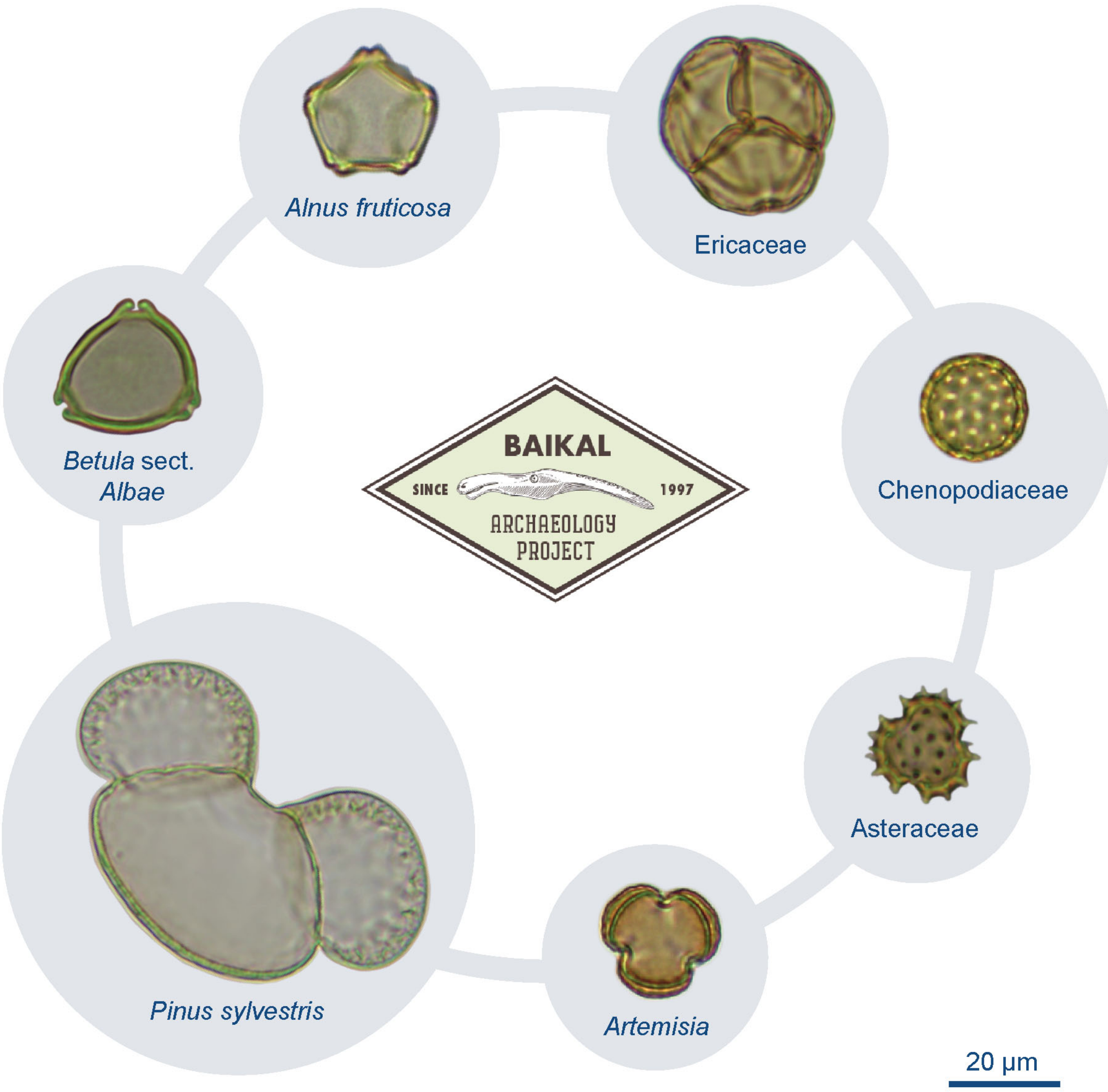
Freie Universität Berlin
Department of Earth Sciences

Palynological records of glacial–interglacial vegetation, climate and fire dynamics in eastern Fennoscandia and the Lake Baikal Region to assess the palaeoecological impacts on hunter-fisher-gatherer populations

Doctoral thesis by
M.Sc. Aleksandra I. Krikunova



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Palynological records of glacial–interglacial vegetation, climate and fire dynamics in eastern Fennoscandia and the Lake Baikal Region to assess the palaeoecological impacts on hunter-fisher-gatherer populations

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To my beloved family and
family I found along the way.

Abstract

The Baikal Archaeology Project (BAP: https://baikalproject.artsrn.ualberta.ca/) is a long-term, multidisciplinary research initiative that has brought together experts from the fields of archaeology, bioarchaeology, ethnoarchaeology, genetics, bio- and geochemistry, and palaeoecology for over two decades to explore the lifeways of prehistoric hunter-gatherer cultures in Northern Eurasia. The focus of the project is on investigating the cultural diversity, change, stability, and resilience of foraging cultures in response to changing environmental conditions in the Lake Baikal Region (LBR) in southern Siberia and the Lake Onega Region (LOR) in Karelia, eastern Fennoscandia. High-resolution continuous sediment sequences from lakes and peatbogs serve as valuable environmental archives, ideally suited for detailed reconstructions of past human-environment relationships in the respective study areas. This dissertation presents robustly dated, high-resolution palynological records and pollen-based biome reconstructions from both BAP regions, providing detailed insights into the climatic and environmental histories and how they may have influenced the hunter-gatherer cultures studied within the BAP.

A pollen record from a 135-cm-long, radiocarbon-dated sediment core from Lake Kamenistoe (67°30'31.4" N, 34°38'53.3" E) provides important insights into the vegetation and climate dynamics of the central Kola Peninsula over the last ca. 13 ka BP. The results improve existing reconstructions of the retreat of the Scandinavian Ice Sheet at the end of the last glacial period, indicating that the region was already ice-free by 13 ka BP. The palaeoenvironmental record, integrated with existing archaeological data, suggests that the initial spread of early Mesolithic hunter-gatherer groups into the region took place no later than 10 ka BP and coincided with the expansion of the boreal forest and a phase of continuous warming. These changes likely prompted the northward migration of reindeer, which were a crucial resource for Mesolithic hunter-gatherers, facilitating the habitation of this region.

The palaeoenvironmental study in the LOR is based on an 885-cm-long sediment core from Razlomnoe Peat (62°27'53" N, 34°26'4" E), composed of continuous deposits from the last ca. 11.8 ka BP. The results of the palynological analysis allowed detailed reconstruction of Lateglacial–Holocene environmental changes and their possible impacts on hunter-gatherer societies in the region. The findings show rapid postglacial afforestation and highlight the sensitivity of the regional vegetation to climatic changes, such as during the 8.2 ka BP and 4.2 ka BP events, which mark the beginning of the Middle and Late Holocene, respectively. The 8.2 ka BP event is characterised by a substantial spread of birch at the expense of pine, indicating markedly cooler winters and an increase in wildfire frequency. These abrupt changes coincide with the peak of use of the Yuzhniy Oleniy Ostrov burial ground (ca. 8250–8000 a BP), suggesting an adaptive response of hunter-gatherer communities to less favourable environmental conditions. The 4.2 ka BP event, often associated with drought in other regions, coincides in the LOR with wetter conditions, which led to the expansion of wetlands and the opening of the landscape.

In a third study, records of pollen and microscopic charcoal particles from sediment cores from Lake Ochaul (54°13’58.4” N, 106°27’53.8” E) in Cis-Baikal and Lake Kotokel (52°47’ N, 108°07’ E) in Trans-Baikal were analysed to reconstruct and compare the vegetation and fire history of the last 32 ka BP in the two regions. In addition to information about the complex relationship between climate, vegetation, and fire activity, these records, in combination with archaeological data, also provide new insights into the activities of hunter-gatherer communities and their impact on the natural environment. Under the cold and dry conditions during the peak (32–18.2 ka BP) of the last glacial period, both records show minimal fire activity, likely due to sparse vegetation cover. The onset of deglaciation around 18.2 ka BP is marked by a gradual spread of woody plants, accompanied by a slight increase in fire activity. Significant differences in the fire records between the two study regions become evident at the end of the Lateglacial. The peak in fire activity in Cis-Baikal is dated to the Early Holocene (9.5–8 ka BP), while in Trans-Baikal, the peak occurred during the Middle Holocene (6–5 ka BP). These differences are likely primarily due to variations in vegetation composition and landscape openness. Charcoal concentrations in both sediment cores show low values during the so-called “cultural hiatus” in the Middle Neolithic (ca. 6660–6060 a BP), suggesting a population decline throughout the LBR. The spread of Late Bronze and Iron Age cultures from 3.5 ka BP onwards is likely related to the recorded increase in fire frequency around Lake Kotokel.

Kurzfassung

Das Baikal Archaeology Project (BAP: https://baikalproject.artsrn.ualberta.ca/) ist eine langfristige, multidisziplinäre Forschungsinitiative, die seit über zwei Jahrzehnten ExpertInnen aus den Bereichen Archäologie, Bioarchäologie, Ethnoarchäologie, Genetik, Bio- und Geochemie sowie Paläoökologie zusammenbringt, um die Lebensweisen prähistorischer Jäger- und Sammlerkulturen in Nordeurasien zu erforschen. Der Schwerpunkt liegt auf der Erforschung kultureller Vielfalt, Wandel, Stabilität und Resilienz von Wildbeuterkulturen auch im Hinblick auf sich verändernde Umweltbedingungen in den Regionen um den Baikal-See (BSR) in Südsibirien und den Onega-See (OSR) in Karelien im östlichen Fennoskandinavien. Hochauflösende, kontinuierliche Sedimentsequenzen aus Seen und Torfen sind wertvollen Umweltarchive und bestens geeignet zur detaillierten Rekonstruktion vergangener Mensch-Umwelt-Beziehungen in den jeweiligen Untersuchungsgebieten. Diese Dissertation präsentiert robust datierte hochauflösende palynologische Aufzeichnungen sowie pollenbasierte Biomrekonstruktionen aus beiden BAP Regionen. Sie geben detaillierte Einblicke in die Klima- und Umweltgeschichte und zeigen, wie diese die im BAP untersuchten Wildbeuterkulturen beeinflusst haben könnten.

Pollenaufzeichnungen aus einem 135 cm langen, radiokarbondatierten Sedimentkern aus dem Kamenistoe-See (67°30'31.4" N, 34°38'53.3" O) liefern bedeutende Einblicke in die Vegetations- und Klimadynamik der zentralen Kola-Halbinsel während der letzten ca. 13000 Jahre. Die Ergebnisse verbessern bestehende Rekonstruktionen des Abtauens des Skandinavischen Eisschilds am Ende der letzten Eiszeit und deuten darauf hin, dass die Region bereits um 13 ka BP eisfrei war. Die paläoökologischen Aufzeichnungen, in Verbindung mit vorhandenen archäologischen Daten, legt nahe, dass die anfängliche Ausbreitung frühmesolithischer Jäger- und Sammlergruppen in die Region nicht später als 10 ka BP stattfand und mit der Ausbreitung des borealen Waldes sowie einer Phase kontinuierlicher Erwärmung zusammenfiel. Diese Veränderungen bedingten wahrscheinlich die nordwärts gerichtete Wanderung von Rentieren, die eine wichtige Ressource für mesolithische Jäger und Sammler darstellten.

Die Studie in der OSR basiert auf einen 885 cm langen Sedimentkern aus dem Razlomnoe-Torf (62°27‘53“ N, 34°26‘4“ O), der sich aus kontinuierlichen Ablagerungen der letzten 11800 Jahre zusammensetzt. Die Ergebnisse der palynologischen Analyse ermöglichen die detaillierte Rekonstruktion der spätglazialen–holozänen Umweltveränderungen und deren mögliche Auswirkungen auf Jäger- und Sammlergesellschaften in der Region. Die rasche postglaziale Bewaldung zeigt, wie empfindlich die Vegetation auf klimatische Veränderungen reagiert, wie etwa während der 8,2 ka- und 4,2 ka-Ereignisse, die den Beginn des mittleren bzw. späten Holozäns markieren. Das 8,2 ka-Ereignis ist durch eine starke Ausbreitung der Birke auf Kosten der Kiefer gekennzeichnet, was auf deutlich kühlere Winter und einen Anstieg der Waldbrandhäufigkeit hinweist. Diese abrupten Veränderungen fallen mit der Hauptnutzungsphase (ca. 8250–8000 a BP) des Bestattungsplatzes Yuzhniy Oleniy Ostrov zusammen und deuten auf eine Reaktion der Jäger- und Sammlergemeinschaften auf die sich verschlechternden Umweltbedingungen hin. Das 4,2 ka-Ereignis, das in anderen Regionen häufig mit Trockenheit verbunden ist, fällt in der OSR mit vergleichsweise feuchteren Bedingungen zusammen, was zur Ausbreitung von Feuchtgebieten und einer Öffnung der Landschaft führte.

In einer dritten Studie wurden Aufzeichnungen von Pollen und mikroskopischer Holzkohlereste aus Sedimentkernen des Ochaul-Sees (54°13’58.4” N, 106°27’53.8” O) in Cis-Baikalien und des Kotokel-Sees (52°47’ N, 108°07’ O) in Trans-Baikalien analysiert, um die Vegetations- und Feuergeschichte der letzten 32000 Jahre in den beiden Regionen zu rekonstruieren und zu vergleichen. Neben neuen Erkenntnissen über die komplexe Beziehung zwischen Klima, Vegetation und Feueraktivität liefern diese Aufzeichnungen unter Berücksichtigung archäologischer Daten auch Einblicke in die Aktivitäten der Jäger- und Sammlergesellschaften und deren Einfluss auf die natürliche Umwelt. Unter den kalten und trockenen Bedingungen während der Hochphase (32–18,2 ka BP) des letzten Glazials zeigen beide Aufzeichnungen minimale Feueraktivität, was auf eine spärlichen Vegetationsdecke zurückzuführen ist. Der Beginn des Rückgangs der Vereisung um 18,2 ka BP ist durch eine allmähliche Ausbreitung von Gehölzen gekennzeichnet, die mit einem leichten Anstieg der Feueraktivität einhergeht. Bedeutende Unterschiede in den Feueraufzeichnungen zwischen den beiden Untersuchungsregionen werden am Ende des Spätglazials deutlich. Der Höhepunkt der Feueraktivität in Cis-Baikalien datiert auf das frühe Holozän (9,5–8 ka BP), während in Trans-Baikalien der Höhepunkt während des mittleren Holozäns (6–5 ka BP) auftrat. Diese Unterschiede lassen sich wahrscheinlich hauptsächlich auf Unterschiede in der Vegetationszusammensetzung und der Offenheit der Landschaft zurückführen. Die Konzentrationen der Holzkohlereste zeigen während der sogenannten "kulturellen Lücke" im mittleren Neolithikum (ca. 6660–6060 a BP) in beiden Sedimentkernen niedrige Werte, was auf einen Bevölkerungsrückgang in der gesamten BSR hindeutet. Die Ausbreitung der Kulturen der späten Bronze- und Eisenzeit ab 3,5 ka BP steht wahrscheinlich im Zusammenhang mit der verzeichneten Zunahme der Feuerhäufigkeit rund um den Kotokel-See.

