research projects; e.g. “Taymyr” (1994–1997), “System Laptev Sea” (1994–1997), “QUEEN” (1996-2000”), “Laptev Sea 2000” (1998–2003). Results of these projects appeared in a number of publications (e.g. Bauch et al., 1999, 2001; Andreev et al., 2002a,b, 2004a,b; Meyer et al., 2002; Schirrmeister et al., 2002a,b; Siegert et al., 2002; Hubberten et al., 2004; Svendsen et al., 2004; Kuzmina & Sher, 2006; Grosse et al., 2006). Furthermore, related research dealt with detailed palaeoclimatic reconstructions using lake sediments and ice-rich permafrost sequences on Taymyr Peninsula (e.g. Hahne and Melles, 1999; Kienel et al., 1999; Siegert et al., 1999; Kienast et al., 2001; Andreev et al., 2003).

Age, kyr BP			W Europe	NE Siberia
~11.7 – 0	Late Quaternary	Late Pleistocene	Holocene	
~25 – 11.7			Late Weichselian	Sartan
~60 – 25			Middle Weichselian	Kargin
~117 – 60			Early Weichselian	Zyrian
~130 – 117			Eem	Kazantsevo

Fig. 1. Stratigraphic chronology of late Quaternary sediments for NE Siberia in comparison with W Europe based on different sources (Vautravers et al., 2004; Fradkina et al., 2005; Velichko and Nechaev, 2005, and references therein; International Commission on Stratigraphy, 2008); ages in calibrated kyr BP.

Results from these studies revealed several alternating cold and warm stages during the late Quaternary period in NE Siberia (Fig. 1). These stages can be well correlated within the northern hemisphere chronology, but intensity and duration of late Quaternary glaciations differ greatly from that in Europe (Svendsen et al., 1999; Astakhov, 2008). Environmental changes around the Laptev Sea coast have been reconstructed through multidisciplinary studies using permafrost sequences from the middle-late Weichselian to the Holocene. Deductive results provide evidence for the continuous existence of a treeless grass/herb dominated vegetation (Andreev et al., 2002b) and very cold winters, attested by the continuous growth of thick ice wedges and by their stable isotope composition (Meyer et a., 2002; Hubberten et al., 2004) during this period. Climate reconstructions based on pollen data show stronger continental conditions for NE Siberia during the last glacial maximum (LGM) than today. Winters were probably much stronger and summers were probably much warmer during this time than today. Most of the investigations imply that dry environmental conditions dominated throughout this period (Tarasov et al., 1999a; Anderson and Lozhkin, 2001; Anderson et al., 2002; Kienast et al., 2005). The mountain belts and plateaus of central Asia and Tibet, as well as the vastness of the landmass, effectively prevented the penetration of humid winds from either the Atlantic or Pacific Oceans (Stauch, 2006). Other investigations concentrate on climate and environmental dynamics during the Holocene period based on multi-proxy analysis, such as for example pollen, plant macrofossils, tree-rings, diatoms, chironomids, and stable isotopes (e.g. Grichuk, 1984; Texier et al., 1997; Kremenetski et al., 1998; Andreev and Klimanov, 2000; Rühland et al., 2000; Wolfe et al., 2000; MacDonald et al., 2000; Tarasov, et al., 1999b, 2000; Pisaric et al., 2001; Solomina and Alverson, 2004). Fluctuations in the arboreal and non-arboreal pollen ratio indicate that during the late glacial-Holocene transition a period of relatively warmer conditions (Bølling-Allerød) occurred. Climate amelioration during this interval is indicated by dominance of shrub tundra vegetation (e.g. Andreev et al., 2003, 2004b). The Younger Dryas cold event is one of the most prominent abrupt climate change events in the past (Sima et al., 2004). For this period (ca. 12.9-11.6 kyr BP) a return to almost glacial conditions within the general warming trend is reported (e.g. Andreev et al., 1997; Velichko et al., 1997; Pisaric et al., 2001). Quantitative palaeoclimatic interpretation of the pollen spectra from central Yakutia suggests that the mean July temperature was 2-4°C higher than present during the early

Holocene (Andreev and Tarasov, 2007). Numerous palaeodata suggest that the climate of the mid-Holocene around 6 kyr BP was quite different from that of today. Generally, the summer in many mid- to high-latitude regions of the northern hemisphere was warmer and palaeobotanical data indicates an expansion of boreal forests north of the modern tree line (e.g. Tarasov et al., 1998). Quantitative climate reconstruction based on lake sediment pollen records from central Yakutia suggests that the mean July temperature was up to 1.5°C higher than present during the mid-Holocene (Andreev and Tarasov, 2007). Late Holocene forest retreat in the study region has been reported by various authors (e.g. Kremenetski et al., 1998; MacDonald et al., 2000) even though the impact rate of human-environmental interactions on the vegetation composition during the past millennia is not exactly known.

Investigations on past vegetation dynamics indicated that a complex of tundra, steppe and forests of larch, pine and birch existed in scattered refugia in southern and central Siberia during the LGM (Grichuk, 1984; Frenzel et al., 1992). The role of refugia as centres of spread and sources of modern genetic diversity was recently discussed by Bennett and Provan (2008). It appears that small populations of trees can endure extreme climatic conditions for tens of thousands of years (Petit et al., 2008). Tarasov et al. (2007) quantitatively reconstructed tree cover density using pollen data from the LGM in northern Asia. The reconstructions indicate relatively low tree cover density during the LGM but not the complete absence of trees. Furthermore, the existence of refugial populations of woody taxa further north than previously proposed has interesting implications regarding postglacial migration rates (Binney et al., 2009).

The region of NE Siberia is long known as important for understanding the magnitude of climatic and environmental changes during the late Quaternary and their consequences for the other temperate regions (e.g. Khotinskiy, 1984; Velichko, 1984; Lozhkin et al., 2007; Kienast et al., 2008). However, this area has been lagged behind other regions in terms of high-resolution palaeoclimatic studies and it is therefore eligible to strengthen further palaeoenvironmental research in this particular region.

1.2 Main objectives of this thesis

The present thesis is defined as an initial palaeoenvironmental study. It first demonstrates a quantitative and qualitative palaeoecological approach that uses pollen, testate amoebae, and partly non-pollen palynomorphs in lake and permafrost sediments from two different sites in Yakutia. Additionally, modern ecological data is analysed to refine the ability of quantitative palaeoenvironmental reconstructions based on pollen and testate amoebae analysis. A broader aim of this research is the comparison of amplitudes and durations of palaeoenvironmental fluctuations with those regionally and globally recorded. Those comparisons may reveal past shifts in atmospheric conditions and may be detected from temporal and spatial patterns of past environments.

As described above the main objectives of this thesis are:

- focus on environmental changes in the Siberian Arctic over the past 50,000 years (the last glacial period with MIS 3 to MIS 1);
- establish a detailed record of palaeoenvironmental changes during this period with the help of permafrost and lacustrine archives from NE Siberia based on multi-proxy analysis (especially pollen and testate amoebae);
- reconstruct the duration and timing of palaeoenvironmental fluctuations within this region;
- expand the modern data sets for pollen and testate amoebae from the study region for detailed characterisation of modern environments and verification of the palaeoenvironmental reconstruction;
- correlate the terrestrial records with other available records from the Siberian Arctic;
- and in a next step correlate the terrestrial records with global signals of climate change during the last 50 kyr.

1.3 General outline and organisation of manuscripts

At the Freie Universität Berlin a doctoral thesis is compiled either as a monograph or as compilation of published articles. For this thesis the latter possibility is the case. The articles contained here have already been published (manuscripts I and II) or are prepared for submission (manuscript III) to a peer-reviewed scientific journal and are represented in chapter 2. Each of these manuscripts is considered as a separate publication and therefore it is not possible to avoid repetition of basic information (regional setting as well as field and laboratory methods). In addition an overview to historical research (chapter 1.1), regional aspects of the study of interest (chapter 1.4) and methodological information (chapters 1.5, 1.6) as well as a section for conclusions (chapter 3) and perspectives of further research (chapter 4) have been included in the thesis to provide more detailed information on the subject of palaeoenvironmental research in NE Siberia that could not be included in the manuscripts. The declaration of my own contribution to each manuscript is listed in percentages in Table 1.

Manuscript I (chapter 2.1) has been published in *Palaeogeography, Palaeoclimatology, Palaeoecology* in 2009. It describes the use of testate amoebae as palaeoenvironmental indicators in permafrost deposits from the Laptev Sea coast (NE Siberia) for the last 45 kyr. It highlighted the benefits of testate amoebae analysis complementary to other palaeoenvironmental proxies to get more detailed information on environmental changes in the past and their causes. We also stressed out the importance of surface sample analysis as precedent condition for reliable information of microhabitats in arctic environments and to quantify observed changes in the fossil testate amoebae records.

Manuscript II (chapter 2.2) has been published in *Climate of the Past* in 2009. Late glacial to Holocene environments in the western Verkhoyansk Mountain region have been reconstructed using a pollen record from Lake Billyakh (NE Siberia). We were able to reconstruct substantial changes in the regional vegetation composition during the last 15 kyr. An important aspect of this research was the proof of uninterrupted growth of larch in the study area during this time confirming an earlier hypothesis of the existence of glacial refugia for boreal trees in this particular region.

Manuscript III (chapter 2.3) is prepared for submission to *Quaternary Science Reviews*. It describes the late Quaternary vegetation and environmental development during the last 50 kyr based on modern and fossil pollen data. A set of 53 surface pollen samples from different regions of Yakutia is used to verify the quantitative approach of the biome reconstruction and attribution of pollen taxa to the regional biomes. The adjusted method was then applied to the fossil pollen records from Lake Billyakh to gain an objective reconstruction of the regional vegetation and environments since about 50 kyr BP. Once more we proofed that larch stands appeared in the study area during the last glacial period. Furthermore we correlated the pollen derived palaeoenvironmental variations in the Lake Billyakh record with North Atlantic climate signals (Dansgaard-Oeschger events) suggesting the stronger influence of the westerly wind system than pacific induced climate changes on the western foreland of the Verkhoyansk Mountains during the last 50 kyr.

Table 1. Table showing my own contribution (%) to the several main components of the manuscripts.

	Concept	Accomplishment	Publication
Manuscript I	50	80	70
Manuscript II	70	90	80
Manuscript III	80	90	80

Manuscript IV and V in Appendix A represent co-authorships in the published articles and have been included in the synthesis because they are dealing with the thesis subject. Manuscript IV demonstrates (Tarasov et al., 2007) the importance of accurate reconstruction of late Quaternary vegetation cover for a better understanding of past vegetation dynamics, the relevance of vegetation feedbacks within glacial-interglacial climate variations as well as for the validation of quantitative vegetation and climate models. It highlighted the importance of modern pollen datasets for application in palaeoenvironmental reconstructions, especially for biome and quantitative climate reconstructions. In manuscript V (Bobrov et al., 2009) an attempt for ecological classification of testate amoebae communities in high arctic palaeoenvironments was made. However, the lack of modern surface samples makes the detailed and comprehensive coverage difficult and points to further subjects of research. This manuscript is currently available in Russian language, but will be translated to English by the journal as soon as possible.

1.4 Study region

The study region is the area of Yakutia (Republic of Russia), situated between ca. 50-75°N and 110-170°E occupying an area of about 3.1 mill. km^2. The region is bounded by the lowlands along the Laptev Sea coast and the Stanovoy Mountain Range in the south including arctic, sub-arctic, and temperate climatic zones. The vegetation is characterised by tundra or light coniferous forests (Lozhkin and Anderson, 1995).

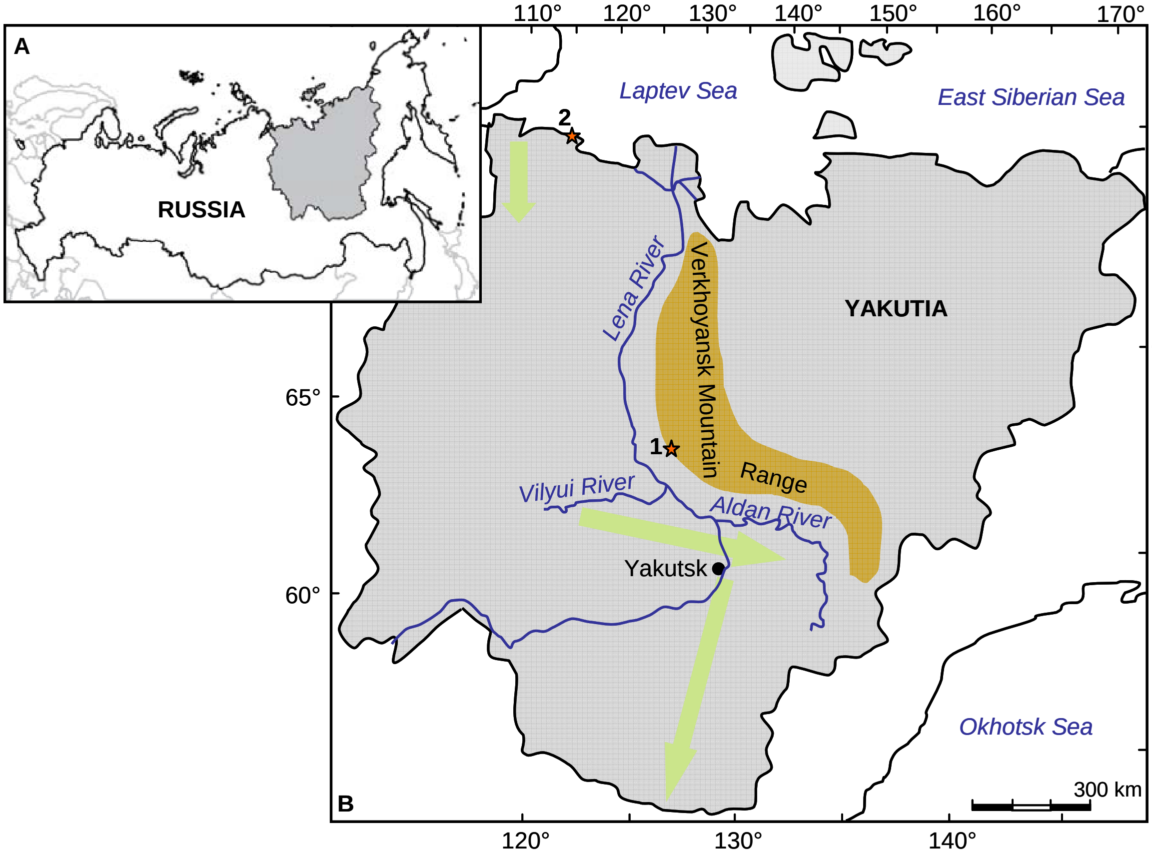

Fig. 2. Map of the study region; (A) general map of Russia and (B) map of Yakutia, stars indicate the investigated sites with 1 - Lake Billyakh (65°17'N, 126°47'E; 340 m a.s.l.) and 2 - Cape Mamontovy Klyk (73°60'-73°63'N, 116°88'-117°18'E; 25-30 m a.s.l.); transects where modern surface samples were taken are marked by green arrows.

The central Yakutian lowland stretches along the great rivers Lena, Aldan, and Vilyui (Fig. 2). This lowland is characterised by relatively uniform geomorphological, hydrological and climatic parameters. In the Verkhoyansk Mountain Range, which extends about 1200 km from the Laptev Sea coast to the south maximum elevations reach 2959 m a.s.l. in the southeastern branch of the mountains. In the northern and central part elevations reach 1400 m and ca. 2000 m a.s.l., respectively (Shahgedanova et al., 2002).

1.4.1 Modern climate

The distinctive peculiarity of the modern arctic climate is the low annual temperature (-10°C in the central part of Yakutia and up to -15.9°C in the very continental area near Verkhoyansk; Fig. 3), which promotes the appearance of polar desert landscapes, tundra, permafrost, and constant sea-ice cover on the Arctic Ocean (Alpat'ev et al., 1976; Lavrushin and Alekseev, 2005). The climate of NE Siberia is characterised by extreme continentality with very cold winters and hot summers. The thermal regimes are mainly influenced by the geographical setting, (i) high-latitude and (ii) continental position (Shahgedanova, 2002).

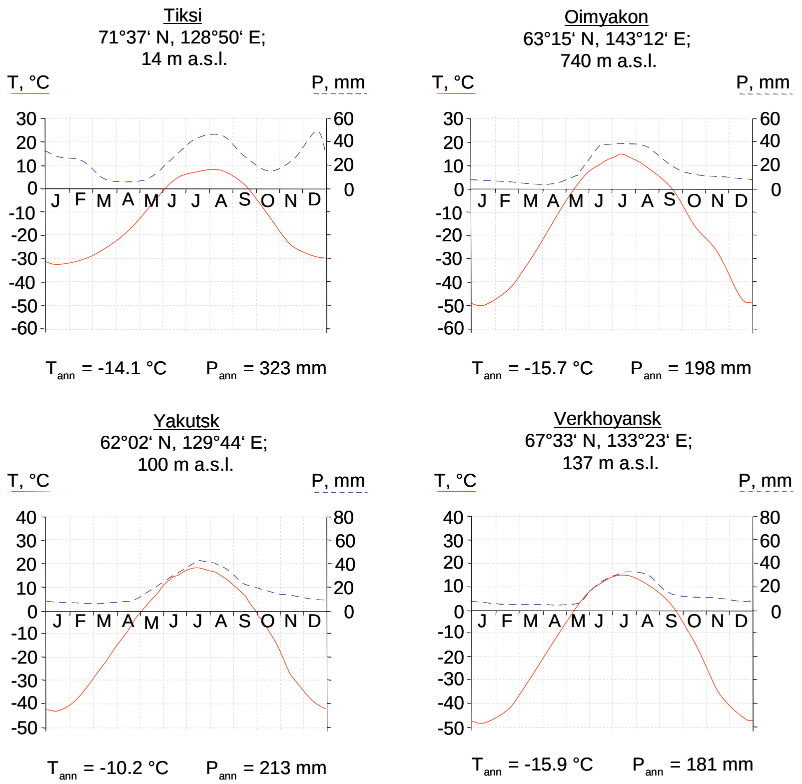

Fig. 3. Climate diagrams of four stations in Yakutia showing mean monthly temperatures and precipitation amounts (Rivas-Martínez 1996-2004; World Meteorological Observation, 2008).

Generally temperatures across northern Siberia are low with large annual ranges. In the western and eastern parts of the region the temperature amplitude is rather low. In central Siberia the temperature amplitude is very high and the absolute temperature range can reach 100°C with maximum summer temperature of 30°C (TVII 15-19°C) and minimum winter temperature of -70°C (TI -40°C) (Walter and Breckle, 1999; Fig. 3). Due to the cold climate during the winter months, the area of Oimyakon is referred to as the 'Pole of Cold' of the northern hemisphere. A strong Siberian anticyclone controls the winter weather (Andreev and Tarasov, 2007). Precipitation in the area is mainly controlled by cyclones coming from the Atlantic Ocean and show large differences between the eastern and the western site of the Verkhoyansk Mountain Range. Therefore, precipitation on the western site of the mountain system reaches values of 250 mm/yr in average, while east of the mountains annual precipitation is only about 100-200 mm (Rivas-Martínez, 1996-2004). About 65% of the annual precipitation falls during the summer months (Andreev and Tarasov, 2007), but evaporation is very high (350-400 mm) and can exceed precipitation amounts six to seven times in arid years (Gavrilova, 1973).

1.4.2 Modern vegetation

The location of the region at high latitudes provides short vegetation periods and harsh long-term changes of insolation throughout the year, conditioned by the existence of polar day and polar night (Lavrushin and Alekseev, 2005). The spatial vegetation distribution clearly reflects the climatic gradients. Various moss, grass, dwarf shrub, and shrubby tundra types (tundra vegetation zone) occupy the arctic lowlands, the upper belt of the mountains and high plateaus (Andreev and Tarasov, 2007; Fig. 4 and 5A, B). Wetland vegetation, mainly composed of sedges, cotton grass, grasses and mosses as well as dwarf shrubs dominates the landscape (CAVM Team, 2003). Dwarf and hemi prostrate shrubs, such as willow (e.g. *Salix polaris* and *S. arctica*, *S. reticulata*) and birch (*Betula exilis*) as well as *Ledum palustre*, *Rubus chamaemorus*, *Dryas* sp., and *Cassiope* sp. are typical plants in the tundra vegetation.

In southern areas of Yakutia, boreal conifer trees (*Larix dahurica = L. gmelinii + L. cajanderi*) merge gradually into tundra, reflecting the forest tundra region (Kienast, 2007; Fig. 5C). Further south light taiga forests follow with larch as the most frequent tree. Taiga forests cover about 47% of Yakutia and are mainly (up to 90%) represented by larch (Wein, 1999).

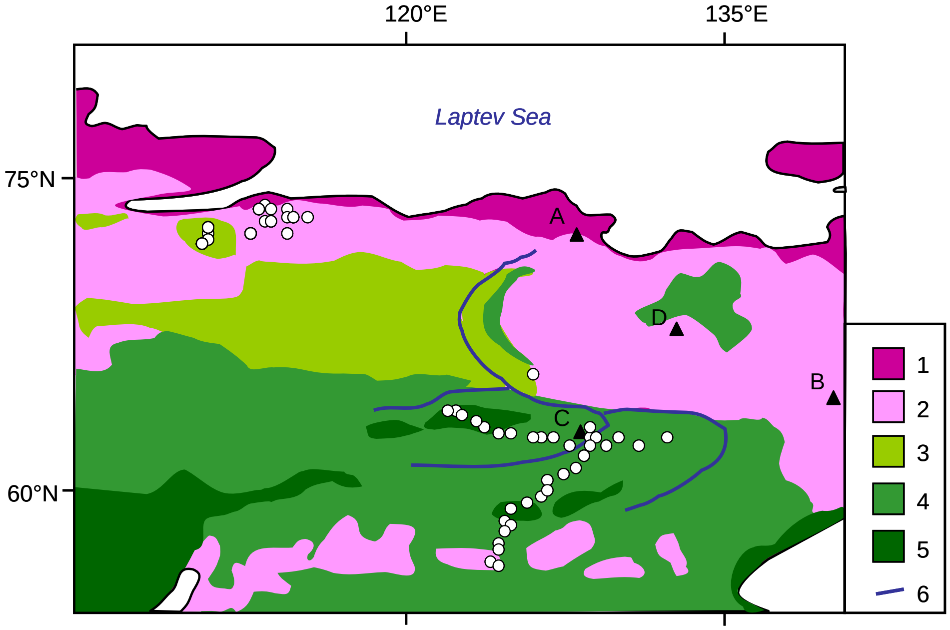

Fig. 4. Vegetation map of Yakutia and adjacent regions with indicated surface sampling sites (white circles); letters correspond to the meteorological stations in/near (A) Tiksi, (B) Oimyakon, (C) Yakutsk, (D) Verkhoyansk; vegetation types are indicated by different colours: 1 - arctic tundra, 2 - typical tundra, 3 - forest tundra, 4 - larch forest, 5 - larch-pine forest, 6 - azonal riparian vegetation (according to Gerasimov, 1964).

Scots pine (*Pinus sylvestris*), Siberian spruce (*Picea obovata*), Siberian dwarf pine (*Pinus pumila*), Siberian pine (*Pinus sibirica*), and fir (*Abies sibirica*) are accompanying trees in central and southern Yakutia. Among deciduous species *Betula platyphylla*, *B. cajanderi* occur in small amounts (Fradkina et al., 2005). In the understorey, heath (Ericales) species, including *Vaccinium vitis-idaea*, *V. uliginosum*, *Arctous alpina*, *Ledum palustre*, *Empetrum nigrum*, are very abundant together with Rosaceae (e.g. *Sanguisorba officinalis*, *Spiraea* sp., *Rosa* sp.), as well as grasses and sedges (Walter, 1974; Fig. 5D, E). Above ca. 450 m a.s.l. forests are replaced by arctic-alpine tundra and dwarf shrub tundra communities with *Pinus pumila*, *Betula nana*, *Empetrum* sp., *Vaccinium vitis-idaea*, *V. uliginosum*, and *Ledum* sp. Broad-leaved trees are mostly represented by cold- and drought resistant birch (*Betula pubescens* and *B. pendula*) (Andreev and Tarasov, 2007). Several boreal forest plants are adapted to rapid colonisation and growth in recently burned areas, such as fireweed (*Epilobium angustifolium*). Also present in central Yakutia are 'alas' (relatively large lakes of thermokarst genesis; see also next chapter) meadows, steppe areas, and 'solonchaks' (salt marshes) with halophytic communities consisting e.g. of *Carex* and *Artemisia* species (Fradkina et al., 2005).

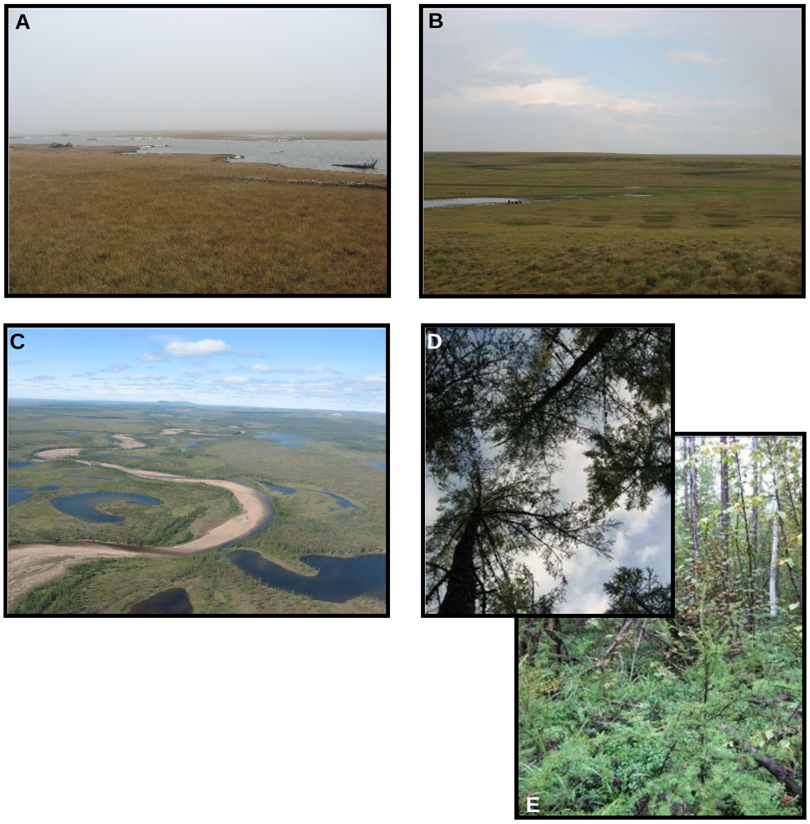

Fig. 5. Pictures showing different vegetation types in Yakutia; (A) northern tundra with sparse vegetation cover, (B) typical tundra, (C) forest tundra with larch bordering lakes and rivers, (D) larch forest with (E) typical understorey communities.

1.4.3 Permafrost

Permafrost is defined as perennially frozen ground or ground in which a temperature less than 0°C has existed continuously for two or more years. Approximately a quarter of the global surface and nearly two third of Russia are affected by perennially frozen ground (Ershov, 1995). During the Pleistocene an additional one fifth was affected to greater or lesser extent by periglacial conditions (French, 2007). Permafrost thickness varies between a few centimetres to several hundred meters. The very cold climate with long winters and short summers causes the large thickness of continuously frozen ground reaching 400-900 m across Yakutia (Gavrilova, 1993; Fig. 6).

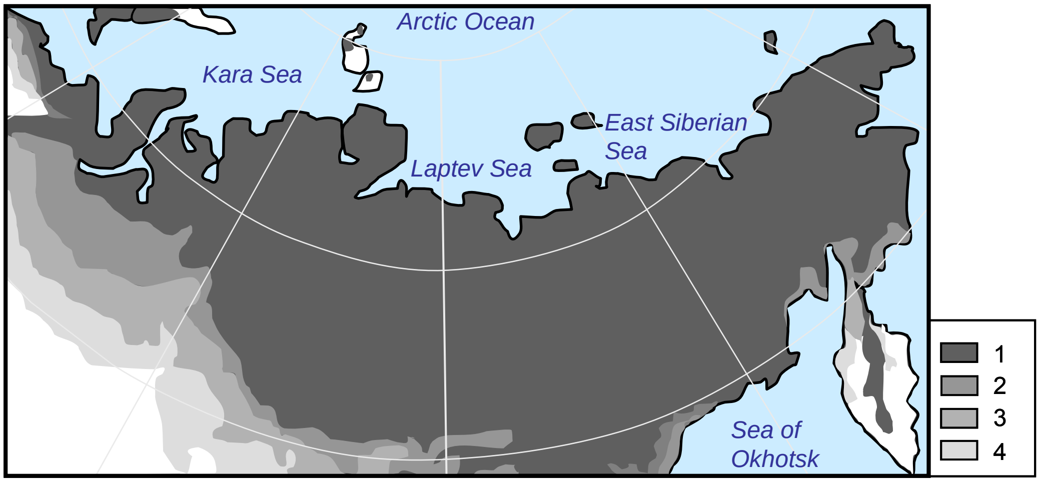

Fig. 6. Distribution of permafrost in NE Asia (according to UNEP/GRID-Arendal, 2009), 1 - continuous permafrost, 2 - discontinuous permafrost, 3 - sporadic permafrost, 4 – isolated permafrost.

As shown in Fig. 6 permafrost is commonly classified in its extent as being continuous, discontinuous, sporadic or isolated (French, 2007). The surface layer of soil that thaws in summer and refreezes in winter is called the active layer. It is usually underlain by permafrost soil and range between 10 to 60 cm (up to 4 m on aeolian sands) in the region depending on the local climate and soil conditions (Shahgedanova et al., 2002). Permafrost causes a number of unique landforms. The most common topographic features in areas with permafrost and seasonal frost are polygons (Fig. 7A). They are associated with thermal contraction cracking of the ground (French, 2007). Intensified summer thawing of the soil surface results in special thermokarst features, like e.g. alas, Bulgunyakh, and frost humps (Fig. 7B-D).

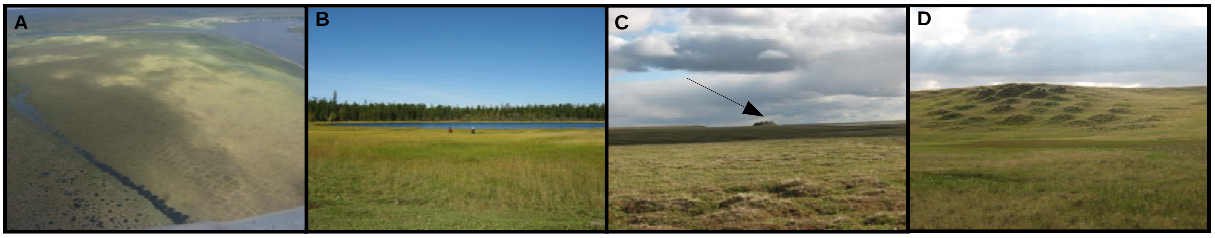

Fig. 7. Common topographic features within the zone of continuous permafrost; (A) low centred polygons, (B) alas, (C) Bulgunyakh, (D) frost humps.

1.5 The use of palynological data in palaeoenvironmental studies

Applications of palaeobotanical data, especially palynological data, for palaeoclimatic reconstructions are justified by the close relations between plants and climate (Velichko and Nechaev, 2005). Plants are sedentary, usually long-lived in the Arctic, and their occurrence and abundance and sometimes growth form responses to the long-term climate in their habitat. Pollen and spores, produced by plants during the reproduction process, can accumulate in sediments and build up a pollen sequence of past vegetation. The analysis of such sequences can provide information on impacts of climate change and human induced changes on environments. The analysis of pollen and spores is usually considered together within the broad term 'palynology'. Fægri and Iverson (1989) defined pollen analysis as ‘a technique for reconstructing former vegetation by means of the pollen grains it produced’. A number of studies on fossil pollen were conducted in the nineteenth century, but the great potential of the method was not realised until Lennart von Post presented the first modern percentage pollen analysis in 1916 (Pearsall, 1989). Von Post demonstrated the usefulness of pollen analysis for environmental reconstruction and stratigraphic correlation (MacDonald, 1990). Today, palynology is one of the most widely used research tools in Quaternary studies. In this introduction chapter only a rough overview relating to the basic principles of this method is therefore given.

Pollen grains are usually spherical or elliptical (Fig. 8A, B), and vary in size from 10-200 µm, depending on species: most are 20-30 µm (Bennett and Willis, 2001). The outer walls (ekt- and endexine) are extremely resistant to decay and are structured in various ways allowing identification reaching as far as to the genus or family level, within some groups even to species level (Birks and Birks, 1980).

Depending on the producing plant, pollen can be dispersed in different ways, but most pollen is either wind-dispersed (anemophilous) or insect-dispersed (entomophilous). The morphology of spores from mosses and ferns slightly differ from that of pollen (Fig. 8C-D), but spores have the same size range and are mostly wind dispersed. Pollen grains are well suited for palaeoecological studies for a number of reasons: (i) they have extremely resistant exines, that can survive in deposits where other fossil types have been destroyed; (ii) they are abundantly produced; (iii) they are widely and evenly dispersed; and (iv) pollen data are easily quantified (Fægri and Iverson, 1989).