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a/ka BP	years/kiloyears before present (i.e. before the year 1950 CE)
a.s.l.	above sea level
AMS	accelerator mass spectrometry
AP	arboreal pollen
APAR	arboreal pollen accumulation rates
AVHRR	advanced very high resolution radiometer
BAP	Baikal Archaeology Project
B−A	Bølling−Allerød
$C_{background}$	background charcoal ("non-fire" episodes)
$C_{interpolated}$	interpolated charcoal
C_{peak}	charcoal peak ("fire" episodes)
CE	Common Era
CHAR	charcoal accumulation rate
CLDE	cold deciduous forest
CONISS	constrained incremental sum of squares
EH	Early Holocene
ESM	Earth system modelling
FRI	fire return interval
FTIR	Fourier Transformed Infrared Spectroscopy
GDD5	growing degree days above 5°C
HF	hydrofluoric acid
LBR	Lake Baikal Region
LG	Lateglacial
LGM	Last Glacial Maximum
LH	Late Holocene
LOI	loss on ignition
LOR	Lake Onega Region

MH	Middle Holocene
MIS	marine isotope stage
NAP	non-arboreal pollen
NGRIP	North Greenland Ice Core Project
NPP	non-pollen palynomorphs
PAR	pollen accumulation rate
PAZ	pollen assemblage zone
PC	pollen concentration
PFT	plant functional types
PZ	pollen zone
rpm	revolutions per minute
sedaDNA	sedimentary ancient DNA
SIS	Scandinavian Ice Sheet
SNI	signal-to-noise index
SSST	summer sea surface temperature
STP	stratigraphical tie point
TAIG	taiga
TUND	tundra
YD	Younger Dryas

1 Introduction

1.1 Preface

The interaction between human evolution and environmental changes has attracted significant interest and discussion in recent decades, driven by the rapid accumulation of archaeological and palaeoenvironmental data and the advancement of interdisciplinary projects (e.g. Dong et al., 2020; Hosfield and Cole, 2019; Mercader et al., 2021; Weber et al., 2013). This doctoral thesis contributes to the Baikal Archaeology Project (BAP), which unites experts in archaeology, bioarchaeology, ethnoarchaeology, genetics, bio- and geochemistry, and palaeoenvironmental research with the aim to improve the current understanding of the dynamism, variability, and resilience of prehistoric hunter-gatherers. The project focuses on two geographically distinct areas in Northern Eurasia: the Lake Baikal Region (LBR) in southern Siberia and Lake Onega Region (LOR) in Karelia, eastern Fennoscandia (https://baikalproject.artsrn.ualberta.ca/about/). Key objectives of the project include: (i) developing detailed reconstructions of individual life histories based on comprehensive examination of human skeletal remains, (ii) establishing high-resolution chronologies through systematic radiocarbon dating of all examined human remains, and (iii) synthesizing archaeological data with high-resolution palaeoenvironmental records within the context of the natural environment.

The interaction between socio-cultural processes and environmental changes in shaping prehistoric human societies is a critical and complex question. This intricate relationship is evident in the archaeological record, where changes in material culture, subsistence strategies, and settlement patterns often align with environmental fluctuations (e.g. Anderson et al., 2007; Gamble et al., 2004; Manninen et al., 2018, 2023; Richerson et al., 2001; Schulting et al., 2022; Weninger et al., 2006, 2009). Palaeoenvironmental research and the acquisition of high-resolution records play a pivotal role in understanding the temporal and spatial dynamics of past environmental conditions, which are essential for reconstructing the contexts in which prehistoric societies evolved.

Eastern Fennoscandia, encompassing parts of Russia, Finland, and northeastern Norway, provides a compelling case study for understanding postglacial environmental changes and human responses to climate variability. The region's numerous lakes, ponds, and peatbogs yield a rich variety of palaeoclimatic and palaeoecological records, including pollen, aquatic invertebrates, plant macrofossils, and other biological proxies (e.g. Erästö et al., 2012; Kremenetski et al., 2004a, 2004b; Meyer-Jacob et al., 2017; Nazarova et al., 2020; Plikk et al., 2019; Seppä et al., 2007, 2008, 2009). The Kola Peninsula, located in the northern part of eastern Fennoscandia and almost entirely within the Arctic Circle, offers a unique context for studying human colonisation of the Arctic and the interaction between early human migrations and extreme environments (e.g. Kotlyakov et al., 2017; Pitul'ko, 1999 and references therein). The search for clear answers to fundamental questions, such as how and why humans colonised circumpolar regions and why only one representative of the genus *Homo* successfully occupied this hostile zone, remains ongoing (Hoffecker, 2019). Lake Onega, located in the southern part of eastern Fennoscandia, presents another valuable research area for producing high-resolution palaeoenvironmental records. Studies aimed at reconstructing the Lateglacial−Holocene environment (e.g. Harrison et al., 1996; Tarasov et al., 1998; Wohlfarth et al., 2007) and the impacts of past climate changes on human populations (e.g. Schulting et al., 2022) have highlighted the importance of the LOR for more detailed palaeoenvironmental research.

The LBR in southern Siberia has also emerged as a critical focal point for palaeoenvironmental and archaeological research, offering unique insights into human-environment interactions spanning many millennia. The region provides an exceptional record of human habitation since the Upper Paleolithic (Weber, 2020; Shichi et al., 2023). Studying human-environment interaction in this region is particularly important considering the documented lack of settlement and mortuary sites in regional archaeological records during the Middle Neolithic in parts of Cis-Baikal (e.g. Weber et al., 2013; Losey and Nomokonova, 2017). The vast size and complex topography of the LBR contribute to spatial-temporal variability in vegetation development during the Late Pleistocene–Holocene interval (e.g. Bezrukova et al., 2005, 2010; Demske et al., 2005; Kobe et al., 2020, 2022a, 2022b; Tarasov et al., 2009, 2017), emphasizing the need for detailed reconstructions of microregional environments.

Although studies in eastern Fennoscandia and LBR have generated numerous palaeoenvironmental records, many of these records exhibit low temporal resolution and insufficient chronological control, are discontinuous, or cover only restricted time intervals, rarely longer than the Holocene (e.g. Demske et al., 2005; Prentice et al., 2000; Tarasov et al., 1999; references in Table 7.1). The use of uncalibrated ^{14}C ages and pollen-based correlations with the Blytt-Sernander bioclimatic classification in many studies from Karelia and the LOR (e.g. Filimonova and Lavrova, 2017) introduces further uncertainties in the chronological frameworks. These limitations cause difficulties in identifying finer-scale climatic events and hiatuses, and complicate regional and interregional correlations. Moreover, the varying temporal and spatial scales of palaeoenvironmental data present significant challenges for palaeoclimatic models (e.g. Kageyama et al., 2001; Texier et al., 1997).

Implementing high-resolution sampling strategies and using precise dating techniques such as AMS radiocarbon dating calibrated with the latest calibration dataset (e.g., IntCal20, Reimer et al., 2020) help to improve chronological control and temporal resolution, providing more detailed and accurate records of past environmental changes. Combining multiple proxies, such as pollen, charcoal, diatoms, stable isotopes, geochemistry and other microfossils to create comprehensive palaeoenvironmental reconstructions can help cross-validate findings and provide a more robust understanding of past climate and environmental conditions (Birks and Birks, 2006). Focusing on obtaining continuous records that span the entire postglacial interval, including the Late Pleistocene and Holocene, is crucial. This can be achieved by targeting sites with well-preserved sedimentary sequences (e.g. lakes and peatbogs) and using robust AMS radiocarbon dating.

The study sites selected for this doctoral project form two longitudinal transects: one in eastern Fennoscandia, stretching from central Kola Peninsula (Fig. 1.1A) to Lake Onega (Fig. 1.1B), and another in southern Siberia, spanning from Lake Ochaul in Cis-Baikal (Fig. 1.1C) to Lake Kotokel on Trans-Baikal (Fig. 1.1D). The study sites were chosen to leverage their well-preserved sedimentary sequences, which are ideal for achieving the high-resolution continuous records necessary to fill a gap in current knowledge.

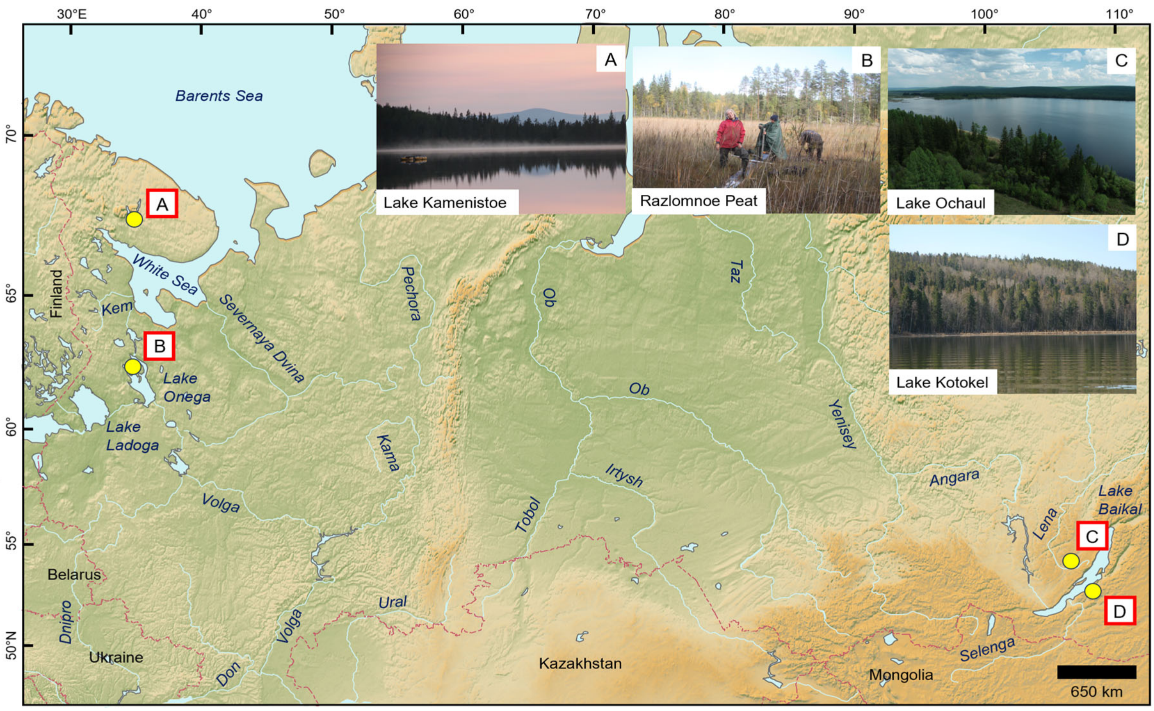

Figure 1.1: Topographic overview map showing locations and landscape photos of the study sites: A – Lake Kamenistoe (photo by N.A. Kostromina), B – Razlomnoe Peat (photo by L.A. Savelieva), C – Lake Ochaul, D – Lake Kotokel (both photos by A.A. Shchetnikov).

Lake Kamenistoe (67°30'31.4" N, 34°38'53.3" E, Fig. 1.1A), a small elongated lake located in the central Kola Peninsula in the northern part of eastern Fennoscandia, provides excellent conditions for continuous sediment accumulation and preservation. The sparse pre-industrial occupation of the Kola Peninsula and the absence of archaeological sites near Lake Kamenistoe suggest that this lake represents a valuable archive of natural vegetation and climate change in the study region.

Razlomnoe Peat (62°27′53″N, 34°26′4″E, Fig. 1.1B) is a riparian peatbog located on the northern shore of Lake Onega in the southern part of eastern Fennoscandia. Previous research focused on reconstructing fluctuations in the erosion basis (Shevelin et al., 1988) has highlighted the peatbog's potential for further analysis. In addition, the large and robustly dated Late Mesolithic burial ground Yuzhniy Oleniy Ostrov (YOO), located ca. 65 km southeast of the peat, offers great potential for correlating palaeoenvironmental and archaeological records (Schulting et al., 2022).

Lake Ochaul (54°13’58.4” N, 106°27’53.8” E, Fig. 1.1C) is a small freshwater lake located in the Upper Lena microregion in Cis-Baikal, ca. 100 km northwest of Lake Baikal. Preliminary investigations have revealed a thick layer of bottom sediments capable of providing environmental records for past ca. 30−40 ka BP. Archaeological surveys conducted between 1913 and 2016 uncovered campsites of prehistoric hunter-gatherers on the terrace north of the lake, indicating intermittent use from the late Upper Palaeolithic to the Early Bronze Age (Aksyonov, 2009; Peskov, 2016). Recent studies have focused on the past 13.5 ka (e.g. Kobe et al., 2022a) and the LGM interval from ca. 27.85 to 20.4 ka BP (Kobe et al., 2022b), reporting results of sediment geochemistry, pollen and ostracod analyses, as well as zooarchaeological data from a coastal archaeological site. Published (Kobe et al., 2022a, 2022b) and partially unpublished results of palynological analysis from the Och18-II core (Lake Ochaul) obtained as part of F. Kobe's BAP-sponsored doctoral project (Kobe, 2022) are used in the current study, together with new results from Lake Kotokel, to reliably reconstruct environmental changes and fire activity in the LBR since about 32 ka BP.

Lake Kotokel (52°47’ N, 108°07’ E, Fig. 1.1D) is one of the key sites chosen for detailed palaeoenvironmental investigations in the BAP research program (Weber et al., 2013). The Holocene sediments of Lake Kotokel were initially studied for pollen and non-pollen microfossils with coarse resolution (Korde, 1968; Vipper and Smirnov, 1979). Recent studies have provided detailed environmental records, using a set of biological and geochemical proxies (Bezrukova et al., 2010; Fedotov et al., 2012; Kostrova et al., 2013; Müller et al., 2014;

Shichi et al., 2009; Tarasov et al., 1994, 2009, 2017, 2019), however, the age of all published records based on a limited number of ^{14}C dates remains ambiguous.

A substantial number of bulk samples were selected from the sediment cores obtained from the abovementioned sites. AMS dating was done in the Poznan Radiocarbon Laboratory by Prof. Dr. Tomasz Goslar. Palynological analysis of the sediment cores from lakes and peats was chosen as a key method in the current project. Pollen records rank very highly among a wide range of proxies, that are used to reconstruct the environmental setting, vegetation and climate histories, and the way of life of past human cultures (Berglund and Ralska-Jasiwichewa, 1986; Beug, 2004; Dimbleby, 1985; Fægri and Iversen, 1989). In addition to palynological investigation designed and performed by the author of this thesis with the assistance of team members, several other research methods were applied, including sediment lithology (all sediment cores), loss on ignition (LOI) analysis (Razlomnoe Peat), and microcharcoal analysis (Lake Kotokel, Lake Ochaul). The LOI analysis is considered to be a simple method to estimate organic matter and carbonate contents of sediments (Beaudoin, 2003; Bendell-Young et al., 2002; Boyle, 2004; Dean, 1974). Sedimentary charcoal records are valuable sources of information about past changes in fire regimes, including fire frequency and intencity (Clark, 1988a; Tinner et al., 1998; Whitlock and Larsen, 2001).

1.2 Scientific goals and objectives

The primary objective of this study is to reconstruct the palaeoenvironmental history of understudied regions in eastern Fennoscandia and the LBR during the Late Pleistocene-Holocene periods. The research seeks to fill existing gaps in the palaeoenvironmental history by providing high-resolution and robustly dated palynological records suitable for qualitative and quantitative reconstructions of regional vegetation, climate dynamics, and human-environmental interactions in the study areas. To achieve this objective, the following specific aims were identified: (i) establish a reliable chronology through radiocarbon dating and age modelling, (ii) conduct detailed pollen analysis and pollen-based biome reconstruction, (iii) perform microcharcoal analysis to reconstruct wildfire history in the LBR, (iv) investigate the sensitivity of environments to global and regional climate changes, and (v) correlate the reconstructed palaeoenvironmental conditions with archaeological records to assess human-environment interactions.

High-resolution palynological analysis and robust age control of sediment cores, together with quantitative biome reconstruction and comparison of the results with published regional and global environmental and climatic records, enabled detailed palaeoenvironmental reconstructions in eastern Fennoscandia and the LBR. Moreover, microcharcoal analysis was conducted to investigate the spatial and temporal variations in fire activity between two sub-regions of the LBR that differ in environmental conditions but are both sensitive to natural and anthropogenic fires. The comprehensive approach employed in this study aims to provide valuable data for validating Earth system modeling experiments and enhance our understanding of the environmental contexts that influenced human adaptation and cultural developments within and across the study regions.

1.3 Structure of the thesis

This doctoral thesis follows a cumulative format and consists of an introduction, three peer-reviewed manuscripts (Krikunova et al., 2022, 2024a, 2024b) and supplementary material including all palynological datasets generated during the project or used for further analysis and inter-regional comparison. The manuscripts published in international scientific journals (open acess) cover a range of palaeoenvironmental, ecological, and archaeological questions, with a particular focus on reconstructing past vegetation and climate dynamics in the study areas and examining the human-environmental interactions. The generated datasets have either already been submitted to the open access PANGAEA Data Publisher for Earth & Environmental Science (https://www.pangaea.de/) or are being prepared for submission.

The first manuscript “Late- and postglacial vegetation and climate history of the central Kola Peninsula derived from a radiocarbon-dated pollen record of Lake Kamenistoe” (Chapter 2; Krikunova et al., 2022) is a detailed study contributing to the broader understanding of climatic and environmental changes in the European Arctic region over the past ca. 13 ka BP. The manuscript presents a comprehensive analysis of a 135-cm sediment core obtained from Lake Kamenistoe. Through pollen analysis and pollen-based biome reconstruction, significant changes in vegetation from the Lateglacial to the Holocene are revealed. The study also discusses the sensitivity of the region's vegetation to climatic changes and the implications for human habitation and paleoenvironmental reconstructions.

The second manuscript “Postglacial vegetation and climate change in the Lake Onega region of eastern Fennoscandia derived from a radiocarbon-dated pollen record” (Chapter 3; Krikunova et al., 2024a) is a review and research article that contributes to the understanding of postglacial environmental history in southeastern Fennoscandia. The manuscript focuses on the analysis of a new ^{14}C-dated pollen record from Razlomnoe Peat, which, unlike all other published palynological studies from the LOR, offers a continuous sedimentation record over the past ca. 11.8 ka BP. The study provides and discusses the first compelling evidence of the

8.2 ka BP event in the region, marked by significant ecological shifts. The 4.2 ka BP event is also identified, although it appears to reflect wetter rather than drier conditions.

The third manuscript "Vegetation and fire history of the Lake Baikal Region since 32 ka BP reconstructed through microcharcoal and pollen analysis of lake sediment from Cis- and Trans-Baikal" (Chapter 4; Krikunova et al., 2024b) is a research paper that contributes to the understanding of long-term environmental changes accross the LBR. This study involves microcharcoal and pollen analysis of two sediment cores: from Lake Ochaul in Cis-Baikal and Lake Kotokel in Trans-Baikal, spanning the interval from the marine isotope stage 3 (MIS 3) to the present. The detailed chronological framework and comprehensive analysis presented in this manuscript provide valuable insights into the vegetation and fire history of the LBR. Table 1.1 provides a summary of all the manuscripts, the author's contribution, and the open-access datasets related to this project.

Table 1.1: Overview of the manuscripts, the author's contribution, and open-access datasets.

Chap.	Title, Authors	Journal/Database, Status of Publication	Contribution of A. Krikunova:
2	**Manuscript:** Late- and postglacial vegetation and climate history of the central Kola Peninsula derived from a radiocarbon-dated pollen record of Lake Kamenistoe *Krikunova, A.I., Kostromina, N.A., Savelieva, L.A., Tolstobrov, D.S., Petrov, A.Y., Long, T., Kobe, F., Leipe, C., Tarasov, P.E.*	Published in Palaeogeography, Palaeoclimatology, Palaeoecology 603, 111191 (2022) https://doi.org/10.1016/j.palaeo.2022.111191	Conceptualization: 70% Methodology: 80% Formal Analysis: 85% Data curation: 90% Visualization: 80% Writing – original draft, review & editing: 65%
	Dataset: A radiocarbon-dated pollen record and pollen-based vegetation (biome) reconstruction of the last 13,000 years derived from Lake Kamenistoe (Kola Peninsula) *(Authorship is identical to the manuscript)*	Published in PANGAEA (2023, open access) https://doi.org/10.1594/PANGAEA.955707	
3	**Manuscript:** Postglacial vegetation and climate change in the Lake Onega region of eastern Fennoscandia derived from a radiocarbon-dated pollen record *Krikunova, A.I., Savelieva, L.A., Long, T., Leipe, C., Kobe, F., Kostromina, N.A., Vasilyeva, A.V., Tarasov, P.E.*	Published in Quaternary International 695, 31–44 (2024a, open access) https://doi.org/10.1016/j.quaint.2024.04.003	Conceptualization: 80% Methodology: 80% Formal Analysis: 90% Data curation: 90% Visualization: 90% Writing – original draft, review & editing: 70%

	Datasets: [1] The 11,800-year pollen record obtained from Razlomnoe Peat in the Lake Onega region (eastern Fennoscandia). [2] The 11,800-year pollen-based vegetation (biome) reconstruction from Razlomnoe Peat in the Lake Onega region (eastern Fennoscandia). *(Authorship is identical to the manuscript)*	Published in PANGAEA (2024c, open access) https://doi.org/10.1594/PANGAEA.971527 Published in PANGAEA (2024d, open access) https://doi.org/10.1594/PANGAEA.971601	
4	Vegetation and fire history of the Lake Baikal Region since 32 ka BP reconstructed through microcharcoal and pollen analysis of lake sediment from Cis- and Trans-Baikal *Krikunova A.I., Kobe F., Long, T., Leipe, C., Gliwa J., Shchetnikov A.A., Olschewski, P., Hoelzmann, P., Wagner M., Bezrukova, E.V., Tarasov, P.E.*	Published in Quaternary Science Reviews 340, 108867 (2024b, open access) https://doi.org/10.1016/j.quascirev.2024.108867	Conceptualization: 80% Methodology: 70% Formal Analysis: 70% Data curation: 50% Visualization: 80% Writing – original draft, review & editing: 65%

1.4 Scientific background

1.4.1 Regional setting and study sites

1.4.1.1 Eastern Fennoscandia

The study area in the central part of the Kola Peninsula (Fig. 1.1A) belongs to northeastern Fennoscandia. This region was covered by an extensive ice sheet during most of the Late Quaternary, and the deglaciation did not start until ca. 15 ka BP (Stroeven et al., 2016; Svendsen et al., 2004). The regional geology is characterised by Precambrian crystalline igneous rocks of the Baltic Shield, overlain by glacial till, glaciofluvial, lacustrine deposits, and widespread Holocene peats. Neotectonics, seismic activity, and glacial processes have significantly shaped the modern relief, with the highest elevations (up to 1000–1200 meters a.s.l.) in the central Khibiny and Lovozero mountain massifs and most of the area below 500 meters. The Kola region's biome distribution (Atlas of the Murmansk region, 1971) reflects modern climate variability but is also affected by local topography and hydrology, leading to mosaic vegetation. For instance, alpine tundra appears in the Khibiny and Lovozero mountains within the forest zone. The main vegetation types in the Kola region are tundra and boreal coniferous forest (taiga), separated by transitional woodland or forest-tundra, where birch and pine are predominant.

Lake Kamenistoe (Fig. 1.1A; 205.3 m a.s.l.) is a small lake with a surface area of ca. 0.15 km² and an average depth of ca. 2.5 m, located about 6 km southeast of Lake Umbozero (149 m a.s.l.), one of the largest and deepest lakes in the Kola region. The two lakes are likely connected through a system of temporary streams. The area surrounding Lake Kamenistoe is covered with boreal forests, wetlands, and swamps. An overview of the modern climatic conditions and vegetation of the study area is provided in Table 1.2 and Chapter 2.3.

Table 1.2: Overview of the regional climate and vegetation characteristics in the study area.

Chap.	Location	Coordinates, elevation	Modern climate	Modern vegetation
2	Lake Kamenistoe, central Kola Peninsula	67°30'31.4" N, 34°38'53.3" E, 205.3 m a.s.l.	Subarctic climate with significant influence from both the North Atlantic and Arctic air masses. Mean temperatures range from −9 °C to −13 °C in January and +9 °C to +14 °C in July. Mean annual precipitation is between 500 and 700 mm and falls primarily in the summer and autumn months (http://www.pogodaiklimat.ru/history/22224.htm)	Predominant tree taxa: birch (*Betula pubescens* ssp. *tortuosa*, *Betula pendula*), scots pine (*Pinus sylvestris*) and spruce (*Picea abies*). Understory includes birch (*Betula* sect. *Fruticosae* and *B.* sect. *Nanae*), willow (*Salix*) and juniper (*Juniperus communis*) shrubs with species of the heath (Ericaceae) family and diverse herbaceous plants, mosses and lichens.
3	Razlomnoe Peat, northern shore of Lake Onega	62°27'53" N, 34°26'4" E, 53 m a.s.l.	Humid, moderately continental climate. Average January temperatures range from −13 to −8.4 °C and July temperatures from +16 to +17.6 °C. Annual precipitation varies from 550 to 750 mm, with the highest amounts during summer (references in Table 3.1)	Dominant tree taxa are scots pine, spruce (*Picea abies*, *P. obovata*) and birch (*Betula pendula*, *B. pubescens*) trees followed by aspen (*Populus tremula*) and alder (*Alnus incana*, *A. glutinosa*). Presence of temperate deciduous taxa such as linden (*Tilia cordata*), elm (*Ulmus glabra*, *U. laevis*), oak (*Quercus robur*) and hazel (*Corylus avellana*) in fertile areas of Lake Onega. Understory includes birch and willow shrubs and semi-shrubs (members of Ericales and Rosaceae), grasses (Poaceae), sedges (Cyperaceae), various herbs, mosses and lichens.

4	Lake Ochaul, Upper Lena River, Cis-Baikal	54°13’58.4” N, 106°27’53.8” E, 641 m a.s.l	Cold continental climate with significant annual precipitation variability (212 to 480 mm, average 318 mm). Mean January temperatures vary significantly, from −36.3 to −24.1 °C, averaging −28.4 °C. Mean July temperatures vary from +14.7 to +19.5 °C, with an average of +17.2 °C. Annual mean temperatures range from −5.2 to −2.4 °C, averaging −4.0 °C (http://www.pogodaiklimat.ru/ history/30622.htm)	Larch-dominated (*Larix*) boreal forest with birch (*Betula* sect. *Albae*), siberian pine (*Pinus sibirica*), spruce (*Picea obovata*), and fir (*Abies sibirica*). The undergrowth is represented by shrubby birches, shrubs of alder (*Alnus fruticosa*), willow and the heath family (Ericaceae).
	Lake Kotokel, eastern shore of Lake Baikal, Trans-Baikal	52°47’ N, 108°07’ E, 458 m a.s.l.	Less continental climate due to proximity to Lake Baikal. Annual precipitation averages 396 mm, with mean January and July temperatures of −18.1 °C and +14.3 °C, respectively (http://www.pogodaiklimat.ru/ history/30731.htm)	The vegetation around the lake is influenced by human activities and represented by reed (Poaceae) and sedge communities, low-growing birch trees and shrubs of the heath family. Surrounding boreal forests composed of siberian and scots pine, larch, birch, fir, spruce and shrub communities.

The LOR is located in the southeasternmost part of Fennoscandia, at the geological boundary between the Baltic Shield and the East European Platform (Alpat’ev et al., 1976). During the last glacial period ca. 20 ka BP, the region was covered by the Scandinavian Ice Sheet (Stroeven et al., 2016; Svendsen et al., 2004). Saarnisto and Saarinen (2001) estimated that Lake Onega was deglaciated around 14 ka BP based on varve counts, although the precise timing is still debated (e.g., Demidov, 2005, 2006; Filatov, 2010). The lake is situated in a climate-sensitive area at the bioclimatic border between the boreal conifer forest (taiga) biome and the cool conifer forest biome (Prentice et al., 1996). Modern climatic conditions and vegetation of the study area are detailed in Table 1.2 and Chapter 3.3.

Razlomnoe Peat (Fig. 1.1B; 53 m a.s.l.) is a nutrient-rich riparian peat, oriented northwest to southeast, covering an area of approximately 0.2 km². It stretches about 2 km in length and 0.1 km in width in its central part. This peat bog occupies a depression that was once a bay of Lake Onega (Elina and Khomutova, 1987) and features a complex bedrock morphology (Shevelin et al., 1988). The surrounding terrain is low-elevated, with altitude variations up to 100 m due to alternating narrow north-south ridges (selkä) and interridge depressions (Lindholm et al., 2015).

1.4.1.2 Lake Baikal Region

The LBR occupies approximately 1.2 million km^2 in the southern part of Eastern Siberia, north of the Russian border with Mongolia. The modern environments are described in detail by Alpat'ev et al. (1976) and Galaziy (1993), while Kobe et al. (2020) summarised the key features of topography, hydrology, vegetation, and climate, that have influenced hunter-gatherer subsistence strategies during the Late Pleistocene and Holocene. The LBR is divided into two large sub-regions: Trans-Baikal to the south and east of Lake Baikal, and Cis-Baikal to the north and west of the lake. Boreal evergreen conifer and cold deciduous forests dominate the LBR (Bezrukova et al., 2010). However, the Selenga and Barguzin River basins, Olkhon Island, and many east- and south-facing slopes feature steppe and rock-steppe vegetation dominated by grasses, forbs, and Rosaceae shrubs (Kobe et al., 2020; Bezrukova et al., 2010).

Lake Ochaul (Fig. 1.1C; 641 m a.s.l.) is a freshwater lake located in the Cis-Baikal, in the upper reaches of the Lena River, about 100 km northwest of Lake Baikal. It covers a surface area of ca. 2.6 km^2 with a catchment area of ca. 170 km^2, stretching up to ca. 2.7 km in length and ca. 1.2 km in width (Boyarkin, 2007). The lake is shallow, with a maximum depth of 2.5 m (Kobe et al., 2020). The lake lies within a trough-shaped valley drained by the Malaya Anga River, which subsequently flows to the Bol'shaya Anga River, a right tributary of the Lena River. The slopes of the valley reach 850–900 m a.s.l. (200–250 m above the lake). The current climatic conditions and vegetation of the study area are described in Table 1.2 and Chapter 4.3.1.1.

Lake Kotokel (Fig. 1.1D; 458 m a.s.l.) is situated in Trans-Baikal, about 2 km from the eastern shore of Lake Baikal. It is connected to Lake Baikal through the Istok, Kotochik, and Turka river system (Kostrova et al., 2013). The lake extends for approximately 15 km in length and 6 km in width, with an average depth of 4–4.5 m and a maximum depth of 15 m (Shchetnikov et al., 2022). Its shoreline is characterised by a complex topography, including hills, low mountain ranges, and floodplains. The natural vegetation around the lake has been influenced by recent human activities. The current climatic conditions and vegetation are described in Table 1.2 and Chapter 4.3.1.2. The meteorological data from nearby stations indicate a less continental climate in comparison to Lake Ochaul and the Trans-Baikal regions to the south and east, attributed to the significant influence of Lake Baikal on the coastal climate (Galaziy, 1993).

1.4.2 Palaeoenvironmental background

The majority of published lake and peat pollen records from the Kola Peninsula (e.g. Korsakova et al., 2021; Kremenetski and Patyk-Kara, 1997; Kremenetski et al., 1999, 2004a, 2004b; MacDonald et al., 2004; Matishov et al., 2005; Snyder et al., 2000; Solovieva et al., 2005) do not cover the entire Holocene. Additionally, the Lateglacial interval in this region remains poorly explored (Lenz et al., 2021; Seppä et al., 2008; Velichko et al., 2017). Well-dated pollen records from Lake Loitsana (Salonen et al., 2013), Lake Poteryanny Zub (Gervais et al., 2002), Lake Imandra (Lenz et al., 2021), and Lake Churozero (Pavlova et al., 2011) similarly demonstrate the gradual expansion of birch-dominated and light pine-birch forests with a significant presence of shrubby and herbaceous associations during the onset of the Holocene. However, the dynamics of forest expansion in northeastern Fennoscandia during the Holocene remain controversial, particularly regarding the origins and spread of pine and spruce forests (Gervais et al., 2002; Matishov et al., 2005). The palaeoenvironmental history of the central Kola Peninsula is detailed in Chapter 2.6.