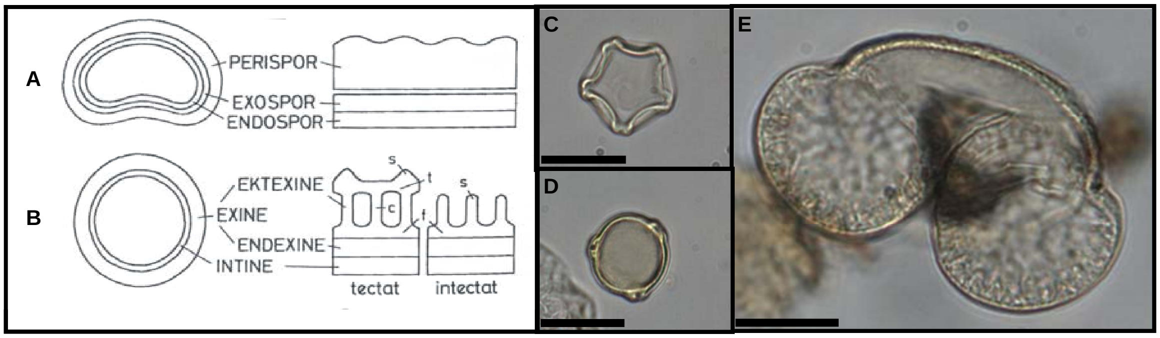

Fig. 8. Structure of spore (A) and pollen (B) wall (from Lang, 1994); (C) modern pollen of shrubby alder (*Duschekia fruticosa*), (D) birch (*Betula* sect. *Nanae*), and (E) tree pine (*Pinus* subgen. *Diploxylon*); scale bar 20 µm.

Pollen percentages correspond in a broad way to the vegetation which produced them. Thus taking surface samples within a known vegetation community permits the vegetation reconstruction not only at one site, but the vegetation over an area at a particular time (Birks and Birks, 1980). At the largest spatial scale, pollen data have been used to reconstruct past changes of biomes, using pollen records from entire modern biomes as a basis (e.g. Prentice et al., 1996; Jolly et al. 1998; Tarasov et al., 1998). By palynological investigations changes in vegetation assemblages and shifts of vegetation zones can be reconstructed. Information about plant biodiversity, stability and ecosystem dynamics during past times can be obtained using pollen data. Anthropogenic influences can also be tracked by pollen from crop plants and pollen from plants of disturbed grounds. In addition, Quaternary palynological data can be used to quantitatively reconstruct past temperature and precipitation rates that can be used for validation of global climatic models. Palynological investigations underlay information on how vegetation responded to local and global environmental changes in the past. The understanding of natural environmental changes in the past, is important for the understanding of today's and even more for future environmental changes.

1.6 The use of testate amoebae in palaeoenvironmental studies

Testate amoebae (Cercozoa and Amoebozoa; hereafter TA) often occur in aquatic and wet environments like peat bogs, but are also frequent in soils (up to 10.000 TA per gram dry weight), especially in soils with a high organic content (Clarke, 2003). TA are one-celled micro-organisms (7-450 µm) with a distinct organic shell (*testa*), which differs in shape, architecture and ornamentation (Fig. 9A-C) and well-defined ecological preferences. The empty shell remains intact after the death of the amoebae and can often be identified to species level (Beyens and Meisterfeld, 2001). An important advantage of TA analysis within palaeoecological investigations is the short generation time, which makes TA sensitive indicators of short-term environmental changes. The occurrence of the fragile shells in fossil sequences also reflects non-disturbed sediment accumulation without reworking.

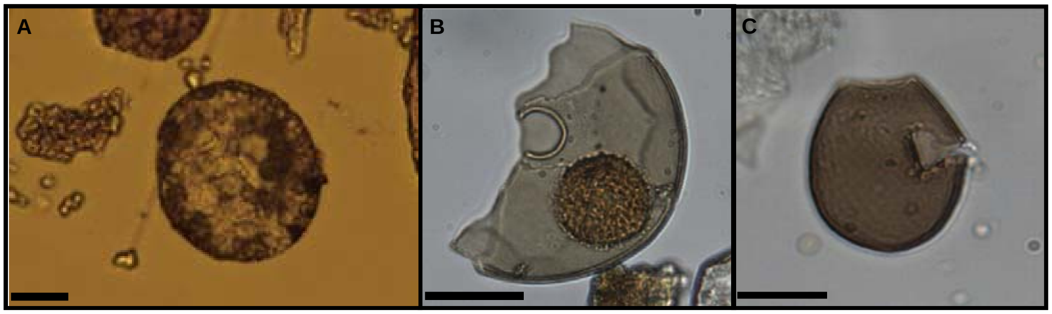

Fig. 9. Photographs of fossil testate amoebae (A) *Centropyxis plagiostoma*, and shells from modern Yakutian surface samples (B) broken *Arcella arenaria* shell (with attached *Lycopodium* spore), and (C) broken *Assulina muscorum* shell; scale bar 20 µm.

Beyens and Chardez (1987) reported that habitat moisture is a parameter of prime importance. TA are therefore getting wider used to reconstruct local hydrological changes in palaeoecological studies. They are sensitive to changing pH-values and changing conductivity. Up until now, studies on TA were conducted in peat bogs (e.g. Schönborn, 1962; Tolonen, 1986), particularly in *Sphagnum*-moss habitats (e.g. Charman, 2001; Mitchell et al., 2004; Gilbert et al., 2003; Schnitchen et al., 2003; Lamentowicz and Mitchell, 2005), and lakes (Ogden and Hedley, 1980). Most of the former studies were done in Europe but only few studies investigated arctic terrestrial moss habitats, like in Greenland (Beyens et al., 1992; Trappeniers et al., 2002), Spitsbergen (Beyens et al., 1986), Canada (Beyens et al., 1990) and Alaska (Beyens and Chardez, 1995). Smith (e.g. 1992, 1996) and Wilkinson (e.g. 1990, 1994) performed case studies focusing on distribution and ecology of terrestrial TA in the Antarctic soil environments. However, until today little has been done to study ecological preferences and distribution of TA species in frozen soils of Siberia, particularly in the late Quaternary sediments (Schirrmeister et al., 2003; Bobrov et al., 2004, 2009; Andreev et al., 2009).

Studies from aquatic environments have shown that TA are good palaeoenvironmental indicators in freshwater environments. For example Medioli and Scott (1988) remarked that TA require a minimum temperature at some time of the year to reproduce successfully. McCarthy et al. (1995) compared palaeotemperatures and precipitation rates inferred from pollen data with TA assemblages from the same sediment. Patterson et al. (1985) found that the divisions between major TA assemblages in small lakes appears to be a function of seasonal temperatures. Dallimore et al. (2000) studied TA communities in lakes of the Canadian Arctic and successfully related modern TA assemblages to varying environmental variables (e.g. summer lake temperature, conductivity) and furthermore to past TA assemblages from lake sediment material. Recent studies of modern ecology of TA have enabled the development of transfer functions (Charman et al., 2007) in western Europe. These are designed to quantify the relationship between TA assemblages and fluctuations in peatland water tables and soil moisture, also for past environments. In NE Siberia the TA analysis of sediments during the last interglacial and Holocene was reported only from Bol'shoy Lyakhovsky Island in the East Siberian Sea (Andreev et al., 2004a; Andreev et al., 2009) and from Bykovsky Peninsula, east of the Lena Delta (Bobrov et al., 2004). Here differences between late Pleistocene and Holocene environmental conditions are convincingly reflected by TA records.

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3. Publications

3.1 Manuscript I

S. Müller, A.A. Bobrov, L. Schirrmeister, A.A. Andreev, P.E. Tarasov, 2009. Testate amoebae record from the Laptev Sea coast and its implication for the reconstruction of Late Pleistocene and Holocene environments in the Arctic Siberia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 271, 301-315. doi:10.1016/j.palaeo.2008.11.003

3.2 Manuscript II

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Climate of the Past

Late Glacial to Holocene environments in the present-day coldest region of the Northern Hemisphere inferred from a pollen record of Lake Billyakh, Verkhoyansk Mts, NE Siberia

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Abstract. In this study, a radiocarbon-dated pollen record from Lake Billyakh (65°17′ N, 126°47′ E; 340 m a.s.l.) in the Verkhoyansk Mountains was used to reconstruct vegetation and climate change since about 15 kyr BP. The pollen record and pollen-based biome reconstruction suggest that open cool steppe (STEP) and grass and sedge tundra (TUND) communities with Poaceae, Cyperaceae, *Artemisia*, Chenopodiaceae, Caryophyllaceae and *Selaginella rupestris* dominated the area from 15 to 13.5 kyr BP. On the other hand, the constant presence of *Larix* pollen in quantities comparable to today's values points to the constant presence of boreal deciduous conifer (CLDE) trees in the regional vegetation during the Late Glacial. A major spread of shrub tundra communities, including birch (*Betula* sect. *Nanae*), alder (*Duschekia fruticosa*) and willow (*Salix*) species, is dated to 13.5–12.7 kyr BP, indicating a noticeable increase in precipitation toward the end of the Last Glaciation, particularly during the Bølling-Allerød Interstadial. Between 12.7 and 11.4 kyr BP pollen percentages of herbaceous taxa rapidly increased, whereas shrub taxa percentages decreased, suggesting strengthening of the steppe communities associated with the relatively cold and dry Younger Dryas Stadial. However, the pollen data in hand indicate that Younger Dryas climate was less severe than the climate during the earlier interval from 15 to 13.5 kyr BP. The onset of the Holocene is marked in the pollen record by the highest values of shrub and lowest values of herbaceous taxa, suggesting a return of warmer and wetter conditions after 11.4 kyr BP. Percentages of tree taxa increase gradually and reach maximum values after 7 kyr BP, reflecting the spread of boreal cold deciduous and taiga forests in the region. An interval between 7 and 2 kyr BP is noticeable for the highest percentages of Scots pine (*Pinus* subgen. *Diploxylon*), spruce (*Picea*) and fir (*Abies*) pollen, indicating mid-Holocene spread of boreal forest communities in response to climate amelioration and degradation of the permafrost layer.

1 Introduction

Global and regional climate models predict noticeable 21st century climate warming, which is expected to be most pronounced in high latitudes of the Northern Hemisphere (ACIA, 2004). In particular, predicted winter warming is expected to exceed the global annual average, causing great reduction of sea-ice cover and significant degradation of permafrost (French and Williams, 2007). All these changes will most certainly destabilize fragile Arctic vegetation and environments and might in turn influence global atmospheric circulation and climate. The International Council for Science (ICSU, 2004) agreed to establish the International Polar Year (IPY) in 2007–2008 in order to "start a new era in polar science; to intensify interdisciplinary research programs focussing on the Arctic and the Antarctic regions and to understand better the strong links these regions have with the rest of the globe".

The investigation presented in this paper is part of the IPY project 106 "Lake Records of Late Quaternary Climate Variability in northeastern Siberia" and the German Research Foundation project "Late Quaternary environmental history of interstadial and interglacial periods in the Arctic reconstructed from bioindicators in permafrost sequences in NE Siberia". Both projects focus on generating high-resolution

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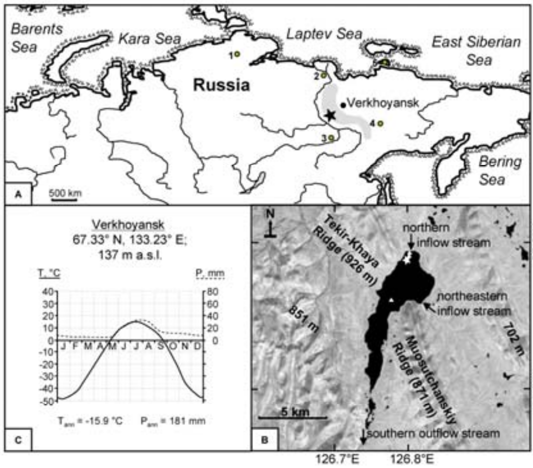


Fig. 1. **(A)** Map of northeastern Eurasia, in which shaded area represents the Verkhoyansk Mountains and green points mark sites mentioned in the discussion: 1 – Levinson-Lessing Lake, 2 – Lake Dolgoe, 3 – Lake Chabada, 4 – Smorodinovoye Lake, 5 – Bol'shoy Lyakhovsky Island. **(B)** Enlarged map showing the Lake Billyakh (65°27′ N, 126°47′ E; 340 m a.s.l.) study area and location of the analysed core PG1756 (a star) and other cores taken during the field campaign in 2005 (triangles). **(C)** Chart showing mean monthly temperature and precipitation at the Verkhoyansk meteorological observatory (Rivas-Martínez, 1996–2004).

vegetation and climate proxy records from the lacustrine sediments along a north-south transect from Yakutia (Sakha) Republic of Russia – the region of Eurasia, which is known for its climate extremes, with the Verkhoyansk Mountain Range being the coldest area in the Northern Hemisphere (Shahgedanova et al., 2002). The coastal and mountain areas are dominated by tundra vegetation, whereas cold deciduous forest and taiga vegetation are widespread in central and southern Yakutia, where mean July temperatures reach 15–19°C (Alpat'ev et al., 1976). Because of its relatively dry continental climate, this part of Siberia did not experience extensive Late Pleistocene glaciation (Stauch, 2006; Popp et al., 2007; Stauch et al., 2007) in contrast to other arctic regions, including northern parts of western Siberia, Europe and North America which were covered by large ice sheets.

Since the second half of the last century peat and lake sediments from the region have been studied by means of pollen analysis, and results were used to reconstruct past vegetation and climate conditions of the Late Quaternary (e.g. Khotinsky, 1977; Velichko et al., 1997). However, detailed reconstructions of the vegetation and climate history were limited by the shortage of reliable radiocarbon data. During the last decade, strengthening of international co-operation in the Arctic facilitated access to several high-resolution and adequately dated pollen records from northeastern Eurasia covering the Late Pleistocene and Holocene periods (e.g. Andreev and Klimanov, 1989; Peterson, 1993; Texier et al., 1997). These records were then used for quantitative vegetation reconstruction in the global vegetation mapping BIOME6000 project (e.g. Tarasov et al., 1998; Prentice et al., 2000). Despite a general progress in the environmental studies of northeastern Eurasia, the Verkhoyansk Mountain area is still poorly investigated.

This paper fills the gap in the earlier pollen studies of the region and presents a high resolution pollen record from Lake Billyakh, located in the central part of the Verkhoyansk Mountain region (Fig. 1). The record spans the last 15 kyr (1 kyr=1000 cal. yr) as suggested by the age model, which is based on seven radiocarbon dates. Both qualitative interpretation of the pollen data and quantitative pollen-based biome reconstruction are used to interpret changes in regional vegetation and climate during the Late Glacial-Holocene time interval. We then discuss these results together with the published results of earlier palaeoenvironmental studies from northeastern Eurasia.

2 Regional setting

The Verkhoyansk Mountain Range (2389 m a.s.l.) is one of the most prominent mountain chains of northeastern Eurasia. It extends along 128° E longitude east of the Lena River for 900 km from the Laptev Sea coast to about 64° N. The southern latitudinal section extends north of the Aldan River (Lena's right tributary) for 350 km between 128° and 136° E (Alpat'ev et al., 1976; Shahgedanova et al., 2002).

Lake Billyakh (65°17′ N, 126°47′ E; altitude 340 m) is situated in the central part of the Verkhoyansk Mountains (Fig. 1a), occupying a longitudinal depression between the Tekir-Khaya Ridge and the Muosutchanskiy Ridge (Fig. 1b). The lake extends for about 11 km from north to south and for about 3 km from west to east. It has an average water depth of 8 m and a maximum depth of about 25 m. The lake is fed by direct precipitation and by several small creeks and streams flowing from the surrounding mountain slopes (Fig. 1b). An outflow stream flows from the southern part of the lake towards the Lena River.

The region is characterised by the world's most extreme continental climate. Verkhoyansk (67°33′ N, 133°33′ E; 137 m a.s.l.) is known as the Northern Hemisphere's Pole of Cold. There the instrumentally measured minimum and maximum temperatures reached −67.8°C and 39°C, respectively. The mean values for January and July temperatures are −48.6°C and 13.9°C and annual precipitation reaches 181 mm (Rivas-Martínez, 1996–2004; Fig. 1c). The very cold and long winters together with short summers cause the large thickness of continuously frozen ground reaching 400–900 m (Gavrilova, 1993).

Floristically the study area belongs to the boreal forest zone. Northern larch (*Larix dahurica*) forest with Scots pine (*Pinus sylvestris*), birch trees (*Betula platyphylla*) and shrubs (*B. middendorfii*, *B. fruticosa*, *Duschekia fruticosa*) dominate the vegetation. In the understorey, heath (Ericales) species are very abundant, including *Vaccinium vitis-idaea*, *V. uliginosum*, *Arctous alpina*, *Ledum palustre*, *Cassiope* sp., *Empetrum nigrum* together with members of Rosaceae family (*Sanguisorba officinalis*, *Rosa* sp., *Spiraea* sp.), grasses (Poaceae) and sedges (Cyperaceae) (Walter, 1974). Common mosses are *Polytrichum* sp., *Dicranum* sp., *Sphagnum* sp. and lichens *Cladonia* sp., *Cetraria* sp. (Walter, 1974). Above approximately 450 m a.s.l., the woodland is replaced by arctic-alpine tundra and dwarf shrub tundra communities with *Pinus pumila*, *Betula nana*, *Empetrum* sp., *Vaccinium vitis-idaea*, *V. uliginosum* and *Ledum* sp.

3 Field and laboratory methods

3.1 Coring and lithology

Sediment coring with an UWITEC piston corer system was performed at one site in the central profundal basin of the lake and at three other sites located near the northern shore (Diekmann et al., 2007; Fig. 1b). A total of 35 m of sediment were recovered from the four sites and transported to Germany for further analyses.

The 660 cm long core PG1756 described in the present study was recovered from a small subbasin about 800 m off the northern shore, from 7.9 m water depth. The core consists of homogenous dark greenish grey sandy silt (0–145 cm), homogenous dark greenish grey clayey silt (145–374 cm), finely stratified dark greenish grey sandy silt (374–429 cm), greyish silt (429–450 cm) and basal dark greyish sand below 450 cm (Fig. 2a).

3.2 Pollen analysis

The core material stored at AWI (Potsdam) was sampled there for pollen analysis. Samples were taken as 1 cm slices every 5 cm, yielding an average temporal resolution of 190 years. Further chemical treatment of the samples and pollen analysis were performed in the pollen laboratory at FU Berlin. Pollen extraction from the samples consisting of 1.5 g sediment was performed according to standard procedures, including 7-μm ultrasonic fine-sieving, HF treatment and acetolysis (Fægri et al., 1989; Cwynar et al., 1979). One tablet of *Lycopodium* marker spores was added to each sample for calculating total pollen and spore concentrations (Stockmarr, 1971). Water-free glycerol was used for sample storage and preparation of the microscopic slides. Pollen and spores were identified at magnifications of 400× and 1000×, with the aid of published keys (Kupriyanova et al., 1972, 1978; Bobrov et al., 1983; Reille, 1992, 1995, 1998; Beug, 2004) and a modern pollen reference collection at FU Berlin.

Preservation of pollen and spores was very good, and corroded grains were found mainly in the lower part of the core below 419 cm, in sediments with a higher sand content. Bisaccate pollen of *Pinus* and *Picea* were frequently broken. The pollen and spore content of the samples was sufficiently high to allow counting of a minimum of 500 terrestrial pollen grains per sample. In total, 71 pollen and spore taxa were identified in the PG1756 core. In this study pollen of *Pinus* was separated into two morphological types, e.g. *P*. subgen. *Diploxylon* and *P*. subgen. *Haploxylon*. In the study area these two pollen types are produced by *P. sylvestris* (tree pine) and *P. pumila* (shrub pine), respectively. *Betula* pollen was also divided into two morphological types: *B*. sect. *Nanae* (shrub birch) and *B*. sect. *Albae* (tree birch). The contribution of re-deposited pollen and spores was unimportant, suggesting non-disturbed pollen assemblages.

Calculated pollen percentages refer to the total sum of terrestrial pollen, which does not include pollen of aquatic plants, spores of pteridophytes and mosses, algae and re-deposited pollen and spore grains. For these taxa, percentages were calculated using the total terrestrial pollen sum plus the sum of palynomorphs in the respective group. The Tilia/Tilia-Graph/TGView software (Grimm, 1993, 2004) was used for calculating pollen percentages and for drawing the pollen percentage diagram. The local pollen zones in the diagram were divided using CONISS (Grimm, 2004) and numbered from the top to the bottom of the core to allow future comparison with longer pollen sequences from Lake Billyakh.

3.3 Quantitative technique for vegetation reconstruction and palaeoclimatic interpretation

Pollen-based vegetation reconstruction was performed using the quantitative method of biome reconstruction first described by Prentice et al. (1996) and adapted for reconstruction of northern Eurasian vegetation types (biomes) by Tarasov et al. (1998). The approach allows the objective assignment of pollen taxa to plant functional types (PFTs) and to biomes on the basis of the modern ecology, bioclimatic tolerance and geographical distribution of pollen producing plants. The biome reconstruction method was successfully tested using an extensive surface pollen data set from northern Eurasia and applied to mid-Holocene and Last Glacial Maximum (LGM) pollen data (Tarasov et al., 1999a, 1999b). The results of biome reconstruction proved to be useful for the objective interpretation of the Late Quaternary vegetation and climate dynamics at global, regional and local scales and for data-model comparison (Texier et al., 1997; Prentice et al., 1996; Prentice et al., 2000; Tarasov et al., 2005).

In this study all identified terrestrial pollen taxa were initially used for the construction of the biome-PFT-taxon matrix. Among them only 28 taxa, which exceed the universal threshold of 0.5% suggested by Prentice et al. (1996) and used by Tarasov et al. (1998), influenced biome

Table 1. Terrestrial pollen taxa identified in the core PG1756 from Lake Billyakh and their attribution to the vegetation types/biomes characteristic for northern Asia. Taxa whose percentages in the pollen spectra do not exceed 0.5% (threshold suggested by Prentice et al., 1996) and do not influence results of biome reconstruction are indicated with an asterisk.

Biome	Terrestrial pollen taxa
TUND/Tundra	*Duschekia fruticosa*, *Betula* sect. *Nanae*, Cyperaceae, Ericales ind., E. *Empetrum*, E. *Vaccinium*, Papaveraceae, Poaceae, *Polemonium**, Polygonaceae ind., *Polygonum bistorta*, *P. viviparum*, *Rumex**, *R. aquatilis**, *Salix*, Saxifragaceae, Scrophulariaceae ind., S. *Pedicularis*, *Valeriana*
CLDE/Cold deciduous forest	*Betula* sect. *Albae*, Ericales ind., E. *Empetrum*, E. *Vaccinium*, *Juniperus**, *Larix*, *Pinus* subgen. *Diploxylon*, *Pinus* subgen. *Haploxylon*, *Salix*
TAIG/Taiga	*Abies*, *Betula* sect. *Albae*, Ericales ind., E. *Empetrum*, E. *Vaccinium*, *Juniperus**, *Larix*, *Picea*, *Pinus* subgen. *Diploxylon*, *Pinus* subgen. *Haploxylon*, *Salix*
COCO/Cool coniferous forest	*Abies*, *Betula* sect. *Albae*, Ericales ind., E. *Empetrum*, E. *Vaccinium*, *Juniperus**, *Larix*, *Picea*, *Pinus* subgen. *Diploxylon*, *Pinus* subgen. *Haploxylon*, *Salix*
STEP/Steppe	Apiaceae*, *Armeria*, *Artemisia*, Asteraceae subfam. Asterioideae ind., A. subfam. A. *Matricaria*, A. subfam. A. *Saussurea*, A. subfam. A. *Senecio*, A. subfam. Cichorioideae, Brassicaceae*, Caryophyllaceae ind., C. *Cerastium*, C. *Minuartia*, C. *Stellaria holostea*, Chenopodiaceae, *Circaea*, *Epilobium*, Fabaceae*, *Knautia**, Lamiaceae*, Liliaceae*, Papaveraceae, *Plantago*, Poaceae, Polygonaceae ind., *Polygonum bistorta*, *P. viviparum*, Primulaceae*, Ranunculaceae, R. *Thalictrum*, Rosaceae +operculum, R. -operculum, R. *Potentilla*, R. *Sanguisorba officinalis*, *Rumex**, *R. aquatilis**, Scrophulariaceae ind., S. *Pedicularis*, *Valeriana*
DESE/Desert	*Artemisia*, Chenopodiaceae, *Ephedra**, Polygonaceae ind., *Polygonum bistorta*, *P. viviparum*

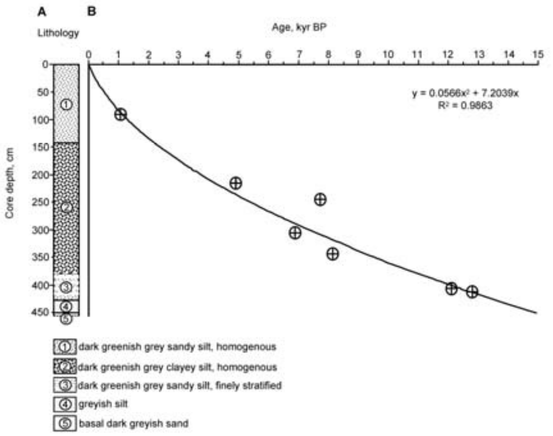


Fig. 2. Lithology **(A)** and age-depth model **(B)** of the PG1756 core from Lake Billyakh.

reconstruction as shown in Table 1. Square root transformation was applied to the pollen percentage values to diminish the influence of the most abundant pollen taxa and enhance the influence of minor taxa. Details of the method, including the equation used to calculate biome scores and discussion of the taxa attribution to the PFTs and to biomes are provided in Tarasov et al. (1998).

3.4 Results

3.5 Age-depth model

Plant material from 7 samples was radiocarbon dated at the Leibniz Laboratory for Radiometric Dating in Kiel. The age model for the PG1756 core takes into account 7 radiocarbon dates, spanning the time interval between 13 and 1 kyr BP (Table 2). Radiocarbon years were converted to calendar years using the CalPal program available online (Danzeglocke et al., 2008). A reasonable time-depth relationship arises from a fit with a polynomial function (Fig. 2b), which then was applied for age calculation of the pollen zone boundaries and their discussion in terms of temporal changes of vegetation and climate. One date (8356±124 yr BP, 244 cm depth) seemed to be slightly older than suggested by the other dates and did not fit in with our age-depth model. The calculation was repeated without this date. However, exclusion of the date from the analysis did not influence the age model. Using the equation in Fig. 2b the bottom of the analysed core can be dated to about 15 kyr BP.

3.6 Pollen analysis

Complete results of the pollen analysis are provided in Appendix A. The simplified pollen percentage diagram is shown in Fig. 3 and the main results of the pollen analysis are

Table 2. Radiocarbon dates from Lake Billyakh. Radiocarbon years are converted to calendar years (68% range) using the CalPal program (Danzeglocke et al., 2008).

Laboratory number	Internal core number	Depth from the core top (cm)	Uncalibrated age (^{14}C yr BP)	Calibrated age (cal. yr BP)
KIA29879	PG1756-2, 90	90	1145±40	1065±62
KIA29880	PG1756-3, 30	214	4400±300	4998±398
KIA34217	PG1756-3, 60	244	7010±40	7861±55
KIA34218	PG1756-3, 120	304	6080±70	6973±116
KIA34219	PG1756-3, 160	344	7460±130	8256±124
KIA34220	PG1756-3, 220	404	10430±160	12282±277
KIA29881	PG1756-3, 226	410	11105±60	13002±119

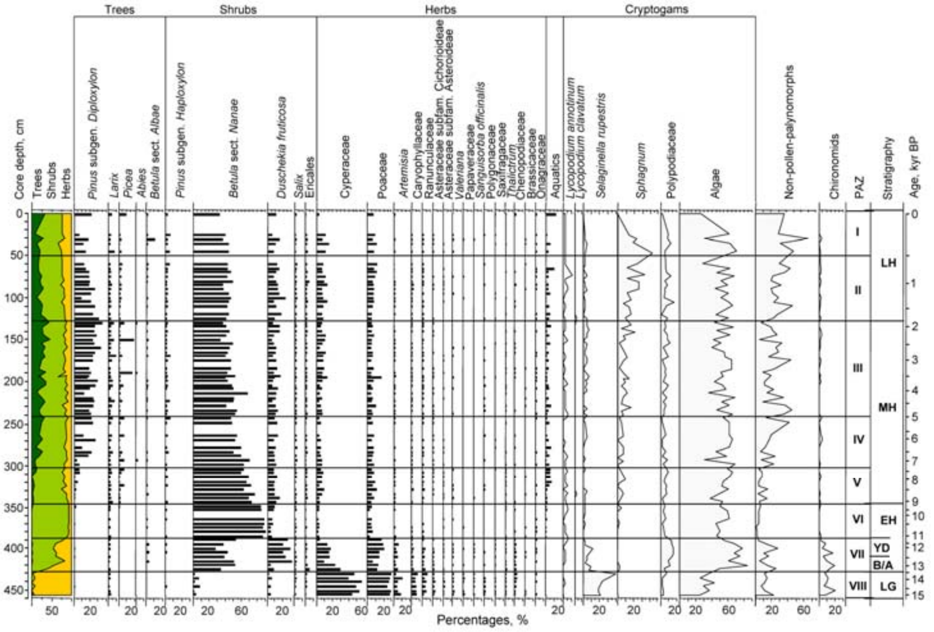


Fig. 3. Pollen percentage diagram of the PG1756 core from Lake Billyakh; LG – Late Glacial, EH- Early Holocene, B/A – Bølling-Allerød, YD – Younger Dryas, MH – Middle Holocene, LH – Late Holocene.

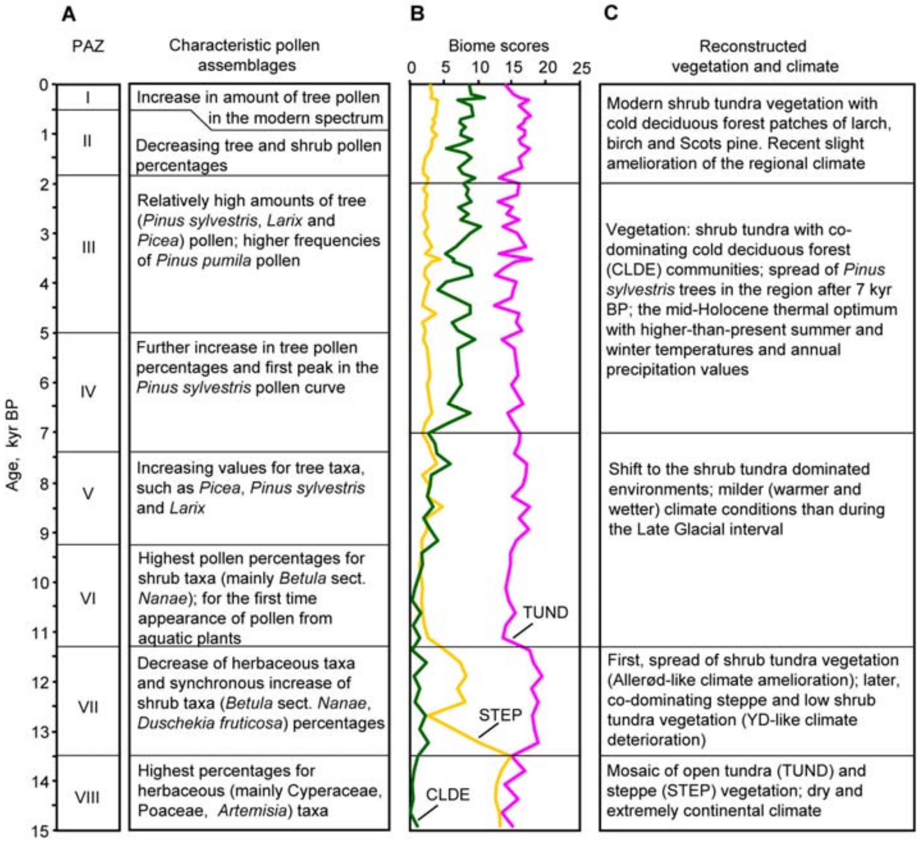
incorporated in the following chapter 4 for further interpretation and discussion.

4 Interpretation and discussion

Our results suggest distinct vegetation and environmental changes around Lake Billyakh since 15 kyr BP related to Late Quaternary regional climate and environmental dynamics. The environmental reconstruction (Fig. 4c) is based on the qualitative interpretation of the pollen record (Figs. 3 and 4a) with quantitative results of the biome reconstruction (Fig. 4b).

4.1 Late Glacial

The pollen assemblages prior to 13.5 kyr BP (PAZ VIII; 455–428 cm, 15–13.5 kyr BP) are characterised by lowest pollen concentrations through the whole record, increasing from 1900 grains/g in the lower part to 7200 grains/g in the upper part of this zone. The pollen assemblages are dominated by herbaceous taxa (89–99%), with the highest proportion of sedge (40–57%) and grass pollen (24–29%) in the whole record, suggesting a wide spread of herbaceous tundra communities (Prentice et al., 1996; Tarasov et al., 1998). On the other hand, Poaceae, *Artemisia*, Caryophyllaceae,



Increase in amount of tree pollen in the modern spectrum

Decreasing tree and shrub pollen percentages

Relatively high amounts of tree (*Pinus sylvestris*, *Larix* and *Picea*) pollen; higher frequencies of *Pinus pumila* pollen

Further increase in tree pollen percentages and first peak in the *Pinus sylvestris* pollen curve

Increasing values for tree taxa, such as *Picea*, *Pinus sylvestris* and *Larix*

Highest pollen percentages for shrub taxa (mainly *Betula* sect. *Nanae*); for the first time appearance of pollen from aquatic plants

Decrease of herbaceous taxa and synchronous increase of shrub taxa (*Betula* sect. *Nanae*, *Duschekia fruticosa*) percentages

Highest percentages for herbaceous (mainly Cyperaceae, Poaceae, *Artemisia*) taxa

Modern shrub tundra vegetation with cold deciduous forest patches of larch, birch and Scots pine. Recent slight amelioration of the regional climate

Vegetation: shrub tundra with co-dominating cold deciduous forest (CLDE) communities; spread of *Pinus sylvestris* trees in the region after 7 kyr BP; the mid-Holocene thermal optimum with higher-than-present summer and winter temperatures and annual precipitation values

Shift to the shrub tundra dominated environments; milder (warmer and wetter) climate conditions than during the Late Glacial interval

First, spread of shrub tundra vegetation (Allerød-like climate amelioration); later, co-dominating steppe and low shrub tundra vegetation (YD-like climate deterioration)

Mosaic of open tundra (TUND) and steppe (STEP) vegetation; dry and extremely continental climate

Fig. 4. Local pollen zones and pollen assemblage characteristics of the PG1756 core **(A)**; time series of individual vegetation types (biomes) dominating in the study area since 15 kyr BP **(B)**; summary of the reconstructed changes in vegetation and climate around Lake Billyakh **(C)**.