In the published pollen records from the LOR, similar critical issues are observed (see Table 7.1 for references), including poor dating control, discontinuity and ambiguous environmental intrepretations of the Lateglacial and Holocene intervals. The presence of birch trees in the region during the Younger Dryas period is still ongoing research due to inconsistencies between pollen data and macrofossil records (Velichko et al., 2017; Wohlfarth et al., 2002, 2004). The rapid afforestation in the Early Holocene is well-documented (Binney et al., 2017; Kremenetski et al., 1998; Velichko et al., 2017; Wohlfarth et al., 2007), yet the precise timing of spruce immigration remains controversial (Elina et al., 2010; Savelieva, 2010; Wohlfarth et al., 2002, 2004). These challenges underscore the need for more comprehensive and accurately dated pollen studies in the region. The palaeoenvironmental development of the LOR is described in Chapter 3.6.

In the past 30 years, extensive coring and paleoenvironmental studies have been conducted in the LBR, focusing on bottom sediments of Lake Baikal (e.g. BDP-93 Baikal Drilling Project Members, 1997; BDP-99 Baikal Drilling Project Members, 2005; Demske et al., 2005; Grachev et al., 1997; Horiuchi et al., 2000; Kashiwaya, 2003; Khursevich et al., 2005; Minoura, 2000; Prokopenko and Williams, 1999; Swann et al., 2005) and peatbogs and small basins around it, containing local vegetation records (e.g. Bezrukova et al., 2005, 2008, 2010; Kataoka et al., 2003; Krivonogov et al., 2004; Takahara et al., 2000). The low temporal resolution and insufficient chronological control of pollen archives remain a serious problem in this region. Often, a palynological approach was applied, but qualitative interpretations predominate over objective pollen-based reconstructions of climate and vegetation. Nonetheless, pollen records and pollen-based reconstructions demonstrate spatial variations in vegetation dynamics within the LBR (e.g. Bezrukova et al., 2010; Kobe et al., 2020, 2022a, 2022b; P.E. Tarasov et al., 2009, 2017), highlighting the need for detailed reconstructions of microregional environments.

The LBR's high fire activity, significant vegetation changes, and human habitation since the Upper Paleolithic (Weber, 2020) make it a particularly promising area to study long-term changes in wildfire regimes. While intensive efforts to generate and discuss Holocene fire records have been undertaken in the boreal forest zone of Fennoscandia (e.g. Clear et al., 2014; Lankia et al., 2012; Magne et al., 2019), a complete fire history of the entire Holocene in the LBR is still missing (Barhoumi et al., 2021; Glückler et al., 2022). Additionally, records of wildfires from the Late Pleistocene are particularly rare (Shichi et al., 2009). The palaeoenvironmental overview of the LBR is discussed in detail in P.E. Tarasov et al. (2017), Kobe et al. (2020), and Chapter 4.5.

1.4.3 Archaeological background

The archaeological significance of the Kola Peninsula lies in its potential to provide insights into early human colonization and adaptation strategies in Arctic environments. Despite being a region of great scientific interest, the timing of initial human immigration and spatiotemporal distribution of settlements remain uncertain due to a lack of reliably dated sites or often poorly preserved materials. Archaeological surveys have identified 70 sites typologically attributed to the Mesolithic period (Shumkin, 2017). Almost all of these sites are predominantly coastal, indicating a reliance on marine resources. Late Mesolithic sites are relatively more numerous along the coasts of the Barents and White Seas, with scattered ones further inland (e.g. north of Lake Umbozero), indicating a broadening of the subsistence strategy (Shumkin, 2017). Excavations of 28 Neolithic–Bronze Age dwellings, including the recently studied Kharlovka 1–6 site dated to ca. 4550–4250 a BP (Kolpakov et al., 2021), revealed well-preserved organic matter and numerous faunal remains, allowing for a detailed reconstruction of the subsistence strategies of the local population at the end of the Middle Holocene. The faunal remains, dominated by marine mammals and seabirds, indicate a strong marine adaptation, while the presence of tundra and forest animals suggests that terrestrial hunting and gathering were also practiced (Kolpakov et al., 2021).

Archaeological research around Lake Onega has intensified over the last decade, however much of the work is still in the early stages and requires systematic analysis. Chronological issues remain the main obstacle in discussing the initial spread of Mesolithic hunter-gatherers and further population dynamics, cultural shifts and human-environment interactions in this large region (A.Yu. Tarasov et al., 2017). The oldest evidence of human habitation around Lake Onega dates back to approximately ca. 10,150 a BP (Pindushi XXXVIII) - 10,200 a BP (Povenchanka V), both located on the northern coast of Lake Onega (Tarasov, 2018), suggesting a dependency on both terrestrial and aquatic resources. The Yuzhniy Oleniy Ostrov (YOO; translated as Southern Reindeer Island) cemetery, one of the largest Late Mesolithic burial grounds (170 burials) in Northern Eurasia, provides insights into social organisation and subsistence strategies (Schulting et al., 2022). The YOO archaeological site is also exceptional for its very robust chronology, suggesting that the main use of the cemetery between ca. 8250 and 8000 a BP coincides remarkably well with the 8.2 ka BP cooling event (Schulting et al., 2022). The LOR is a very promising region for examining the impacts of Holocene climate change on the regional environments and human populations; however, the joint efforts of geoscientists and archaeologists are needed to refine the chronological framework and understand the broader cultural dynamics in this region.

The LBR offers a very well-documented archaeological history of the Neolithic and Early Bronze Age hunter-fisher-gatherer cultures (Weber, 2020). The Cis- and Trans-Baikal reveal surprisingly many finds of archaeological cemeteries (Weber, 2020; Kradin et al., 2021, and references therein). Key periods of interest include the Early Neolithic Kitoi culture (7560–6660 a BP) and the subsequent "cultural hiatus" during the Middle Neolithic (ca. 6660–6060 a BP), characterised by a significant population decline in Cis-Baikal, which took place around the time of maximum forest expansion (Kobe et al., 2020). Even though the region did not become completely depopulated (e.g. Kobe 2022a), the lack of formal cemeteries or settlements and the limited number of archaeological ^{14}C dates indicate an extremely low and scattered population (Weber, 2020).

1.5 Material and methods

1.5.1 Coring

In July 2018, a 135-cm-long sediment core was retrieved from Lake Kamenistoe by a team from the Geological Institute of the Kola Science Centre of the Russian Academy of Sciences, led by Dr. Vasily V. Kolka. Coring was conducted from a platform positioned in the deepest part of the lake at a depth of 4 m. The location for coring was chosen based on the results of water depth measurements with an echo sounder. A visual description of the core lithology was made on-site. Afterwards, the core was transported to the pollen laboratory of St. Petersburg

State University, subsampled, and preserved at a low temperature. The core comprises two major sedimentary units: organic gyttja and low-organic sediments (see Chapter 2.5.1).

In 2019, a core from Razlomnoe Peat (RZ19) was recovered by a team from the Laboratory of Palaeogeography and Geomorphology of Polar Countries and the World Ocean, Saint Petersburg State University, led by Dr. Larisa A. Savelieva. The 885-cm-long sediment core was extracted using a hand-held peat corer from the central part of the peat, which had the thickest layer of undisturbed sediments. It was transported to the pollen laboratory of St. Petersburg State University, then subsampled and stored at a low temperature. The initial lithological descriptions were made in situ with subsequent refinement in the laboratory. The RZ19 consists of four main lithologic units described in Chapter 3.5.1.

In 2018, a 724-cm-long sediment core was retrieved from Lake Ochaul (Och18-II) by a research team from the Institute of Geochemistry (Irkutsk), Siberian Branch of the Russian Academy of Sciences, under the leadership of Prof. Elena Bezrukova and Dr. Alexander Shchetnikov. The coring took place in the lake's deepest, central part at a water depth of about 2.5 m, using a UWITEC percussion piston corer and platform acquired via the BAP. The core, which was divided into five sections, was subsequently stored at consistently low temperatures. In March 2019, the core sections were halved longitudinally, photographed, documented, and subsampled. The sediments in the Och18-II core included a partly laminated layer of soft biogenic gyttja, a transitional layer of laminated silty clay, and a layer of finely laminated, viscous silty clay (see Kobe et al., 2022a, 2022b for details).

In 2019, the team extracted the longest sediment core to date from Lake Kotokel (KTK19-II), measuring 14.5 m. This core was obtained at a water depth of 3.6 m in the southern part of the lake, where the bottom is nearly flat and the layer of undisturbed sediments is the thickest (Zhang et al., 2013). The sediment structure of the core was analysed for its paleomagnetic properties, although it was not directly dated (Shchetnikov et al., 2022). The sediment profile includes several distinct layers: biogenic gyttja, alternating biogenic gyttja with silty clay, laminated silty clay, and a layer of massive silty clay (see Shchetnikov et al., 2022 for details).

1.5.2 Radiocarbon dating

In three studies, the radiocarbon dates were calibrated using the newest IntCal20 calibration curve (Reimer et al., 2020). The calibration was performed using the OxCal v.4.4 software (Bronk Ramsey, 1995). All calibrated ages are given as calendar ages before present (a BP), where "present" stands for the year 1950 CE. After calibration, the age-depth relationship was modelled using the rbacon software package v.2.5.7 (Blaauw and Christen, 2011) on the R v.4.1.2 platform (R Core Team, 2016), both median ages and 95% probability ranges are provided.

Each study used specific constraints and tie points to improve the accuracy of the models. The age-depth model of Lake Kamenistoe (Table 2.1, Fig. 2.3d) is based on the four bulk samples and constrained at the core top with an age of −68 a BP, corresponding to the recovery year of the core. The obtained ^{14}C ages suggest continuous sedimentation during the last ca. 13 ka BP.

A total of 10 bulk sediment samples were ^{14}C-dated from the Razlomnoe Peat (Table 3.2, Fig. 3.3). Two stratigraphic tie points were introduced: one at 0 cm depth with an age of –69 a BP, and another at 868 cm depth with an age of 11,650 a BP, marking the Pleistocene/Holocene boundary (Walker et al., 2012). The derived model suggests a continuous sedimentary record spanning the last ca. 11.8 ka BP.

The age-depth model of Lake Ochaul (Fig. 4.3), based on extensive AMS ^{14}C dating published in Kobe et al., 2022b, was applied to date sediment samples from unpublished sections, thereby covering the past ca. 31.5 ka. The age-depth model of Lake Kotokel (Table 4.1, Fig. 4.4) is based on 26 evenly distributed samples and covers the last ca. 30.7 ka. The model was constrained at the core top with –69 a BP and excluded dates exhibiting age-depth reversals due to reworked organic material.

1.5.3 Pollen analysis

The extraction and analysis of pollen and non-pollen palynomorphs (NPPs) involve several steps, from sub-sampling to visual representation of data. The methodology was applied to 30 samples from the Lake Kamenistoe sediment core (detailed in Chapter 2.4.3) and 97 samples from the Razlomnoe (RZ19) core (described in Chapter 3.4.3). Moreover, it was applied to 124 samples from the Lake Ochaul (Och18-II) core (Kobe, 2022; Kobe et al. 2022a, 2022b). Recently, an additional 47 samples from this core were analysed (see Chapter 4.3.3). The analysis also included 104 samples from the Lake Kotokel (KTK19-II) core (see Chapter 4.3.3).

Before starting the treatment, a *Lycopodium clavatum* spore tablet was added to each sediment sample with a volume of 1 or 2 cm^3. These tablets contain a known quantity of spores and are used to calculate the pollen concentration (Stockmarr, 1971) and pollen accumulation rate (PAR, Knight et al., 2022). For technical reasons, different chemical methods of pollen extraction were applied to the sediment samples in the laboratories of St. Petersburg State University (Lake Kamenistoe and Razlomnoe Peat) and Freie Universität Berlin (Lake Ochaul and Lake Kotokel), respectively. However, these differences did not affect the results of the current study.

1.5.3.1 Alkaline method

Peat and gyttja sediments from the RZ19 core were treated using the alkaline method (Fægri and Iversen, 1989). The process begins by dissolving carbonates and calcareous materials, including those in the *Lycopodium* tablets. To accomplish this, each sample, placed in a 50 ml tube, was mixed with ca. 25 to 30 ml of 10% hydrochloric acid (HCl). After centrifugation, the samples were rinsed twice with distilled water to remove any remaining HCl. Afterwards, the samples undergo an alkaline treatment to dissolve organic impurities. Each sample was supplemented with ca. 25 to 30 ml of a 10% sodium hydroxide (NaOH) solution and heated in a water bath at 90°C for 6−7 minutes. The timing is crucial to degrade unwanted organic material while preserving the pollen grains. Following the alkaline treatment, the samples were rinsed once more with distilled water to remove NaOH and dissolved organic materials. In the final stage, the pellet was suspended in a small amount of glycerine (1 to 2 ml) and gently mixed to ensure even distribution.

1.5.3.2 Hydrofluoric acid method

The samples from RZ19 and Lake Kamenistoe core, which contain significant siliceous material, were treated by using the hydrofluoric acid method (Berglund and Ralska-Jasiwichewa, 1986). This procedure shares its initial steps with the alkaline method. After the alkaline treatment, the samples are subjected to hydrofluoric acid (HF) treatment. For this step, ca. 7−8 ml of HF is added to each sample. Since HF is highly corrosive and poses severe health risks, it is vital to observe strict safety measures, including wearing the appropriate protective equipment (gloves, goggles, lab coat), as well as working in a highly ventilated fume hood. Following these precautions, the samples are heated in a water bath at 90°C for exactly 3 minutes. This ensures that the silica materials are dissolved without exposing the samples to HF for too long, which could damage the pollen grains. Next, the samples are rinsed with distilled water. The liquid containing dissolved impurities and HF residue is carefully decanted and discarded, leaving the pellet of pollen grains. The last step involves ultrasonic sieving with a 250-µm mesh to remove the larger debris. Lastly, a small amount of glycerine is added to each sample.

1.5.3.3 Dense media separation method

The dense media separation procedures were applied to samples from Och18-II and KTK19-II cores following the protocol described in Leipe et al., 2019. The treatment begins with the addition of HCl to the sediment samples to dissolve carbonates. Each sample, contained in a 50 ml tube, is filled with ca. 25 to 30 ml of 10% HCl. Following this, the samples are washed twice with distilled water to remove residual HCl. Afterwards, the samples are subjected to alkaline treatment using potassium hydroxide (KOH). Approximately 25 ml of a 10% KOH solution is added to each sample. The samples are then placed in a hot (90°C) water bath and heated for 15 minutes. After heating, the samples undergo repeated washing using a low-speed centrifugation technique. This method involves centrifugating the samples at a low speed (2200 rpm) for 3 minutes. The supernatant, containing fine clay particles and impurities, is decanted until the liquid becomes clear. Slow-speed centrifugation is preferred over ultrasonic sieving, which, while faster, can be destructive, especially to fragile or poorly preserved pollen grains.

In the next step, the samples are transferred to 15 ml tubes for dense media separation using sodium polytungstate (SPT). SPT is a heavy liquid with a high density (2.1 g/cm³) that enables centrifugation (1800 rpm) for 15 minutes (Fig 1.2b). In that way, denser particles (debris) sink down to the tube's bottom while the lighter fraction comprising of both pollen and NPPs will the separation of particles according to their density. Approximately 7 to 8 ml of SPT is added to each sample and thoroughly mixed (Fig. 1.2a). The samples are then subjected to low-speed stay in the supernatant liquid (Fig. 1.2c). The supernatant is carefully decanted into a new 50 ml tube (Fig. 1.2d), washed twice with distilled water to remove any residual SPT (Fig. 1.2e),

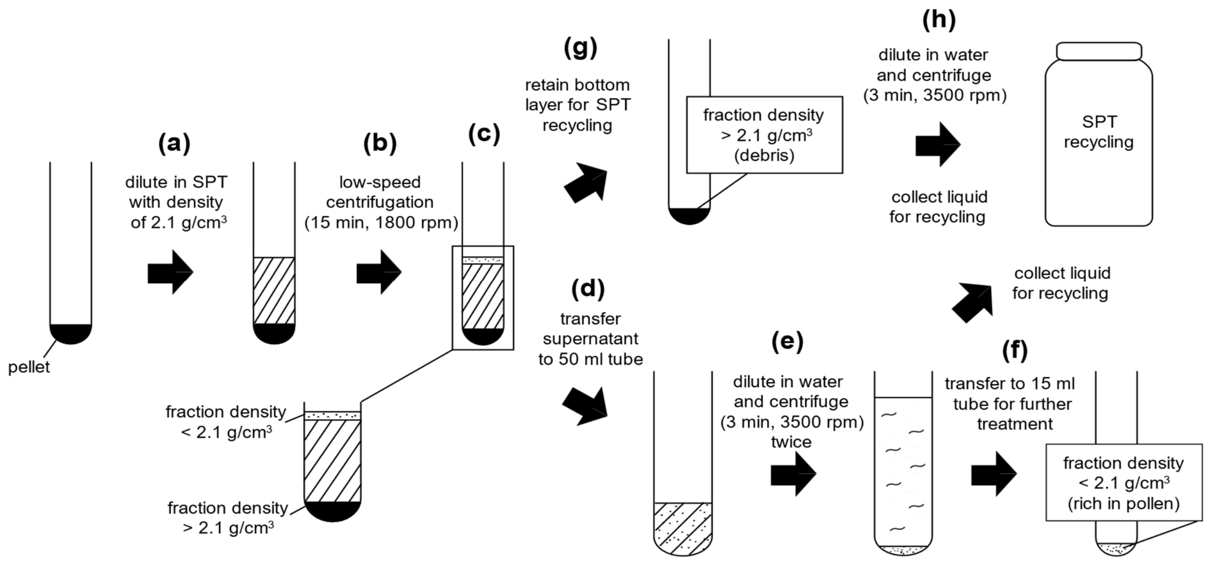

Figure 1.2: Schematic outline of the dense media separation process described in the text (modified after Nakagawa et al., 1998).

and transferred again to a 15 ml tube (Fig. 1.2f). The debris layer is also washed with distilled water to collect the remaining SPT for recycling (Fig. 2g–h).

One of the advantages of SPT is that it can be recycled and reused, making it economically and environmentally friendly. After collecting the supernatants, they are filtered for solid contaminants (Fig. 1.3a) and then slowly heated, preferably using a magnetic stirrer (Fig. 1.3b). The heating process concentrates the SPT by reducing the water level. This is followed by adjusting the density of the SPT back to 2.1 g/cm³ using an areometer or density hydrometer (Fig. 1.3c). Although the recycling process is time-consuming, it significantly improves the overall performance of SPT consumption and waste minimisation, making it a sustainable option compared to hazardous HF (Liepe et al., 2019).

Following the dense media separation, the samples are dehydrated using 15 ml of glacial acetic acid (CH_3COOH). This removes any residual water and prepares the samples for acetolysis. Treating the samples with acetolysis requires mixing acetic anhydride $(CH_3CO)_2O$ and concentrated (95–99%) sulfuric acid (H_2SO_4) in a 9:1 ratio. To prevent a brisk reaction, the sulfuric acid is gradually added to the acetic anhydride drop by drop. Each sample is treated with 3 to 4 ml of the acetolysis mixture and heated in a water bath for 3 minutes only. This brief treatment is enough to process the samples without damaging the pollen grains. To stop the reaction, glacial acetic acid is quickly added to the samples. After that, the samples are centrifuged and washed three times with distilled water to remove all the remaining acetolysis agents. Acetolysis should be performed under safety precautions, including the use of protective

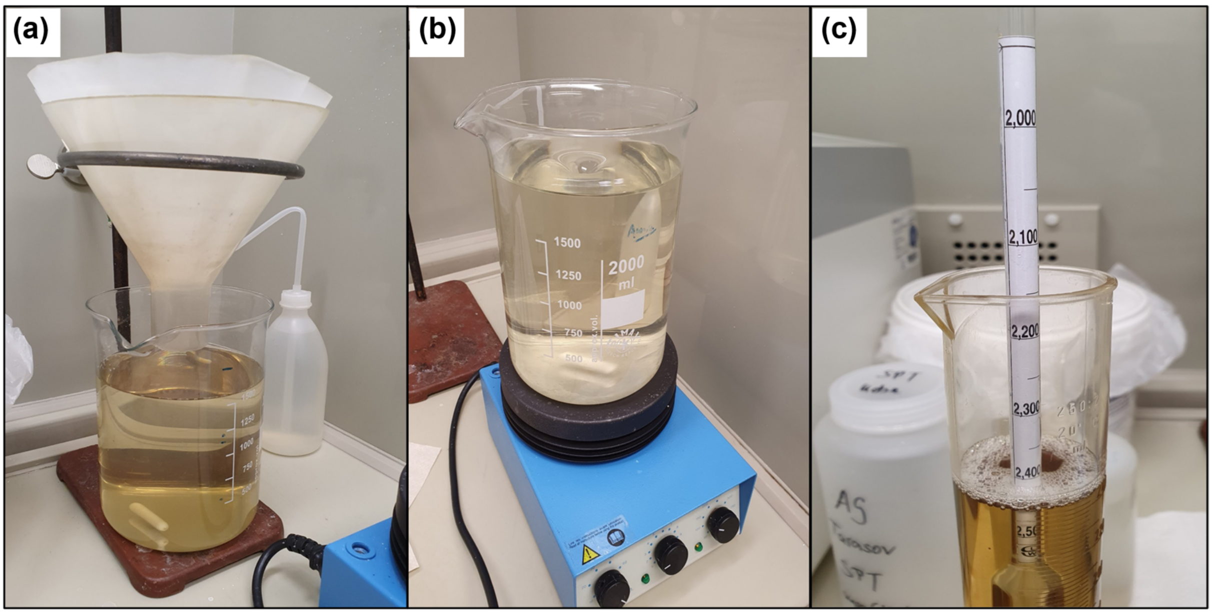

Figure 1.3: SPT recycling process: (a) filtering for solid contaminants, (b) heating and concentration of SPT, (c) adjusting the density with areometer (photos by Dr. F. Kobe).

clothing and working in a well-ventilated space. Moreover, the supernatants received during glacial acetic acid washing, acetolysis, and at least the first following washing should be disposed of according to established waste management protocols. After washing, each sample is transferred to a 5 ml tube and covered with a small amount of glycerine.

The samples treated with the alkaline method (Fig. 1.4a) exhibit a higher presence of impurities, which may complicate the process of pollen counting. The hydrofluoric acid method (Fig. 1.4b) results in cleaner samples with clearer pollen grains. Although this method significantly reduces the amount of debris, the pollen grains appear paler, which might affect the pollen identification. The dense-media separation method (Fig. 1.4c) produces the cleanest samples, with the least organic and mineral remains and more prominent, coloured, and enlarged pollen grains, providing a more efficient analysis.

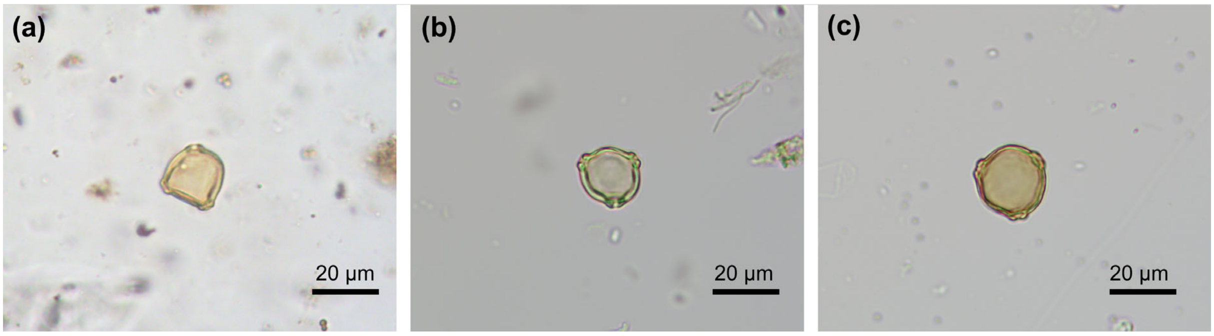

Figure 1.4: Pollen of *Betula* sect. *Albae* in samples treated with: (a) alkaline method (Lake Kamenistoe, photo by N.A. Kostromina), (b) hydrofluoric acid method (Razlomnoe Peat, photo by A.I. Krikunova), (c) dense-media separation method (Lake Kotokel, photo by Dr. F. Kobe).

1.5.3.4 Pollen identification and visualization

After the treatment, the samples are stored in a dark place with low temperature of +4°C (e.g. fridge). Initially, a drop from the well-mixed sample is placed on a slide and then covered with a coverslip. Using a light microscope at 400x magnification, pollen grains and NPPs are counted row by row without any overlap. This process continues until at least 300–400 terrestrial pollen grains are obtained. Pollen grains and NPPs were identified using regional atlases and reference collections (Beug, 2004; Bobrov et al., 1983; Kupriyanova and Aleshina, 1972, 1978; Moore et al., 1991; Reille, 1992, 1995, 1998; Savelieva et al., 2013; van Geel, 2001).

Tilia software version 1.7.16 (Grimm, 2011) was used to calculate the relative percentages of different taxa and create a pollen diagram. The percentages for terrestrial pollen types are based on the total sum of arboreal pollen (AP) and non-arboreal pollen (NAP), taken as 100%. For aquatic plants, terrestrial cryptogams, and other NPPs, percentages are calculated based on the sum of terrestrial pollen plus the palynomorphs in their respective group. The constrained incremental sum of squares (CONISS) method was used to define pollen zone boundaries. This tool, integrated in the Tilia software, is particularly effective for analysing stratified data (Grimm, 1987).

1.5.4 Pollen-based vegetation reconstruction

The qualitative analysis of the pollen data was enhanced by the biomization technique, developed by Prentice et al. (1996). This approach relies on current ecological, bioclimatic and geographic data on pollen-producing plants to systematically assign pollen spectra to major vegetation types (biomes). Robust testing against modern reference datasets (Prentice et al., 1996; Tarasov et al., 1998) and application in various geographical regions (Kageyama et al., 2001; Prentice and Webb III, 1998; Prentice and Jolly, 2000; Tarasov et al., 2000, 2022; Wohlfarth et al., 2006, 2007) have well-validated the technique.

All terrestrial pollen taxa in a sample were identified and assigned to their respective plant functional types (PFTs) and regional biomes. This is achieved using a biome-taxon matrix (see Table 3.3. for an example) that categorises each pollen taxon based on its ecological role and functional characteristics (Prentice et al., 1996). After that, affinity scores of biomes were calculated to quantify the relationship between the pollen spectrum and potential biomes. The equation first published by Prentice et al. (1996) incorporates the pollen percentage values for each taxon. The method excludes taxa that do not exceed a universal threshold of 0.5%, thereby reducing noise and focusing on ecologically relevant taxa (Prentice et al., 1996). Furthermore, a square root transformation was used to increase the importance of minor pollen taxa. After calculating affinity scores, the biome with the highest score was assigned to the pollen spectrum. If several biomes have comparable scores, the biome defined by a smaller number of plant functional types (PFTs) was preferred.

In addition to biomization, the degree of landscape openness was estimated by calculating the difference between the maximum affinity score for forest biomes (e.g., cold deciduous forest, taiga, cool coniferous forest) and open biomes (e.g., tundra or cold steppe). A higher value implies a more forested landscape, while a smaller or negative difference indicates a more open landscape (Tarasov et al., 2013).

1.5.5 Palynological charcoal analysis

Charcoal analysis is a crucial method in palaeoenvironmental reconstructions, providing valuable information on past fire regimes and their relationships with vegetation dynamics and climate change (Clark, 1988a; Tinner et al., 1998; Whitlock and Larsen, 2001). Additionally, changes in charcoal accumulation can indicate human-induced alterations to fire regimes, particularly during periods of known human activity (Bowman et al., 2011). This technique involves the identification, quantification, and interpretation of charcoal particles preserved in sedimentary records. Palynological charcoal analysis has been applied to 171 samples representing the entire Och18-II core from Lake Ochaul (courtesy of F. Kobe). In the current study, 104 samples from the KTK19-II sediment core (Table 7.10) were analysed with the same approach for compatibility and both datasets were used to reconstruct the fire regimes in Cis-Baikal and Tarns-Baikal subregions.

The quantitative theory on the source area, transport, and deposition demonstrates that particle sizes correlate with their origin (Clark, 1988b). Larger particles (>100 µm) tend to deposit close to the fire source, while smaller particles (<100 µm) can travel greater distances and may represent regional fire events (Clark, 1988b; Clark et al., 1998; Ohlson and Tryterud, 2000). Clark (1988b) noted that particles smaller than 10 µm likely represent subcontinental or global fire sources, as they can be transported over long distances by atmospheric currents. Duffin et al. (2008) demonstrated that particles larger than 50 µm have a stronger correlation with nearby fires, whereas smaller particles may indicate regional fires or may not reliably reflect fire events. In this research, charcoal particles were categorised into three size classes based on their longest axis: 10–50 µm, 50–100 µm, and >100 µm.

The analysis of macrocharcoal (>100 µm) was conducted using the CharAnalysis program through MATLAB (Higuera et al., 2009). This software decomposed the record into peaks representing fire events (C_{peak}) and low-frequency background "non-fire" charcoal ($C_{background}$). Charcoal concentration was interpolated ($C_{interpolated}$) to produce equally spaced intervals, allowing for the calculation of charcoal accumulation rates (CHAR, particles/cm^2/year). The background charcoal ($C_{background}$) was estimated using a locally weighted regression (lowess) with window widths of 200 years for Lake Kotokel and 250 years for Lake Ochaul, optimised to maximise the signal-to-noise index (SNI, Brossier et al., 2014). Fire frequency and fire return intervals (FRI), i.e. the number of years between two fire events, were smoothed over a 1000-year period, providing a long-term perspective on fire regime changes. This approach allows for the identification of significant shifts in fire activity and their potential correlation with climatic changes, vegetation dynamics, and human activities.

2 Manuscript I

Late- and postglacial vegetation and climate history of the central Kola Peninsula derived from a radiocarbon-dated pollen record of Lake Kamenistoe

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Highlights

- Archive of natural vegetation and climate change over the last ca. 13,000 years.
- The study site in the central Kola Peninsula was ice-free at 13 ka BP.
- Highest pine pollen percentages mark a thermal optimum ca. 8.2–4.2 ka BP.
- Climate cooling, increasing moisture levels and spread of taiga from 6 ka BP.
- Postglacial human occupation may have followed the migration of reindeer.

2.1 Abstract

A radiocarbon-dated sediment core collected from the small freshwater Lake Kamenistoe, in the central part of the Kola Peninsula, provides a pollen record of vegetation and climate history of this part of Fennoscandia and the European Arctic during the past ca. 13,000 years. In contrast to existing Scandinavian Ice Sheet reconstructions, the record shows that the study site was ice-free at 13 ka BP, thus allows to improve our knowledge on deglaciation dynamics in North Europe. The biome reconstruction results together with other pollen records from the wider region suggest that forest-tundra surrounded Kamenistoe at the end of the Bølling–Allerød interstadial and that the reconstructed presence of trees is not determined by far-distance pollen transport. The spread of pine in the study region started ca. 9.3 ka BP, and maximum pollen percentages during 8.2–4.2 ka BP mark the Holocene thermal optimum. Progressive climate cooling accompanied by increasing moisture levels from 6 ka BP is indicated by the spread of spruce (boreal evergreen conifer), reflecting the expansion of taiga forests. In contrast to some previous interpretations, we argue that the spread of pine in the Early Holocene and spruce in the Middle Holocene did not follow zonal expansions, but rather originated from scattered small populations withing the study region. Archaeological records from northern Fennoscandia suggest that postglacial human occupation on the Kola Peninsula began no later than 10,000 years ago. This northward expansion of hunter-gatherers was likely related to the continuous Early Holocene warming, which not only resulted in less harsh climatic conditions for human occupation, but may have also pushed reindeer populations to the study region. This game animal, which has been a major resource for humans, prefers July temperatures below 12–13 °C and thus may have migrated to cooler environments during the Early Holocene.