Asteraceae subfam. Cichorioideae and some other taxa attributed to the steppe biome can successfully grow in the mountain steppe and meadow communities and on the dry slopes of southern exposition (Walter, 1974). A wide spread of the dry environments is suggested by the high percentages of *Selaginella rupestris* spores (20–40%). This species of spike-moss usually occurs in dry and cold rocky places with disturbed or thin soil cover. Permanent presence of arctic and alpine shrubs and dwarf shrubs represented by *Betula* sect. *Nanae*, *Duschekia fruticosa* and *Salix* (0.5–10%) in the pollen spectra supports the interpretation of local occurrence of shrub tundra patches in the regional vegetation. The presence of *Larix* (0.5–2%) in the pollen spectra moreover points to the growth of larch around the lake already during the early Late Glacial about 15 kyr ago. This conclusion is based on the consideration that larch pollen is usually strongly underrepresented in the pollen diagrams and poorly transported far from the pollen-producing tree (Tarasov et al., 1998; Pisaric et al., 2001).

Results of the biome reconstruction demonstrate almost equally high scores for the tundra and steppe biomes and low scores for the cold deciduous forest biome, suggesting the reconstruction of generally open tundra-steppe vegetation between 15 and 13.5 kyr BP. Grichuk (1984) pointed out that such plant communities were typical for the periglacial steppe or "tundra-steppe" vegetation of the LGM, which was widely distributed in northern Eurasia. Predominance of herbaceous steppe-like vegetation prior to 13.7 kyr BP is suggested by the pollen record from Levinson-Lessing Lake (74°28′ N; 98°38′ E) in the northeastern Taymyr Peninsula (Andreev and Tarasov, 2007; Table 3). At that time dwarf shrub tundra had limited coverage and survived only in the locally wet habitats. Similar vegetation cover is reconstructed from the Lake Dolgoe (71°52′ N, 127°04′ E) pollen record in the lower Lena River before 14.5 kyr BP (Pisaric et al., 2001). According to the Biome 4 vegetation model, dominance of herbaceous vegetation in the Arctic can be explained by the extremely continental climate with low

Table 3. Summary of major vegetation changes and climate trends reported for the sites mentioned in the discussion.

Site	Period, age	Pollen assemblages and vegetation characteristics	Climate reconstructions	References
1. Levinson-Lessing Lake; 74°28′ N, 98°38′ E; 47 m a.s.l.	until 13.7 kyr BP	Scarce steppe-like vegetation	Severe continental climate	Andreev and Tarasov, 2007
	after 13.7 kyr BP	Dramatic increases in shrub birch and willow pollen and in total pollen concentration	Climatic amelioration, summer temperature 2–4°C higher than present	
	between 13 and 12 kyr BP	Increase in sedge, grass, and herb pollen		
	About 11.5–11.2 kyr BP	Shift in vegetation from herb-dominated to shrubby birch-willow tundra	Summer temperature 3–4°C higher than today, precipitation about 100 mm higher	
	After 6.3 kyr BP		Summer temperature became similar to present	
	After 3.2 kyr BP	Vegetation became similar to the modern herb tundra		
2. Lake Dolgoe; 71°52′ N, 127°04′ E; 40 m a.s.l.	12.3 ^{14}C kyr BP	Herb and shrub dominated tundra		Pisaric et al., 2001
	between 11 and 10 ^{14}C kyr BP yr BP	Decrease in shrub birch and increases in grass and herbaceous plants	cooling	
	Between 8.5 and 3.5 ^{14}C kyr BP	Spread of forests in the region		
	After 3.5 ^{14}C kyr BP	Establishment of modern vegetation		
3. Lake Chabada; 61°59′ N, 129°22′ E; 290 m a.s.l.	ca. 13.4 kyr BP	Quick afforestation	warming	Tarasov et al., 2007
	between 13 and 12 kyr BP	Low woody cover	cooling	
	After 12 kyr BP	Expansion of birch and larch dominated forests		
	After 7 kyr BP	Spread of *Pinus sylvestris*		
4. Smorodinovoye Lake; 64°46′ N, 141°06′ E; 798 m a.s.l.	Until 10.8 ^{14}C kyr BP	Glacial tundra		Anderson et al., 2002
	Ca. 10.8–10.2 ^{14}C kyr BP	transitional shrub tundra	Mean July temperatures between 10 and 12°C	
	Ca. 10.2–9.9 ^{14}C kyr BP	Herb dominated tundra	Summer temperatures <10°C	
	Ca. 9.6 ^{14}C kyr BP	Arrival of larch in the lake area		
	Ca. 6.1 ^{14}C kyr BP until today	Development of modern forests		
	Between 6 and 4 ^{14}C kyr BP		Occurence of maximum post-glacial summer temperatures	
5. Bol'shoy Lyakhovsky Island; 73°20′ N, 141°30′ E; <35 m a.s.l.	11.6–11.3 ^{14}C kyr BP	grass-sedge dominated vegetation	Summer temperatures were 4°C higher than today	Andreev et al., 2009
	ca. 11–10 ^{14}C kyr BP	Grass-sedge, few shrubs, low pollen concentration	Climate deterioration	
	between 9 and 7.5 ^{14}C kyr BP kyr BP	Predominance of shrub alder and dwarf birch tundra		
	after 7.6 ^{14}C kyr BP	Establishment of modern tundra environments	Slightly warmer than today	

precipitation and severe winter conditions (Kaplan, 2001). The model also suggests that in such environments, snow thickness of less than 15 cm during the winter would result in disappearance of perennial shrubs from the tundra vegetation.

During the second half of the Late Glacial (13.4–11.3 kyr) both pollen assemblages composition and the dominant biome scores (Fig. 4b) suggest a distinct two-step change in the vegetation and environment of the study area, which roughly corresponds to the Bølling-Allerød Interstadial and the Younger Dryas Stadial. PAZ VII (427–387 cm, 13.4–11.3 kyr BP) is characterised by a noticeable increase in pollen concentrations from 13 500 to 72 700 grains/g. Recorded increases in *Betula* sect. *Nanae* (26–52%) and *Duschekia fruticosa* (up to 29% at 114 cm) pollen percentages indicate that birch- and alder-dominated shrub tundra communities started to play a greater role in the study area between 13.4 and 12.5 kyr BP. A great reduction of the drought tolerant vegetation communities is also suggested by a significantly lower content of the rock spike moss spores (3–10%).

4.1.1 Bølling-Allerød Interstadial

Biome reconstruction shows a pronounced decrease in steppe biome scores and highest scores for the tundra biome, suggesting replacement of the former tundra-steppe vegetation by the herb and shrub tundra communities. Such change in the vegetation would imply a quick shift to wetter environments caused by increased precipitation and/or melting of permafrost due to summer warming and decreasing winter temperature during the Bølling-Allerød Interstadial (Grichuk, 1984). A dramatic increase in shrub birch and willow pollen associated with a significant decrease in herbaceous pollen taxa occurs in the pollen record from Levinson-Lessing Lake after 13.7 kyr BP (Andreev and Tarasov, 2007), and establishment of shrub birch tundra between 14.5 and 13 kyr BP is reconstructed from the Dolgoe Lake pollen record (Pisaric et al., 2001) in response to the climate amelioration during the Allerød interval. Reviewing climate changes in East Europe and Siberia at the Late Glacial–Holocene transition, Velichko et al. (2002) provided a quantitative reconstruction of the Allerød climate anomalies at two sites from central Yakutia. The pollen-based reconstructions suggest that mean January temperatures were 1.5–3°C, mean July temperature were 1°C and annual precipitation was 25–60 mm below the present-day values.

4.1.2 Younger Dryas Stadial

After 12.5 kyr BP both the pollen spectra composition and the steppe biome score demonstrate a short-term strengthening of the herbaceous vegetation communities compared to the shrub tundra vegetation, suggesting a decrease in available moisture and possibly a decrease in winter temperatures. This episode of climate deterioration deduced from the Lake Billyakh record is dated to 12.4–11.3 kyr BP, thus falling well within the age limits of the Younger Dryas Stadial known for its generally colder and dryer climate, particularly in the North Atlantic sector. Velichko et al. (2002) also reconstructed severe climate deterioration in Siberia, particularly during the winter time. Consistent with earlier climate reconstructions in this region, our record suggests that the Younger Dryas climate around Lake Billyakh was not as cold and dry as during the 15–13.5 kyr BP interval. The presence of *Larix* in the pollen record and likely in the vegetation cover, as well as relatively high contents of birch and alder shrub pollen and high tundra biome scores, reflects moisture availability. Summer temperatures were high enough to sustain the survival of boreal trees and shrubs.

4.2 Early Holocene

After 11.3 kyr BP the pollen record suggests a shift to shrub tundra dominated environments and milder climate conditions than during the Late Glacial. PAZ VI (386–347 cm, 11.2–9.3 kyr BP) includes the highest pollen concentration (up to 211 900 grains/g) and PAZ V (346–303 cm, 9.2–7.4 kyr BP) is characterised by a relatively high pollen concentration (up to 97 500 grains/g). Shrub taxa absolutely dominate in the pollen spectra (up to 95%), and steppe biome scores reach minimum values through the whole record. These changes inferred from the PG1756 record indicate the onset of the Holocene Interglacial, in line with other records from the region (Fradkina et al., 2005; Pisaric et al., 2001; Andreev and Tarasov, 2007). However, the Lake Chabada (61°59′ N; 129°22′ E, 290 m a.s.l.) pollen record from central Yakutia demonstrates a locally quick spread of boreal forest soon after 12 kyr BP (Tarasov et al., 2007). Location of the lake on the ancient erosion-accumulative plain of the Lena River, which provides locally favourable conditions for arboreal vegetation, may explain this difference in low scores of the forest biome in the Lake Billyakh record during the Early Holocene. The already mentioned under-representation of larch – the dominant taxon in the regional cold deciduous forest – in the pollen records from larger lakes is another possible explanation. The fact that more or less constant amounts of *Larix* pollen (0.5–4%) occur throughout the whole record provides support for such interpretation.

The Early Holocene (11–8 kyr BP) thermal maximum in the Arctic is explained by a combined effect of higher-than-present Northern Hemisphere summer insolation and much lower-than-present sea level (Lozhkin and Anderson, 2006). The substantial warming at the Late Glacial-Holocene transition is recorded in various arctic regions of the Northern Hemisphere (e.g. MacDonald et al., 2000a; Andreev et al., 2004; Kaufman et al., 2004; Kaplan and Wolfe, 2006), including Smorodinovoye Lake (64°46′ N; 141°06′ E; 798 m a.s.l.) east of the Verkhoyansk Mountains (Anderson et al., 2002) as well as at sites from central Yakutia west of the Verkhoyansk Range (Velichko et al., 1997). However, the latter study suggests that both January and July temperatures and annual precipitation were lower than today by 1°C, 0.5°C and 25 mm/yr, respectively. Summer temperatures at least 4°C warmer than present are reconstructed at the Bol'shoy Lyakhovsky Island (Andreev et al., 2009) in the East Siberian Sea, suggesting that warming was more pronounced in northern Yakutia than in central and southern Yakutia. This corroborates the inference of an initial spread of boreal forest across northern Asia after 11.5 kyr BP, the advance towards the current Arctic coastline between 10 and 8 kyr BP, and its retreat to its present position after 4.5 kyr BP (MacDonald et al., 2000a).

4.3 Middle Holocene

The pollen spectra of PAZ IV (302–242 cm, 7.3–5 kyr BP) and PAZ III (241–129 cm, 5–1.8 kyr BP) are characterised by relatively high (80 200–104 100 grains/g) and moderately high (40 200–87 000 grains/g) pollen concentrations and closely resemble modern surface pollen spectra from the study area, suggesting that vegetation around Lake Billyakh became similar to modern vegetation already in the Middle

Holocene after 7 kyr BP. Biome reconstruction demonstrates an increase in the forest biome scores, suggesting that cold deciduous and taiga forests strengthened their positions in the region. Our pollen record shows a fourfold increase in *Pinus* subgen. *Diploxylon* percentages (12–34%), reflecting the spread of *Pinus sylvestris* in the region after 7 kyr BP. This feature is in good agreement with other study results carried out in northeastern Siberia (Andreev et al., 1997, 2002; MacDonald et al., 2000a; Pisaric et al., 2001; Andreev and Tarasov, 2007). MacDonald et al. (2000b) pointed out that lower-than-present winter insolation and associated cold and dry winter conditions might have caused desiccation and root damage of *Pinus sylvestris*, restricting its earlier spread in northern Eurasia. In turn, warmer-than-present mid-Holocene summers in conjunction with an orbitally-induced increase in winter insolation and sea-level rise caused further degradation of permafrost and promoted the spread of Scots pine and in a broader regional context, spruce and Siberian pine taiga forest (Andreev and Tarasov, 2007). The appearance of wind transported *Abies* in PAZ IV and III of our record is consistent with the mid-Holocene amelioration of the regional climate, since fir is one of the most sensitive Siberian trees to winter temperature and moisture availability (Tarasov et al., 2007). The Smorodinovoye Lake pollen record (Anderson et al., 2002) indicates that mid-Holocene climatic changes in the upper Indigirka basin resemble those in the Lake Billyakh area. Both records suggest that maximum postglacial warming occurred after 7 kyr BP, thus a few thousand years later than in the northern and northeastern records of the arctic region. Actually, this timing of maximum warming is more consistent with postglacial climate development in central and northern Europe (e.g. Davis et al., 2003), suggesting strong climate teleconnections to Europe via the westerly wind system.

4.4 Late Holocene

The Late Holocene pollen spectra from Lake Billyakh are characterised by a decrease in pollen concentrations to 22 300 grains/g in PAZ II (128–50 cm, 1.8–0.5 kyr BP) and to 15 300 grains/g in PAZ I (49–0 cm, 0.5–0 kyr BP). The spectra show a progressive increase in the amount of herbaceous (11–29%) pollen during the last 2 kyr. This trend is accompanied by a distinct minimum in the *Pinus* subgen. *Diploxylon* (11%) pollen percentages about two to three hundred years ago. The later change might be associated with intensified human activities (e.g. the migration and spread of semi-nomadic Yakuts into the Middle Lena region since early medieval time) and/or with climate deterioration during the "Neoglacial" and particularly during the Little Ice Age. Popp et al. (2006) inferred a cold signal from stable-isotope composition of ground ice younger than 1 kyr BP in the Verkhoyansk Mountains Foreland. However, the question of human-environmental interactions in the region during the past millennia needs further investigation.

5 Conclusions

In the recent study we present first detailed and well dated pollen record from the Verkhoyansk Mountains, the coldest region of Eurasia and Northern Hemisphere. The pollen record is then interpreted in terms of Late Glacial and Holocene vegetation and climate dynamics. Our reconstruction demonstrates substantial changes in the regional vegetation during the past 15 kyr. Major changes in the pollen assemblages and vegetation can be associated with well recognised large-scale palaeoclimatic events, the Allerød warming and Younger Dryas cooling, the onset of the Holocene and Middle Holocene thermal optimum.

The most severe cold and dry conditions are documented in the oldest part of our record, between 15–13.5 kyr BP when the landscape was mainly covered by mosaic herbaceous (tundra and steppe) and rock spike moss vegetation. During 13.4–12.5 kyr BP the region experienced climate amelioration and spread of shrub tundra communities associated with the Bølling-Allerød Interstadial, followed (12.4–11.3 kyr BP) by a return to the relatively cold-dry conditions associated with the Younger Dryas Stadial. The Younger Dryas climate, however, was less severe than conditions before 13.5 kyr BP, as suggested by higher percentages of tree and shrub pollen. Climate amelioration associated with the onset of the Holocene is dated to 11.2 kyr BP. Subsequently, steppe elements played a minor role in the vegetation cover, shrub tundra communities became dominant and boreal woods started to play a greater role in the vegetation cover. Both species richness and spatial extent of the forests reached their maximum between 7 and 2 kyr BP.

Another important aspect of the Lake Billyakh pollen record is that it demonstrates the uninterrupted growth of larch in the study area during the past 15 kyr, as indicated by the persistence of *Larix* pollen in the whole record. This conclusion confirms an earlier hypothesis of Grichuk (1984), who postulated the existence of many scattered refugia where boreal shrubs and trees could survive periods of harsh glacial climate and quickly spread with the onset of warmer conditions. We suggest that small populations of larch in the Verkhoyansk foreland and in the nearby Lena River valley had locally sufficient water supplies and high enough summer temperatures for growth and reproduction during the Late Glacial. To verify the presence of larch around Lake Billyakh during the LGM we intend to perform a detailed pollen analysis of the 9 m long PG1755 sediment core, which covers the time interval since 50 kyr BP until today.

Appendix A

Results of the pollen analysis of the PG1756 core from Lake Billyakh (65.27° N, 126.75° E; 340 m a.s.l.). Absolute count values are provided for each identified taxon at each analysed level. Sample ages (cal. yr BP) are calculated using age-depth model discussed in the text. All raised palynological data are available in the PANGAEA data information system (see doi:10.1594/PANGAEA.708170).

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3.3 Manuscript III

Late Quaternary vegetation and environments in the Verkhoyansk Mountains region (NE Asia) reconstructed from modern and fossil pollen data

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Abstract

Detailed radiocarbon-dated pollen records from Lake Billyakh (65°17′N, 126°47′E; 340 m a.s.l.) situated in the western foreland of the Verkhoyansk Mountains, where the *Larix*-dominated cold deciduous forest is the most widely distributed modern vegetation type. A set of 53 surface pollen samples from the larger region representing tundra, cold-deciduous forest and taiga vegetation is used to verify the quantitative approach of the biome reconstruction and attribution of pollen taxa to the regional biomes. The adjusted method is then applied to the fossil pollen records from Lake Billyakh to gain an objective reconstruction of the regional vegetation and environments since about 50 kyr BP (calibrated radiocarbon ages before present are consistently used throughout this paper). Pollen analysis of the 936 cm long PG1755 core and PG1756 core from Lake Billyakh and pollen-based biome reconstruction suggest that herbaceous tundra and steppe communities dominated the area from 50.7 to 13.5 kyr BP. Low pollen concentrations and high percentages of herbaceous pollen, suggesting scarce vegetation cover and dominance of steppe-like plant communities during the last glacial maximum (LGM) representing driest and coldest interval of the entire record. A major spread of shrub tundra communities is reconstructed about 13.4–12.5 kyr BP, indicating improved moisture conditions, particularly during the Bølling-Allerød (B-A) interstadial. Between 12.4 and 11.3 kyr BP pollen percentages of herbaceous taxa rapidly increased, suggesting strengthening of the steppe communities in response to the relatively colder and drier than present climate of the Younger Dryas (YD). The onset of the Holocene interglacial is marked in the pollen record by the highest values of shrub taxa, suggesting warmer and wetter conditions. Pollen percentages of arboreal taxa increase gradually and reach maximum values after 7 kyr BP, reflecting the spread of boreal forests in the region as a response to the mid-Holocene climatic optimum. The pollen records in hands indicate absence of the continuous forest cover in the study area during the late Pleistocene (MIS 3 and 2). However, almost constant presence of *Larix* pollen in PG1755 and PG1756 cores from Lake Billyakh and the radiocarbon-dated cones and needles in the nearby YD peat sediment suggest that larch could survive the last glacial (ca. 50.7-11.6 kyr BP) in locally favourable environments. Noticeable variations in larch pollen abundances and reconstructed biome scores point to the multiple short-term warming episodes synchronous to the Dansgaard-Oeschger events found in the North Atlantic records.

1. Introduction

The studies on modern plant and animal communities in the Russian Arctic present vivid examples of the ecosystem dynamics under the globally and regionally increasing temperatures (Chernov and Matveyeva, 1997). Pollen and plant macrofossil records stored in the late Quaternary peat and lake sediments from the Russian Arctic prove to be valuable palaeoenvironmental archives, which greatly extend our knowledge on the ecosystem development under extreme climatic conditions; serve for a better understanding of the climate system, carbon cycle and genetic diversity and can inform current predictions and conservation strategies (e.g. Prentice et al., 1992; Tarasov et al., 2007; Petit et al., 2008). The accurate reconstruction of the regional vegetation, particularly, of the tree-line position during the last glacial interval is highly significant to decipher past climate (e.g. Kremenetski et al., 1998; MacDonald et al., 2000a) and to validate climate models (e.g. Texier et al., 1997).

The extent of *Larix* in Russia is farther to the north than that of other coniferous trees because of its resistance to extremely low winter temperatures due to its deciduous status. Pollen and plant macrofossil records from high-latitude regions of Europe and North America indicate that boreal forests "became established during the Holocene interglacial (past 11.6 kyr) as a result of population invasion from southern glacial refugia and local expansion of small tree populations that survived the last glacial maximum (LGM; ~21 kyr ago) in cryptic refugia" (e.g. Petit et al., 2008). An extensive dataset of radiocarbon-dated macrofossils from northern Asia provides evidence that boreal trees advanced close to the current arctic coastline between 9 and 7 kyr ago (MacDonald et al., 2000a). Lacking wood macrofossils older than 10 kyr from the ~2000×2500 km region of eastern Siberia between 108° and 145°E, there is no agreement on whether trees could persist there during the coldest phases of the last glacial period (Johnsen et al., 2001), including the Younger Dryas (Werner et al., submitted) and the LGM (Grichuk, 1984; Frenzel et al., 1992; Tarasov et al., 2000, 2007; Edwards et al., 2000; Andreev et al., 2002). LGM vegetation maps compiled by Grichuk (Grichuk, 1984; Frenzel et al., 1992) show boreal conifer and deciduous trees in southern and central Siberia between 55 and 65°N, suggesting many scattered refugia from which tree vegetation could quickly spread as climate ameliorated.

Under the framework of the International Polar Year research project 106 "Lake Records of Late Quaternary Climate Variability in northeastern Siberia" and the German Research Foundation project "Late Quaternary environmental history of interstadial and interglacial periods in the Arctic reconstructed from bioindicators in permafrost sequences in NE Siberia" we attempt to generate high-resolution vegetation and climate proxy records from the lacustrine sediments along a north-south transect from Yakutia (Sakha) Republic of Russia. This region of Eurasia is known for its climate extremes, with the Verkhoyansk Mountain Range being the coldest area in the Northern Hemisphere (Shahgedanova et al., 2002). Here the absolute temperature range is about 100°C, with maximum summer temperature rising up to 30°C and minimum winter temperature falling to -70°C (Walter and Breckle, 1999).

The pollen analysis of the Lake Billyakh record from the sediment core PG1756 for the first time suggested the uninterrupted growth of larch in the study area during the past 15 kyr (Müller et al., 2009). To verify the presence of larch around Lake Billyakh during the last glacial including the LGM interval we performed a detailed pollen analysis of the 936 cm long PG1755 sediment core, which covers the time interval since 50.6 kyr BP until today. In the current study we present (i) radiocarbon-dated pollen record from the PG1755 core and (ii) the recently compiled data set of 53 surface pollen samples from the region. The latter data set is used to (iii) verify biome reconstruction method in order to make it more sensitive to the reconstruction of regional vegetation from the PG1755 and PG1756 pollen records from Lake Billyakh (iv). Results of the pollen-based vegetation reconstruction are then used to (v) discuss the late Quaternary vegetation and environmental dynamics in a more regional and extra-regional context.

2. Study sites and regional setting

2.1 Site locations

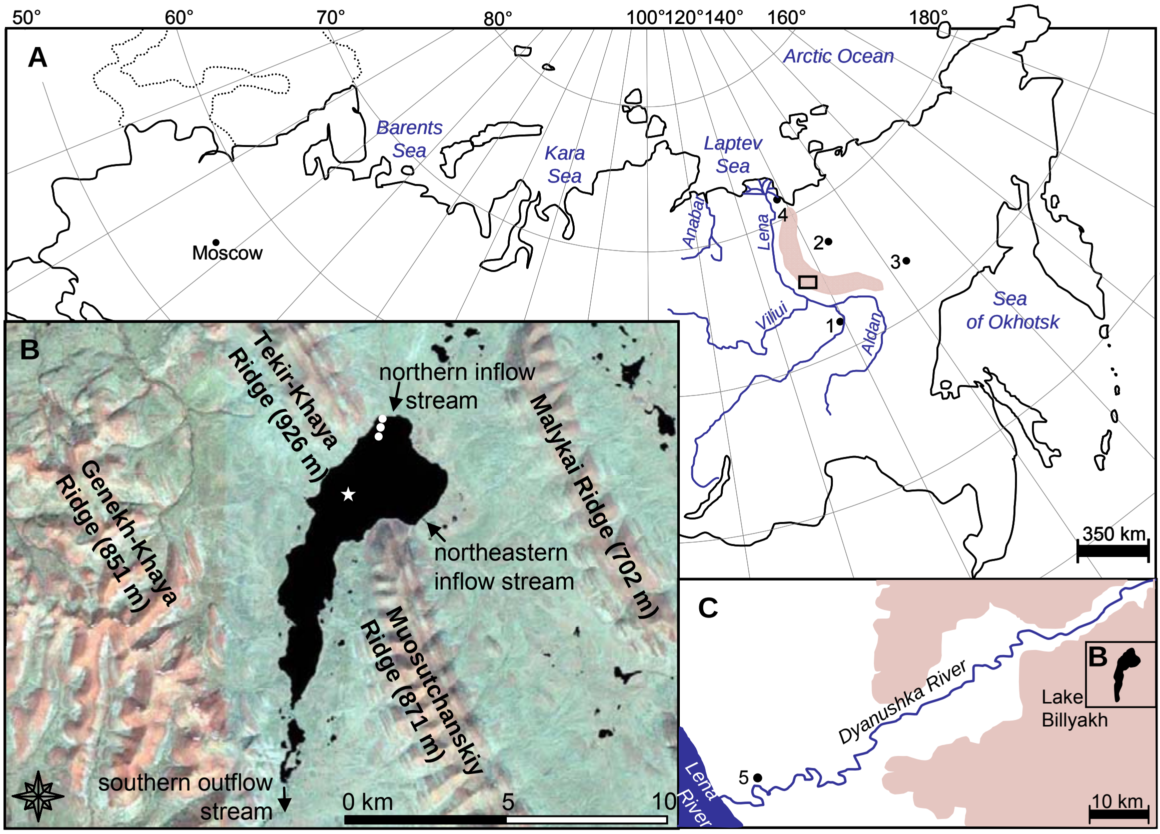


Fig. 1. (A) Map of Russia, location of cities with meteorological stations in the study region are indicated by numbers: 1 – Yakutsk, 2 – Verkhoyansk, 3 – Oimyakon, 4 – Tiksi; shaded area represents the Verkhoyansk Mountain Range; (B) Simplified map of the Lake Billyakh (65°27′N, 126°47′E; 340 m a.s.l.) study area showing the location of the 4 cores taken during the field campaign in spring 2005, core PG 1755 is marked by a star; (C)Map showing the location of the nearby peat profile K7/P2 (5) on the Dyanushka River shore.

Lake Billyakh (65°17′ N, 126°47′ E; altitude 340 m) is situated in the middle part of the western foreland of the Verkhoyansk Mountains (Fig. 1A), occupying a longitudinal depression between the Tekir-Khaya Ridge and the Muosutchanskiy Ridge (Fig. 1B). The lake extends for about 11 km from north to south and for about 3 km from west to east. It has an average water depth of 8 m and a maximum depth of about 25 m (Müller et al., 2009). The lake is fed by direct precipitation and by several small creeks and streams flowing from the surrounding mountain slopes (Fig. 1B). An outflow stream flows from the southern part of the lake towards the Lena River. Fig. 1C illustrates the position of the Dyanushka peat profile (K7/P2; 65°02'N, 125°02'E, 123 m a.s.l.). The profile is located on the right bank of the Dyanushka River, which originates in the Verkhoyansk Mountains and is a right tributary of the Lena River (Werner et al., submitted).

2.2 Modern climate and vegetation

Modern climate of the study area (Fig. 2A, Table 1) is extremely continental with a mean temperature of −40°C in January and 15-19°C in July and annual precipitation of 300-400 mm (e.g. Gerasimov, 1964; Alpat'ev et al., 1976). Very cold and long winters together with short summers cause the large thickness of continuously frozen ground reaching 400–900m (Gavrilova, 1993). During the summer months melting within the 40–90-cm thick active layer provides considerable amounts of plant-available water in addition to the moderately low atmospheric precipitation (Chernov and Matveyeva, 1997).

Table 1. Mean max and min temperatures (°C) for the warmest month of the year (July) and the coldest month of the year (January) in Tiksi, Oimyakon, Verkhoyansk and Yakutsk (after Rivaz- Martínez, 1996-2004).

Meteorological station	Distance from Lake Billyakh, km	July T_{min}	July T_{max}	January T_{min}	January T_{max}
Oimyakon	830	5.1	21.8	-51.2	-41.9
Tiksi	715	4.4	11.1	-34.4	-29.4
Verkhoyansk	390	7.2	20.6	-50.6	-46.7
Yakutsk	370	11.7	24.4	-43.9	-39.4

Cold deciduous forests with larch (*Larix dahurica = L. gmelinii + L. cajanderi*) are dominating and abundant shrubs are growing in the understorey occupying lower elevations; while tundra vegetation occurs above 450 m. Together with larch, Scots pine (*Pinus sylvestris*), birch trees (*Betula platyphylla*) and shrubs (*B. middendorfii*, *B.*

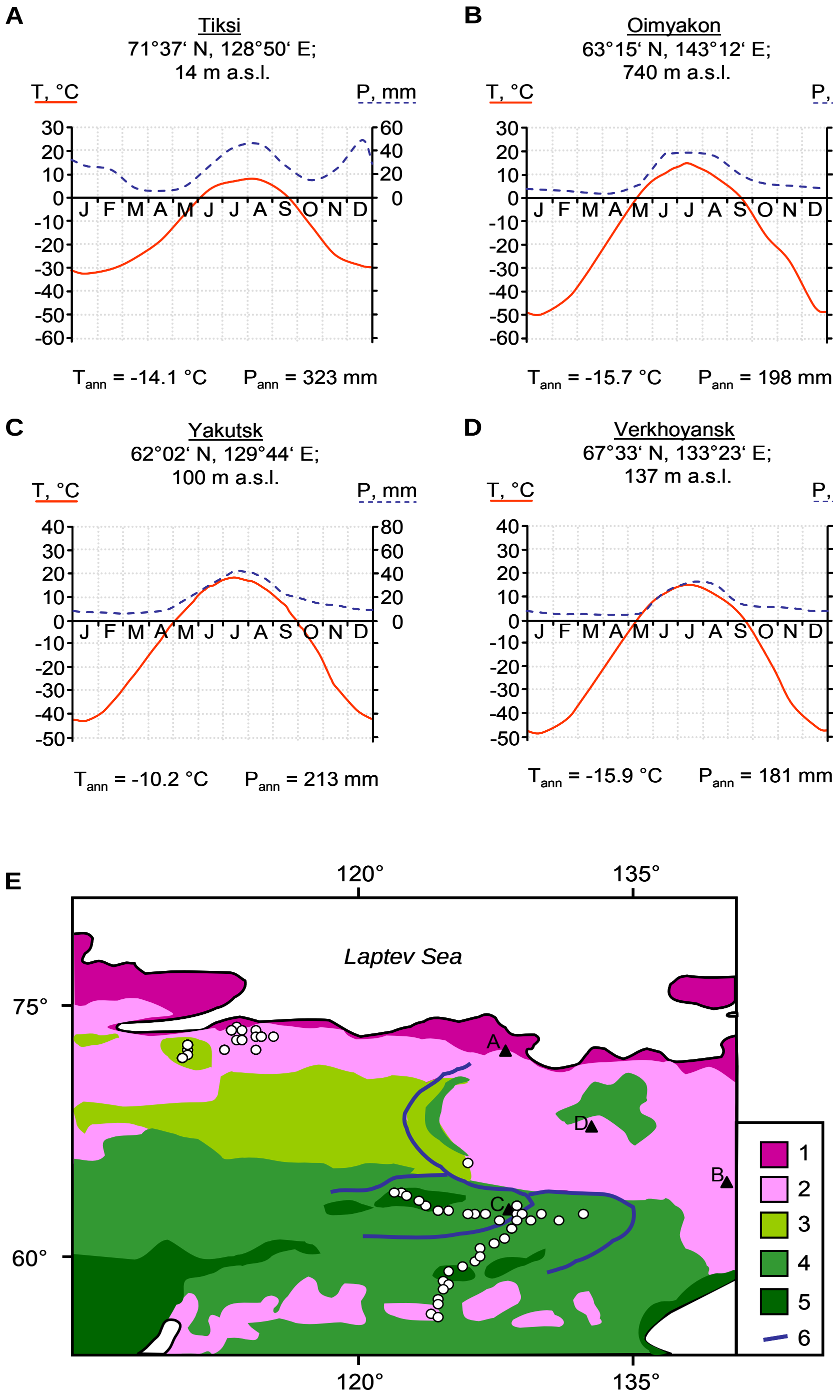


Fig. 2. (A-D) Climate diagram of four stations in the study region showing mean monthly temperature and precipitation (Rivas-Martínez, 1996-2004; World Meteorological Observation (WMO), http://www.worldweather.org/107/c01040.htm); (E) Map showing the modern vegetation distribution and the location of sites with modern pollen data (circles); 1 – Arctic steppe and arctic tundra (heath, moss, low shrubs, lichens), 2 – Typical tundra (moss, lichens, low shrubs, shrubs), 3 – Forest tundra (*Larix dahurica*), 4 – Larch forests (*L. dahurica*), 5 – Pine (*Pinus sylvestris*) and larch-pine forest, blue line – azonal riparian vegetation (according to Gerasimov, 1964).

fruticosa, *Duschekia fruticosa = Alnus fruticosa*) are well represented in the vegetation cover. In riparian areas spruce (*Picea obovata*) and alder trees (*Alnus hirsuta*) are growing with locally moister and warmer microclimatic conditions (Alpat'ev et al., 1976). In the understorey, heath (Ericales) species are very abundant, including *Vaccinium vitis-idaea*, *V. uliginosum*, *Arctous alpina*, *Ledum palustre*, *Cassiope* sp., *Empetrum nigrum* together with members of Rosaceae family (*Sanguisorba officinalis*, *Rosa* sp., *Spiraea* sp.), grasses (Poaceae) and sedges (Cyperaceae) (Walter, 1974). Common mosses are *Polytrichum* sp., *Dicranum* sp., *Sphagnum* sp. and lichens *Cladonia* sp., *Cetraria* sp. (Walter, 1974). Above approximately 450 m a.s.l., the woodland is replaced by arctic-alpine tundra and dwarf shrub tundra communities with *Pinus pumila*, *Betula nana*, *Empetrum* sp., *Vaccinium vitis-idaea*, *V. uliginosum* and *Ledum* sp. Figure 2B illustrates the modern vegetation distribution based on the vegetation map of the USSR (Gerasimov, 1964).