3 Manuscript II

Postglacial vegetation and climate change in the Lake Onega region of eastern Fennoscandia derived from a radiocarbon-dated pollen record

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Highlights:

- First robustly dated continuous Holocene pollen record from the Onega Region.
- Rapid Holocene afforestation, but still more open than today prior to 11.4 ka BP.
- Marked increase in birch/decrease in pine pollen displays the 8.2 ka BP event.
- Distinct Greenlandian/Northgrippian and Northgrippian/Meghalayan transitions.
- Forest retreat after 4 ka BP due to paludification, not dry climate or human impact.
- Reconstructed impact of the 8.2 ka BP cooling helps explain socio-ecological stress.

3.1 Abstract

With its numerous environmental archives stored in lake and peat sediments and relatively low human pressure, the Lake Onega region in eastern Fennoscandia is regarded as a particularly promising area for studying past changes in vegetation and climate since the Lateglacial period. The 885-cm-long sediment core RZ19 (62°27′53″N, 34°26′4″E) was collected from Razlomnoe Peat on the northern shore of Lake Onega in 2019, radiocarbon-dated and analysed for pollen and cryptogam spores. The age-depth model suggests continuous sedimentation since ca. 11,800 a BP (all ages given in years (a) or kiloyears (ka) before present (BP) with BP referring to 1950 CE). The results of pollen analysis and pollen-based biome reconstruction show rapid afforestation of the area in the Early Holocene, although the scores of the tundra biome remain relatively high prior to ca. 11,450 a BP, suggesting that the vegetation was likely more open than today. Between 8300 and 8000 a BP, *Betula* sect. *Albae* shows a marked increase in pollen percentage, while *Pinus sylvestris* experiences a marked decrease. These changes coinciding with the 8.2 ka BP cooling event indicate less favourable conditions for Scots pine while being beneficial for fast-growing birch. The transition from the Early to Middle Holocene (i.e. from Greenlandian to Northgrippian) is marked by an increase in pollen productivity, spread of *Picea* and further afforestation of the area. The decrease in arboreal and *Picea* pollen percentages and the abrupt increase in landscape openness after ca. 4000 a BP mark the onset of the Late Holocene (i.e. Northgrippian-Meghalayan transition) and likely reflect the combined effect of insolation-induced temperature decrease and associated paludification and forest retreat rather than a decrease in atmospheric precipitation and/or spread of Late Neolithic agriculture.

4 Manuscript III

Vegetation and fire history of the Lake Baikal Region since 32 ka BP reconstructed through microcharcoal and pollen analysis of lake sediment from Cis- and Trans-Baikal

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Highlights

- Spatiotemporal complexity in the AMS-dated vegetation and fire records from Siberia.
- Increase in fire activity coincides with the onset of deglaciation ca. 18.2 ka BP.
- Peak fire activities occur in the Early (Cis-Baikal) and Middle Holocene (Trans-Baikal).
- Climate change and vegetation composition controlled glacial-interglacial fire activity.
- Holocene fire trends partially correlate with human activities in the Lake Baikal Region.

4.1 Abstract

With the increase in global wildfire activity in response to global climate warming, the reconstruction of long-term fire histories and their links to environmental and anthropogenic factors has recently become an important focus of palaeoenvironmental research. Here we compare the precisely radiocarbon (^{14}C) dated long-term histories of vegetation change and fire activity from lakes Ochaul (Cis-Baikal) and Kotokel (Trans-Baikal) in the Lake Baikal Region (LBR) of Siberia, a known source region of wildfires whose past and future relationships with climate, vegetation structure and human economy are still poorly understood. Our results show that under cold and dry glacial climate conditions (32–18.2 ka BP) fire frequencies in both study regions were low. Deglaciation, which was characterised by the spread of woody plants, began around 18.2 ka BP, accompanied by a slight increase in fire activity. Differences in the fire records from both subregions are observed from the end of the Lateglacial (LG), with peak fire activity in Cis-Baikal during the Early Holocene (EH) and in Trans-Baikal during the Middle Holocene (MH). During the Late Holocene (LH) both regions are marked by generally low fire activity. We propose that the long-term spatiotemporal differences in fire activity during the EH–MH interval are primarily driven by vegetation composition and landscape openness and the resulting changes in fire regime. Interestingly, both peaks are also observed in a global-scale fire record, which suggests spatiotemporal complexity of the Holocene fire history. Low charcoal accumulation rates in both records during the Middle Neolithic (ca. 6660–6050 a BP) “cultural hiatus” archaeologically documented for Cis-Baikal suggest an LBR-wide population decline. On the other hand, the spread of Late Bronze and Iron Age cultures into the LBR from 3.5 ka BP may have at least partly driven the increase in fire frequency around Lake Kotokel.

5 Conclusions and future perspective

5.1 Summarizing conclusions

This doctoral thesis presents three multi-proxy studies aimed at reconstructing the last glacial–interglacial environments in eastern Fennoscandia and the LBR. Sediment cores obtained from Lake Kamenistoe (Kola Peninsula), Razlomnoe Peat (LOR), Lake Ochaul (Cis-Baikal), and Lake Kotokel (Trans-Baikal) represent unique and detailed archives of the past climatic and environmental changes in these understudied regions, which lack high-resolution palaeoenvironmental records with reliable age control. The primary method employed is pollen analysis, which, together with quantitative pollen-based biomization and charcoal analysis, has allowed for the reconstruction of vegetation, climate, and fire history, with a particular focus on the Lateglacial–Holocene interval. The principal findings of this doctoral thesis are presented in three internationally published peer-reviewed journal articles.

The first article (Chapter 2) presents a detailed palaeoenvironmental reconstruction of the central Kola Peninsula for the last ca. 13 ka BP, based on a 135-cm-long radiocarbon-dated pollen record from Lake Kamenistoe (67°30′31.4″ N; 34°38′53.3″ E, 205.3 m a.s.l). Contrary to previous models, which suggested the presence of the Scandinavian Ice Sheet in the area at 13 ka BP (Fig. 2.5a), the Lake Kamenistoe record indicates that the region was already ice-free at that time, as shown by the lacustrine sedimentation and the presence of tundra vegetation (Fig. 2.4). The study underscores the sensitivity of the region's vegetation to both local and extra-regional climatic changes. The detailed pollen analysis and biome reconstructions are closely in line with broader climatic trends, such as changes in summer insolation, sea surface temperatures, and global ice volume (Fig. 2.6), indicating a coherent response of the region's ecosystems to global climatic drivers. The palaeoenvironmental reconstruction integrated with existing archaeological data suggests that the initial spread of hunter-gatherer populations into the region occurred during the expansion of the boreal forest and a phase of continuous warming in the Early Holocene (ca. 10.5–10.2 ka BP). The study proposes that these environmental changes played a crucial role in facilitating the postglacial human coloniation of the region, which was likely prompted by the northward migration of key game species, such as reindeer, driven by rising summer temperatures.

The second article (Chapter 3) presents a robustly dated high-resolution pollen record (RZ19) from Razlomnoe Peat (62°27'53" N, 34°26'4" E) in the LOR for the past ca. 11.8 ka BP. The study provides the first conclusive evidence of the environmental impact of the 8.2 ka BP cooling, which resulted in a substantial shift in vegetation, notably the spread of birch at the expense of pine and a reduction in alder and other temperate taxa. This change is interpreted as a response to severe winter cooling, low precipitation, and increased fire frequency. The abrupt vegetational shifts during the 8.2 ka BP event likely influenced human subsistence strategies, as evidenced by the increased complexity of mortuary practices at the Yuzhniy Oleniy Ostrov site (Schulting et al., 2020). The timing of the main use of this burial site ca. 8,250–8,000 a BP coincides with the most prominent vegetation changes documented in the RZ19 record, suggesting a possible response of hunter-gatherers to deteriorating environmental conditions. The pollen data indicates that after 4.2 ka BP, the study area did not experience aridification but increased waterlogging, leading to a shift towards more open landscapes. The study confirms the high sensitivity of regional vegetation to hemispheric-scale climate dynamics throughout the Holocene. The shifts in pollen assemblages and biome reconstruction (Fig. 3.4–3.5, Table 3.4) at key climatic transitions (e.g. Younger Dryas–Greenlandian, Greenlandian–Northgrippian, Northgrippian–Meghalayan) correlate well with global climate changes (Fig. 3.6), highlighting the region's responsiveness to broader climatic trends. The appearance of rye pollen around 750 a BP corresponds with the onset of land clearance for crop cultivation in the late 13th century CE in the region (Vuorela et al., 2001), indicating the beginning of more intensive human activity.

The third publication (Chapter 4) presents a comparative high-resolution study of vegetation changes and fire histories in the Cis- and Trans-Baikal regions of the LBR, covering the last 32 ka. The study is based on pollen and microcharcoal analyses of sediment cores from Lake Ochaul (54°13’58.4” N, 106°27’53.8” E) and Lake Kotokel (52°47’ N, 108°07’ E) and provides robust chronologies for both sediment sequences (Fig. 4.3–4.4) and new insights into the long-term dynamics of the regional environment and human-environment interactions. The study identifies the onset of deglaciation in the LBR at ca. 18.2 ka BP, which is notably earlier than the beginning of the Bølling–Allerød warming (ca. 14.7 ka BP) inferred from the NGRIP $\delta^{18}O$ record. This finding suggests that rising summer insolation directly influenced regional climate and vegetation long before similar changes occurred in other parts of the Northern Hemisphere. The pollen records from both lakes indicate that boreal trees and shrubs spread fast during this period, suggesting the existence of vegetation refugia where cold-tolerant species survived the harsh climatic conditions of the LGM. These refugia likely played a crucial role in the reforestation of the region during the Late Pleistocene, a topic that has been previously underexplored. The study also reveals distinct fire regimes in the Cis-Baikal and Trans-Baikal subregions, with notable differences in timing and intensity of fire activity. In Cis-Baikal, fire activity peaked during the Early Holocene (ca. 9.5–8 ka BP), while in Trans-Baikal, the highest fire activity occurred during the Middle Holocene (ca. 6–5 ka BP). This spatiotemporal pattern likely reflects differences in vegetation composition and landscape openness between the two subregions, which were influenced by climatic conditions. During the Mesolithic and Neolithic, the LBR experienced significant climatic shifts that led to changes in vegetation and fire regimes, which in turn influenced human subsistence strategies. For instance, the study suggests that the dramatic landscape changes during the Early Neolithic (ca. 7560–6660 BP) were associated with increased fire activity, possibly connected with expanded human settlement and more intensive land use. The "cultural hiatus" observed in the Middle Neolithic (ca. 6660–6060 a BP) corresponds with reduced fire activity, potentially linked to lower population densities. In the Late Bronze Age and Iron Age, the introduction of animal husbandry and agriculture from 3.5 ka BP had a pronounced impact on the environment, especially in Trans-Baikal, where semi-open landscapes facilitated these practices. The study's findings suggest that these human-induced changes in land use are associated with higher fire frequencies, as evidenced by increased charcoal concentrations in the analysed sediment sequence from Lake Kotokel.

The new well-dated records from eastern Fennoscandia and southern Siberia allow for a comparison of environmental changes in these two parts of northern Eurasia with long histories of hunter-fisher-gatherer occupation. Both regions exhibit a clear three-part division of the Holocene, with well-defined boundaries that closely agree with the internationally accepted chronostratigraphic subdivisions (Walker et al., 2018): the Early Holocene (Greenlandian, 11,650–8186 a BP), the Middle Holocene (Northgrippian, 8186–4200 a BP), and the Late Holocene (Meghalayan, 4200 a BP to present). In eastern Fennoscandia, the distribution of archaeological sites during the Mesolithic, Neolithic, and Eneolithic periods indicates a strong dependence on marine and lacustrine resources for subsistence. However, hunting of game such as reindeer, elk, and smaller mammals, supplemented by gathering, also played an important role in the subsistence strategies of these populations (e.g. Askeyev et al., 2023; Kolpakov et al., 2021; Lobanova and Filatova, 2014; Mannermaa et al., 2008; O'Shea and Zvelebil, 1984; Savvateev and Vereshchagin, 1978; Shumkin, 2017). The presence of pollen from cultivated cereals and associated weeds from ca. 1000 a BP in the northern part of Lake Onega suggests the beginning of agriculture in the region (Lavrova, 2005). The RZ19 record further reveals the presence of single grains of rye pollen from ca. 750 a BP, corresponding with findings by Vuorela et al. (2001) in southern Pegrema Bay, which point to the beginning of land clearance for crop cultivation in the late 13th century CE and a shift to more intensive cultivation by the 15th century.

In contrast, southern Siberia witnessed a different trajectory of human activity, characterised by a spatially non-uniform transition from foraging to agropastoralism. The spread of the Late Bronze and Iron Age cultures from ca. 3.5 ka BP marked the introduction of animal husbandry and crop cultivation (Losey and Nomokonova, 2017), particularly in Trans-Baikal where semi-open environments were conducive to agropastoralism (Kradin et al., 2021). The population in the northern part of the LBR, remained hunter-fisher-gatherers.

During the glacial period (32–18.2 ka BP), the LBR experienced minimal fire activity (Fig. 4.9g–h), which can be attributed to the treeless, cold, and dry landscape, where limited biomass and efficient burning of herbaceous material resulted in minimal charcoal production. As the climate warmed after ca. 18.2 ka BP, the expansion of woody vegetation increased fuel availability, resulting in a moderate rise in fire activity. The observed temporal differences in the peak fire activity between Cis-Baikal (during the Early Holocene, ca. 9.5–8 ka BP) and Trans-Baikal (during the Middle Holocene, ca. 6–5 ka BP) likely reflect the regional variations in vegetation composition and landscape openness. In the Late Holocene, a general decline in fire activity is noted within the LBR; however, this trend contrasts with an observed increase in fire frequency from around 4 ka BP to 500 a BP, particularly within the Trans-Baikal region (Fig. 4.9k–l). This pattern suggests a shift toward more frequent but potentially smaller or less intense fires. Modern fire regimes in the Siberian taiga are predominantly characterised by low- to moderate-intensity surface fires.

Similarly, the rapid post-glacial vegetation expansion and increase in fuel availability in eastern Fennoscandia appear to have driven an Early Holocene increase in biomass burning (Fig. 3.6i). During the Middle Holocene, fire activity in eastern Fennoscandia became relatively subdued, likely due to the increasing dominance of spruce, which contributed to a denser and less flammable forest structure (Clear et al., 2014). Nonetheless, periods of reduced precipitation and elevated summer temperatures, such as the 8.2 ka BP event, could have temporarily enhanced fire activity in the region (Schulting et al., 2022). The expansion of agriculture, particularly slash-and-burn practices, increased the fire frequencies during the Late Holocene. However, the transition to modern agriculture and forestry, along with active fire suppression strategies, resulted in a significant reduction in fire activity across the region by the 20th century CE (Clear et al., 2014).

5.2 Future perspectives

This three-year doctoral research project has generated four high-resolution and accurately dated palaeoenvironmental records, offering detailed insights into the vegetation and climate histories of eastern Fennoscandia and the LBR. The findings underscore the great potential of lake and peat sedimentary archives for future in-depth palaeoenvironmental research. Proxies such as green algae, ostracods, mollusks, and chironomids could be incorporated into future studies to reconstruct past aquatic environments and changes in water chemistry, temperature, and ecological conditions. Expanding the geographical scope with high-resolution and well-dated records will provide data crucial for testing predictive models of vegetation response to climate change. The study also highlights the importance of systematic archaeological surveys in combination with robust cultural chronologies based on radiocarbon dating to better understand the timing and nature of human responses to environmental changes.

The research conducted in the LOR presents unique evidence of substantial environmental impacts associated with the 8.2 ka BP and 4.2 ka BP events. The notable expansion of birch at the expense of pine during the 8.2 ka BP event indicates a rapid vegetation shift likely driven by cooling and changes in moisture availability. This finding underscores the necessity of investigating the underlying mechanisms of vegetation dynamics during abrupt climate events, which is essential for predicting the potential responses of boreal ecosystems to future climate changes. Similarly, the increased landscape openness observed after the 4.2 ka BP event points to a complex interaction between climatic cooling, hydrological shifts, and vegetation structure. High-resolution palaeoecological and hydrological modelling could help to identify the detailed moisture balance changes that drove these shifts, particularly focusing on the role of paludification in transforming the regional landscape.

The detailed reconstructions of past fire activities are crucial for understanding the vegetation-fire-human dynamics within the LBR's ecosystem over historical periods. While the correlation between vegetation cover and fire regime is generally acknowledged, there remains a considerable gap in understanding the extent to which human activities and large herbivores have influenced fire dynamics in the region over time. Traditional method using microcharcoal for estimating fire activity has limitations, especially in distinguishing the type of fire. The use of advanced technologies like Fourier Transformed Infrared Spectroscopy (FTIR) as indicated by Gosling et al. (2019) offers a promising alternative. FTIR can provide the combustion temperatures of historical fires with greater accuracy through analysis of charcoal's chemical properties. This chemical differentiation is important because the impacts that fire have on ecosystems are significantly influenced by the temperatures at which they burn. Therefore, integrating charcoal analysis with FTIR can substantially enhance our understanding of past fire regimes and their ecological consequences.

The available long-term (up to ca. 1.2 Ma) sedimentary records from Lake Baikal obtained through the Baikal Drilling Project (e.g. BDP-93 Baikal Drilling Project Members, 1997; BDP-99 Baikal Drilling Project Members, 2005) provide valuable insights into the region's palaeoenvironment. However, low sedimentation rates, reliance on paleomagnetic reversals for chronological control, potential hiatuses, and the complex depositional environments associated with these records limit the ability to detect rapid climatic shifts. While previous studies have mainly focused on peat and lake sediments from around Lake Baikal (e.g. Bezrukova et al., 2005, 2008, 2010; Kataoka et al., 2003; Krivonogov et al., 2004; Takahara et al., 2000), there has been a noticeable lack of research on Olkhon Island, the largest island in Lake Baikal. Olkhon Island features a unique ecological setting with distinct vegetation zones: forested areas in the eastern, higher (600–1274 m a.s.l.) regions of the island and steppe vegetation in the lower western part of the island. The excavation of the Tyshkine-III settlement and four burial sites provides evidence of human presence on the island from the Late Neolithic (Goriunova, 1984, 1997). The occurrence of fragmented axes, components of composite fishhooks, and harpoons, suggests a subsistence strategy characterised by the complex use of natural resources, where fishing was combined with hunting and gathering (Novikov and Goriunova, 2005).

Supported by the BAP, a 750-cm sediment core was extracted from Lake Nurskoye in the southwestern part of Olkhon Island, providing a continuous record spanning the last ca. 13.5 ka BP. The study of this core supported by a robust chronological framework will provide a high-resolution pollen and charcoal analysis of this improratant archaeological microregion. The outcomes are expected to clarify the relationship between vegetation cover change, climatic fluctuations, and fire events on Olkhon Island during the Late Pleistocene–Holocene and enable a detailed comparison with the sedimentary records from Lake Baikal and its surroundings, particularly in terms of sensitivity to climate change and human impact. However, a limitation of the pollen analysis lies in the challenge of distinguishing between locally, regionally, and long-distance transported pollen, which can complicate the interpretation of vegetation cover changes on Olkhon Island. This limitation could be addressed by integrating sedimentary ancient DNA (sedaDNA) analysis, which can provide information on the local presence of key species, thus strengthening the robustness of palaeoenvironmental reconstructions.

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7 Appendix

7.1 Supplementary data: Manuscript II

7.2 Newly generated palynological records

7.2.1 Lake Kamenistoe

This section presents the results of the palynological analysis of 30 sediment samples from Lake Kamenistoe (Chapter 2), which are organized into three tables. Table 7.2 provides information on the sample core depth (cm), sample age (a BP), loss on ignition (LOI, %), pollen concentration (CONC, grains/g), as well as counts of tree and high shrubs (T) taxa, and boreal shrubs (S) taxa. Table 7.3 summarizes the counts of herbs (H) taxa. Table 7.4 presents the results of the pollen-based biome reconstruction, including affinity scores of regional biomes and landscape openness, and dominant biomes. The percentage data and non-pollen palynomorph counts can be accessed in the PANGAEA database (Table 1.1).

Table 7.2: Results of the palynological analysis of the Lake Kamenistoe sediment core, including sample core depth (cm), age (a BP), loss on ignition (LOI, %), pollen concentration (CONC, grains/g) and counts of tree and high shrubs (T), and boreal shrubs (S) taxa.

Sample depth (cm)	Sample age (a BP)	LOI (%)	Pollen CONC (grains/g)	*Picea*	*Pinus*	*Alnus*	*Betula sect. Albae type*	*Carpinus*	*Corylus*	*Tilia*	*Quercus*	*Ulmus*	*Alnus fruticosa*	*Betula* sect. *Nanae/ Fruticosae* type	*Ephedra*	Ericales	*Hippophae*	*Salix*
				T	T	T	T	T	T	T	T	T	S	S	S	S	S	S
2.5	185	98.171	83965	38	170	7	178	0	1	1	0	0	0	12	0	7	0	1
12.5	827	98.434	124232	67	206	4	64	1	4	0	0	0	0	19	0	7	0	0
18.5	1277	97.882	118944	32	218	7	107	0	0	0	0	0	0	5	0	6	0	1
24.5	2371	98.041	124949	66	200	7	155	1	0	0	0	1	0	12	0	6	0	0
30.5	2814	97.915	97247	88	180	7	102	0	0	0	0	1	0	1	0	3	0	0
36.5	3839	97.687	104717	106	300	15	200	1	2	0	1	0	0	8	0	10	0	1
42.5	4634	97.82	149291	65	220	3	57	0	0	1	0	1	0	3	0	4	0	0
48.5	5619	97.423	226667	49	300	3	90	0	0	0	1	1	0	7	1	3	0	1
54.5	6300	97.864	151543	10	263	11	175	0	0	0	0	1	0	17	0	5	0	1
60.5	6544	98.214	309833	37	684	16	242	0	2	1	0	0	0	9	0	5	0	1
66.5	6785	98.419	253968	22	280	19	185	1	1	0	0	0	0	14	0	5	0	0
72.5	7078	98.507	228551	19	594	9	295	0	4	0	0	0	3	8	0	3	0	3
78.5	7440	97.83	648425	1	203	6	161	0	0	0	0	3	0	10	0	1	0	0
82.5	7636	97.631	502451	1	260	8	117	0	2	0	0	1	1	11	0	2	0	0
86.5	7856	97.8	189153	0	173	5	98	0	0	0	0	0	0	6	0	1	0	1
90.5	8142	97.709	175566	0	469	15	365	0	6	0	0	0	4	71	0	0	0	0
92.5	8356	97.683	157533	1	162	4	251	0	0	0	0	2	0	14	0	0	0	1
96.5	8865	97.458	243590	0	42	0	260	0	1	0	0	1	1	39	0	1	1	4
101.5	9566	93.577	189258	0	12	0	480	0	0	0	0	2	0	45	0	15	0	1
104.5	9910	84.6	141888	0	6	0	135	0	0	0	0	0	0	26	0	63	0	4
105.5	10064	64.202	23347	0	3	0	40	0	0	0	0	0	0	10	0	23	0	2
109.5	10671	72.962	29038	0	5	0	69	0	0	0	0	0	0	27	0	2	0	18
110.5	10818	57.915	30495	0	11	0	54	0	0	0	0	0	0	10	0	1	0	4
112.5	11117	39.122	5052	0	2	0	33	0	0	0	0	0	0	1	0	1	0	11
116.5	11500	25.099	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120.5	11882	29.142	2050	0	1	0	4	0	0	0	0	0	0	3	0	0	0	6
122.5	12126	37.488	5818	0	0	0	13	0	0	0	0	0	0	11	0	0	0	2
128.5	12698	29.523	1600	3	0	4	0	0	0	0	0	0	0	0	0	0	0	0
130	12833	30.226	1864	1	0	5	0	0	0	0	0	0	0	0	0	0	1	0
134	13235	30.792	2624	2	0	10	0	0	0	0	0	1	7	0	0	0	5	0

Table 7.3: Results of the palynological analysis of the Lake Kamenistoe sediment core, including sample core depth (cm), age (a BP), counts of herbs (H) taxa, along with the amount of unidentified taxa (UNID).

Sample depth (cm)	Sample age (a BP)	Apiaceae	*Artemisia*	Asteraceae	Caryophyllaceae	Chenopodiaceae	Cyperaceae	Fabaceae	*Gentiana*	*Polemonium*	Poaceae	*Polygonum sp.*	*Rumex*	Ranunculaceae	*Thalictrum*	Rosaceae	*Potentilla*	*Rubus chamaemorus*	Pollen UNID
		H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
2.5	185	0	2	0	0	1	4	0	0	0	5	0	0	1	0	4	0	0	0
12.5	827	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18.5	1277	0	1	0	0	0	4	0	0	0	2	0	0	0	0	0	0	0	1
24.5	2371	0	1	0	0	0	4	0	0	0	4	0	0	0	0	0	0	0	0
30.5	2814	0	1	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0
36.5	3839	1	2	0	0	0	12	1	0	0	4	0	0	0	0	2	0	0	0
42.5	4634	0	1	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	1
48.5	5619	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0
54.5	6300	0	1	0	0	1	4	0	0	0	1	0	0	0	0	0	0	1	0
60.5	6544	0	0	0	0	0	3	0	0	0	0	0	0	0	0	2	0	0	1
66.5	6785	0	1	2	0	0	8	0	0	0	5	0	0	0	0	1	0	0	0
72.5	7078	0	4	1	0	1	2	0	0	0	5	0	0	0	0	0	0	0	0
78.5	7440	0	2	0	0	0	2	0	0	0	1	0	0	0	0	1	0	0	0
82.5	7636	0	1	0	0	0	4	0	0	0	1	0	1	0	0	0	0	0	0
86.5	7856	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	1
90.5	8142	0	9	2	0	0	6	0	0	0	21	0	2	0	0	0	0	0	0
92.5	8356	0	1	0	0	0	1	0	0	0	9	0	0	0	0	1	0	0	0
96.5	8865	1	2	2	0	1	9	0	0	0	13	0	0	0	0	2	0	0	1
101.5	9566	0	4	0	0	1	9	0	0	0	19	0	3	0	0	0	8	0	2
104.5	9910	0	5	0	0	3	16	0	0	0	10	0	0	0	1	3	0	0	3
105.5	10064	0	2	0	0	1	12	0	0	0	6	0	0	0	1	1	0	0	1
109.5	10671	0	11	0	0	2	21	0	0	0	6	1	0	0	1	4	0	0	6
110.5	10818	0	7	1	0	0	7	0	0	0	1	1	1	0	0	3	0	0	0
112.5	11117	0	8	0	0	3	8	7	0	0	39	0	0	2	2	2	3	0	5
116.5	11500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120.5	11882	0	7	0	0	2	4	0	0	0	15	0	0	0	0	3	0	0	0
122.5	12126	0	2	0	0	0	5	0	1	0	24	0	0	0	0	4	0	0	0
128.5	12698	1	0	0	1	4	0	0	0	2	0	1	0	0	1	0	0	4	0
130	12833	2	0	0	0	1	0	0	0	3	0	0	0	0	0	0	0	0	0
134	13235	5	5	1	4	8	0	0	1	7	0	0	0	0	1	0	0	0	0

Table 7.4: Results of the pollen-based vegetation (biome) reconstruction from the Lake Kamenistoe sediment core, including core depth (cm), age (a BP), affinity scores of regional biomes and landscape openness, and dominant biome.

Sample depth (cm)	Sample age (a BP)	Tundra/TUND	Cold deciduous forest/CLDE	Taiga/TAIG	Cool coniferous forest/COCO	Cold steppe/STEP	Dominant biome	Landscape openness
2.5	185	4.03	14.73	17.61	17.61	1.46	TAIG	13.58
12.5	827	3.31	13.39	17.56	18.32	0.19	COCO	15.01
18.5	1277	2.82	14.93	17.74	17.74	0.15	TAIG	14.92
24.5	2371	3.58	14.28	18.01	18.01	0.61	TAIG	14.42
30.5	2814	0.53	13.58	18.30	18.30	0.00	TAIG	17.78
36.5	3839	3.30	14.43	18.36	18.36	0.32	TAIG	15.06
42.5	4634	1.37	13.10	17.30	17.30	0.00	TAIG	15.94
48.5	5619	1.40	13.21	16.40	16.40	0.00	TAIG	14.99
54.5	6300	3.00	15.25	16.49	16.49	0.00	TAIG	13.49
60.5	6544	0.63	14.14	15.93	15.93	0.00	TAIG	15.30
66.5	6785	3.72	15.31	17.19	17.19	0.65	TAIG	13.47
72.5	7078	0.74	14.06	15.29	15.29	0.16	TAIG	14.54

Table 7.4 (continue)

Sample depth (cm)	Sample age (a BP)	Tundra/TUND	Cold deciduous forest/CLDE	Taiga/TAIG	Cool coniferous forest/COCO	Cold steppe/STEP	Dominant biome	Landscape openness
78.5	7440	1.54	14.57	14.57	15.08	0.11	CLMX	13.54
82.5	7636	2.17	14.43	14.43	14.43	0.00	CLDE	12.26
86.5	7856	1.26	14.67	14.67	14.67	0.00	CLDE	13.41
90.5	8142	4.25	14.03	14.03	14.38	1.94	CLMX	10.13
92.5	8356	2.85	14.07	14.07	14.07	1.23	CLDE	11.21
96.5	8865	6.94	12.23	12.23	12.23	2.20	CLDE	5.29
101.5	9566	6.70	11.57	11.57	11.57	2.99	CLDE	4.87
104.5	9910	12.86	14.06	14.06	14.06	4.49	CLDE	1.20
105.5	10064	14.71	13.76	13.76	13.76	5.65	TUND	−0.95
109.5	10671	13.23	12.01	12.01	12.01	7.07	TUND	−1.22
110.5	10818	8.86	13.06	13.06	13.06	6.91	CLDE	4.20
112.5	11117	12.12	9.70	9.70	9.70	16.36	STEP	−6.66
120.5	11882	14.69	7.79	7.79	7.79	14.08	TUND	−6.90
122.5	12126	15.79	6.18	6.18	6.18	10.27	TUND	−9.61
128.5	12698	8.16	8.94	8.94	8.94	12.64	STEP	−3.70
130	12833	10.12	11.52	11.52	11.52	8.61	CLDE	1.41
134	13235	15.66	8.74	8.74	8.74	13.98	TUND	−6.92

7.2.2 Razlomnoe Peat

The detailed results of the palynological analysis and pollen-based reconstruction conducted on 97 samples from the Razlomnoe Peat (RZ19) sediment core (Chapter 3) are summarized in three tables. Table 7.5 provides the sample core depth (cm), sample age (a BP), pollen concentration (CONC, grains/cm^3), and counts of trees and high shrubs (T) and shrubs (S) taxa. Table 7.6 summarizes the results of the pollen analysis for herbs (H) taxa. The pollen percentage ratio of coniferous and broadleaved trees (Fig. 3.6) and results of biomization (affinity scores) are provided in Table 7.7. All the mentioned data, presented in percentage form, is available in the PANGAEA database with open access (Table 1.1).

Table 7.5: Results of the palynological analysis from the RZ19 sediment core, including core depth (cm), age (a BP), pollen concentration (CONC, grains/cm^3) and counts of tree and high shrubs (T) and shrubs (S) taxa.