3. Material and methods

3.1 Fossil pollen samples

The core material stored at AWI (Potsdam) was sampled there for pollen analysis. In total 107 one-cm-thick slices were taken with 5 to 10-cm step. Further treatment of the samples, including pollen extraction and microscopic analysis were performed at FU (Berlin). Pollen was extracted from the samples consisting of 1.5 g sediment according to standard procedures, including 7-μm ultrasonic fine-sieving, HF treatment and acetolysis (Fægri et al., 1989; Cwynar et al., 1979). One tablet of *Lycopodium* marker spores was added to each sample for calculating total pollen and spore concentrations (Stockmarr, 1971). Water-free glycerol was used for sample storage and preparation of the microscopic slides. Pollen and spores were identified at magnifications of 400× and 1000×, with the aid of published pollen keys and atlases

(Kupriyanova et al., 1972, 1978; Bobrov et al., 1983; Reille, 1992, 1995, 1998; Beug, 2004) and a modern pollen reference collection at FU Berlin.

Preservation of extracted pollen and spores was generally good and corroded grains were rarely found. Bisaccate pollen grains of *Pinus* and *Picea* were frequently broken, but easily identifiable. The pollen and spore content of the samples was relatively high to allow counting of a minimum of 300 terrestrial pollen grains per sample. In total, 94 pollen and spore taxa were identified in the 80 samples from PG1755 core. In this study pollen of *Pinus* was separated into two morphological types. In the study area these two pollen types are produced by *P. sylvestris* (*Diploxylon* type) and *P. pumila* and *P. sibirica* (*Haploxylon* type), respectively. *Betula* pollen was also divided into two morphological types: *B.* sect. *Nanae* + *Fruticosae* (shrub birches) and *B.* sect. *Albae* (tree birches). The contribution of re-deposited pollen and spores was rather low, suggesting non-disturbed pollen assemblages.

Calculated pollen percentages refer to the total sum of terrestrial pollen, which does not include pollen of aquatic plants, spores of pteridophytes and mosses, algae and redeposited pollen and spore grains. For these taxa, percentages were calculated using the total terrestrial pollen sum plus the sum of palynomorphs in the respective group. The Tilia/Tilia-Graph/TGView software (Grimm, 1993, 2004) was used for calculating pollen percentages and for drawing the pollen percentage diagram. The local pollen assemblage zones in the diagram were divided using CONISS (Grimm, 2004) and numbered from the top to the bottom of the core to allow comparison with the Holocene pollen sequences from core PG1756.

3.2 Surface pollen samples

In total, 53 surface pollen spectra were collected from different regions in Yakutia between 56-73°N and 111-133°E at the elevations from 2 to 1 188 m a.s.l. (Table 2). The samples were taken from different plant communities representing all regional vegetation zones (Gerasimov, 1964), including arctic tundra, typical tundra, forest tundra, larch forest, larch-pine forest along the north-south transect (Fig. 2B). Among the analysed surface samples, 52 samples are moss pollsters and one is the top sample from the PG1756 core from Lake Billyakh (Table 2). The latter one was treated as the fossil samples described above, while the moss surface samples were treated differently, e.g. 5 g of moss material was stored over night in a beaker filled with distilled water; sieving (400 µm) and chemical treatment with KOH and acetolysis followed.

Table 2. Location of surface sampling sites and observed vegetation type. Samples number 1-52 are moss polsters, sample number 53 is the uppermost sample from lake sediment core PG1756 from Lake Billyakh (Müller et al., 2009).

Sample number	Sample name	Latitude, °N	Longitude, °E	Elevation, m	Vegetation zone (after Gerasimov, 1964)
1	07-SAS-01	72.478	114.077	20	Typical tundra
2	07-SAS-02	72.600	113.856	6	Typical tundra
3	07-SAS-03	73.254	114.293	7	Arctic tundra
4	07-SAS-04	72.953	114.950	5	Typical tundra
5	07-SAS-05	72.885	115.755	17	Typical tundra
6	07-SAS-06	72.964	115.345	17	Typical tundra
7	07-SAS-07	72.077	114.914	2	Typical tundra
8	07-SAS-08	73.128	114.869	3	Arctic tundra
9	07-SAS-09	73.214	113.614	4	Arctic tundra
10	07-SAS-10	73.381	113.934	5	Arctic tundra
11	07-SAS-11	72.320	111.189	86	Typical tundra
12	07-SAS-12	72.070	111.105	61	Typical tundra
13	07-SAS-13	72.074	111.113	37	Forest tundra
14	07-SAS-14	71.747	111.132	52	Forest tundra
15	07-SAS-15	71.503	110.819	84	Forest tundra
16	07-SAS-LY	72.068	113.092	184	Forest tundra
17	07-NA-01	62.206	129.486	212	Larch forest
18	07-NA-02	62.171	129.514	155	Larch forest
19	07-NA-03	62.857	129.368	198	Larch forest
20	07-NA-04	62.856	129.468	190	Larch forest
21	07-NE-01	61.305	128.927	107	Larch forest
22	07-NE-02	60.877	128.716	418	Larch forest
23	07-NE-03	60.565	128.054	476	Larch forest
24	07-NE-04	60.224	127.355	574	Larch forest
25	07-NE-05	59.783	127.210	416	Larch forest
26	07-NE-06	59.381	126.992	414	Larch forest

27	07-NE-07	59.040	126.474	534	Larch forest
28	07-NE-08	58.862	125.70	451	Larch forest
29	07-NE-09	58.449	125.418	919	Larch forest
30	07-NE-10	58.028	125.491	924	Larch forest
31	07-NE-11	57.633	125.175	1188	Larch forest
32	07-NE-12	57.258	124.896	1010	Larch forest
33	07-NE-13	56.880	124.896	750	Larch forest
34	07-NE-14	56.430	124.742	920	Larch forest
35	07-NE-15	55.993	124.902	1053	Larch forest
36	07-NE-16	61.526	129.152	101	Larch forest
37	07-WI-01	62.084	129.192	229	Larch forest
38	07-WI-02	62.055	128.401	260	Larch forest
39	07-WI-03	62.233	127.746	257	Larch forest
40	07-WI-04	62.128	127.030	293	Larch forest
41	07-WI-05	62.378	126.592	270	Larch forest
42	07-WI-06	62.508	125.600	293	Larch forest
43	07-WI-07	62.611	124.904	265	Larch forest
44	07-WI-08	62.869	124.312	234	Larch forest
45	07-WI-09	63.136	123.988	198	Larch forest
46	07-WI-10	63.374	123.466	166	Larch forest
47	07-WI-11	63.610	123.054	158	Larch forest
48	07-WI-12	63.777	122.635	125	Larch forest
49	07-YT-01	62.032	130.003	139	Larch forest
50	07-YT-02	62.158	130.816	155	Larch forest
51	07-YT-03	62.087	131.604	260	Larch forest
52	07-YT-04	62.148	133.134	157	Larch forest
53	PG1756-1, 0-1	65.280	126.770	340	Forest tundra

3.3 Sediment characteristics and radiocarbon dating

In spring 2005, the 936 cm long sediment core (PG1755) was recovered from 7.8 m water depth in the central part of Lake Billyakh (Fig. 1B). Coring was carried out using an UWITEC piston corer system. A total of 35 m of sediment were recovered from the four sites. The core lithology of PG1755 is dominated by green-greyish silty clays that are partly laminated. The upper 150 cm part of the core reveals an increased concentration of fine-grained organic gyttja in the siliclastic mud accumulated since about 15 kyr BP. In this study we used the 660-cm long PG1756 core in order to refine the late glacial and Holocene vegetation and environmental history. This core was recovered from a small sub-basin about 800 m off the northern shore, from 7.9 m water depth (see Müller et al., 2009 for further details).

Plant and sediment material from 11 samples from the PG1755 core was AMS-dated in Leibniz Laboratory for Radiometric dating in Kiel and in Poznań Radiocarbon Laboratory. The sample ages span the interval from 10 677±56 to 49 196±2 802 cal yr BP (Table 3) and provide a basis for construction of the last glacial interval chronology. In addition 7 AMS dates from PG1756 core (Table 1) were used to construct age model for the late glacial and Holocene.

Table 3. Radiocarbon dates for the PG1755 and PG1756 core from Lake Billyakh; KIA - Leibniz Laboratory for Radiometric dating and Stable Isotope Research, Kiel; Poz - Poznań Radiocarbon Laboratory; radiocarbon years are converted to calendar years using CalPal online (Danzeglocke et al., 2009).

Lab number	Internal core number	Compo Depth (cm)	Radiocarbon Age (^{14}C yr BP)	Cal. Age (yr BP)	Dated material
Lake Billyakh core PG1755					
KIA29876	PG1755-2, 142	133	9 450±40	10 677±56	Plant material
Poz-26997	PG1755-2, 160	151	18 150±120	21 880±354	Organic bulk
Poz-26998	PG1755-3, 50	197	18 680±120	22 339±354	Organic bulk
Poz-28093	PG1755-3, 67	214	21 490±110	25 603±371	Organic bulk
Poz-24211	PG1755-3, 140	287	22 960±230	27 545±454	Organic bulk
KIA34216	PG1755-4, 140	532	27 220±200	31 894±164	Organic bulk
Poz-24085	PG1755-5, 60	707	30 400±500	34 696±490	Organic bulk
Poz-28094	PG1755-5, 103	750	43 000±900	46 699±1 712	Organic bulk
Poz-28149	PG1755-5, 177	842	52 300±3 100	-	Organic bulk
Poz-28150	PG1755-5, 268	915	47 300±1 700	49 196±2 802	Organic bulk
Lake Billyakh core PG1756					
KIA29879	PG1756-2, 90	90	1 145±40	1 065±62	Plant material
KIA29880	PG1756-3, 30	214	4 400±300	4 998±398	Plant material
KIA34217	PG1756-3, 60	244	7 010±40	7 861±55	Plant material
KIA34218	PG1756-3, 120	304	6 080±70	6 973±116	Plant material
KIA34219	PG1756-3, 160	344	7 460±130	8 256±124	Plant material
KIA34220	PG1756-3, 220	404	10 430±160	12 282±277	Plant material
KIA29881	PG1756-3, 226	410	11 105±60	13 002±119	Plant material

3.4 Biome reconstruction

Pollen-based vegetation reconstruction can be objectively performed using the quantitative method of biome reconstruction first published by Prentice et al. (1996). The approach allows the objective assignment of pollen taxa to plant functional types (PFTs) and to biomes on the basis of the modern ecology, bioclimatic tolerance and geographical distribution of pollen producing plants. The regionally adapted biome reconstruction method was successfully tested using an extensive surface pollen data set from northern Eurasia (Tarasov et al., 1998) and applied to the mid-Holocene and LGM pollen records (Tarasov et al., 1999a, 1999b, 2000). The biome reconstruction results proved to be useful for the objective interpretation of the late Quaternary vegetation and climate dynamics at global, regional and local scales and for data-model comparison (Texier et al., 1997; Prentice et al., 1996; Prentice et al., 2000; Tarasov et al., 2005). Müller et al. (2009) applied the taxa-biome matrix used in the BIOME6000 project (Tarasov et al., 1998, 2000) for the reconstruction of the late glacial and Holocene vegetation around Lake Billyakh. The latter study shows a noticeable increase in the cold deciduous forest biome scores during the Holocene, reflecting spread of the forest vegetation. However, tundra biome scores exceed that of cold deciduous forest. Therefore, according to the biome reconstruction tundra remains the predominant vegetation type throughout the Holocene record in contradiction with the modern dominance of cold deciduous forest/woodland in the region.

In order to address this problem we tested the biome reconstruction method using 53 surface pollen spectra compiled for this study. In addition we made two modifications in the biome-taxon matrix applied in the first study on Lake Billyakh (Müller et al., 2009). The modifications are based on the following considerations concerning birch (*Betula* sect. *Nanae + Fruticosae*) and alder (*Duschekia fruticosa*) shrubs. Both taxa were originally attributed to the arctic and alpine dwarf shrub PFT and consistently used to distinguish tundra biome from the boreal forest and cool steppe biomes (Tarasov et al., 1998). However, the morphology of birch and alder pollen proves to be variable. This makes it difficult to separate shrubby taxa from tree taxa by means of pollen analysis with a high degree of confidence. The problem can be overcome by grouping birch and alder pollen into broader categories, e.g. *Betula* undif. and *Alnus* undif. (e.g. Anderson et al., 2002) and attributing these taxa to tundra and boreal/temperate forest biomes (e.g. Prentice et al., 1996). Assuming that both birch and alder shrubs are typical members of the shrubby tundra, forest-tundra and cold deciduous forest ecosystems in the study region (Shumilova, 1962; Walter, 1964), we attributed them to the tundra and cold deciduous forest biomes. Comparison of the biome reconstruction results obtained with the published and modified schemes obtained for all surface pollen spectra is presented in the result section.

All terrestrial pollen taxa identified in the surface and fossil data sets were used for the construction of the biome-PFT-taxon matrix. Among them only 37 taxa, which exceed the universal threshold of 0.5% suggested by Prentice et al. (1996), influenced the biome reconstruction as shown in Table 4. Square root transformation was applied to the pollen percentage values to increase the importance of the less abundant pollen taxa. Further details of the method, including the equation used to calculate biome scores and discussion of the taxa attribution to the PFTs and to biomes are published elsewhere (e.g. Prentice et al., 1996; Tarasov et al., 1998).

Table 4. Terrestrial pollen taxa identified in the modern surface samples and the core PG1755 from Lake Billyakh and their attribution to the vegetation types/biomes characteristic for northern Asia. Taxa whose percentages in the pollen spectra do not exceed 0.5% (threshold suggested by Prentice et al., 1996) and do not influence results of biome reconstruction are indicated with an asterisk.

Biome	Modern pollen taxa	Fossil pollen taxa
TUND / Tundra	*Duschekia fruticosa*, *Betula* sect. *Nanae*, Cyperaceae, Ericales ind., E. *Empetrum*, E. *Vaccinium*, Gentianaceae*, Papaveraceae, Poaceae, Polygonaceae ind., *Polygonum*	*Duschekia fruticosa*, *Betula* sect. *Nanae*, Cyperaceae, Ericales ind., E. *Empetrum*, E. *Vaccinium*, Gentianaceae, Papaveraceae, Poaceae, *Polemonium**, Polygonaceae ind.,

	bistorta, *P. viviparum*, *Rumex**, Rosaceae *Dryas*, *Salix*, Saxifragaceae, Scrophulariaceae ind., S. *Pedicularis*, *Valeriana*	*Polygonum bistorta*, *P. viviparum*, *Rumex**, Rosaceae *Dryas*, *Salix*, Saxifragaceae, Scrophulariaceae ind., S. *Pedicularis*, *Valeriana*
CLDE / Cold deciduous forest	*Duschekia fruticosa*, *Betula* sect. *Albae*, *Betula* sect. *Nanae* Ericales ind., E. *Empetrum*, E. *Vaccinium*, *Larix*, *Pinus* subgen. *Diploxylon*, *Pinus* subgen. *Haploxylon*, Rosaceae *Rosa canina*, *Salix*	*Duschekia fruticosa*, *Betula* sect. *Albae*, *Betula* sect. *Nanae* Ericales ind., E. *Empetrum*, E. *Vaccinium*, *Juniperus*, *Larix*, *Pinus* subgen. *Diploxylon*, *Pinus* subgen. *Haploxylon*, Rosaceae *Rosa canina*, *Salix*
TAIG / Taiga	*Abies*, *Betula* sect. *Albae*, Ericales ind., E. *Empetrum*, E. *Vaccinium*, *Larix*, *Picea*, *Pinus* subgen. *Diploxylon*, *Pinus* subgen. *Haploxylon*, *Salix*	*Abies*, *Betula* sect. *Albae*, Ericales ind., E. *Empetrum*, E. *Vaccinium*, *Juniperus*, *Larix*, *Picea*, *Pinus* subgen. *Diploxylon*, *Pinus* subgen. *Haploxylon*, *Salix*
COCO / Cool coniferous forest	*Abies*, *Betula* sect. *Albae*, Ericales ind., E. *Empetrum*, E. *Vaccinium*, *Larix*, *Picea*, *Pinus* subgen. *Diploxylon*, *Pinus* subgen. *Haploxylon*, *Salix*	*Abies*, *Betula* sect. *Albae*, Ericales ind., E. *Empetrum*, E. *Vaccinium*, *Juniperus*, *Larix*, *Picea*, *Pinus* subgen. *Diploxylon*, *Pinus* subgen. *Haploxylon*, *Salix*
STEP / Steppe	Apiaceae*, *Artemisia*, Asteraceae subfam. Asterioideae ind., A. subfam. A. *Matricaria*, A. subfam. A. *Saussurea*, A. subfam. A. *Senecio*, A. subfam. Cichorioideae, Brassicaceae, Caryophyllaceae ind., C. *Cerastium*, C. *Stellaria holostea*, Chenopodiaceae, *Epilobium*, Fabaceae, Lamiaceae, Linaceae*, Papaveraceae, *Plantago*, Plumbaginaceae*, Poaceae, Polygonaceae ind., *Polygonum bistorta*, *P. viviparum*, Primulaceae*, Ranunculaceae, R. *Pulsatilla*, R. *Thalictrum*, Rosaceae +operculum, R. -operculum, R. *Potentilla*, R. *Sanguisorba officinalis**, Rubiaceae, *Rumex**, Scrophulariaceae ind., S. *Pedicularis*, *Valeriana**	Apiaceae, *Artemisia*, Asteraceae subfam. Asterioideae ind., A. subfam. A. *Matricaria*, A. subfam. A. *Saussurea*, A. subfam. A. *Senecio*, A. subfam. Cichorioideae, Brassicaceae, Caryophyllaceae ind., C. *Cerastium*, C. *Gypsophila*, C. *Minuartia*, C. *Stellaria holostea*, Chenopodiaceae, *Epilobium*, Fabaceae, Lamiaceae, Liliaceae, Linaceae*, Onagraceae, Papaveraceae, Plantaginaceae, Plumbaginaceae, Poaceae, Polygonaceae ind., *Polygonum bistorta*, *P. viviparum*, Primulaceae, Ranunculaceae, R. *Pulsatilla*, R. *Rumex*, R. *Thalictrum*, Rosaceae +operculum, R. -operculum, R. *Potentilla*, R. *Sanguisorba officinalis*, Rubiaceae, Scrophulariaceae ind., S. *Pedicularis*, *Valeriana*
DESE / Desert	*Artemisia*, Chenopodiaceae, Polygonaceae ind., *Polygonum bistorta*, *P. viviparum*	*Artemisia*, Chenopodiaceae, *Ephedra**, Polygonaceae ind., *Polygonum bistorta*, *P. viviparum*

4. Results

4.1 Age-depth model

Among the 11 radiocarbon dated samples (Table 3), four dates were taken out of the age-depth calculation. Three ages (21 880±354 yr BP, 151 cm depth; 46 699±1 712 yr BP, 750 cm, 25 603±371 yr BP, 214 cm) seemed to be slightly older than suggested by the other dates. Another age (52 300±3 100 ^{14}C yr BP, 842 cm) demonstrates an age rather unreliable because of the limitation of the ^{14}C method. The older ages in younger sediments are maybe related to the scarcity of organic material.

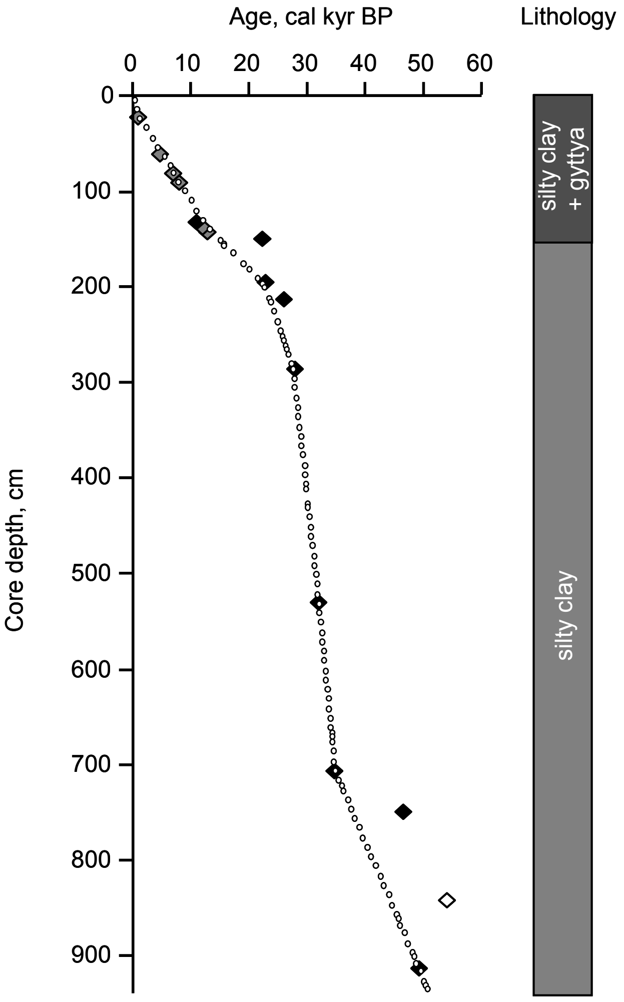
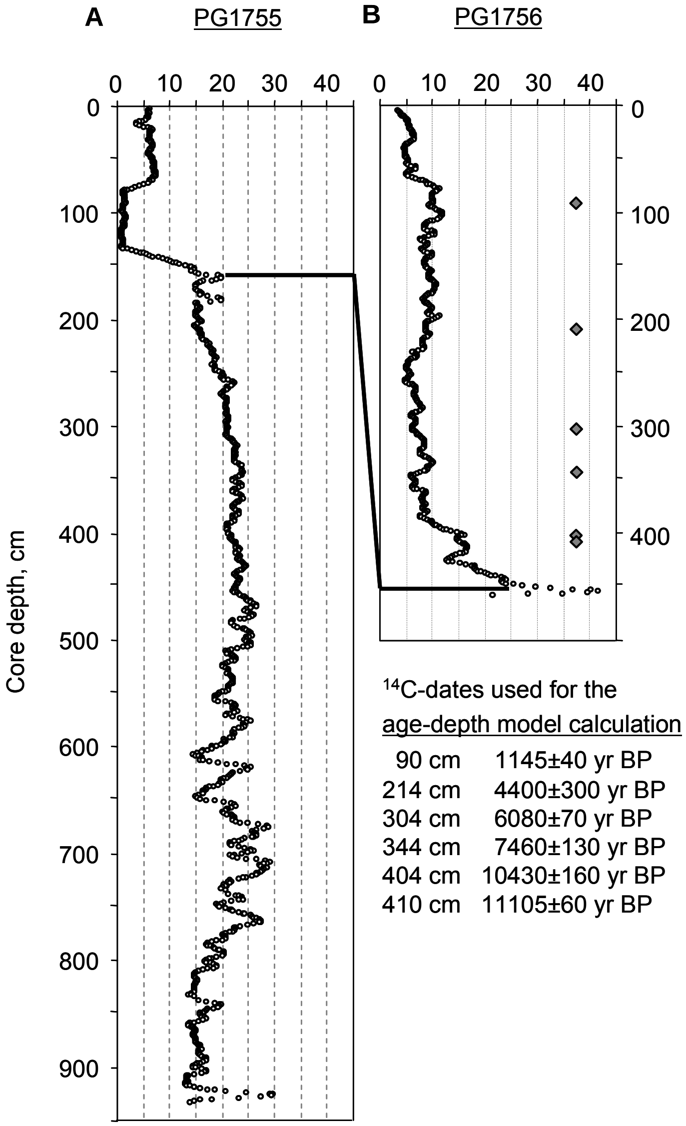


Fig. 3. Age-depth model of the PG1755 core from Lake Billyakh, dots – positions of the samples analysed for pollen, black rhombi – radiocarbon dates, open rhombus – ^{14}C date exceeding the limits of the ^{14}C-dating method (>50 ^{14}C kyr BP), grey rhombi – correlated ages based on the pollen and magnetic susceptibility correlation with core PG1756 (Müller et al., 2009); and lithology characteristics of PG1755.



^{14}C-dates used for the age-depth model calculation

90 cm	1145±40 yr BP
214 cm	4400±300 yr BP
304 cm	6080±70 yr BP
344 cm	7460±130 yr BP
404 cm	10430±160 yr BP
410 cm	11105±60 yr BP

Fig. 4. Magnetic susceptibility curves for sediment core PG1755 (A) and PG1756 (B); the line indicates the correlated depths.

In order to construct an adequate age–depth model for the PG1755 core (Fig. 3) and to verify the reliability of its single date for the early Holocene period we decided to include in the analysis ^{14}C dates obtained from the PG1756 core from Lake Billyakh (Müller et al., 2009). This 6.6 m core was recovered from a small subbasin about 800 m off the northern shore, from 7.9 m water depth (Fig. 1B). The distance between the PG1755 and PG1756 coring sites is approximately 3 km. The near-shore location of the PG1756 site in the subbasin and high organic content of the core sediment allowed obtaining a sequence of seven ^{14}C dates (Table 3). For the preparation of the age-model we (i) calibrated the radiocarbon dates from the cores PG1755 and PG1756, (ii) correlated the magnetic susceptibility curves from core PG1756 and PG1755 (Fig. 4) in order to get reliable ages for the Holocene period of the PG1755 sediment core, and (iii) applied the established age–depth model from PG1756 to the PG1755 pollen record. We also compared PG1755 and PG1756 pollen records for the Holocene period and transferred ages of all coinciding changes in the relative abundances of the terrestrial pollen taxa commonly identified in both records from the PG1756 age model to the PG1755 record. We used the resulting calibrated ages inferred via pollen-based correlation of two records to construct the age–depth model for the PG1755 Holocene record presented in this study (Fig. 3). As a result of this method the early Holocene date from the PG1755 core (Table 3) fitted well into the newly constructed age–depth model, thus strengthening the PG1755 chronology.

4.2 Surface pollen samples

For modern pollen analogues and interpretation of the fossil record from Lake Billyakh, moss polsters are generally used as a suitable medium of pollen deposition from the surrounding vegetation (Hicks and Birks, 1996). A total of 52 modern pollen samples were taken during a field campaign in July-August 2007 (Table 2) spanning north/south and east/west transects in Yakutia. It is assumed that these moss samples are reflecting the pollen input for 1-2 years (Räsänen et al., 2004). In general, the pollen concentration was lower in the moss samples from tundra environments (2 600 grains/5g) than that from forest environments (10 800 grains/5g). The samples were divided into four pollen zones corresponding to 5 different vegetation zones (Fig. 5). Tree pollen percentages are higher from forested regions (up to 93%) than from tundra environments (up to 26%) suggesting rather low contribution of long transported pollen. Pollen zone I contains the samples from the arctic and typical

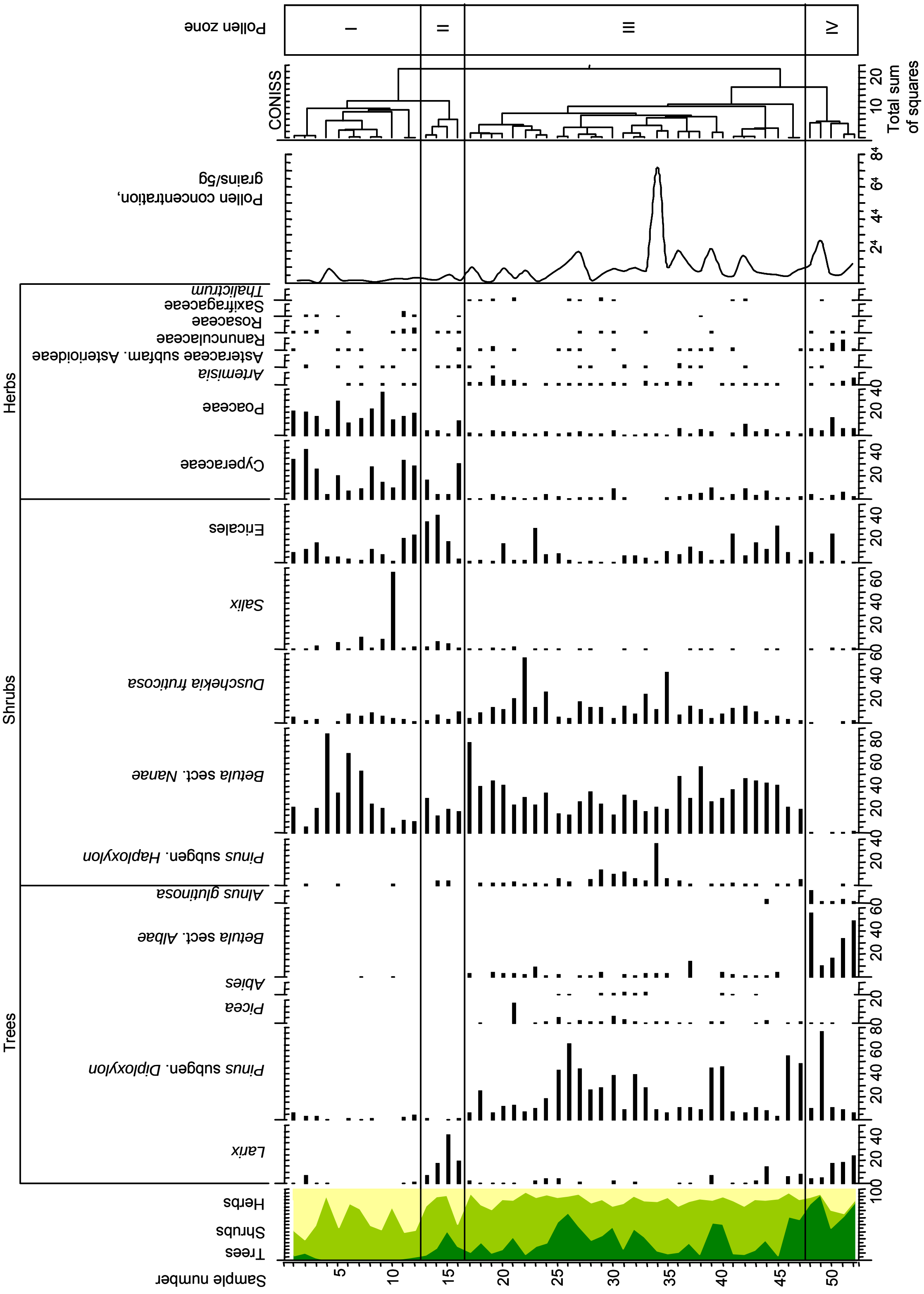


Fig. 5. Simplified pollen percentage diagram of the 52 moss polster samples.

tundra vegetation zone (Gerasimov, 1964), where percentages of shrubs (*Betula* sect. *Nanae*, *Salix*, Ericales) and grasses dominate the pollen spectrum. Pollen zone II corresponds to the forest tundra zone and includes high percentages of larch pollen (up to 42%), while shrubs (73%) and herbs (47%) are still dominating the pollen spectrum. In pollen zone III tree pollen percentages, especially *Pinus* subgen. *Diploxylon*, are high (up to 66%) and percentages of herbs, especially from sedges and grasses, are very low (1-23%). Notable for this zone are the increasing percentages of shrubby alder (up to 55%). Together with pollen zone IV this zone corresponds to the cold deciduous forest dominated by larch (*Larix dahurica*) and pine (*Pinus sylvestris*). In pollen zone IV tree pollen percentages are dominating reaching up to 93% (*Larix*, *Pinus* subgen. *Diploxylon*, *Betula* sect. *Albae*). Shrubs are represented mainly by Ericales (1-24%) and herbs by Poaceae (4-15%), *Artemisia* (0-5%) and Ranunculaceae (1-8%).

The biomization results for the 52 moss polster samples are shown in Fig. 6. The pollen spectra are arranged via the latitude along north-south transects. We compare the following three approaches: (i) according to the adapted version by Tarasov et al. (1998), where pollen of shrubby birch (*Betula* sect. *Nanae*) and alder (*Duschekia fruticosa*) were assigned to the tundra biome (TUND); (ii) no differentiation between shrubby birch/tree birch and shrubby alder/tree alder, respectively, *Betula* undiff. and *Alnus* undiff. were included in the in tundra biome, (iii) shrubby birch and alder were included in the in tundra and cold deciduous forest (CLDE) biomes. The biome reconstruction for samples 1-11 (73.4-72.5°N) shows that tundra biome scores have the highest values in all three approaches. In these samples biome scores of cold deciduous and taiga biomes are low reflecting low percentages of tree pollen taxa. Except for the last sample of this first group, where the scores for cold deciduous biome exceed the others, suggesting already the transition from tundra to forest tundra environments. Cold deciduous forest and tundra biomes are reconstructed for the next four samples (72.1-71.5°N) well reflecting the increasing amounts of larch pollen percentages within these pollen assemblages. The following larch forest vegetation zone (63.8-56°N) is reconstructed best by the third approach. Here cold deciduous forest biomes dominate in almost all samples, except for two tundra and three reconstructed taiga biomes. In the other two approaches tundra and taiga biomes are more frequently dominating.

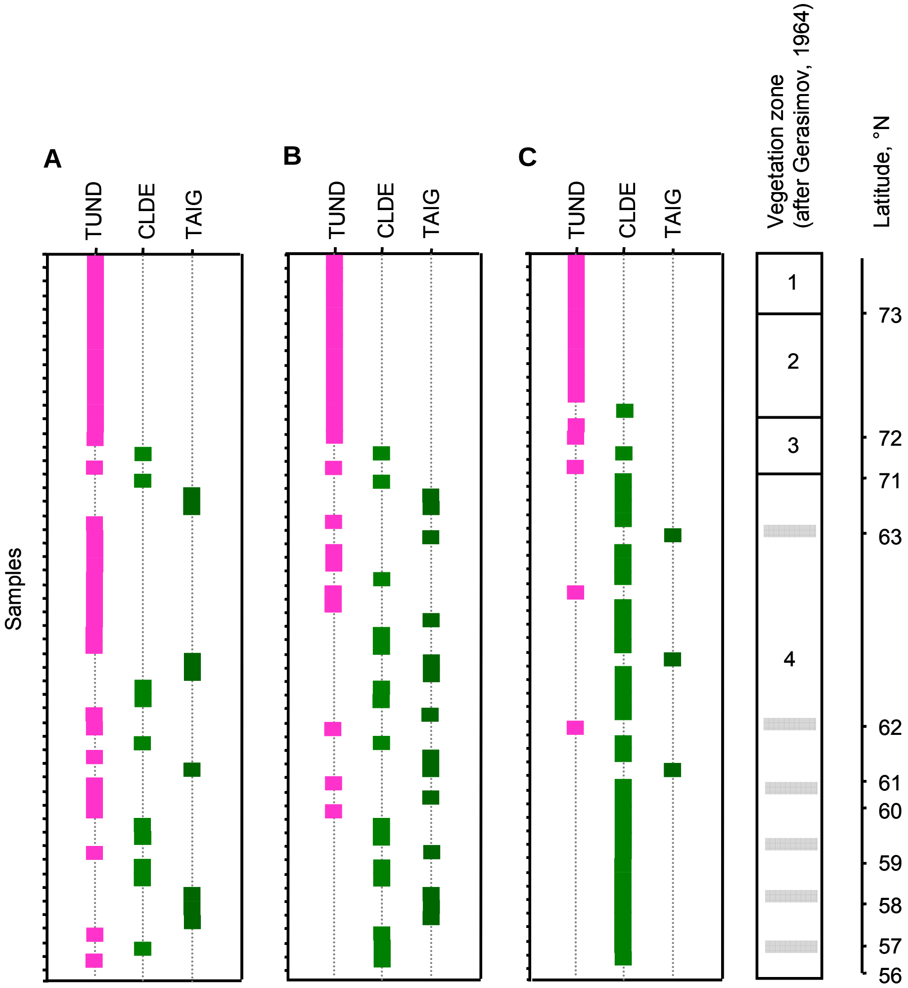


Fig. 6. Dominant biomes of the surface pollen data; (A) According to the adapted version by Tarasov et al. (1998), where shrubby birch (*Betula* sect. *Nanae*) and alder (*Duschekia fruticosa*) were included in the TUND biomes, (B) No differentiation between shrubby and tree birch/alder were done, (C) Shrubby birch and alder were included in the in TUND and CLDE biomes; and vegetation zonation after Atlas Mira (1964) 1 – Arctic tundra 2 – Typical tundra, 3 – Forest tundra (*Larix dahurica*), 4 – Larch forest, shaded area – Pine (*Pinus sylvestris*) and larch-pine forest.

4.3 Fossil pollen record

The PG1755 pollen diagram from Lake Billyakh (Fig. 7) is subdivided into ten pollen assemblage zones (PAZ) on the basis of changing pollen taxa composition and abundance. Below we provide a brief characteristic of the PG1755 PAZ from the bottom to the top of the core. Unfortunately the resolution in time during the Holocene section of the PG1755 core was rather low. Thus we discuss the Holocene period (PAZ VIII-I), including the Bølling-Allerød (B-A) and YD events, together with the reviewed PG1756 pollen record (Müller et al., 2009).

PAZ X (936-473 cm; 50.7-30.9 kyr BP)

Within this PAZ the pollen concentration reaches 29 600 grains/g at 40.3 kyr BP (787 cm depth). The pollen assemblages are dominated by herbaceous taxa (99-43%) and within the depth 936-492 by frequently changing percentages of especially shrub pollen taxa (*Betula* sect. *Nanae* and *Duschekia fruticosa*). Algi and Polypodiaceae percentages are increasing together with high shrub pollen amounts. Larch pollen are relative constantly abundant and reach up to 6%. Selaginella rupestris spores reach their maxima at 522 cm depth with 70%, when at the same time (31.7 kyr BP) *Betula* sect. *Nanae* percentages are decreasing to 0%.

PAZ IX (472-167 cm; 30.8-15.4 kyr BP)

The pollen concentration within this zone is rather low (on average 4 422 grains/g) compared to the PAZ X (10 100 grains/g). Like in the previous PAZ pollen assemblages are dominated by herbaceous taxa (80-100%), mainly Cyperaceae and Poaceae, as well as *Artemisia* (up to 21%), Caryophyllaceae (up to 7%), Ranunculaceae (up to 6%) and Asteraceae subfam. Chichorioideae (up to 11%). Shrub species are very rare (0-17%) and larch pollen almost disappear (0-3%). The sum of unidentified pollen taxa increases up to 10% as well as redeposited pollen (up to 5%). Fungi, mainly coprophilous, are increasing at the first half of this PAZ (up to 9%) and then decreasing dramatically. *Selaginella rupestris* spores are slowly decreasing (to 2-4%) towards the end of this zone.

PAZ VIII (166 cm; 15.3-13.5 kyr BP)

This PAZ corresponds to the zone VIII (late glacial) in the PG1756 sediment core of Lake Billyakh. The pollen concentration reaches on average 27 400 grains/g. Shrubby birch and alder percentages are increasing within this PAZ (21%), while herbaceous taxa are slightly decreasing to 80%. Larch pollen are almost absent within this zone.

PAZ VII (165-142 cm; 13.4-11.3 kyr BP)

This PAZ corresponds to the zone VII (B-A and YD periods) in the PG1756 sediment core of Lake Billyakh. Within this zone the pollen concentration reaches 45 300 grains/g. Percentages of shrub pollen taxa dominate (63-78%). Herbaceous pollen taxa (mainly grasses and sedges) reach up to 35% and tree pollen taxa are almost absent.

PAZ VI (141-101 cm; 11.2-7.4 kyr BP)

This PAZ corresponds to the zone VI (early Holocene) in the PG1756 sediment core of Lake Billyakh. It is characterised by the highest pollen concentrations (up to 198 900 grains/g; 121 cm) for the whole record. Shrub taxa, mainly birch (up to 89%) and alder (up to 54%) are dominating the pollen spectra. Larch pollen percentages reach up to 7%. Herbaceous taxa, like grasses, sedges and *Artemisia*, are reaching up to 16%. Algi and aquatic macrophytes are increasing dramatically from 150 to 350% and 10 to 20%, respectively.

PAZ V-III (100-35 cm; 7.3-1.8 kyr BP)

This PAZ corresponds to the zone V-III (middle Holocene) in the PG1756 sediment core of Lake Billyakh. The pollen concentration is decreasing from the bottom to the top of this zone from 120 600 to 35 500 grains/g. Percentages of shrub pollen taxa are decreasing from 60 to 44%, while tree pollen percentages, mainly *Pinus* subgen. *Diploxylon* (up to 36%) and *Larix* (up to 6%) are increasing from 34 to 52%. Herbaceous pollen taxa reach only up to 13%.

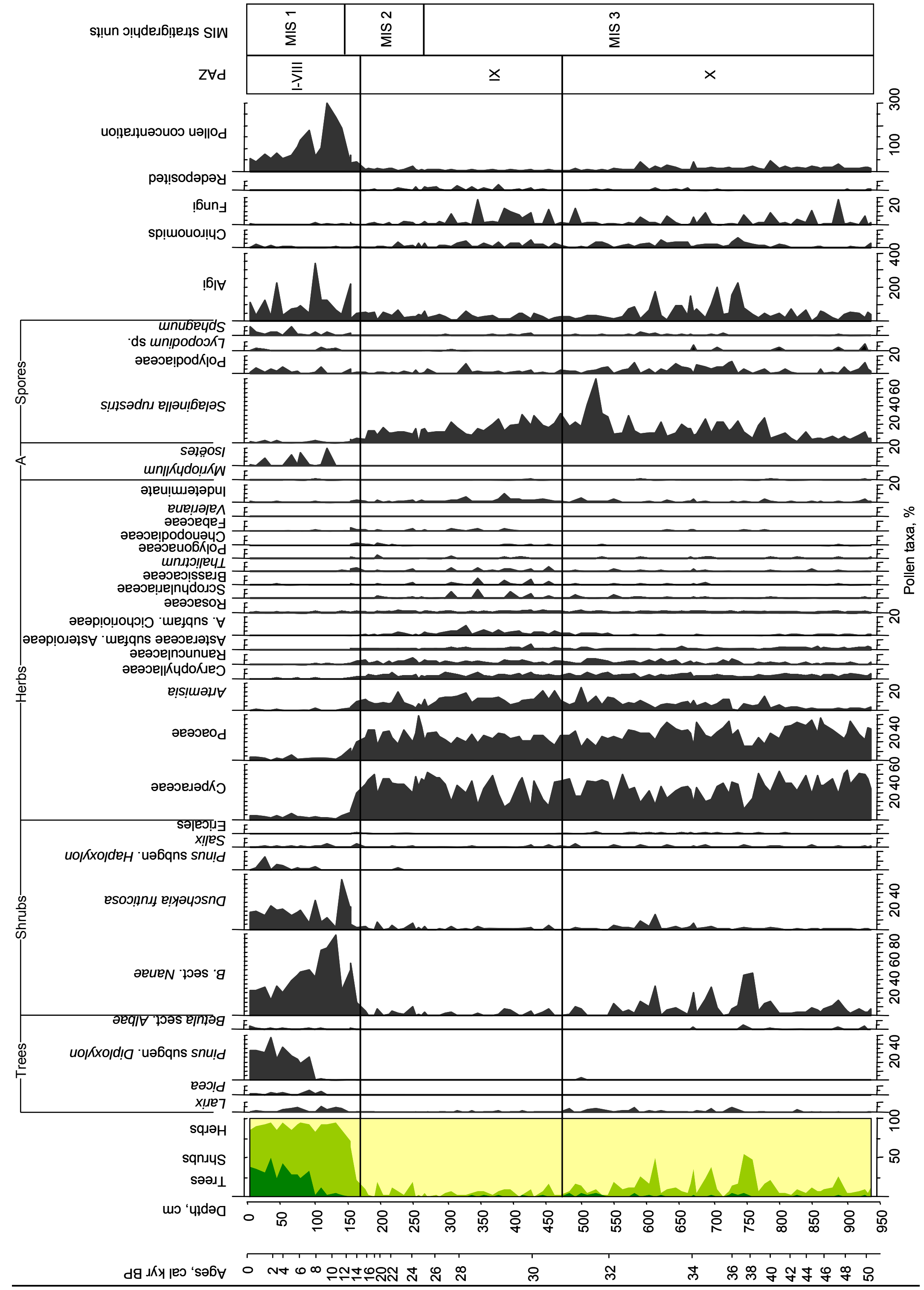


Fig. 7. Simplified pollen and spore percentage diagram of the PG1755 core from Lake Billyakh.

PAZ II, I (34-0 cm; 1.7-0 kyr BP)

This PAZ corresponds to the zone II and I (late Holocene) in the PG1756 sediment core of Lake Billyakh. Pollen percentages reach on average 38 400 grains/g. Shrub pollen taxa (*Betula* sect. *Nanae*, *Duschekia fruticosa*, *Pinus* subgen. *Haploxylon*) reach up to 62%. Tree taxa percentages (*Pinus* subgen. *Diploxylon*, *Betula* sect. *Albae*, *Larix*) are slightly decreasing to 39% and herbaceous pollen taxa remain nearly the same as in the previous PAZ (14%).

5. Interpretation and discussion

5.1 Regional vegetation reconstruction

The reconstruction results suggest distinct vegetation and environmental changes around Lake Billyakh for the last 50 kyr related to late Quaternary regional climate and environmental dynamics. For detailed interpretation and vegetation reconstruction for the Holocene period we show in Fig. 8 the results of the PG1756 sediment core (Müller et al., 2009) as well as the new results for the adapted biome reconstruction for this core. The environmental reconstruction (Fig. 9) is based on the qualitative interpretation of the pollen record (Fig. 7) with quantitative results of the biome reconstruction (Fig. 8).

The middle Weichselian interstadial (MIS 3) spans the time interval from 60-25 kyr BP (Vautravers et al., 2004). Thus we can give an environmental reconstruction for almost the whole interstadial based on the pollen record PG1755 from Lake Billyakh. Already Kind (1974, 1975) distinguished within the palaeoclimate reconstructions for the Middle Weichselian (Karginsky interstadial) (i) the early Karginsky warming (older than 50 ^{14}C kyr BP), followed by a short cooling episode around 43.5 ^{14}C kyr BP, the middle Karginsky climatic optimum (ca. 42–35 ^{14}C kyr BP), followed by another short cooling around 33 ^{14}C kyr BP, and the late Karginsky warm interval characterized by progressive climatic deterioration towards the Sartan glacial period (late Weichselian; MIS 2) which started 25 kyr BP. The PG1755 from Lake Billyakh is in agreement with most of the climate reconstructions reported above. Environmental conditions before 50 kyr BP we cannot reconstruct, but the short cooling periods at around 43.5 and 33 kyr BP are resembled in the pollen record by dominating herbaceous plants (89-96% and 84%, respectively), mainly grasses and sedges as well as *Artemisia* and Caryophyllaceae, suggesting a wide spread of herbaceous tundra communities (Prentice et al., 1996; Tarasov et al., 1998). Shrub species, like *Betula* sect. *Nanae* and *Duschekia fruticosa* are decreasing from 49 to 14% at 33 kyr BP. The pollen concentration is very low with 5 000 grains/g compared to the average concentration within the MIS 3 period (10 100 grains/g). Climate amelioration during the period from 42-35 kyr BP is resembled in the pollen record as well as in the biome reconstruction. Although, the vegetation is still dominated by herbaceous plants, shrubs are reaching 50% and trees 6% during that time. The biome reconstruction shows clearly dominated tundra vegetation but the cold deciduous biome scores are increasing and exceed the steppe scores at around 38 kyr BP indicating favourable environmental conditions during that time (Anderson and Lozhkin, 2001; Andreev et al., 2002; Schirrmeister et al., 2002; Wetterich et al., 2008; Andreev et al., 2009; Müller et al., 2009). The abundance of Ericales dwarf shrubs (e.g. *Vaccinium*, *Empetrum*, *Ledum*, *Arctostaphylos*) are increasing during the interval from 42.4-32.4 kyr BP indicating winter precipitation high enough to built up a thick, protective snow cover and acidic soils, both characteristic of interglacials and warmer stages, respectively (Kienast, 2006). However, the environments were still more severe than the present-day ones reflected by the small shrub and tree fraction in the vegetation community. Between 30.3 and 22.7 kyr BP redeposited pollen are frequently present and reflect scarce vegetation cover due to climate deterioration during that time. A sharp turn towards a dry climate is reconstructed after 30.8 kyr BP, causing the retreat of tundra and spread of steppe communities.

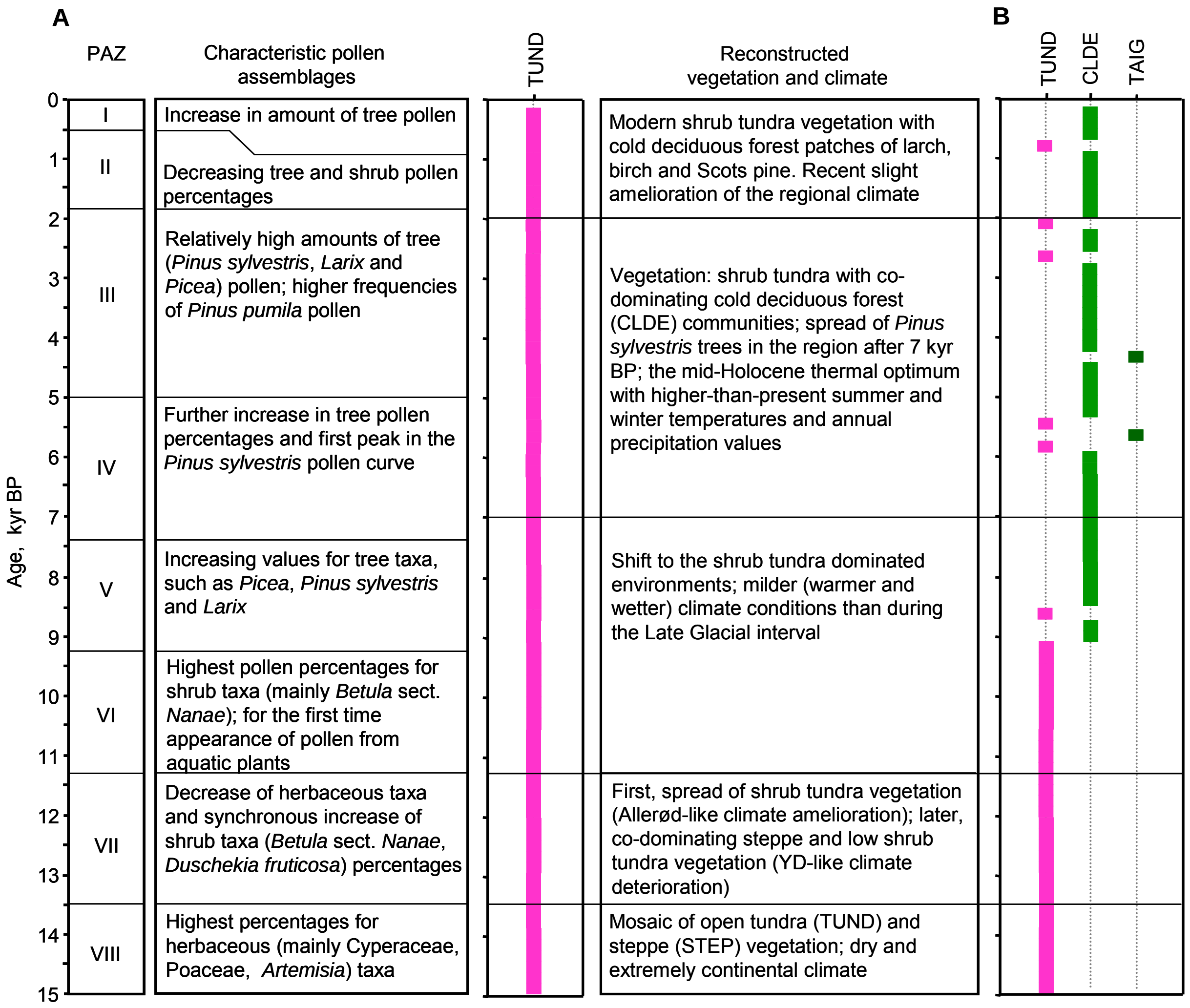


Fig. 8. Review of the results for the PG1756 sediment core; (A) Local pollen zones and pollen assemblage characteristics, dominant biomes, summary of the reconstructed changes in vegetation and climate around Lake Billyakh; (B) Dominant biomes according to the new biomization approach.

Cool grasses and shrubs dominated the vegetation in the area until ca. 19 kyr BP. Wetterich et al. (2008) reconstructed scarce vegetation and low pollination for 17 kyr BP. These features mark the late Weichselian (Sartan stadial) 25-15 kyr BP. A wide spread of the dry environments until 15.4 kyr BP is suggested by the high percentages of *Selaginella rupestris* spores (up to 80% during the end of MIS 3 and 30% during MIS 2). This species of spike-moss usually occurs in dry and cold rocky places with disturbed or thin soil cover.

Results of the biome reconstruction for PG1755 demonstrate almost equally high scores for the tundra and steppe biomes and low scores for the cold deciduous forest biome, suggesting the reconstruction of generally open tundra-steppe vegetation between 27.5 and 19 kyr BP. Grichuk (1984) pointed out that such plant communities were typical for the periglacial steppe or "tundra-steppe" vegetation of the LGM, which was widely distributed in northern Eurasia.

Because the late glacial (inclusive B-A and YD events) and Holocene periods are compressed in the PG1755 sediment core we would like to discuss these rather together with results of the PG1756 core (Müller et al., 2009). A quick spread of tundra vegetation would imply a quick shift to wetter environments caused by increased precipitation and/or melting of permafrost due to summer warming and decreasing winter temperature during the B-A Interstadial (Grichuk, 1984). After 12.4 kyr BP both the pollen spectra composition and the biome reconstruction demonstrate a short-term strengthening of the herbaceous vegetation communities compared to the shrub tundra vegetation, suggesting a decrease in available moisture and possibly a decrease in winter temperatures. This episode of climate deterioration deduced from the Lake Billyakh record PG1756 is falling well within the age limits of the YD interval known for its generally colder and dryer climate, particularly in the North Atlantic sector (Velichko et al., 2002; Andreev and Tarasov, 2007). However, the presence of *Larix* in both pollen records (PG1755 and PG1756) and likely in the vegetation cover, as well as relatively high contents of birch and alder shrub pollen and high tundra biome scores, reflects moisture availability. Thus the summer temperatures were high enough to sustain the survival of boreal trees and shrubs.

The substantial warming at the late glacial-Holocene transition can be detected at ca. 11.3 kyr BP. Both records suggest a shift to shrub tundra dominated environments and milder climate conditions than during the late glacial. This transition is recorded in various arctic regions of the Northern Hemisphere (e.g. MacDonald et al., 2000a;

Andreev et al., 2004; Kaufman et al., 2004; Kaplan and Wolfe, 2006), for example west (Werner et al., submitted) and east of the Verkhoyansk Mountains (Anderson et al., 2002) as well as at sites from central Yakutia west of the Lena River (Velichko et al., 1997). However, the latter study suggests that both January and July temperatures and annual precipitation were lower than today by 1°C, 0.5°C and 25mm/yr, respectively. Summer temperatures at least 4°C warmer than present are reconstructed at the Bol'shoy Lyakhovsky Island (Andreev et al., 2009) in the East Siberian Sea, suggesting that warming was more pronounced in northern Yakutia than in central and southern Yakutia, where continentality is more pronounced.

The biomization method is based on the idea that the biome with the highest score has a greater likelihood to be dominant in the vegetation close to the site (Prentice et al., 1996). As we decided to use the new developed approach for the biome reconstruction we also got new results for the PG1756 sediment core (Fig. 8) spanning the last 15 kyr. This new results demonstrate unchanged highest tundra biome scores from 15 until 9.3 kyr BP. But dominating biome scores for the cold deciduous forest biome since 9.2 kyr BP when pollen concentration is relatively high (up to 97 500 grains/g) and shrub taxa absolutely dominate (up to 95%) in the pollen spectra (Müller et al., 2009). The strengthening influence of cold deciduous and taiga forests after 9 kyr BP in the region can be seen in both records. This feature is in good agreement with other study results carried out in northeastern Siberia (Andreev et al., 1997, 2002; MacDonald et al., 2000a; Pisaric et al., 2001; Andreev and Tarasov, 2007). Maximum postglacial warming occurred after 7 kyr BP, thus a few thousand years later than in the northern and northeastern records of the arctic region. The progressive increase in the amount of herbaceous pollen (11–29%) during the last 2 kyr recorded in the PG1756 record is not that significant in the PG1755 record (4-14%). But it is also recognised by the biome reconstruction method, where tundra biomes are more frequently reconstructed since ca. 2.8 kyr BP. This might be associated with intensified human activities in the region.

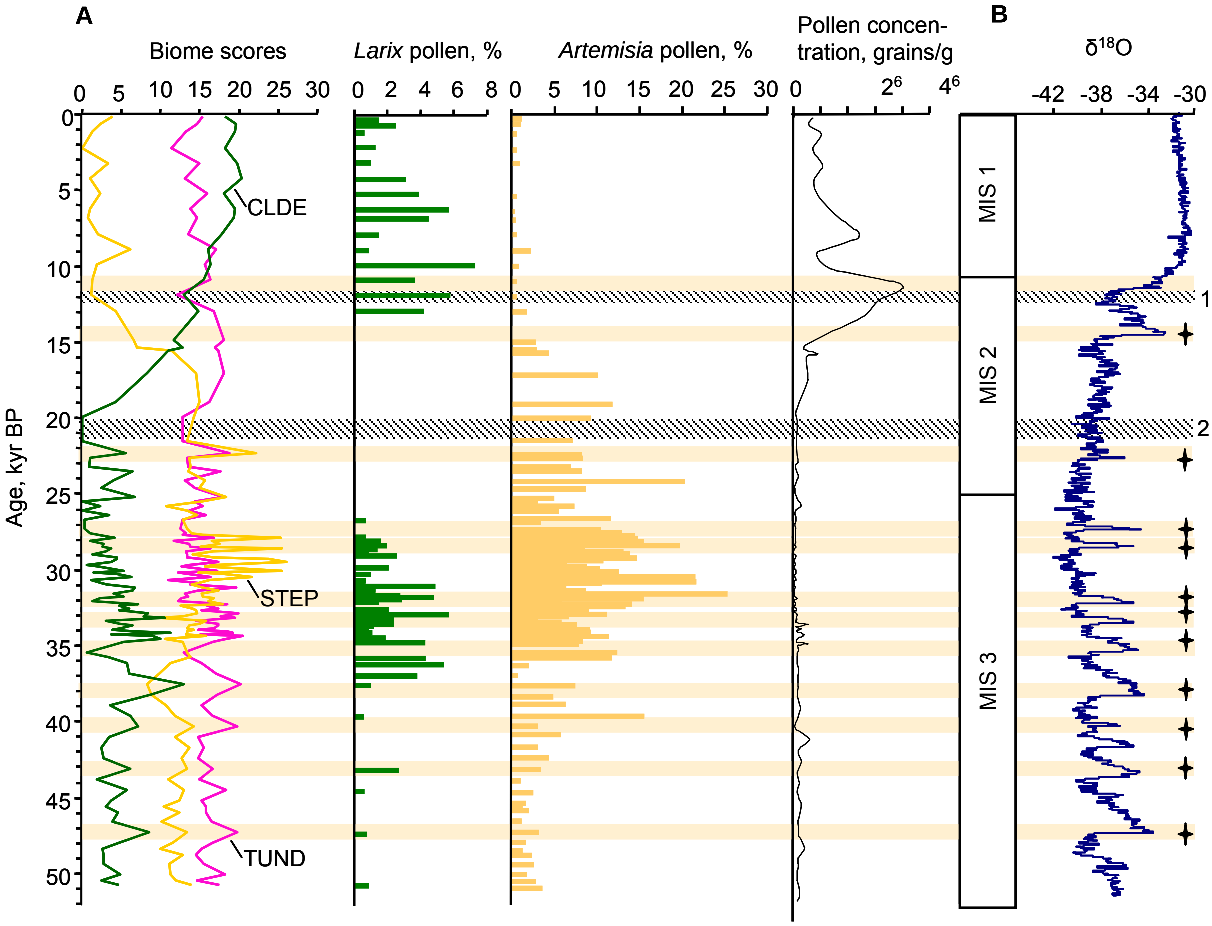


Fig. 9. Results of the biomization reconstruction (A) for the PG1755 sediment core (shrubby birch (*Betula* sect. *Nanae*) and alder (*Duschekia fruticosa*) were included in the in TUND and CLDE biomes) in comparison with (B) Greenland ice core δ^{18}O (North Greenland Ice Core Project Members, 2004); stars indicate Dansgaard-Oeschger events resembled in the PG1755 sediment core from Lake Billyakh; (1) marks the Younger Dryas cold event and (2) the Last Glacial Maximum.

Recently, a study of *n*-alkanes in bog sediments close to Lake Baikal (Ishiwatari et al., 2009) was published. They concluded that these organic parameters can be used as an indicator of expansion or retreat of woody plants vs. herbaceous plants (and probably gymnosperms vs. angiosperms). As the *n*-alkane distribution of many tree species are dominated by the homologues C27, whereas in grasses C31 and/or C33 predominate, the C27/C31 is traditionally used to distinguish between tree and grass dominance. In total, 18 samples from depth 75-738 cm were analysed so far for *n*-alkanes applying the method described by Zech and Glaser (2008). In all samples the tree alkanes dominated reaching values from 75-98%. The highest values are reached during the time intervals from 6.3-18.1 kyr and 36.2-36.9 kyr BP, while lower values can be found during the interval from 20-27.3 kyr BP. These results strengthen the pollen derived interpretation of more or less uninterrupted growth of larch trees in the surrounding area of the lake.

5.2 Local larch forest history

Many arctic-alpine plants have large present-day ranges across Eurasia, but their refugial history, range and postglacial expansion is poorly understood. Quaternary refugia represent areas of special value for the long-term persistence of biodiversity (Taberlet and Cheddadi, 2002). Recently, Bennett and Provan (2007) examined the definition of the term ‘refugia’. According to their differentiation of several types of refugia we can assume that larch was outliving in cryptic refugia (habitats of favourable microclimatic conditions).

The PG1756 core pollen record from Lake Billyakh, demonstrates continuous presence of larch pollen during the past 15 kyr (Müller et al., 2009). A peat bog pollen record from the Dyanushka River (Werner at al., submitted), ca 80 km from Lake Billyakh (Fig. 1C), demonstrates that larch trees and abundant shrubs grew near the site between 12.5 and 11.2 kyr ago, spanning the YD and the early Holocene (Fig. 10). The AMS radiocarbon dates on the fossil wood, cone and needles support the reconstruction of the larch woodland. The 936 cm long PG1755 core recovered from the central part of Lake Billyakh provides an even longer record, showing quasi-continuous presence of larch pollen since about 50 kyr ago (Fig. 7). Larch pollen is known for its short-distance dispersal from the pollen-producing tree and poor preservation (Tarasov et al., 2007; MacDonald et al., 2000a). This fact may explain its low percentages even in the Holocene pollen spectra from Lake Billyakh. The presence of larch pollen grains in the YD sediment from Lake Billyakh supports our interpretation that local population of larch could persist in the region through the last glacial. Taking in consideration that larch pollen is usually strongly underrepresented in the pollen diagrams and poorly transported far from the pollen-producing tree (Tarasov et al., 1998; Pisaric et al., 2001). This conclusion confirms an earlier hypothesis of Grichuk (1984), who postulated the existence of many scattered refugia where boreal shrubs and trees could survive periods of harsh glacial climate and quickly spread with the onset of warmer conditions. We suggested that small populations of larch in the Verkhoyansk foreland and in the nearby Lena River valley had locally sufficient water supplies and high enough summer temperatures for growth and reproduction during the last glacial.

Present-day extension of larch in the Arctic is limited mainly by the mean July isotherm of 10-12°C (Atlas Arktiki, 1985). Also the snow cover thickness is important for larch outliving the harsh winter temperatures reaching -43.9°C in the Yakutsk region and -51.2°C in the Oimyakon basin (Table 4). Via the westerly humid air masses are reaching mainly only the western part of the Verkhoyansk Mountains and thus provide 50 cm snow thickness, whereas in the eastern part less than 30 cm snow cover is reached (Shahgedanova et al., 2002). Southern slopes are getting one month earlier snow free than slopes with northern exposition (Berg, 1959). Also permafrost limits the northward and eastward distribution of major conifer species (*Picea obovata*, *Abies sibirica*, *Pinus sibirica*). By contrast *Larix dahurica* is able to grow on frozen shallow soils with thaw depth from 10-30 cm (Pozdnyakov, 1993). In fact, in the dryer Siberian interior (200-300 mm precipitation), forests are dependent on permafrost melting to provide moisture, otherwise steppe or semi-desert evolve (Shumilova, 1962). It is also very plausible that the western foreland of the Verkhoyansk Mountains with its numerous lake and river valleys provided enough moisture and warm microhabitats buffering larch trees against climatic extremes. The presence of larch populations during the YD likely explains quick reforestation of eastern Siberia by the early Holocene (MacDonald et al., 2000a) and supports the molecular-based hypothesis suggesting the existence of high-latitude plant refugia during past glaciations (Abbott et al., 2000).

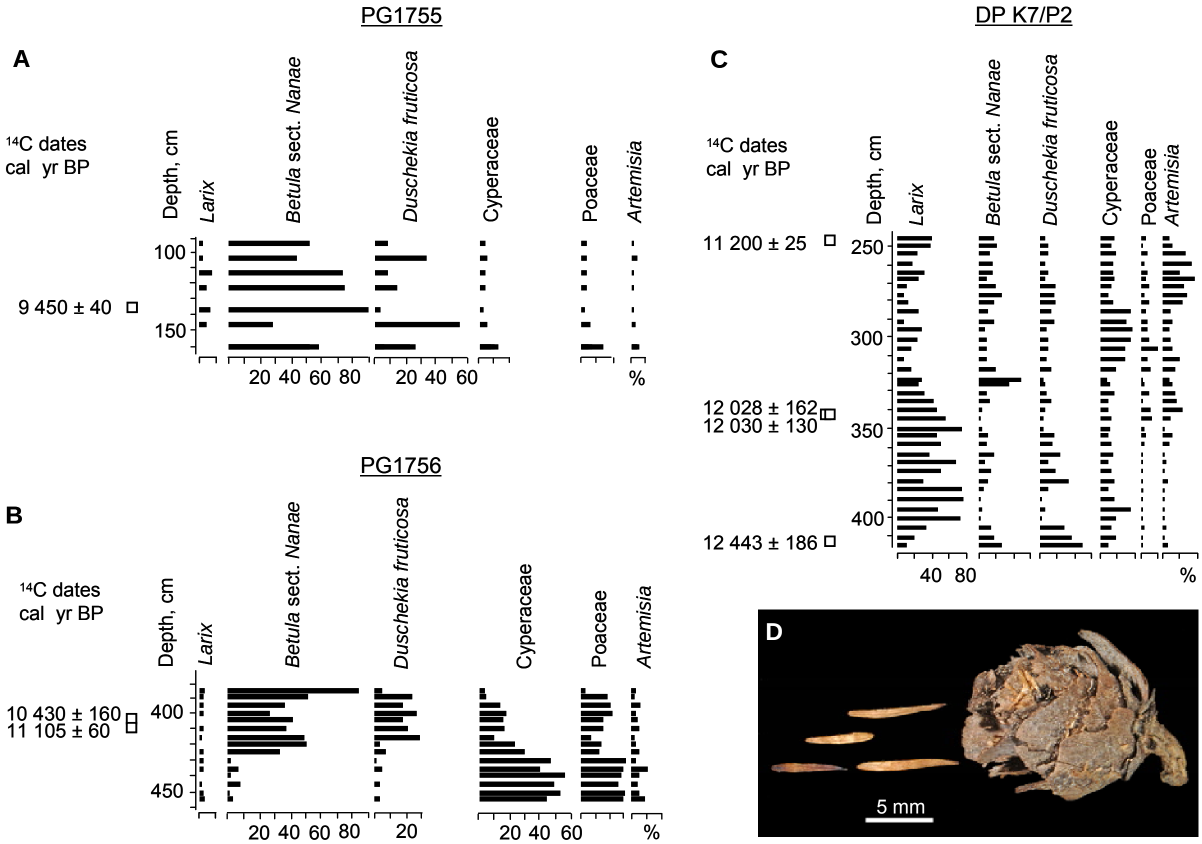


Fig. 10. Comparison of pollen spectra for selected taxa from PG1755 (A), PG1756 (B) and Dyanushka peat profile K7/P2 (DP) (C) for the Younger Dryas period; (D) photograph of larch cone and needles from the DP profile dated to 10 270±50 ^{14}C yr BP (12 030±130 cal yr BP).

5.3 Extra-regional environmental reconstruction

Based on our chronology we can give a basic comparison of globally recorded climatic shifts, which are in agreement with other records from continental archives. As for example Prokopenko et al. (2001) stated out understanding the nature of the palaeoclimate signals in continental interiors would contribute greatly to realizing the global importance of climatic instabilities recorded in the Greenland ice cores, like for instance Dansgaard-Oeschger events (D-O). They successfully correlated pronounced drops in diatom abundance during the MIS 3 Interstadial with short-term cooling phases recognised as Bond cycles in the North Atlantic (Prokopenko et al., 2001). In Fig. 9 we present our results from the continental Lake Billyakh together with the $\delta^{18}O$ curve from Greenland ice core (North Greenland ice Core Project Members, 2004) and indicated D-O. Except for D-O 10 we could detect all events in the PG1755 record during the last 50 kyr based on qualitative data from the pollen analysis and the biome reconstruction. Extreme unfavourable climate conditions were reconstructed for the period from 30.8-19 kyr BP were steppe biomes dominate the tundra and cold deciduous forest biomes. Harsh environmental conditions during the MIS3-MIS2 transition were also reconstructed for the Laptev Sea (Andreev et al., 2009) and Northern Taymyr (Andreev et al., 2003). Increasing aridity during the last glacial (Hubberten et al., 2004, Svendsen et al., 2004) can be confirmed with our data from Lake Billyakh, especially for the period from 30.8 to 19 kyr BP. Pollen studies for the period of the LGM confirm the assumption of an extreme cold and dry climate during this phase (Klimanov, 1997; Tarasov et al., 1999b, 2000; Anderson et al., 2002; Hubberten et al., 2004; Edwards et. al., 2005; Kienast et al., 2005). The greater continentality in the NE Siberian region is characterized by higher summer temperatures (Hubberten et al., 2004; Kienast et al., 2005) and lower winter temperatures (Popp et al., 2006) compared to today. The specific position of Central Yakutia is furthermore highlighted as stable oxygen isotopes show lightest values in ice-wedges from the Verkhoyansk Region (Popp et al., 2006) resembling extreme continental conditions in this region until today.

Herbaceous tundra communities were dominating until 15.4 kyr BP until the onset of the late glacial. MacDonald et al. (2000b) pointed out that winter insolation was lower than present during the early Holocene and that the susceptibility of *Pinus sylvestris* to desiccation and root damage due to cold winters may have restricted the spread of the species earlier in this region. Increased summer temperatures in periglacial landscapes during the Holocene optimum until now caused degradation of the permafrost layer (Andreev and Tarasov, 2007), which also benefited the establishment of *Pinus sylvestris* in the region.

6. Conclusions

In this study we discussed reconstructed late Quaternary environmental changes for the extremely continental area of the western part from the Verkhoyansk Mountain Range based on pollen data. In conclusion we can provide:

- continuous pollen record containing the last 50.7 kyr BP and thus providing uninterrupted vegetation reconstruction for the Lake Billyakh vicinity. During the MIS 3 (Karginsky interstadial) herbaceous and shrubby tundra communities dominated the area, meanwhile larch was growing in frequencies comparable to that in the present-day forest tundra vegetation. During the MIS 3-MIS 2 transition cold deciduous conifer trees and shrub communities are decreasing and until the end of the MIS 2 open grass and sedge tundra and steppe communities are dominating in the vegetation. Holocene climate amelioration is reflected by the dominance of shrubby tundra communities and increase of tree taxa abundances, especially within the mid-Holocene climatic optimum;

- the proof for larch stands in the study area during the last glacial period. It is very plausible that the western foreland of the Verkhoyansk Mountain Range with its numerous lake and river valleys provided enough moisture and warm microhabitats buffering larch trees against climatic extremes;
- verification of the palaeoenvironmental reconstruction using 53 newly available modern pollen samples from the study region by use of the biomization technique;
- correlation of the pollen derived palaeoenvironmental variations with North Atlantic signals (D-O events) suggest the stronger influence of the westerly wind system than pacific induced climate changes at the western foreland of the Verkhoyansk Mountains during the last 50.7 kyr;
- the confirmation for ongoing investigations in this special region of continuously frozen ground for detection of climate induced signals on not only regional but also global scales. In the Lake Billyakh area vegetation composition like it is today could not be detected for the last 50.7 kyr. We assume that ongoing permafrost degradation processes and climate warming will lead to the expansion of boreal conifer trees, where nowadays tundra and forest tundra vegetation prevail.

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Appendix A

Results of the pollen analysis of the PG1755 core from Lake Billyakh (65.27°N, 126.75°E; 340 m a.s.l.). Absolute count values are provided for each identified taxon at each analysed level. Sample ages (cal yr BP) are calculated using age-depth model discussed in the text. All raised palynological data are available in the PANGAEA data information system ().

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4. Conclusions

The study presented here provides new insights in late Quaternary palaeoenvironmental changes over NE Siberia, including the coldest region of the northern hemisphere, inferred from pollen and testate amoebae analysis. The main conclusions can be described as follows:

- Detailed records of palaeoenvironmental changes during the last 50 kyr with the help of terrestrial archives (permafrost and lake sediments) from NE Siberia, based on testate amoebae and pollen analysis, have been established.
- Description of distinct changes of local permafrost environments during the past 45 kyr, where the testate amoebae record mostly co-varies with lithology and other proxy results.
- Significant fluctuations in vegetation composition in NE Siberia during the late Quaternary have been reconstructed showing distinct short-term variations in response to large-scale palaeoclimatic events (MIS 3, MIS 2, Bølling-Allerød, Younger Dryas, onset of the Holocene and mid-Holocene thermal optimum).
- The results from the studied terrestrial records have been correlated with other available records from the Siberian Arctic and show comparable findings in most cases.
- The correlation of the pollen derived palaeoenvironmental variations with global signals of climate change (e.g. Dansgaard-Oeschger events) during the last 50 kyr suggests a stronger influence of the westerly wind system than pacific induced climate changes in the study region.
- Evidence for larch stands in the area during the last glacial are proof for the existence of glacial refugia in the western foreland of the Verkhoyansk Mountains.
- Modern data sets for pollen and testate amoebae from the study region have been expanded for detailed characterisation of modern environments and verification of the quantitative palaeoenvironmental reconstruction.
- The results confirm ongoing investigations in this special region of continuously frozen ground by means of high-resolution studies to detect climate induced environmental variations on regional and global scales and their driving mechanisms.

5. Perspectives

Although the principal glacial and non-glacial events of the last 130 kyr in NE Siberia now have a relatively reliable chronology, comparable to the corresponding records of western Europe and North America, the environmental history of many areas of this huge region is still not entirely reconstructed. More detailed sedimentological and palaeontological descriptions from aquatic and terrestrial archives are needed covering the Siberian Arctic. Significant fluctuations in vegetation composition during the late Quaternary have been reconstructed to be temporarily shifted in comparison with western Siberia and Europe. This asymmetric pattern of glacial and interglacial periods needs to be further investigated to understand atmospheric conditions which could cause these shifts.

Since most of the terrestrial studies are focussed on the coastal lowlands of the Arctic Ocean and on western Siberia, the late Quaternary environment of the continental areas across NE Siberia remain poorly understood. Within this thesis it was proven that this region has big potential for further investigations of palaeoenvironmental studies. One important aspect of further research could be the study of human-induced environmental change during the past millennia. Today, and most probably during the past, the region of Yakutia has a very low number of inhabitants. Therefore it is suggested that anthropogenic influence was rather low. However, especially in central Yakutia anthropogenic influences on the environment can be recognised concerning agricultural activities.

The details in respect to the existence of “cryptic refugia” of larch stands in the study area of the western foreland of the Verkhoyansk Mountains during cold stages have to be intensively investigated. A combination of fossil and genetic data may provide much more information about the disposition of small populations during the last glaciation as well as to the movement directions of post-glacial population spread.

Testate amoebae react sensitive to various ecological variables. It is known that salinity, temperature, oxygen saturation, and chemical composition of the water or sediment influence the occurrence of testate amoebae species. We are able to describe distinct changes in past environments, where the testate amoebae record mostly co-varies with lithology and other proxy results. However, a quantification of the reconstructed variables is often missing, but needed for compilation of climate models. Within future research objectives it is aspired to refine the indicator ability of testate amoebae and to use their described potential for aspects in late glacial and Holocene palaeoecological research in NE Siberia. As well as for pollen, it is possible to calibrate surface testate amoebae assemblages according to local climate variables. Then it would be possible to apply the calibrations to stratigraphic sequences in order to reconstruct the vegetation and climate history at particular sites.

6. Appendix A

6.1 Data tables - Testate amoebae

Table 1. Count sheet of fossil testate amoebae shells in permafrost deposits from Cape Mamontov Klyk.

Sample name/Taxa name	*Arcella arenaria* v. *compressa*	*A. artocrea*	*A.* cf. *crenulata*	*A. discoides* v. *scutelliformis*	*A. rotundata* v. *aplanata*	*Bullinularia gracilis*	*B. indica*	*Trigonopyxis arcula*	*T. minuta*	*C. aculeata* f.A	*C. aerophila*	*C. aerophila* v. *minuta*	*C. aerophila* v. *sphagnicola*	*C. cassis*	*C. constricta*	*C. constricta* v. *minima*
MAK 1-12	0	0	0	0	0	0	0	2	0	0	11	35	0	0	6	7
MAK 1-13	0	0	0	0	0	0	0	6	0	0	7	29	21	0	5	1
MAK 1-14	0	0	0	0	0	0	0	0	0	0	28	5	16	0	2	14
MAK 2- 3	0	0	0	2	0	1	0	0	0	0	10	21	0	0	0	10
MAK 2- 4	0	0	0	0	0	0	0	0	0	0	1	9	0	0	1	0
MAK 2- 5	0	0	0	0	0	0	0	0	0	0	2	4	3	0	0	2
MAK 2- 6	0	0	0	0	0	0	0	0	0	0	5	0	0	0	4	1
MAK 2- 8	0	0	0	0	0	0	0	0	0	0	3	1	0	0	1	2
MAK 2- 9	1	0	0	0	0	0	0	0	0	3	2	4	4	1	5	2
MAK 3- 5	1	0	0	0	0	0	0	0	0	0	5	17	7	0	0	4
MAK 3- 7	0	0	0	0	0	0	0	0	0	0	3	4	2	0	3	3
MAK 3-10	0	0	0	0	0	0	0	0	0	0	1	2	4	0	0	2
MAK 3-14	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
MAK 3-16	0	0	0	0	0	0	0	0	0	0	2	7	0	0	1	0
MAK 3-17	0	0	0	0	0	0	0	0	0	0	4	20	0	0	0	0
MAK 5- 3	0	0	0	0	0	0	0	1	4	0	3	19	0	0	1	1
MAK 8- 3	0	0	0	0	0	0	0	0	0	0	4	10	1	0	0	1
MAK 9- 3	0	0	0	0	0	0	0	0	0	0	1	15	2	0	0	4
MAK 9- 4	0	0	0	0	0	0	0	0	0	0	0	32	6	0	2	8
MAK 9- 5	0	0	0	0	0	0	0	0	0	0	2	6	3	0	1	2
MAK 10- 5	1	0	0	0	0	0	0	0	0	0	12	21	3	0	1	9
MAK 10- 7	0	0	0	0	0	0	0	0	0	0	2	5	1	0	1	5
MAK 10- 8	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	3
MAK 10-11	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	7
MAK 11- 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11- 7	0	0	0	0	0	0	0	0	0	0	1	9	0	0	0	0
MAK 11- 9	0	0	0	0	0	0	0	0	0	0	2	13	0	1	3	5
MAK 11-10	0	0	0	0	0	0	0	0	0	0	8	53	1	4	4	5
MAK 11-11	0	0	0	0	0	0	0	0	0	0	11	33	0	0	1	2
MAK 12- 1	0	0	0	0	0	0	0	0	0	0	4	18	0	0	0	5
MAK 12- 2	0	0	0	1	0	0	0	0	0	0	4	17	0	0	2	3
MAK 12- 4	2	0	0	0	0	0	0	0	0	0	13	29	1	0	0	12
MAK 12- 5	0	0	0	0	0	0	0	0	0	0	2	13	0	0	1	7
MAK 13- 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
MAK 14- 4	0	0	0	0	0	0	0	0	0	0	2	3	0	0	0	3
MAK 14- 5	0	0	1	0	0	0	0	0	0	0	1	2	0	0	0	0
MAK 14- 6	0	0	0	0	0	0	1	0	0	0	1	2	2	0	2	0
MAK 14- 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 17- 3	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	1
MAK 19- 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. Continued.

Sample name/Taxa name	*C. discoides*	*C. gibbosa*	*C. orbicularis*	*C. plagiostoma*	*C. plagiostoma* v. *terricola*	*C. plagiostoma* f. *major*	*C. plagiostoma* f. *minor*	*C. plagiostoma* f. *longa*	*C. platystoma*	*C. sylvatica*	*C. sylvatica* v. *globulosa*	*C. sylvatica* v. *microstoma*	*C. sylvatica* v. *minor*	*Cyclopyxis arcelloides*	*C. eurystoma*	*C. eurystoma* v. *parvula*
MAK 1-12	1	0	0	13	0	0	1	0	0	36	0	0	2	0	8	12
MAK 1-13	0	0	0	22	0	0	0	0	0	31	0	0	12	0	7	6
MAK 1-14	0	0	0	58	0	1	25	0	0	52	0	6	57	3	3	17
MAK 2- 3	0	1	0	9	0	0	0	0	0	7	0	0	0	0	0	8
MAK 2- 4	0	0	0	1	0	1	0	0	0	6	0	2	4	0	0	1
MAK 2- 5	0	0	0	3	0	1	0	0	0	5	0	0	15	0	0	0
MAK 2- 6	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	5
MAK 2- 8	0	0	0	2	0	0	4	0	0	7	0	1	10	0	0	3
MAK 2- 9	0	0	0	6	0	0	6	0	0	1	0	0	1	0	1	3
MAK 3- 5	0	0	2	18	0	0	0	0	0	22	0	0	27	0	0	0
MAK 3- 7	0	0	2	24	0	1	1	0	0	3	0	0	10	0	1	1
MAK 3-10	0	0	0	4	0	0	1	0	0	3	0	0	16	0	7	6
MAK 3-14	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-16	0	0	0	8	0	0	1	0	0	2	0	2	11	0	0	1
MAK 3-17	0	0	0	12	0	0	0	0	0	1	0	0	10	0	1	6
MAK 5- 3	0	0	1	31	0	3	2	0	0	16	1	24	38	0	1	2
MAK 8- 3	0	0	0	0	0	0	0	0	0	3	0	1	13	0	1	0
MAK 9- 3	0	0	4	86	0	5	0	0	0	8	0	10	22	0	3	3
MAK 9- 4	0	0	0	3	0	0	1	0	0	6	0	10	5	0	0	13
MAK 9- 5	0	0	0	27	0	2	2	0	0	25	0	0	30	0	0	2
MAK 10- 5	0	0	13	11	0	0	0	0	0	20	0	0	52	0	3	16
MAK 10- 7	0	0	3	1	0	0	1	0	0	12	0	0	17	0	0	2
MAK 10- 8	0	0	0	0	0	0	1	0	0	4	0	0	4	0	1	0
MAK 10-11	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
MAK 11- 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
MAK 11- 7	0	0	0	0	0	0	3	0	6	0	0	0	4	10	0	0
MAK 11- 9	0	0	0	7	1	0	2	0	1	11	0	0	65	0	1	7
MAK 11-10	0	0	0	5	0	0	5	1	0	2	0	0	11	0	0	3
MAK 11-11	0	0	0	22	0	0	9	0	0	6	0	0	41	0	0	3
MAK 12- 1	0	0	0	14	2	1	1	0	0	6	0	2	17	2	2	6
MAK 12- 2	0	0	0	6	0	3	2	0	0	2	0	0	14	0	2	7
MAK 12- 4	0	0	0	9	0	1	3	0	0	11	0	6	20	0	3	8
MAK 12- 5	0	0	0	1	0	0	0	0	0	7	0	2	5	0	0	1
MAK 13- 7	0	0	3	0	0	1	0	0	0	4	0	0	0	0	0	0
MAK 14- 4	0	0	0	0	0	0	0	0	1	1	0	0	4	0	0	2
MAK 14- 5	0	0	0	1	0	0	0	0	5	0	0	0	1	1	0	0
MAK 14- 6	0	0	0	0	0	0	0	0	1	1	0	2	0	0	1	4
MAK 14- 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 17- 3	0	0	1	2	0	0	2	0	0	0	0	1	1	0	0	5
MAK 19- 4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Table 1. Continued.

Sample name/Taxa name	*C. kahli*	*C. kahli* cf. *minor*	*Plagiopyxis bathystoma*	*P. callida*	*P. declivis*	*P. minuta*	*P. penardi*	*Heleopera petricola*	*H. petricola* v. *amethystea*	*H. petricola* v. *humicola*	*H. sphagni*	*Nebela bigibbosa*	*Nebela collaris*	*N. lageniformis*	*N. parvula*	*N. penardiana*
MAK 1-12	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
MAK 1-13	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 1-14	18	0	1	0	0	0	0	2	0	0	0	0	1	0	0	0
MAK 2- 3	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
MAK 2- 4	2	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
MAK 2- 5	8	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
MAK 2- 6	0	0	0	0	0	0	0	2	0	0	1	0	0	0	0	0
MAK 2- 8	2	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0
MAK 2- 9	1	0	0	0	0	0	0	3	1	0	0	0	0	1	0	0
MAK 3- 5	2	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
MAK 3- 7	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
MAK 3-10	3	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0
MAK 3-14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 5- 3	2	0	0	2	0	5	5	0	0	0	0	0	0	0	0	0
MAK 8- 3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
MAK 9- 3	5	0	0	4	0	0	28	0	0	0	0	0	0	0	0	0
MAK 9- 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 9- 5	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
MAK 10- 5	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 10- 7	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
MAK 10- 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 10-11	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
MAK 11-6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11- 7	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11- 9	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
MAK 11-10	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
MAK 11-11	0	0	0	0	0	0	5	0	0	0	0	0	1	0	0	1
MAK 12- 1	0	0	0	4	0	0	7	0	0	0	0	0	0	0	0	0
MAK 12- 2	1	1	0	4	0	0	1	0	0	0	0	0	0	0	0	0
MAK 12- 4	3	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
MAK 12- 5	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 13-7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 14- 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 14- 5	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
MAK 14- 6	2	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
MAK 14-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 17- 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 19-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. Continued.

Sample name/Taxa name	*N. tincta*	*N. tincta f. stenostoma*	*Argynnia* sp.	A. sp. f. *minor*	*Schoenbornia humicola*	*Sch. viscicula*	*Difflugia cratera*	*D. globulus*	*D. difficilis*	*D. lucida*	*D. microstoma*	*D. minuta*	D. cf. *oblonga*	D. oblonga longicollis cf.	*D. penardi*	D. cf. *pristis*
MAK 1-12	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
MAK 1-13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 1-14	0	0	5	0	0	0	0	5	0	1	1	1	0	0	4	1
MAK 2- 3	0	0	3	0	0	0	0	3	0	1	0	1	0	0	0	0
MAK 2- 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 2- 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 2- 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 2- 8	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0
MAK 2- 9	0	0	0	0	0	0	0	2	0	1	0	0	0	0	1	0
MAK 3- 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3- 7	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
MAK 3-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-17	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 5- 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 8- 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 9- 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 9- 4	0	0	1	0	0	0	0	1	0	2	0	0	0	0	0	0
MAK 9- 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 10- 5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 10- 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 10- 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 10-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11- 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11- 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11- 9	0	0	0	0	0	0	0	9	0	0	0	3	1	0	0	0
MAK 11-10	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0
MAK 11-11	0	0	0	0	0	0	0	8	0	0	0	0	0	0	1	0
MAK 12- 1	0	0	1	0	0	0	0	3	0	0	0	0	0	0	0	1
MAK 12- 2	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 12- 4	2	0	1	0	0	0	0	1	0	3	0	0	0	0	0	0
MAK 12- 5	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
MAK 13- 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 14- 4	0	0	1	0	0	0	0	6	0	0	0	0	0	0	0	0
MAK 14- 5	0	0	0	0	0	0	2	3	0	0	0	1	0	0	0	0
MAK 14- 6	0	0	0	0	0	0	1	1	0	1	0	0	0	1	0	0
MAK 14- 8	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
MAK 17- 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 19- 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. Continued.

Sample name/Taxa name	*D.* cf. *pristis*	*D.* cf. *pyriformis*	*Phryganella acropodia*	*Ph. acropodia* cf. v. *australica*	*Ph. hemisphaerica*	*Paraquadrulla irregularis*	*Assulina muscorum*	*Valkanovia delicatula*	*Euglypha ciliata*	*E. ciliata* f. *glabra*	*E. cuspidata*	*E. dolioliformis*	*E. laevis*	*E. strigosa* f. *glabra*	*Trinema enchelys*	*T. lineare*
MAK 1-12	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
MAK 1-13	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 1-14	1	1	13	5	0	0	0	0	0	0	0	0	0	0	0	0
MAK 2- 3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
MAK 2- 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 2- 5	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0
MAK 2- 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 2- 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 2- 9	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3- 5	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3- 7	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-10	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-16	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 3-17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 5- 3	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 8- 3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 9- 3	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 9- 4	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0
MAK 9- 5	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 10- 5	0	0	4	4	1	0	0	0	0	0	0	0	0	0	0	0
MAK 10- 7	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 10- 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 10-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11- 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11- 7	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11- 9	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11-10	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
MAK 11-11	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
MAK 12- 1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 12- 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 12- 4	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 12- 5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 13- 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 14- 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 14- 5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 14- 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 14- 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 17- 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAK 19- 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. Continued.

Sample name/Taxa name	*T. penardi*	*Corythion dubium*	*Pseudodifflugia* cf. *gracilis*	*P. gracilis* v. *terricola*	Total sum	N, species
MAK 1-12	0	0	0	0	142	16
MAK 1-13	0	0	0	0	154	13
MAK 1-14	0	0	0	0	346	32
MAK 2- 3	0	0	1	0	81	17
MAK 2- 4	0	0	0	1	31	15
MAK 2- 5	0	0	0	0	48	12
MAK 2- 6	0	0	0	0	20	8
MAK 2- 8	0	0	0	0	43	15
MAK 2- 9	0	0	0	0	51	24
MAK 3- 5	0	0	0	1	114	13
MAK 3- 7	0	0	0	0	63	17
MAK 3-10	0	0	0	0	59	13
MAK 3-14	0	0	0	0	3	3
MAK 3-16	0	0	0	0	36	10
MAK 3-17	0	0	0	0	56	9
MAK 5- 3	0	0	0	0	171	19
MAK 8- 3	0	0	0	0	38	11
MAK 9- 3	0	0	0	0	209	16
MAK 9- 4	0	0	0	0	94	15
MAK 9- 5	0	0	0	0	107	14
MAK 10- 5	0	0	0	0	185	17
MAK 10- 7	0	0	0	0	53	13
MAK 10- 8	0	0	0	0	17	7
MAK 10-11	0	0	0	0	11	4
MAK 11- 6	0	0	0	0	1	1
MAK 11- 7	0	0	3	0	40	10
MAK 11- 9	0	0	0	0	138	22
MAK 11-10	0	0	1	1	113	18
MAK 11-11	0	0	0	0	147	16
MAK 12- 1	0	0	0	0	96	19
MAK 12- 2	0	0	0	0	73	19
MAK 12- 4	0	0	0	1	133	23
MAK 12- 5	0	0	0	0	44	15
MAK 13- 7	0	0	0	0	10	4
MAK 14- 4	0	0	0	0	23	10
MAK 14- 5	0	0	0	0	21	13
MAK 14- 6	0	0	1	0	27	20
MAK 14- 8	0	0	0	0	1	1
MAK 17- 3	0	0	0	0	25	9
MAK 19- 4	0	0	0	0	1	1

6.2 Data tables - Pollen

6.2.1 Modern pollen samples

Table 2. Count sheet of pollen from modern surface samples (Yakutia); samples counted by Steffi Gartz are indicated with an asterisk.

Sample name/ Taxa name	*Alnus glutinosa*	*Betula* sect. *Albae*	*Carpinus*	*Juglans*	*Larix*	*Picea*	*Pinus* subgen. *Diploxylon*	Pinaceae	*Betula* sect. *Nanae*	*Duschekia fruricosa*	*Pinus* subgen. *Haploxylon*	*Salix*	Cyperaceae	Poaceae	*Artemisia*	Asteraceae
07-SAS-01					2		18		68	14		2	108	65		
07-SAS-02					21		10	9	15	7	1	2	130	60		
07-SAS-03					2		10	9	67	9		9	81	49		
07-SAS-04					1		1		288				12	15		
07-SAS-05								4	117	2	2	19	68	100		
07-SAS-06							4		231	26		1	24	36	1	
07-SAS-07		2					2		192	22		39	32	52	1	
07-SAS-08							4	2	79	27		5	86	71		
07-SAS-09								3	68	19		28	45	117	1	
07-SAS-10		2							12	12	1	218	30	45		
07-SAS-11					1		8		37	10		6	113	56	2	
07-SAS-12					3		12		34	4		9	95	65	3	
07-SAS-13					28		3	4	115	9		9	64	16		
07-SAS-14					56				49	21	11	24	14	14		
07-SAS-15					154		1	5	76	10	13	17	16	5		
07-SA-LY					59		3		55	28		4	94	37		3
07-NA-01		11			9		24	1	301	13		1	1	9	6	
07-NA-02*							47	42	194	31	5	3		8	12	
07-NA-03*		4			3		17	14	172	29		4	17	9	11	1
07-NA-04*		6			4		16	26	164	55			8	9	14	
07-NE-01		4			26	70	83		70	27	6	6	5	5	6	
07-NE-02		4			24		40		125	163	1		2	6	1	
07-NE-03		6			24	2	48	1	85	34	2		4	3		
07-NE-04		5			12	3	58		110	83	3	1	11	8	1	
07-NE-05*		1			30		124	93	76	23	13		6	7	2	
07-NE-06*					12		185	71	52	16	2		1	12	4	
07-NE-07		4			4	9	163		98	68		1	3	9	1	
07-NE-08		1			12	1	139		114	33	5		1		2	
07-NE-09*					1	1	87	92	101	29	6	1	3	1		
07-NE-10		1			13	9	146		60	20	10		45	11		
07-NE-11*					2	12	57	121	105	27	2		6	6	1	
07-NE-12		1			32	2	164		116	25	8				1	
07-NE-13*					2		68	56	130	73		1		6	2	
07-NE-14*							216	111	93	29	12		1		3	
07-NE-15*					2		29	64	166	102			1	1	1	
07-NE-16					69	2	74		162	15	1		7	23	8	
07-WI-01		7			7	1	58	2	211	37			2	10		
07-WI-02							33		222	44		3	20	18		
07-WI-03					31	4	193	2	114	16	2	1	40	13		
07-WI-04*		1			7		147	15	104	25			6		2	
07-WI-05*					5	1	37	13	140	40		4	8	8	6	
07-WI-06		7			5	2	27	3	171	98			23	43	6	
07-WI-07		1			16	1	60		161	18			6	19		
07-WI-08	12	4			62	11	33	12	185	10		3	30	19	2	
07-WI-09		9				2	29		180	24		1	8	9		
07-WI-10					18	2	179	1	71	8	1		4	8		
07-WI-11					33	5	192	40	82	6	19		9	4		
07-WI-12	57	318			24	2	57		2	2		4	20	32	2	
07-YT-01	4	42			20	2	320						2	16		
07-YT-02	2	75			80	3	48	3	1			6	14	69	4	
07-YT-03	9	136	1	1	76		36		2	4	2	1	24	25	8	
07-YT-04	8	421			207	6	53	3	12	13		7	14	47	43	

Table 2. Continued.

Sample name/ Taxa name	A. *Matricaria* -Type	A. *Saussurea* -Type	A. *Senecio* -Type	A. subfam. Cichorioideae	Brassicaceae	Caryophyllaceae	C. *Stellaria holostea* -Type	Chenopodiaceae	*Epilobium*	Ericaceae	E. *Empetrum* -Type	E. *Vaccinium* -Type	Fabaceae	Fumariaceae	Gentianaceae	Gerianiaceae
07-SAS-01						1				13	6	7	2			
07-SAS-02		1	4			4				10		24				
07-SAS-03						3	1			12		43	4			
07-SAS-04											1	16	1			
07-SAS-05			1									18				
07-SAS-06												9	2			
07-SAS-07			2							1		6				
07-SAS-08										6		31				
07-SAS-09	2		1							2	5	16				
07-SAS-10		1										4				
07-SAS-11						5						73				
07-SAS-12					1	3						80	1			
07-SAS-13						2				14	9	114				
07-SAS-14			2								15	121				
07-SAS-15	1										12	54				
07-SA-LY	1	1	1			1				3		6				
07-NA-01			2					1			1	4				1
07-NA-02*								1			5			7		
07-NA-03*			1		1	1		1	4				5			
07-NA-04*											53					
07-NE-01								1				3				
07-NE-02												2				
07-NE-03												98				
07-NE-04										3	2	16				
07-NE-05*										28						
07-NE-06*										5						
07-NE-07	1											1				
07-NE-08																
07-NE-09*										3						
07-NE-10												2				8
07-NE-11*			2						1	25						
07-NE-12												15				
07-NE-13*				2						9						
07-NE-14*										5						
07-NE-15*								1		31						
07-NE-16			2	4	1	3		2				24				
07-WI-01			1								5	66				
07-WI-02	1		2							11		26				
07-WI-03					1					3	1	4				
07-WI-04*										7						
07-WI-05*					1					76			1			
07-WI-06	3	2	1									19				
07-WI-07				1								74				
07-WI-08											6	42				
07-WI-09											1	91				
07-WI-10										17	2	10			1	
07-WI-11									2	7						
07-WI-12			1							2	3	43	1			
07-YT-01		3									5					
07-YT-02				6		3					7	106	2			
07-YT-03				36	2							6				
07-YT-04				7		1						1				

Table 2. Continued.

Sample name/ Taxa name	Indeterminate	Lamiaceae	Liliaceae	Linaceae	Malvaceaeae	Papaveraceae	*Plantago*	Plumbaginaceae	Polygonaceae	P. *Polygonum bistorta* -Type	P. *P. viviparum* -Type	Primulaceae	Ranunculaceae	R. *Pulsatilla* -Type	R. *Thalictrum*	Rosaceae - operc.
07-SAS-01	4												1			
07-SAS-02	1					1			1							3
07-SAS-03	3										1					4
07-SAS-04					1											
07-SAS-05	3												2			
07-SAS-06	1						1						1			1
07-SAS-07	6	1							1			1	1			
07-SAS-08	1															
07-SAS-09	9			1												
07-SAS-10	2															2
07-SAS-11	4	1											2			7
07-SAS-12	8										1		1			10
07-SAS-13	4															
07-SAS-14	1															
07-SAS-15	2	1														
07-SA-LY	4												3			
07-NA-01															1	
07-NA-02*	3		2												4	
07-NA-03*	3												14		2	1
07-NA-04*	5							1					1			
07-NE-01	2														4	
07-NE-02																1
07-NE-03	2															
07-NE-04	1															
07-NE-05*	4															
07-NE-06*	1							1					2			
07-NE-07	2												3		2	
07-NE-08																
07-NE-09*	6												7		1	
07-NE-10		1						1	4	1					2	
07-NE-11*	5	1											2			
07-NE-12	1														1	
07-NE-13*	1												1		1	3
07-NE-14*													1			
07-NE-15*	2															
07-NE-16																
07-WI-01	1												6			
07-WI-02	6											1	2			
07-WI-03													5			1
07-WI-04*	5		1										3		2	
07-WI-05*	5												6			1
07-WI-06	1												2		2	
07-WI-07	2														1	
07-WI-08	2															
07-WI-09	1															
07-WI-10	1															
07-WI-11													1			
07-WI-12	1												3			
07-YT-01														4	1	
07-YT-02	2					1							24			
07-YT-03	1					3			1				33			1
07-YT-04	3	2							1				5		5	

Table 2. Continued.

Sample name/ Taxa name	Rosaceae + operc.	R. *Dryas*	R. *Rosa canina*	*Rumex*	*Sanguisorba officinalis* -Type	Saxifragaceae	*Scabiosa*	Scrophulariaceae	*Valeriana*	*Potamogeton*	*Botryococcus*	*Pediastrum*	*Botrychium*	*Dryopteris filix-mas*	*Equisetum*	*Lycopodium annotinum*
07-SAS-01		2							1						1	1
07-SAS-02					1	2					5	9			9	1
07-SAS-03						3		1					23		1	
07-SAS-04																
07-SAS-05						1			1						2	2
07-SAS-06																
07-SAS-07													1			
07-SAS-08																
07-SAS-09																
07-SAS-10																
07-SAS-11	3					14		1	1				1		1	
07-SAS-12	1					4									3	
07-SAS-13									1							
07-SAS-14	1														2	
07-SAS-15	1			1											2	
07-SA-LY		3				1				1						
07-NA-01																
07-NA-02*															2	
07-NA-03*					13			1							4	
07-NA-04*			1												1	
07-NE-01								1								
07-NE-02				1												
07-NE-03							1	1						1		
07-NE-04								1								
07-NE-05*					2											
07-NE-06*															1	
07-NE-07			1													
07-NE-08																
07-NE-09*								1								
07-NE-10																
07-NE-11*						2										
07-NE-12								2								
07-NE-13*						2										
07-NE-14*																
07-NE-15*																
07-NE-16					2											
07-WI-01																
07-WI-02						1		1								
07-WI-03																
07-WI-04*															1	
07-WI-05*					1										1	
07-WI-06					3			2								
07-WI-07																
07-WI-08					1											1
07-WI-09								1								
07-WI-10															1	
07-WI-11																
07-WI-12	1		3												3	
07-YT-01																1
07-YT-02			4					3								1
07-YT-03								1								
07-YT-04						1									3	

Table 2. Continued.

Sample name/ Taxa name	Polypodiaceae	*Riccia*	*Selaginella rupestris*	*Sphagnum*	trilete spore	*Arcella* sp.	*Arcella arenaria*	*Assulina muscorum*	*A.* sp.	*Centropyxis aerophila*	*C.* sp.	*Nebela* sp.	Testaceae sp.	*Trigonopyxis* sp.	"Asco spore"	*Macrobiotus ambiguus*
07-SAS-01				2		1		154			76		4			
07-SAS-02	1			4	8						6		7			
07-SAS-03	4			2	2	5	3	32			21	14	9			2
07-SAS-04								5			1					
07-SAS-05	1			1				21			3					
07-SAS-06								23			4					
07-SAS-07								26			7					
07-SAS-08				2				47			5		1			
07-SAS-09						1		22					2		14	
07-SAS-10								2			3					
07-SAS-11						2		72			11					
07-SAS-12						2		28							3	
07-SAS-13				1				77			2					
07-SAS-14				1		1		44			2					
07-SAS-15						1	2	206			5					
07-SA-LY				2		1		145			353				5	
07-NA-01							2	36	2	1	192					
07-NA-02*					2			49			35		2			
07-NA-03*						24		115			332	9				
07-NA-04*						6		38			47					
07-NE-01					2	1		23			47				1	
07-NE-02						3		13			33	1				
07-NE-03	1							121			56	4				
07-NE-04								79			800	10	1		1	
07-NE-05*						7					396					
07-NE-06*					3	2		1			70	4	2			
07-NE-07					1			42			74				2	
07-NE-08								13			15					
07-NE-09*						1		25			37	14				
07-NE-10				1	4	11					19				1	
07-NE-11*					1	4		34			12					
07-NE-12					2	2		42			7	1				
07-NE-13*				2	3	3		63			23					
07-NE-14*				1				3			8	16				
07-NE-15*				2	1			27			12	2				
07-NE-16					1	6		24			94					
07-WI-01						1		21			63					
07-WI-02								118			257					
07-WI-03						1	5	59			62					
07-WI-04*				1	1	6		108			191		1	2		
07-WI-05*					2	9		101			140					
07-WI-06				1	3	4		6			39	4				
07-WI-07		1			2	7		84			43	6	5			
07-WI-08				4		7	10	264			177					
07-WI-09					28	2		97			16		4	14		
07-WI-10				4		1	5	71								
07-WI-11			28			6		74			22					
07-WI-12				5		1	1	104			50					
07-YT-01				2		4	2	105								
07-YT-02				5		1	16	104			22					
07-YT-03				1			8	166			38					
07-YT-04			1			1	7	396			140					

Table 2. Continued.

Sample name/ Taxa name	*M. areolatus-richtersi*	*M. harmsworthi-echinogenitus*	*M. hufelandii*	*Delitschia*	*Gelasinospora* sp.	*Glomus*	Microthyrium sp.	*Podospora*	scalariform perforation plate	s-spore	Stomata	Tracheids	Type 8C	Type 187	Type 225	Type 354
07-SAS-01			2				3									
07-SAS-02						4	1		10		6					
07-SAS-03	3						14				17					
07-SAS-04							2									
07-SAS-05							8	3	3							
07-SAS-06							3								1	
07-SAS-07			3				24									
07-SAS-08							4				2					
07-SAS-09							5									1
07-SAS-10							5									
07-SAS-11							6		1		13					1
07-SAS-12							15				12					
07-SAS-13	1		1				24				4		24			
07-SAS-14							3			1	1		21			
07-SAS-15							6		2		2		27			
07-SA-LY			5				49		2							7
07-NA-01			2				3									
07-NA-02*																
07-NA-03*	5						1				2					
07-NA-04*							6									
07-NE-01	1		1								1					1
07-NE-02			1				2									
07-NE-03		7									5					
07-NE-04							1									
07-NE-05*																
07-NE-06*		1														
07-NE-07																
07-NE-08																
07-NE-09*							1									
07-NE-10						1			1							
07-NE-11*																
07-NE-12			1				2									
07-NE-13*			1													
07-NE-14*																
07-NE-15*			1				1									
07-NE-16			1				1				1					
07-WI-01			6													
07-WI-02						2	2		3			114				
07-WI-03			4	2				2			1		10			1
07-WI-04*			2				1									
07-WI-05*							2									
07-WI-06							1				1			2		
07-WI-07		1	2													
07-WI-08			2	3			8				2					
07-WI-09							8									
07-WI-10							3						23			
07-WI-11							3		2			18	2			
07-WI-12			1				4									
07-YT-01					2						7	1				
07-YT-02											5					
07-YT-03			1				6				10	6				
07-YT-04			13				11				4					

Table 2. Continued.

Sample name/ Taxa name	U2	U2a	Zygnemataceae	zool. remain	chironomids	*Lycopodium* marker spores	Total sum
07-SAS-01				35		447	314
07-SAS-02	6	1	13	28	1	374	307
07-SAS-03			53			1152	311
07-SAS-04				6		79	336
07-SAS-05				78		354	338
07-SAS-06				74		376	338
07-SAS-07				63		392	361
07-SAS-08				37		890	312
07-SAS-09				54		474	317
07-SAS-10				41		249	329
07-SAS-11				48		292	344
07-SAS-12				7		217	335
07-SAS-13				100		327	392
07-SAS-14				91		289	329
07-SAS-15				41		150	369
07-SA-LY				53		335	308
07-NA-01				13		81	386
07-NA-02*				28		547	364
07-NA-03*				73		547	328
07-NA-04*				10		83	363
07-NE-01				27		212	319
07-NE-02				15		102	370
07-NE-03				27		589	311
07-NE-04				22		156	318
07-NE-05*				16		96	409
07-NE-06*				1		53	364
07-NE-07				17		41	370
07-NE-08				3		280	308
07-NE-09*				6		131	340
07-NE-10				8		79	334
07-NE-11*				17		105	377
07-NE-12				4		80	368
07-NE-13*				11		96	357
07-NE-14*				4		14	471
07-NE-15*				8		80	400
07-NE-16				11		42	399
07-WI-01				11		76	414
07-WI-02				80		109	391
07-WI-03				41		43	431
07-WI-04*				32		122	325
07-WI-05*				21		178	353
07-WI-06				6		52	420
07-WI-07				4		99	360
07-WI-08				17		155	434
07-WI-09				30		143	356
07-WI-10				14		152	323
07-WI-11				22		100	400
07-WI-12						114	578
07-YT-01						34	419
07-YT-02				18		168	463
07-YT-03		1		13		166	409
07-YT-04				22		151	860

6.2.2 Fossil pollen samples – PG1756

Table 3. Count sheet of pollen from fossil samples of sediment core PG1756 from Lake Billyakh.

Core depth, cm	*Betula* sect. *Albae*	*Pinus* subgen. *Diploxylon*	*Picea*	Pinaceae	*Abies*	*Larix*	*Duschekia fruticosa*	*Betula* sect. *Nanae*	*Salix*	*Pinus* subgen. *Haploxylon*	*Juniperus*	*Ephedra*	Cyperaceae	Poaceae	Apiaceae	*Armeria*	*Artemisia*
1	3	120	50			17	54	180	5	9			17	31			4
25	2	139	9	3		8	25	235	3	34			66	51		1	
30	59	98	12			5	79	211	5	12	1		35	30		1	6
35	5	63	5			7	48	255	2	12			87	61			1
45		107	18			44	50	349	4	28			83	57			7
60	9	61	19			6	57	219	10	21			39	58		2	1
65	3	73	12	2		6	68	226	9	9			27	35		3	1
70		125	5			11	71	334	3	8			44	73			1
75	4	101	16	11		10	37	231	4	10			57	43			1
80	1	133	6			9	67	340	5	5			62	37			4
85		100	12			16	67	203	3	3			72	36			2
90		154	13			14	73	223	6	10			35	42			2
95		107	8			6	71	237	4	9			35	33			2
100	6	46	14	11		3	120	273	11	4			44	35			6
105		117	9			9	38	250	4	7			75	40			2
110	1	184	8			15	73	312	8	13			59	38			2
120		123	2			4	91	246	6	3			31	20			3
125		184	6			11	44	243	3	3			45	23		2	1
130	3	186	29		1	24	30	195	3	6			29	24			
135		151	6			10	80	242	6	1			29	30			1
140	2	191	6			13	106	349	7	11			42	33			4
145		160	6			11	35	233	4	5			62	39			1
150	9	113	90	1		25	20	172	4	4			48	22			3
155		155	3			10	43	305	4	1			40	26	1		4
160	2	220	2			9	64	299	5	7			24	23			4
165		140	5			6	49	235	5	3			58	26			2
170	7	175	24			61	40	307	5	33			62	42			5
175		151	5			16	67	318	11	13			48	23			2
185		119	4			7	67	301	10	1			58	42			
190		126	101		1	7	43	266	3	2			44	22			3
194		88	4			11	43	224	5	2			74	91			
195		109	7			4	91	309	4	8			32	19			9
200	4	188	12	2		22	35	270	3	9			41	36			
204	6	177	31			27	33	324	1	13			24	19			6
209	2	123	7			4	80	331	6	2			39	32			2
214		69	6				59	392	6				20	16			6
219	1	150	2			10	58	332	6				33	31			1
224	2	154	25			38	32	320	3	22			19	24			2
229		170	7			25	65	306	6	7			37	65			2
234	1	118	8			3	79	360	9	11			34	24			3
239		125	5			6	56	321	7	2			38	34			3
244	2	132	35			23	46	285	6	28			16	18		2	2
249		142	11			11	72	310	8	4			27	34			2
264		74	38	1		22	78	376	5	13			19	46		2	
269		153	5			8	36	310	7			1	24	25			
279		53	5			4	51	354	11	6			25	39			3

Table 3. Continued.

Core depth, cm	*Betula* sect. *Albae*	*Pinus* subgen. *Diploxylon*	*Picea*	Pinaceae	*Abies*	*Larix*	*Duschekia fruticosa*	*Betula* sect. *Nanae*	*Salix*	*Pinus* subgen. *Haploxylon*	*Juniperus*	*Ephedra*	Cyperaceae	Poaceae	Apiaceae	*Armeria*	*Artemisia*
284	1	112	17			22	34	266		12			16	30			
289		93	8			7	41	325	5				24	28		1	
294	2	13	37		10	4	51	461	12				35	25			2
299		35	4	1		12	57	385	3	1			35	42			1
304		35	39			10	42	412	3	1			31	28			8
309		40	13			17	41	352	7				43	40			5
314		2	3			8	102	621	7	19		1	54	35			4
319		22	1			5	44	408	4				36	47			2
324	1	2	33			9	45	459		11			18	30			4
329		10	9			10	45	365	3				51	58			
334	13	2	4			4	53	530	5				42	30			5
339		4	11			9	80	401	4				16	40			2
344			13			33	77	550	9	15			26	22		2	4
349		7	1			6	40	461	1				12	20			1
354						7	54	653	7	6		1	18	12		1	5
364	1			1		4	30	663	5	4		1	7	27			
369		3					32	468	2				12	17		1	
374	2			2		3	18	576	8				17	24		1	3
379							16	554	4				7	30		1	
384						14	24	654	4	1			15	18			14
389						4	167	367	3				24	113		2	5
394	18					4	99	204	1	1			68	100			24
399		1				3	179	174					109	131			11
404	14			1			98	226	2	2			79	72			13
409		2		1		2	115	208	4				88	70			18
414	17			1		1	159	271	5				46	29			3
419							15	300	1				136	70		1	13
424				1		5	37	190	3				162	63			22
429						3	1	9	2				261	159			11
434						2	16	32	4				208	140	1	1	55
439				1				4	1				306	137		1	21
444		1				1	11	38	2	2			270	133			17
449						2		2					305	157			24
454				5		9	11	13	2		1		226	140	1		41

Table 3. Continued.

Core depth, cm	Asteraceae subfam. Asterioidae ind.	A. subfam. A. *Matricaria*	A. subfam. A. *Saussurea*	A. subfam. A. *Senecio*	Asteraceae subfam. Cichorioideae	Brassicaceae	Caryophyllaceae ind.	C. *Cerastium*	C. *Minuartia*	C. *Stellaria holostea*	Chenopodiaceae	*Circaea*	*Epilobium*	Ericales ind.	Ericaceae *Empetrum*	Ericaceae *Vaccinium*	Fabaceae
1											2		1			2	
25					1		1						1	6		1	
30					1	2	1								7	5	
35		1			1	1	2						2	6	1	1	
45				2	2		4						1	12	3		
60						1	3	1							5	2	
65				1			1						1	1			
70							5				1		2	14			
75				1	1		2			1			2	4			1
80				2			2							16	2	1	1
85		1			2		5				2		1	7	3		1
90				1	1	1	3			2			1	7			
95		1					1							5			
100							1									3	
105			1				3				1			12	1		
110							1				1			8			
120							1						1	6		1	
125					1		3						1	4		1	
130					1		3							4			
135							3							6	1	1	
140					1					3	1		1	9	3		
145					2									2		4	
150																2	
155							2				1			3		3	1
160							3				1			6		1	
165					1		1			1	1		2	3		3	
170			1				1						1	3			
175				1			1							4		1	
185					2	1	2				1		1	3		2	
190				1	1		5				2		2	1		2	1
194					1		4				1		1			6	
195					1		4			1				3		1	
200							2						1	1	2	1	
204							3							4			
209				2	1	1							1	3			2
214					2		1									1	
219			1	1		1	2			1				3			
224							2						2	2		1	
229					1	1	2							6		4	
234					1		1				1			2			
239					1							1	1	6		3	
244					2								1	4			
249					1		2							1			
264					1		5				1			8			
269				1	3		2							2		4	
279		1			1		2				1			3			

Table 3. Continued.

Core depth, cm	Asteraceae subfam. Asterioidae ind.	A. subfam. A. *Matricaria*	A. subfam. A. *Saussurea*	A. subfam. A. *Senecio*	Asteraceae subfam. Cichorioideae	Brassicaceae	Caryophyllaceae ind.	C. *Cerastium*	C. *Minuartia*	C. *Stellaria holostea*	Chenopodiaceae	*Circaea*	*Epilobium*	Ericales ind.	Ericaceae *Empetrum*	Ericaceae *Vaccinium*	Fabaceae
284				1	1		4						1	7		1	
289							1									1	
294					1		1									1	
299				1	2		1				1		1	1			
304					1		4							4		2	
309			1	1	1		3							6		2	
314	1				1	3	1				1			3	2	2	
319			1		1		1									1	
324				2									1	3		1	
329					2		5			2				6		2	
334				1	2	2							1		2	1	
339			1											5		5	
344							1				1			1			
349																	
354											1			2	1		
364				1									2			1	
369																	
374			1			1	1						1		2	4	
379							1				1	1					
384						2	1							1			1
389				1	1		2				1	1	1				1
394				2			3			1	4					3	
399		1			1		6		1		2		3	3		2	
404				1	3	2	2				7		1			2	
409			1	2	2	1	7	1		1	3			3			
414					2					2	1		1				
419					4		3	1			6			5	1	8	
424				2	6		8				7			10		10	
429		1		3	7		27			8	9		1	7		1	
434		2			3		18				8			1		1	
439				5	9		15	1	1		2		1	1		2	1
444		1	3	2	7		24	1		2	3			4			
449			1	1	9	1	24		1	2	1						1
454				3	7	1	21	5		3	1		3	1	1		

Table 3. Continued.

Core depth, cm	Indeterminate	*Knautia*	Lamiaceae	Liliaceae	Papaveraceae	*Plantago*	*Polemonium*	Polygonaceae ind.	*Polygonum bistorta*	*P. viviparum*	*Rumex* ind.	*Rumex aquatilis*	Primulaceae	Ranunculaceae	R. *Thalictrum*	Rosaceae + operculum	R. - operculum
1	4														1		
25								1						4			
30	2	1			1									1			
35	1													7	1		
45	5													7			
60	2								1					1			
65	1													2			
70	1													2	1		2
75	1				1									3			
80	2													8			
85	1							1					1	6			
90																	2
95														6			
100	3				1										1		
105	2													2			
110	1													3			
120														2	2		1
125	1							1						2			
130	1													4			
135	3											1		3			
140	1													2	3		
145											1	1					
150														1			
155											2		1	1	1		
160	1				3			1						1			
165	2													3	1		
170	2						1							2	1		
175	1							1						4			
185	1													6	3		2
190	3														1		
194								1					2	1			1
195	1													1			1
200	2												1	3			
204								3						2	1		
209	2													6	1		
214														1	3		1
219	1							1						2			
224																	
229	3							1						8	2		
234								2							2		
239	2													2			
244	1													4		1	
249														4	1		
264	2							2									
269	1													4			
279	2													3		1	

Table 3. Continued.

Core depth, cm	Indeterminate	*Knautia*	Lamiaceae	Liliaceae	Papaveraceae	*Plantago*	*Polemonium*	Polygonaceae ind.	*Polygonum bistorta*	*P. viviparum*	*Rumex* ind.	*Rumex aquatilis*	Primulaceae	Ranunculaceae	R. *Thalictrum*	Rosaceae + operculum	R. - operculum
284														4	1		
289	2													2			
294	1								1								
299	3													3	1		1
304	2														1		
309	1													5	1		1
314	3													2	2	2	
319	3													1	1		
324								1						1	1	1	
329			1					1						7			
334	1														1		
339														1			
344	1													1	3		
349															1		
354	1														1		
364	1																
369	1													1			
374					1												
379	1													1			
384	1													4	1		
389	1													7	2	1	
394	4		1												2		
399	2				1									20	5		
404	3		2							1				3	5		
409	1					1								8			
414	2													1	3		
419	6				1			1						3	1		1
424	5		1											13	10	1	1
429	9				2	4								28	3		
434	12		1		7			2						9	1		1
439	6				3	1			3					18	1		
444	6		1					1	1					17	1	1	2
449	2				1	1	1	3			1		1	23	2		1
454	11		1		5			1					1	6	1		

Table 3. Continued.

Core depth, cm	*R. Potentilla*	*R. Sanguisorba officinalis*	Saxifragaceae	Scrophulariaceae ind.	*S. Pedicularis*	*Valeriana*	*Myriophyllum*	*Nuphar*	*Potamogeton*	*Botrychium*	*Cystopteris fragilis*	*Dryopteris filix-mas*	*Equisetum*	*Isoëtes*	*Lycopodium annotinum*	*Lycopodium clavatum*	Polypodiaceae
1			1						1					62	2		3
25			1			1			2	7			3	5	1		6
30		1				3						1			1		11
35			1						1	8		1	5	23	2		10
45						2		1					4	14	2		11
60															1		9
65				3					1				1	49	3		8
70												3	2	17	8		10
75						1			1	4		1	2	13	2		12
80													2	5	1		8
85										1			3	12	4		13
90												1		15	5		7
95			1			2						1		23	1		6
100			1											2			5
105												5	1	3	2		18
110												2		24	1		7
120													2	26			2
125			1									2	2	22	2	2	8
130												1	1	6	1		6
135												1	1	30	2		6
140										1			1	7			5
145									1			2	1	16	2		9
150														1	3		9
155			1											26			13
160						2								5			4
165									2		1	1		13	1		6
170				1		1						1		12	2		12
175									1			1	3	15			2
185							1					1	1	16	1		6
190														5			6
194			1			2	2		1			1		5	2		9
195													1	3	2		7
200							2		2		1	1	1	5	4		2
204												1	1	15			10
209						1			1			2	2	18	2		6
214									2			1			1	1	2
219				1	1				4			2	1	12	1		7
224														3	1		4
229										1		1		37	2		7
234									2			3		12	3		2
239						1	2		2			1		7	3		4
244													4	10			1
249									4			1	2	21			2
264													1	8			8
269			1						1			1	3	11	1		1
279			1						1				2	33			3

Table 3. Continued.

Core depth, cm	R. *Potentilla*	R. *Sanguisorba officinalis*	Saxifragaceae	Scrophulariaceae ind.	S. *Pedicularis*	*Valeriana*	*Myriophyllum*	*Nuphar*	*Potamogeton*	*Botrychium*	*Cystopteris fragilis*	*Dryopteris filix-mas*	*Equisetum*	*Isoëtes*	*Lycopodium annotinum*	*Lycopodium clavatum*	Polypodiaceae
284														5	5		7
289									1				3	16	1		2
294									1			2			1		8
299														21	1		4
304			1	2		1			1				2	28	3		8
309	1										3	1	5	26	1		7
314									4			1		39	1		6
319									4				1	36	5		5
324						1			2				2	21			8
329						1			2			1	7	6	5		6
334									3	1		1			1	2	7
339		1				2	1		1				1	5	2		3
344									1				2	7	3		4
349											2	3	1	2	4	1	1
354									1				3	10	2	1	4
364						1								9			7
369													4		2		2
374									2			1			1		2
379									4				4		4		5
384									4						4		6
389			1									3	3		1		13
394		3	1			1						4					12
399		3	4			1							2		1		19
404		2		1		1									1		18
409		4	1			1						6	3		2		12
414												3					8
419			3			1				1			1				13
424				1									1				5
429	1	1				7											9
434		1	2			3							1		2		2
439		1	1			4											3
444		2	1			1											2
449			1			8											4
454		2	1			3											4

Table 3. Continued.

Core depth, cm	*Riccia*	*Selaginella rupestris*	*Sphagnum*	*Woodsia*	*Arcella* sp.	*Nebela* sp.	"Asco spore"	*Gelasinospora* sp.	*Glomus*	*Macrobiotus hufelandii*	*Microthyrium* sp.	Podospora	scalariform perforation plate	Sordariales	s-spore	Stomata	Tracheids
1		1	1										3		5		
25		3	19										26			3	3
30		3	33										4				
35	1	5	30										22	1		5	7
45		2	85				1				1		41		19	8	5
60		3	32										5			2	3
65			15							1			10	2	4	2	7
70		4	55										36			3	8
75		1	15										17	1	2	3	13
80		3	39										14			3	4
85	1	3	41										15			7	8
90	1	5	37										16			2	6
95			13										8		4	3	5
100		3	22										3			1	
105	2	2	11						1				14		1	8	3
110		2	17										16			3	3
120			21										10			1	6
125	1	4	12										8			2	5
130		4	20				1						14		1	1	3
135		7	6										3	1	2		4
140		6	30										31			1	12
145	1	6	10									1	5		1	5	3
150			11	1									2				
155		6	2						1				9				3
160		2	8										5			1	2
165		2	11										19			5	2
170	1	4	16						1				31		7	1	3
175		4	8										13			2	5
185			2										5			4	
190		7	11	1			1	1					13				1
194		4	17								1		20	2		3	6
195		3	8										9			1	3
200		4	10		1	1							14	1			4
204		3	5									1	11		2	1	2
209		5	10										4	1		2	2
214		1	14						1				10			1	
219		1	7									1	6	2		2	3
224		1	4										10		6		3
229		5	21									1	16	1	1	1	1
234			6										9		2	2	2
239		4	7										7		3	3	2
244		1	2									2	1		23		4
249		3	4										11		1	1	1
264		5	8				1						23		24		2
269		2	1					1					7		2	1	2
279		1	7										6	1	3	1	

Table 3. Continued.

Core depth, cm	*Riccia*	*Selaginella rupestris*	*Sphagnum*	*Woodsia*	*Arcella* sp.	*Nebela* sp.	"Asco spore"	*Gelasinospora* sp.	*Glomus*	*Macrobiotus hufelandii*	*Microthyrium* sp.	Podospora	scalariform perforation plate	Sordariales	s-spore	Stomata	Tracheids
284		1	7										8				1
289		3	1										4			1	1
294		1	7										3		1		
299													7		2	2	1
304		2	4										4		2		
309		1	5										16			1	3
314		1	10										6		2		2
319		1	3										5			1	
324		1	1										8		2		
329	1	4	6						1				18		2	3	1
334		2	8										9				1
339		2	6									1	5			3	
344		2	1										10			1	1
349		2	5						1				5		4	1	
354		2						1					4				
364												1	2				
369		3	2								1				2	2	
374													1				
379															3	1	2
384													4				1
389		2							1	1					6	3	
394		2	1						2				3			3	
399		12						1	1				19	1	21	2	3
404		4											3				
409	1	5							2		1		4		22		
414		3											1				
419	2	9	2							1			3		30		
424	2	8	2						2		1		5	2	88		1
429	4	40	1						5		4	2	14				
434		23							2				16		31	1	
439	3	22							2				8	5	4		
444	1	18	1						4				6	1	11		
449		19							4			1	11	2			
454	3	22							1				54		3	2	2

Table 3. Continued.

Core depth, cm	*Trichocladium*	*Thekaphora*	Type 119	Type 187	Type 225	Type 307B	Type 354	U2	U2a	zool. remain	chironomids	*Botryococcus*	Copepoda spermatophore	*Mougeotia*	*Pediastrum*	Zygnemataceae	spore red.
1					159					24	1	27			10		
25					83		1	1	2	31	1	86			75	3	
30					315		3		2	22	4	42			1	1	
35					88		4	1	4	33		53			114	5	
45					124		3	6	4	40	2	118			125	3	
60					109		10		1	28	2	34			7		
65					135		10		4	56	3	85			81	1	
70				1	108		6	1	1	23	3	63	2		21	4	
75					55		3	2	1	19	1	115			93	2	
80					58		3	3		17	3	83			19	2	
85					108		4			23	2	90	3		61		
90					53		5	1	1	16		55	3		24	1	
95					73		1	1	3	15	1	107			47		
100			8		126			1		11	3	87			15	3	
105					68		2		2	21	2	100			59	2	
110					181		11	1		30	2	113			78		
120					101		9	1		15		61	1		21	2	
125					63		3	2	1	32	3	69			82	1	
130		1			2		1			15		61			14		
135					62		6	1	1	21	1	118			81	5	
140					42		8	1		15	3	76			12		
145					94		6	3	3	17	4	96			76		
150			4		13					5	2	57			14	2	
155					138	1	2	1		19	2	42			62	1	
160					115		2	1		8	2	22	2		43	3	
165					106		2		4	12	1	69			53	1	
170					26		4			17		93			38		
175					169		4	6		33	3	115	1		68	3	
185					99		8		1	2		100			73	10	
190			11		5			1		16		93			11	2	
194					89		2			6	3	78			38	3	
195					77	1	9			6		86			33	8	
200		1			21		4			13	3	63			14		1
204					14		7	2		18	1	88			23	2	
209					93		5	2		9		84			48	2	
214					51			3	3	9		42			12	2	
219					149		5	3	1	15	1	118			97	3	1
224					14	1	3			13		94			15		
229					158		7	3	1	6	1	78			84	1	
234					198	1	16			11		56			27	4	
239					156		6	2	1	7		93			99	3	
244					24		2	1		11	4	106			13		
249					188		7	1		12		95			65	2	
264					34		1	5		10	3	147			14	1	
269					66		5			6	5	113			81	2	
279					38		7			10		103			57	2	

Table 3. Continued.

Core depth, cm	*Trichocladium*	*Thekaphora*	Type 119	Type 187	Type 225	Type 307B	Type 354	U2	U2a	zool. remain	chironomids	*Botryococcus*	Copepoda spermatophore	*Mougeotia*	*Pediastrum*	Zygnemataceae	spore red.
284					15		2			4	1	73			8	1	
289					101	1	2	4		18		74			64	1	
294					29					4		44			1		
299					88		9			10	2	165			57	1	
304					3		3	2		5		118			31	1	
309					6		5	2		10		144			46	2	
314					17		7		1	5	3	131			31	5	
319					2		5			5	1	82	1		37	2	
324					4		2			5	1	98			11	3	
329					36		3	2		13	1	91	1		57	4	
334					3					3	2	91			5	2	
339					41	1	4	2	1	8		39	9		22		
344						1	1			9	2	103			12		
349					2		1	2	1	15	2	78			24	1	
354							7			8		118			27		
364										17	1	152			11	1	
369							1	1	2	11	1	65			19		
374										5		74			14	1	
379										5		61			40		
384										5	3	78			8		
389						1				10	3	57			68	3	
394				1				31		20	9	62			145	1	
399					1	1	3	51	2	37	5	82			258	9	
404		2	2			2		2		27	18	64			146	2	
409						1	2	10		43	6	63			224	6	
414								10		7	10	54			102		
419							2	12		17	20	53			475	7	
424							3	2		21	14	34			64	3	
429		1						9		31	8	18			21	21	1
434		3			2			3		11	12	19			8	7	
439	1	1						4		36	10	15			36	26	1
444		1						2		12	7	20		1	9	13	
449		3				1		5		24	21	32			13	14	
454					1		2	25	1	23	8	18			8	7	

Table 3. Continued.

Core depth, cm	*Lycopodium* spores	Total sum
1	156	502
25	178	595
30	95	579
35	107	572
45	137	786
60	65	518
65	103	485
70	72	703
75	113	544
80	60	703
85	91	545
90	38	590
95	61	528
100	22	583
105	94	573
110	72	727
120	36	543
125	81	580
130	67	543
135	72	574
140	87	788
145	58	567
150	68	514
155	58	608
160	37	678
165	81	549
170	75	775
175	51	668
185	82	634
190	95	637
194	59	566
195	88	605
200	64	639
204	77	674
209	57	649
214	67	585
219	76	643
224	39	648
229	77	718
234	79	661
239	47	618
244	36	608
249	60	634
264	88	693
269	57	588
279	53	567
284	60	530
289	36	539
294	30	658
299	43	591
304	43	628
309	64	581
314	46	883
319	55	582
324	45	626
329	81	580
334	46	702
339	57	584
344	37	760
349	33	550
354	26	771
364	43	749
369	18	537
374	33	667
379	25	621
384	17	759
389	46	705
394	87	544
399	112	663
404	97	543
409	147	545
414	50	544
419	131	581
424	196	558
429	641	565
434	351	531
439	359	547
444	420	556
449	448	576
454	1322	527

6.2.3 Fossil pollen samples – PG1755

Table 4. Count sheet of pollen from fossil samples of sediment core PG1755 from Lake Billyakh.

Core depth, cm	*Betula* sect. *Albae*	*Larix*	*Picea*	*Pinus* subgen. *Diploxylon*	Pinaceae	*B. sect.nanae*	*Duschekia fruticosa*	*Ephedra*	Ericales	E. *Empetrum*	E. *Vaccinium*	*Juniperus*	*Pinus* subgen. *Haploxylon*	*Ribes*	*Salix*	Cyperaceae	Poaceae
5	20	7	5	166		141	96				1		1		1	20	22
15	5	12	7	163		141	99				4		16		2	21	18
25	3	3	3	193	1	196	95		1		2		89		10	18	13
35	6	6	14	230		87	127				1		4		1	12	2
45	6	7	5	176		243	158		1		3		49		7	32	16
55	6	15	15	182		132	111				3		23			10	8
65		17		119		170	70		1			1	2		8	30	25
75	3	25	2	102		196	82						9		2	12	7
81	2	16	4	69		174	76						4		4	10	4
91	8	6	21	112		219	29						7		2	8	12
101	5	7	8	1		380	289				3		32		16	28	28
111	6	36	16	6		363	39								7	10	14
121		15		1		311	53						2		14	9	9
131		30		2		468	11									3	10
141		20		1		134	261		1						3	19	23
153					1	190	79				1				1	29	49
156				1		450	220		1	1	3				5	55	32
157	4					193	17				2				1	34	21
166		1				50	8		5						13	103	73
177		1			1	20	13				1				2	138	92
183		1			1		1		1							156	118
192		1		1												158	108
197				1		23	26								1	90	55
202					3	2										146	102
212					1	4	1								2	177	125
217	3				1	20	14		2	1					5	146	92
227			2		4	10							9		1	130	60
237					2	6	4						1			139	120
247	1			1	1	34	23		1		1				4	103	75
252		1							1							152	95
257					1	7	5									126	173
262					1											136	111
267						15	11									171	89
272		2							1							179	102
282					2	1										158	110
287		1			2	2	2									155	87
297		2			2	8										132	79
307				3		19	13				2					83	78
317		5			1	1			1							131	86
327					5	3	4									93	62
337		6			1	3									3	134	90
347	2					10	11									53	66
357		4			4	3	1		2						1	104	86
367		3			1	2	1		3							183	91
377		8			5	4	4									89	94
387						24	3		3							41	86
397	2	1				22	3								1	60	80
407		1			3	2	1									169	109
412		7			4	1	1									164	76
427	2			1		21	7			4					11	62	97
432		1			3				1							130	83
442		3		3	5	14			1							71	90
452		1		1	1	23	13			1					8	46	67
462		2			3	1										127	51

Table 4. Continued.

Core depth, cm	*Betula* sect. *Albae*	*Larix*	*Picea*	*Pinus* subgen. *Diploxylon*	Pinaceae	*B. sect.nanae*	*Duschekia fruticosa*	*Ephedra*	Ericales	E. *Empetrum*	E. *Vaccinium*	*Juniperus*	*Pinus* subgen. *Haploxylon*	*Ribes*	*Salix*	Cyperaceae	Poaceae
472		2			5	3			3						4	183	118
482		17		1	1	4			2				1			157	97
492	4				1	59	10								22	147	185
502		4		9	4	23	1								2	87	49
512		10			3	1	3		3							158	89
522		16			6		2		6		2		2			138	52
532		11			3	2										169	102
542		5		1	1	1			2						1	146	85
552		1				40	15								7	57	82
562		8				17	10				1				1	194	91
572		8			1	27	10		3	1	2					142	141
582		20			1	8	1		6							128	115
592	2					93	50				3				12	103	173
602		10				43	15		7		1					136	128
612	2	6				168	82		1		1					83	118
622		11			2	3	3		2		4				1	173	165
632	1	5				27	2			2					14	102	186
642		3				34	14		3		1					123	137
652		3			1	18	5		8							134	122
662		6				8	11		1		3		1		1	215	203
667						47	14		8	1					1	140	127
672	15	5				149	40			1					6	105	91
677		8			1	11	4		1				1			156	188
687	3	5				94	10			2	7				13	105	143
697		18				133	13		2		1				1	96	106
707	1					36	6		1		4					154	135
717		1			1	1	1		3							149	136
722		16		1		7	1									109	166
728		24			1	36	1		4							187	127
738		15		1		47	2		1		4					158	138
747	24	4				198	11			1	2				10	51	67
757					1	200	3				4					100	67
767		1				25	2			2	5				1	243	124
777		2			1	58	3	1	1	2	2				3	164	78
787	6			1	2	84	8								10	155	153
797					1	11	2		3		1				4	237	108
807		1			2	16			4		3				1	226	206
817					1	13			2		3				1	192	182
827	3	13		1		22	5			3		3			4	156	204
837						14										165	132
847	3	2				35	5				1				13	121	191
857					4	23	1									191	120
862		1			2	17			3						2	148	181
868					3	30	3		1		1					146	150
877					1	40	1				3					161	119
887	24	5			1	132	7	2		4				3	15	216	220
897					6	38	1				4				2	208	100
902					2	20	2									204	112
908					3	11	1								1	131	143
917					1	34					1				2	226	126
927	11					12	1			2					3	150	69
932		1				17	1		2							184	145
936		3			1	29			1				1		7	123	124

Table 4. Continued.

Core depth, cm	Apiaceae	*Armeria*	*Artemisia*	Asteraceae subfam. Asteroideae	A. subfam. A. *Matricaria*	A. subfam. A. *Saussurea*	A. subfam. A. *Senecio*	Asteraceae subfam. Cichorioideae	Brassicaceae	Caryophyllaceae ind.	C. *Cerastium*	C. *Gypsophila*	C. *Minuartia*	C. *Stellaria holostea*	Chenopodiaceae	*Cuscuta*	*Drosera*
5			3						3								
15		2	4														
25			3														
35			2														
45			6						12	1					1		
55								1									
65			2														
75			1							1							
81			1														
91		3	2														
101			18			1			5	3					2		
111			3														
121			2												1		
131			2														
141			8												1		
153			10					2		4							
156			24		3			1	12	1							
157			14			1			5	1					5		
166			35				2	2		6					7		
177			42		1			3		7	1				3		
183			32			1	3			17					6		
192			22			1	3	3		9					2		
197			25		4			2	4	7	2				7		
202	1		26				2	6		14				1	3		
212			26				5	5		16					1		
217			29				4	7		21				4	3		
227			67			1	1	11	1	7					1		
237			31				4	11	1	8	1		1	2	1		
247	3		17		2		1	1	8	9			1		1		
252			9		1		2	5	2	12					1		
257			25														
262			16				1	5		11					1		
267	1		46		1	2	2	15		8					1		
272		1	11				4	10		10							
282			35		1			4		8	1						
287			43				4	9		9				2			
297		1	48			1	3	13	1	19	2				1		
307			62		8			22	13	10	12				1		
317			52			1	2	17	3	15				1			
327			61			7		34		7							
337			26		1	3		6		12	1		1				
347			43		2	2		11	23	17	5						
357			41		1	2		19		10			1				
367			50				2	10	2	8							
377			46		1		2	20		15							
387	1		32		3			8	14	10	2		1		3		
397		2	20		1	4	1	14	6	6	3	1			4		1
407			36			2	4	18		21				2			
412			36			1	3	7		13					1		
427	2		56		11	10	5	7	26	21	10				3		
432			36		3	1		13	1	12							
442			69	1		1	2	13	1	11					1		
452	1		38		2		2	5	11	7	8				4		
462			66		2	1	2	17		10							

Table 4. Continued.

Core depth, cm	Apiaceae	*Armeria*	*Artemisia*	Asteraceae subfam. Asteroideae	A. subfam. A. *Matricaria*	A. subfam. A. *Saussurea*	A. subfam. A. *Senecio*	Asteraceae subfam. Cichorioideae	Brassicaceae	Caryophyllaceae ind.	C. *Cerastium*	C. *Gypsophila*	C. *Minuartia*	C. *Stellaria holostea*	Chenopodiaceae	*Cuscuta*	*Drosera*
472			45		1	1	1	9		16							
482		1	22		2		1	10	1	18							
492	1		49				1	2	9	9	6				3		
502			82		2	2	1	8		9	3						
512			27		1	2	3	8		25							
522			51					8		12					2		
532			22			1	4	5	3	18			3		5		
542	1		49			1	4	8		24							
552	2		40		1	1		2	3	3	7				1		
562			25		1	2	2			18							
572			38			3		3		16					1		
582			27		1	1	2	3		14	3			1			
592	1		63				6	3	7	2	1				1		
602			28			1	3	1	1	13	2			1	1		
612			15				1	2		8				1	1		
622		1	27		1		5	6		21			1			1	
632			33				3	2	4	9	3			4	1		
642		1	25		1	1	3	2	2	14			1	1			
652			34		3	5	6	2		14	1		1	4			
662	1		54		1		5	4	1	29				1			
667			24		3			1		22		1		5			
672	1		65				3		8	10	1			3	1		
677			23		1		2	4		13			1	1			
687	1		42					2	16	12	3			1			
697			21		1		4	1		12							
707			33		2	1	4	3		15		2		3			
717			46				2	2		10					1		
722			44				3	1		11							
728			8			1	5			12	2				1		
738			2			1	1	2	1	2	2		1	3			
747			32				2	1		7	2						
757			20		3		1			8							
767			30				1	3		15				4	1		
777			68		2	2	1	1	1	12							
787		1	15				5	1	4	10	6			1	1		
797	1		25		8			5		15	1			3			
807	1		16		8	1	1	4	2	26		2		5	1		
817			20		3	2	5	9	1	22					1		
827			16		3		6	5	1	20	2			1			
837			3				6	2		10				1			
847	1		10				3		3	9	9	1					
857			6		13			6		11			1	1			
862			4				3	6		8							
868			7				6	6		13			1	2			
877			3			1	2	3		14			1	1			
887	1		23				6	3	9	13	2				9		
897			6			1	5	4		17							
902			4				2	4		14				3			
908			7			1	2	5		13	1		2	2			
917			11		5	3	1	3		16				2			
927			5				7	2	2	6	1			4	1		
932			11		1	1	11	7		14							
936			12			2	6	3	1	12	2			4			

Table 4. Continued.

Core depth, cm	*Epilobium*	Fabaceae	*Galium*	Gentianaceae	Geraniaceae	Indeterminate	Lamiaceae	L. *Galeopsis*	Liliaceae	*Linum*	Papaveraceae	*Plantago*	*Polemonium*	Polygonaceae	P. *Polygonum bistorta*	P. *P. viviparum*	P. *Rumex*
5						9											
15																	
25						1								1			
35						1											
45						10	5										
55						2											
65																	
75																	
81																	
91						2											
101		8				11	13								1		
111																	
121																	
131		1															
141		1				1											
153						3											
156	1	30	2			4								1	1		
157		11	2			4	2								3	1	
166		2				10					1				1		
177		4				6					3	3					
183						3					2	3					
192												2			1		
197		5	1			8								8			3
202						2			2		1	1		1			
212						6						2		1			
217						1	2							2			
227	1					6	1				3						
237		1				4					1			2			1
247		8	3			10											
252					1	2	1				4					2	1
257						7											
262						7											
267		2				8					3			2			
272						5											
282		1				4					1	2				1	
287						7	1				1			2			
297						5					1	1					
307		10	3	2		10	1			2				5			6
317		2				10					1	2					
327						18											
337	1	2				3	2					1		1			
347		9		3		7								1			
357		1				3					2	1					
367	2	1				6								2			
377	1	1				12					1			1			1
387		7		1		31								6			
397		4				13					3	1		1			1
407						15	1				3		1	5			
412	1					8								4			
427					1	11											3
432						8							1	2			
442						14					3						
452	1	1		1		9								1			
462						6								1			

Table 4. Continued.

Core depth, cm	*Epilobium*	Fabaceae	*Galium*	Gentianaceae	Geraniaceae	Indeterminate	Lamiaceae	L. *Galeopsis*	Liliaceae	*Linum*	Papaveraceae	*Plantago*	*Polemonium*	Polygonaceae	P. *Polygonum bistorta*	P. *P. viviparum*	P. *Rumex*
472						9					2	2		2			
482						2					2			1			
492	1	2				15	1	3			1			3	1		1
502						15					7			1			1
512	1					5	1				1			3			
522						4					6						
532						6	3				1	2		4			
542						4						2		3			
552						11	2			1				1			
562						1					2			2	1		
572						4	1				2			3	1		
582	1					1					1	1		2			
592	1					4	1	1						5	2		
602						6	1				2	1					
612						3					3			4			
622						4					3			2			
632		2				10					1			2			
642						1	1							3			
652	2					2					2						
662	3	1				8					2	2		3	1		1
667		2				5	2						1	8			
672		6		2		22	2							1	2		1
677						4	2				1			4			
687	2					8	1							8			
697						2								7			
707	1	1				4					2		2	2			
717						2					1			2			
722						3	1				3						
728	1	1				5					1	2		1			
738											6	1					
747	1	3				8									2		
757						3					3			1			
767						1	1				2					1	
777		3				19	1				5			1			
787		1				9	1	1						8			
797	1					3										2	
807						3	1				5			2			
817						5	1				2						
827	1					1		4			2			3	2		
837	1																
847		1				7								3	1		
857	2					2	2							3			
862						6						1					
868						2								1			
877														2			
887	1	1				13					1		1	4	5		
897						3					3				1		
902						2											
908		1				1											
917	3					5	1									3	
927		1		1		11	1				1			2			
932						6	1										
936	1					7					2			4			

Table 4. Continued.

Core depth, cm	Primulaceae	Ranunculaceae	R. *Pulsatilla*	R. *Thalictrum*	Rosaceae - operc.	Rosaceae + operc.	R. *Dryas*	R. *Potentilla*	R. *Sanguisorba officinalis*	Rutaceae	Scrophulariaceae	S. *Pedicularis*	Saxifragaceae	*Valeriana*	*Valerianella*	*Myriophyllum*	*Potamogeton*
5	7	1		3													2
15		1							1								
25				1													
35																	
45	2	2		2		1			1		1						
55																	
65				2													
75		1															
81				1									1				
91		1															
101	11	4		6	2									1		7	
111				1													
121		2															
131		1															
141		1		8	1												
153		3															
156	3	9		5	1						2						
157	1	2		8													1
166		11		12		1			2				1				
177		15		1					1				1				
183		3											1				1
192		7															
197	13	11		4	2	1					9			1			
202				1					1		3			1			
212		12		1		1					2						
217		2		1					2					1			
227		10				2		3						2			
237		13		1		1			2		1			2			
247		23		10		2			1		4			2			
252	1	14		1	1			1	1					3			
257		5															
262		7									3			1			
267		17		1	1								3	1			
272		12		1		1					1			1			
282		10		2													
287		5							1				2	1			
297		10		1		1			1				2				
307		9		14	3	1					29			1			1
317		5		1							2		1				
327		9											5	3			
337		5				2								2			
347	12	9		12							30		2	2			
357		8				2			1				1	2			
367	1	3		6										3			
377		3		2		2								3			
387	6	12		7	1									1			
397	12	11		8		3	1				25		1	3			
407	1	12						2					2		3		
412	1	16		1		1		3	1					2			
427	16	8		12	6				1		24		3	3			4
432		4		1					3								
442		8			4	3					1		3				
452	22			16		1					8			1			
462		10		1	1			1	1		2			1			

Table 4. Continued.

Core depth, cm	Primulaceae	Ranunculaceae	R. *Pulsatilla*	R. *Thalictrum*	Rosaceae - operc.	Rosaceae + operc.	R. *Dryas*	R. *Potentilla*	R. *Sanguisorba officinalis*	Rutaceae	Scrophulariaceae	S. *Pedicularis*	Saxifragaceae	*Valeriana*	*Valerianella*	*Myriophyllum*	*Potamogeton*
472	2	12		1		3							5	4	1		
482		7		1									1	3			
492	3	2		10	1	1					19						
502		2			3	1		1	1		4		1	2			
512	1	21		1					4					1			
522		20		2		2							2	1			
532	1	17		3	1						1			1			
542	2	10							1					1			
552	6	2		8							11						
562		8		3					1				2				
572	1	12		1					2					3			
582		10		1							3			2			
592	1	8		8		2		1	2		7		1	1		3	1
602		18		2				1	3					3			
612		8		2					1					3			
622		28		4	1				1				2	4			
632		9		3			2				1	2	5	4			
642		16							3				2	1			
652	2	1		2	1				1				4	1			
662		16		3					5			1	1	2			1
667	1	12			1				3					1			
672	4	2		13	2				5		5		2	2			2
677		8		1	1	1			3				2	1			
687	21			6	1						5		5	2			
697	2	2		1					3								
707		2		3					4		2			3			1
717	1	15							1					1			
722		7				1			2		1		1	1			
728		23		1	1				1					1			
738		15		2									1	2			
747	1			2		1					2		4	1			2
757		1		3					4								
767	2		8	2					3				2	2			
777	1	2						1	4			1		1			
787	5	9		5					1		4		1	1		3	
797	1	1	4	2					5				2				
807	1	14		2					1					2			
817		1		2					3				1	1			
827				1					3		2		2	1			2
837		6		1													
847				9													
857		4		2					4								
862		1		1					2					1			
868		4		2					3				1				1
877	1	2			2				1					1			
887	2	11		8	1	1		1	4				2	4			
897		6		1										3			
902		4							1					1			
908		6							2								
917			1						1								
927				1	1		1		1		2		2	1			3
932		1							3		1						
936		6											3	1			

Table 4. Continued.

Core depth, cm	*Botrychium*	*Cystopteris fragilis*	*Dryopteris filix-mas*	*Encalypta*	*Equisetum*	*Huperzia selago*	*Isoëtes*	*Lycopodium annotinum*	*Lycopodium clavatum*	Osmundaceae	Polypodiaceae	*Pteridium*	*Riccia*	*Selaginella rupestris*	*Sphagnum*	trilete spore	Woodsia-Type
5	2						2	1			2			1	10		
15			1					3			6				3	2	
25							9	2			2			2	1		
35								1			5				3		
45	1		6								3			2	4		
55								1			8						
65			2				12				2				9		
75							1	1			3				1		
81							15				1				1		
91					1		1	1						1			
101	4		7								2			2	3		
111			2		1		2	1	3		7			1			
121							19	2			1				3		
131					3			3			1						
141								1			1						
153			5								5			1	2		
156		1	8								4			3			
157											1			2			
166								1			2			4			
177											2			3			
183		1												13		2	
192														13		1	
197	1		1		1				1		2		3	8			
202											2			16		5	
212											1		1	11		1	
217	1										2			11			
227	1													12			
237								1			3			12			
247			2								1			9			
252											4			15		2	
257											1						
262														14		1	
267								1			2			15			
272											5			10		1	
282					1									12		4	
287														12			
297											1			12	1	3	
307						1		2					1	22			
317								1			1			17		4	
327											11			9			
337											2		1	8		4	
347	1					1		1			3		1	15			1
357											2			13		7	
367											2		1	20	1		
377											3		1	26		1	
387			1		1	1							1	13			
397			1								2			19	1		
407											3		1	20			
412											2		1	31	1		
427						2					4			19	2		
432											1			30			
442											2			19		3	
452	2					1		1			1			16			
462						1					1			21		3	

Table 4. Continued.

Core depth, cm	*Botrychium*	*Cystopteris fragilis*	*Dryopteris filix-mas*	*Encalypta*	*Equisetum*	*Huperzia selago*	*Isoëtes*	*Lycopodium annotinum*	*Lycopodium clavatum*	Osmundaceae	Polypodiaceae	*Pteridium*	*Riccia*	*Selaginella rupestris*	*Sphagnum*	trilete spore	Woodsia-Type
472								1			4		1	32			
482	1							1			3			18		1	
492						1					3		1	22	1		
502								1						18		5	
512											3		3	41			
522											4			70		4	
532					1						6		1	32	1		
542											7			29			
552	1													9			
562											4		1	10		1	
572											5			30	1		
582						1					12			13		7	
592											1			9	3		
602											5			11	1		
612											1			11	2		
622											5			23		3	
632											3			7	1		
642											11		1	10			
652									1		7		1	20	1		
662					1						6			15			
667											5			15	1		
672								6			1			8			
677					1						10			9			
687											7			26			
697			1								5			11	1		
707			1		1			2	2		8			22			
717											7			22	2		
722											12		3	13		3	
728						1					13			15		3	
738			2		1						1			24			
747	1				1						5			12			
757											1			5			
767					1			1		1	3			19			
777											5			27			
787	1													4			
797								4			2			8			
807											5			10			
817											2			5			
827	6					1					1	1	1	1			
837	1				1						1		1	12		2	
847														3			
857											1			4			
862					2						5			4		1	
868													1	3			
877											2			7			
887								4					1	3	1		
897					1						8			7			
902											4			4		1	
908					1						2			3			
917						1		1			5		1	8			
927								8			12		3	12			
932					1						5			5		1	
936					1						3		1	5		3	

Table 4. Continued.

Core depth, cm	*Botryococcus*	*Pediastrum*	*Arcella*	*Assulina muscorum*	"Asco spore"	Copepoda spermatophore	*Delitschia*	cf. *Endofragmiella* sp.	*Gelasinospora* sp.	*Geumannomyces*	*Glomus*	*Macrobiotus coronifer-islandicus*	*M. hufelandii*	*Microthyrium* sp.	Podospora	scalariform perforation plate	Sordariales
5	99	10			1	24			1							7	
15	25	8				2										3	
25	123	3				14										1	
35	17	8		1												1	
45	220	7			4	4								1		6	
55	17	15														1	
65	58	14				7										4	
75	64	17														1	
81	82	10				7											
91	38	6														1	
101	330	10		1	8	3			2							6	
111	111	9											1				
121	118	7				3	1									1	
131	63	5															
141	19	23													1	7	
153	71	143												1		2	
156		20			3				2					1		6	
157		13			2				1								
166	11	33			3											1	
177	42	11														4	
183	30	7			2										1	3	
192	28	11															
197		1			10	2			1							1	
202	28	12			1								1			3	
212	14	13			2		1				1				1	3	
217	17	5			2											5	
227	25	37			1											4	
237	6	13			1						3				1	6	
247	20	6			7					1						3	2
252	12	5			2											1	
257	15	22				1										4	
262	24	4									1					2	
267	19	31									3	1				7	1
272	8	4			1						1					4	
282	11	15			1		1									4	
287	9	26					1				3	1				17	
297	15	4			1		1									6	
307	4	2					4			1					7	4	
317	1	6													1	10	
327	22	31														32	
337	8	8			1											9	
347	10	1				1	5		1					2	16	8	6
357	8	11					1							1	2	20	
367	4	24									2					14	1
377	5	6				1					2					41	
387	6	4					7			1					7	20	3
397	8	2			8		6			3						10	5
407	5	19									9			2		19	1
412	8	28					1				3				1	9	1
427	4	2					4							5	7	10	2
432	8	33									1					17	
442	6	15			1											15	
452	3				10		1			3						19	6
462	7	14														15	

Table 4. Continued.

Core depth, cm	*Botryococcus*	*Pediastrum*	*Arcella*	*Assulina muscorum*	"Asco spore"	Copepoda spermatophore	*Delitschia*	cf. *Endofragmiella* sp.	*Gelasinospora* sp.	*Geumannomyces*	*Glomus*	*Macrobiotus coronifer-islandicus*	*M. hufelandii*	*Microthyrium* sp.	Podospora	scalariform perforation plate	Sordariales
472	5	11									2			1		38	
482	2	5	1											2		21	1
492	8								1	2				2		35	7
502	10	9											1			15	1
512	8	11									1					34	
522	16	18													2	78	
532	10	11			1								1			35	
542	14	4									1					22	
552	13					3										8	
562	25	3														12	
572	58	6									2					29	
582	72	4														22	
592	17								1	1						26	6
602	57	6														17	3
612	161	8									1		1		1	8	
622	17	14														16	
632	10	1								1						11	8
642	61	26											2			3	3
652	83	1														4	
662	28	4											2	1		20	
667	141	1						1								23	
672	51								3	1						5	5
677	56	7			1						1					29	
687	19						2			1						16	10
697	93	5														11	
707	198	4												1		4	
717	25	10														10	
722	26	18													1	13	
728	129	22									1					9	
738	179	35														4	
747	79		1						3	4						7	4
757	35	4														4	
767	5	7									1			1	1	6	1
777	24	16					2							1		13	
787	8	10			1		2		1	3						13	7
797	12	20									1					9	
807	5	6					1				1				1	5	
817	21	33														7	
827	11	4			1									1		5	6
837	19	32												1		1	1
847	1						1		2	1							12
857	9	9														10	
862	15	31			2											2	
868	17	14													1	1	
877	7	5									1					2	
887	3				6		2		1	5				3		57	19
897	14	7												1		5	1
902	10	13			1											2	
908	27	8			2										1	4	
917	24	6														4	
927	1	16					1			1							8
932	9	24			1											3	
936	28	11			2						2			1			

Table 4. Continued.

Core depth, cm	*Spirogyra* sp.	*Sporomiella*	s-spore	Stomata	*Thekaphora*	Conifer-Tracheids	*Trichocladium asperum*	Type 8C	Type 74	Type 119	Type 187B	Type 225	Type 307B	Type 354	U2	U2a	zool. remain
5			97							2		750		24		15	25
15			157			2						488			1		34
25			200	1		1						300		8		1	23
35			178									381					18
45			180									460				32	15
55			145			2						250		2		1	22
65			159			2						228			1		4
75			211									198		3			10
81			303			2						189			1		2
91			100									117					5
101			109									460			17	42	3
111			135									115					7
121			147									1		2			2
131			156											1			2
141			238			2						1					1
153			211									1			1		6
156			402											1	13		4
157			288												14	9	2
166			315			1								1	1		1
177			2												4		4
183			1												10	1	11
192			2		2										4		7
197			103					1							7	2	2
202			3												8		8
212			63										2		4	1	28
217															13		1
227	1														8		50
237															4		12
247			119					2	3			3		4	20	6	5
252															1		11
257						2											23
262															6		4
267																	20
272															2		14
282			4														10
287						2									4	2	20
297			2	1		1									3		8
307			57						5						1		3
317												1			3		15
327			2		2												31
337			7									1			5		8
347			42						3						7	1	6
357						4									1		22
367			3				1								1		15
377						3									5	2	23
387	1		115			1						1			7	3	6
397			89			2						20				1	15
407			3		1	1								1		1	29
412					1									1	1	2	27
427			55			4						3					21
432			3												3		31
442			8			3	1								1	2	27
452		5	116			1	2							4			3
462													1		2		19

Table 4. Continued.

Core depth, cm	*Spirogyra* sp.	*Sporomiella*	s-spore	Stomata	*Thekaphora*	Conifer-Tracheids	*Trichocladium asperum*	Type 8C	Type 74	Type 119	Type 187B	Type 225	Type 307B	Type 354	U2	U2a	zool. remain
472					1										2	1	21
482												2			1		20
492		6	128				2							3		4	1
502			4	2											2		16
512			2	1			2								5		17
522			8												2		20
532			2											2	3		6
542			2										1		1		19
552			111	1			1								1		9
562															3		9
572													1		1	2	19
582			4	1		1	1										9
592			306			1										3	8
602				1		2					1				3		15
612			3												1		4
622				2		1									5		11
632		1	32												306	4	
642											4				5		10
652												1			4		10
662			5												8	3	21
667			1	1											11	1	6
672			250											3		3	
677			5			1									6		4
687			345											2			10
697					1										4		2
707															3		9
717			21													1	4
722			9												1		6
728			17	1		1									7		4
738			4													1	
747			126			2											9
757			2														16
767											2				9	1	11
777															3		11
787			297			1								7		2	3
797															18	2	7
807			2									1			16		1
817															39		1
827			40									37				1	3
837			1		2							35			31		1
847			7	1								138					1
857												1			17	1	1
862															7	1	4
868												11			21		6
877															12		4
887			92	1								43		7		9	3
897												2			10	1	5
902			1		1	1									9		4
908					1							1			20		3
917															34	2	3
927			3			1									4	1	3
932			3												11	4	3
936			3							4					18	3	13

Table 4. Continued.

Core depth, cm	Chironomids	Zygnemataceae	spore red.	*Betula* red.	Pinaceae red.	*Lycopodium* marker spores	Total pollen sum
5	1					68	508
15	4					82	496
25						59	633
35	3					66	493
45						66	747
55	2					63	508
65	2					45	447
75	1					29	443
81		1				19	366
91						17	432
101						97	890
111		1				35	501
121						10	419
131	2					16	528
141	1					18	483
153	1	5				82	372
156	1					91	868
157		1				67	333
166	2					60	346
177	1	3				292	359
183	1	11				216	350
192	1	14			1	274	318
197	2	7				179	313
202	2	11				300	319
212		11				212	388
217	1	15				238	363
227	7	5			2	508	333
237	2	5			1	268	361
247	3	5				116	350
252		11			3	314	314
257	5	2				647	349
262	1	5				363	300
267	5	8	2		1	784	400
272		11			2	413	341
282	1	10			3	355	341
287	3	5			1	382	336
297	3	7				645	334
307	2	6				384	423
317	5	5			5	924	340
327	8	5				2507	311
337	2	18	2		1	351	306
347	2	11				634	332
357	5	9			2	968	300
367	2	8				344	380
377	6	5	1	1	4	1375	315
387	1	4				618	303
397	5	8				294	319
407	5	24			1	602	413
412	2	10				559	352
427	9	8			2	460	448
432	4	9				723	303
442	4	4			1	834	322
452		8				308	300
462	5	1				892	306
472	3	11				591	434
482		20				496	352
492		5				340	572
502	2					691	325
512	1	16				365	372
522	6				1	1416	334
532	6	8				280	388
542	4	1	1			747	352
552	1	4				176	304
562	3	3				279	390
572	4	11				307	426
582	2	11				352	353
592	4	1				94	569
602	5	2				407	428
612	2	5			2	164	513
622	9	3				336	476
632	5	1				110	439
642	6	2	1			177	393
652	6	5				330	379
662	7	4	2			486	595
667	2	5				380	430
672	2	3				102	577
677	3	8				235	443
687	4					270	518
697	4	1				187	426
707	4	1		1		285	427
717	2	5				245	376
722	3	6				175	379
728	7	7				223	447
738	11	9				233	408
747	6	1				265	439
757	4	2				145	422
767	3	11				259	481
777	3	8				411	441
787		8				82	512
797	4	14				225	446
807	3	12				184	557
817		16				282	473
827	1	8				200	492
837		14				221	341
847		1				130	428
857	2	7				161	396
862	2	13				191	387
868	1	25				165	383
877	1	9				152	359
887		6				170	755
897		17				234	409
902	1	23			1	183	375
908	2	21				232	333
917	1	14				311	445
927		4				115	305
932	3	18			1	152	407
936	5	4			1	248	355

6.3 Additional manuscripts

6.3.1. Manuscript IV

P. Tarasov, J.W. Williams, A. Andreev, T. Nakagawa, E. Bezrukova, U. Herzschuh, Y. Igarashi, S. Müller, K. Werner, Z. Zheng, 2007. Satellite- and pollen-based quantitative woody cover reconstructions for northern Asia: verification and application to late-Quaternary pollen data. *Earth and Planetary Science Letters* 264, 284-298. doi:10.1016/j.epsl.2007.10.007

6.3.2 Manuscript V

A.A. Bobrov, S. Müller, N.A. Tschischikova, L. Schirrmeister, A.A. Andreev, 2009. Testate amoebae in Late Quaternary sediments from Cape Mamontov Klyk (Yakutia). *Ecology* 4, 1-11 (in Russian).

The original manuscript is not online available, please contact S. Müller for requests.

7. Appendix B

7.1 Erklärung

Hiermit erkläre ich, dass alle verwendeten Hilfsmittel und Hilfen angegeben sind und versichere auf dieser Grundlage die vorliegende Arbeit selbstständig verfasst zu haben. Diese Arbeit ist nicht schon einmal in einem früheren Promotionsverfahren eingereicht worden.

Berlin, den 28.05.2009

Stefanie Müller

7.2 Lebenslauf

Der Lebenslauf ist in der Online-Version aus Gründen des Datenschutzes nicht enthalten.

7.3 Publikationsliste

S. Müller, A.A. Bobrov, L. Schirrmeister, A.A. Andreev, P.E. Tarasov, 2009. Testate amoebae record from the Laptev Sea coast and its implication for the reconstruction of Late Pleistocene and Holocene environments in the Arctic Siberia. Palaeogeography, Palaeoclimatology, Palaeoecology 271, 301-315. (Manuscript I)

S. Müller, P.E. Tarasov, A.A. Andreev, B. Diekmann, 2009. Late Glacial to Holocene environments in the present-day coldest region of the Northern Hemisphere inferred from a pollen record of Lake Billyakh, Verkhoyansk Mts, NE Siberia. Climate of the Past 5, 73-84. (Manuscript II)

S. Müller, P.E. Tarasov, A.A. Andreev, K. Werner, M. Zech, S. Gartz, B. Diekmann, preparedfor submission. Late Quaternary vegetation and environments in the Verkhoyansk Mountains region (NE Asia) reconstructed from modern and fossil pollen data. (Manuscript III)

P. Tarasov, J.W. Williams, A. Andreev, T. Nakagawa, E. Bezrukova, U. Herzschuh, Y. Igarashi,S. Müller, K. Werner, Z. Zheng, 2007. Satellite- and pollen-based quantitative woody cover reconstructions for northern Asia: verification and application to late-Quaternary pollen data. Earth and Planetary Science Letters 264, 284-298. (Manuscript IV)

A.A. Bobrov, S. Müller, N.A. Tschischikova, L. Schirrmeister, A.A. Andreev, 2009. Testateamoebae in Late Quaternary sediments from Cape Mamontov Klyk (Yakutia). Ecology 4, 1-11 (in Russian). (Manuscript V)

K. Werner, P. Tarasov, A. Andreev, S. Müller, F. Kienast, M. Zech, W. Zech, B. Diekmann,submitted to Boreas. A 12.5-ka history of vegetation dynamics and mire development with evidence of the Younger Dryas forest presence in the Verkhoyansk Mountains, East Siberia, Russia.