Sample depth (cm)	Sample age (a BP)	Pollen CONC (grains/cm^3)	*Abies*	*Picea*	*Pinus*	*Alnus*	*Betula* sect. *Albae* type	*Carpinus*	*Corylus*	*Fraxinus*	*Rhamnus*	*Quercus*	*Tilia*	*Ulmus*	*Alnus fruticosa*	*Betula* sect. *Nanae*/ *Fruticosae* type	*Ephedra*	Ericales	*Salix*
			T	T	T	T	T	T	T	T	T	T	T	T	S	S	S	S	S
2.5	−45	48762	0	27	109	3	72	0	0	0	0	0	0	1	0	2	0	0	1
12.5	54	38509	1	18	92	19	56	0	0	0	0	1	0	0	0	4	0	0	1
22.5	153	177067	0	30	180	15	68	0	0	0	0	1	0	1	0	2	0	2	3
32.5	253	10991	0	16	64	4	32	0	0	0	0	0	0	0	0	1	0	2	1
42.5	352	12283	0	6	64	14	30	0	0	0	0	0	0	0	0	7	0	1	0
52.5	451	19666	0	10	73	14	35	0	0	0	0	0	0	0	0	6	0	0	1
57.5	501	40891	0	11	60	7	16	0	0	0	0	0	0	0	1	4	0	0	0
67.5	600	86815	0	12	107	4	24	0	0	0	0	0	0	0	3	4	0	0	2
72.5	650	36136	0	20	134	8	24	0	0	0	0	0	0	0	0	1	0	4	0
82.5	749	40516	0	14	77	9	17	0	0	0	0	0	0	0	0	0	0	1	1

Table 7.5 (continue)

Sample depth (cm)	Sample age (a BP)	Pollen CONC (grains/cm^3)	*Abies*	*Picea*	*Pinus*	*Alnus*	*Betula* sect. *Albae* type	*Carpinus*	*Corylus*	*Fraxinus*	*Rhamnus*	*Quercus*	*Tilia*	*Ulmus*	*Alnus fruticosa*	*Betula* sect. *Nanae*/ *Fruticosae* type	*Ephedra*	Ericales	*Salix*
			T	T	T	T	T	T	T	T	T	T	T	T	S	S	S	S	S
92.5	849	25780	0	12	55	14	19	0	0	0	0	0	0	0	0	1	0	4	1
102.5	948	22769	0	18	48	49	20	0	0	0	0	1	0	0	0	2	0	3	0
112.5	1047	24020	0	16	51	11	14	0	0	0	0	0	0	0	0	1	0	1	1
122.5	1147	7698	0	20	59	10	23	0	0	0	0	0	0	0	0	1	0	3	1
132.5	1246	16606	0	25	43	8	40	0	0	0	0	0	0	0	0	0	0	0	0
142.5	1345	39750	0	29	66	23	24	0	0	0	0	0	0	0	0	1	0	2	0
152.5	1445	31572	0	28	52	9	50	0	0	0	0	0	0	0	0	0	0	2	3
162.5	1544	41626	0	26	58	6	21	0	1	0	0	0	0	0	0	0	0	1	0
172.5	1643	94856	0	51	76	21	65	0	2	0	0	0	1	0	0	10	0	2	0
182.5	1742	89614	0	56	70	24	56	0	1	1	1	0	1	0	0	0	0	0	1
192.5	1842	50980	0	56	76	0	40	0	0	0	0	0	0	0	0	0	0	0	1
201.5	1931	64328	0	55	79	15	34	0	1	0	0	1	0	0	0	3	0	0	1
213.5	2050	46792	0	55	43	7	30	0	0	0	1	0	0	0	0	3	0	0	0
223	2145	146104	0	106	57	13	24	0	1	0	0	1	0	0	0	3	0	1	0
234.5	2259	178811	0	94	91	14	50	0	2	0	0	0	0	2	0	5	0	0	0
244.5	2358	226666	0	90	99	33	60	0	4	1	4	0	0	3	0	6	0	1	1
254.5	2582	157005	0	54	73	13	95	0	3	0	0	1	0	1	0	16	0	0	1
264.5	2873	154559	0	68	100	22	43	0	1	0	0	1	0	0	0	14	0	0	2
274.5	3164	79283	0	62	85	0	22	0	0	0	0	0	0	0	0	28	0	3	3
284.5	3454	264135	0	153	245	19	76	0	2	0	0	0	0	0	0	32	0	0	3
294.5	3745	81047	0	110	145	6	42	0	0	0	0	0	0	0	0	20	0	0	2
304.5	4036	169375	0	90	102	8	12	0	1	0	0	0	0	0	0	4	0	0	0
314.5	4327	207339	0	79	170	5	21	0	0	0	0	0	0	0	0	8	0	0	0
324.5	4618	184994	0	63	185	8	11	0	0	0	0	0	0	1	0	5	0	0	0
334.5	4908	199149	0	76	179	6	42	0	0	0	0	0	0	0	0	11	0	0	3
344.5	5199	107645	0	65	142	30	33	0	1	0	0	0	0	2	0	8	0	0	2
354.5	5490	110243	0	57	102	6	7	0	0	0	0	0	0	0	0	12	0	0	1
364.5	5668	80750	0	99	203	3	18	0	0	0	0	0	0	0	0	38	0	0	2
374.5	5834	89309	0	30	88	7	13	0	0	0	0	0	0	0	0	12	0	1	8
384.5	6000	193583	0	70	141	7	27	0	2	0	0	0	0	3	0	28	0	0	3
394.5	6165	177915	0	51	80	3	39	0	0	0	0	0	0	0	0	17	0	0	0
404.5	6331	413310	0	27	67	8	24	0	0	0	0	0	0	1	0	16	0	0	0
414.5	6497	155079	0	21	66	24	39	0	3	0	0	2	0	1	0	7	0	0	0
424.5	6662	94977	0	31	100	17	26	0	3	0	0	1	0	4	0	2	0	0	1
434.5	6828	240251	0	33	82	42	80	0	2	0	0	0	1	1	0	0	0	0	0
444.5	6937	901155	0	21	43	15	66	0	3	0	1	0	0	4	0	1	0	0	0
454.5	6988	238545	0	43	145	32	63	0	3	0	0	0	0	4	0	10	0	0	0
464.5	7039	138414	0	25	56	15	39	0	4	0	0	0	0	5	0	8	0	0	2
474.5	7090	186813	0	31	156	15	32	0	3	0	0	0	0	2	0	3	0	0	2
484.5	7141	459368	0	27	124	16	74	0	2	0	0	0	0	7	0	3	0	0	8
494.5	7192	314069	0	66	135	12	41	0	2	0	0	0	0	1	0	5	0	0	0
504.5	7243	244773	0	14	131	28	29	0	0	1	0	1	0	1	0	2	0	0	0
514.5	7294	839940	0	30	204	34	53	0	0	0	0	1	0	1	0	1	0	0	1
524.5	7380	687820	0	32	288	30	51	0	2	0	0	0	0	2	0	5	0	0	1
534.5	7519	341490	1	6	71	26	120	0	2	1	0	0	0	2	0	9	0	0	4
544.5	7657	686175	0	30	266	29	63	0	1	0	0	0	0	6	0	3	0	0	0
554.5	7795	492737	0	5	186	37	122	0	1	0	0	1	1	5	0	3	0	0	0
564.5	7933	672263	0	2	100	56	132	0	3	0	0	2	0	4	0	5	0	0	1
570.5	8016	306449	0	6	149	60	170	0	1	0	0	2	0	5	0	11	0	0	2
574.5	8072	375504	0	3	123	38	117	0	1	0	0	0	0	2	0	6	0	0	4
577.5	8113	340644	0	7	170	62	290	0	5	0	0	2	3	7	0	15	0	0	4
580.5	8147	526555	0	2	104	46	209	0	0	0	0	0	1	7	0	7	0	0	5
584.5	8186	248288	0	5	140	44	154	0	0	0	0	0	0	3	0	11	0	0	8
587.5	8216	308724	0	0	153	33	171	0	1	0	0	0	0	2	0	10	0	0	5
590.5	8246	346817	0	3	137	44	192	0	2	0	0	0	0	4	0	15	0	0	4
594.5	8285	274215	1	2	153	29	146	0	1	0	0	0	0	4	0	8	0	0	2

Table 7.5 (continue)

Sample depth (cm)	Sample age (a BP)	Pollen CONC (grains/cm^3)	*Abies*	*Picea*	*Pinus*	*Alnus*	*Betula* sect. *Albae* type	*Carpinus*	*Corylus*	*Fraxinus*	*Rhamnus*	*Quercus*	*Tilia*	*Ulmus*	*Alnus fruticosa*	*Betula* sect. *Nanae*/ *Fruticosae* type	*Ephedra*	Ericales	*Salix*
			T	T	T	T	T	T	T	T	T	T	T	T	S	S	S	S	S
596.5	8305	230977	0	2	167	24	128	0	3	0	0	0	3	4	0	15	0	0	7
599.5	8334	315634	0	2	308	59	164	0	0	0	0	0	4	0	0	47	0	2	0
604.5	8384	284123	0	3	131	46	100	1	3	1	0	0	0	2	0	13	0	0	4
614.5	8522	213396	0	5	173	32	108	0	0	1	0	0	0	2	0	6	0	0	2
624.5	8720	243244	0	3	144	42	88	0	5	0	0	0	0	0	0	26	0	0	3
634.5	8918	206088	0	3	137	6	148	0	3	0	0	0	0	3	0	6	0	0	1
644.5	9116	204352	0	5	263	0	269	0	3	0	0	0	0	4	0	104	0	0	20
654.5	9314	271702	0	3	144	1	192	0	1	0	0	1	0	0	0	17	0	0	3
664.5	9512	335976	0	2	152	1	180	0	0	0	0	0	0	2	0	17	0	0	8
674.5	9710	267923	0	2	120	0	185	0	0	1	0	0	0	1	0	5	0	0	2
684.5	9878	202510	0	2	163	2	128	0	1	0	0	0	0	1	0	8	1	0	3
694.5	9975	325822	0	1	250	0	151	0	0	0	0	0	0	4	0	28	0	0	6
704.5	10071	215701	0	0	223	0	150	0	0	1	0	0	0	5	0	27	0	0	4
714.5	10168	202335	0	0	193	1	92	0	0	0	0	0	0	1	0	18	0	0	6
724	10259	188390	0	3	250	1	152	0	0	2	0	0	0	3	0	45	0	0	11
734	10356	189329	0	1	253	0	120	0	0	1	0	0	0	2	0	22	0	0	4
744	10453	399837	0	1	300	0	77	0	0	1	0	0	0	1	0	29	0	0	10
754	10549	238743	0	4	552	0	105	0	0	0	0	0	0	3	0	52	0	0	18
764	10646	220031	0	0	250	0	121	0	0	0	0	0	0	1	1	29	0	0	9
774	10742	233372	0	0	205	1	112	0	1	0	0	0	0	1	0	42	0	0	8
784	10839	175158	0	3	158	0	30	0	0	0	0	0	0	0	0	9	0	0	5
794	10935	77094	0	0	118	0	23	0	0	0	0	0	0	0	0	19	0	0	1
804	11032	38157	0	1	83	0	14	0	0	0	0	0	0	0	0	30	0	0	3
814	11129	50035	0	5	38	1	93	0	0	0	0	0	0	0	1	73	0	0	2
824	11225	52120	0	2	99	4	31	0	1	0	0	0	0	1	0	38	0	0	4
834	11322	42243	0	1	58	3	49	0	1	0	0	0	0	1	0	29	0	0	5
844	11418	14177	0	3	47	1	39	0	2	0	0	0	0	1	0	63	0	0	4
854	11515	22403	0	2	21	0	49	0	0	0	0	0	0	0	0	96	1	0	10
864	11611	9380	0	0	12	0	9	0	0	0	0	0	0	0	1	80	1	1	17
874	11708	11253	0	0	7	0	6	0	0	0	0	0	0	0	0	22	0	0	6
884	11805	8862	0	1	12	0	8	0	0	0	0	0	0	0	2	17	0	0	0

Table 7.6: Results of the palynological analysis from the RZ19 sediment core, including core depth (cm), age (a BP), and counts of herbs (H) taxa.

Sample depth (cm)	Sample age (a BP)	Apiaceae	*Artemisia*	Asteraceae subfam. Asteroideae	Asteraceae subfam. Cichorioideae	Brassicaceae	Cannabaceae	Caryophyllaceae	Chenopodiaceae	Cyperaceae	Lamiaceae	Poaceae	*Secale*	Polygonaceae	Ranunculaceae	Rosaceae	*Potentilla*	Oher herbs
		H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
2.5	−45	0	0	0	0	0	0	0	0	8	0	1	0	0	0	0	0	0
12.5	54	0	0	0	0	0	0	0	1	14	0	2	1	0	0	0	1	0
22.5	153	0	0	0	0	0	0	0	2	35	0	2	0	0	0	2	0	0
32.5	253	0	0	0	0	0	0	0	0	11	0	1	0	0	0	0	0	0
42.5	352	0	0	0	0	0	2	0	1	21	0	3	0	1	0	2	3	0
52.5	451	0	0	0	1	0	0	0	0	18	0	0	0	2	0	0	0	0
57.5	501	0	0	0	0	0	0	0	0	13	0	15	0	0	0	0	2	0
67.5	600	1	1	0	0	0	0	0	0	31	0	5	0	1	0	1	0	1
72.5	650	1	0	0	0	0	0	0	0	15	0	4	0	0	0	5	0	0
82.5	749	0	0	0	0	0	0	0	0	5	0	5	1	0	0	0	18	0
92.5	849	1	0	0	0	0	0	0	1	7	0	0	0	0	0	2	0	0
102.5	948	0	0	0	0	0	0	0	0	12	0	2	0	0	0	0	0	0
112.5	1047	1	0	0	0	0	0	0	0	16	0	1	0	0	0	0	0	0

Table 7.6 (continue)

Sample depth (cm)	Sample age (a BP)	Apiaceae	*Artemisia*	Asteraceae subfam. Asteroideae	Asteraceae subfam. Cichorioideae	Brassicaceae	Cannabaceae	Caryophyllaceae	Chenopodiaceae	Cyperaceae	Lamiaceae	Poaceae	*Secale*	Polygonaceae	Ranunculaceae	Rosaceae	*Potentilla*	Oher herbs
		H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
122.5	1147	0	1	0	0	0	0	0	0	17	0	7	0	0	0	2	0	0
132.5	1246	0	0	0	0	0	0	0	0	24	0	10	0	0	0	9	0	0
142.5	1345	0	1	0	0	0	0	0	0	37	1	9	0	0	0	5	0	0
152.5	1445	0	0	0	0	0	0	0	0	17	0	2	0	0	0	3	0	0
162.5	1544	0	0	0	0	0	0	0	1	16	0	1	0	0	1	5	0	0
172.5	1643	0	1	0	1	0	0	0	1	33	1	4	0	0	0	29	0	0
182.5	1742	0	1	0	0	0	0	0	1	44	0	5	0	1	1	22	0	0
192.5	1842	0	0	2	0	0	0	0	0	18	0	1	0	0	0	17	0	0
201.5	1931	1	1	0	0	0	0	0	0	25	0	1	0	0	1	29	0	0
213.5	2050	0	0	0	0	0	0	0	0	20	0	6	0	0	0	10	0	0
223	2145	0	1	0	0	0	0	0	0	28	0	4	0	1	0	14	1	0
234.5	2259	0	2	0	0	0	0	0	1	39	0	5	0	0	0	16	0	0
244.5	2358	0	0	1	0	0	0	0	0	53	0	1	0	0	0	16	0	0
254.5	2582	0	0	0	0	0	0	0	1	42	0	3	0	0	0	17	0	1
264.5	2873	0	1	0	0	0	0	0	0	43	0	1	0	0	0	20	0	0
274.5	3164	0	0	0	0	0	0	0	0	14	0	0	0	0	2	21	0	0
284.5	3454	0	0	1	0	0	0	0	0	45	0	1	0	0	0	2	0	0
294.5	3745	0	1	0	0	0	0	0	0	79	0	1	0	0	0	17	0	0
304.5	4036	0	0	0	0	0	0	0	0	3	0	0	0	0	0	1	0	0
314.5	4327	0	0	0	0	0	0	0	0	5	0	0	0	0	0	15	0	0
324.5	4618	0	0	0	0	0	0	0	0	4	0	0	0	0	0	3	0	0
334.5	4908	0	3	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0
344.5	5199	0	0	0	0	0	0	0	0	18	0	3	0	0	0	5	0	0
354.5	5490	0	0	0	0	0	0	0	0	8	0	1	0	0	0	0	0	0
364.5	5668	0	0	0	0	0	0	0	0	5	0	1	0	0	0	23	0	0
374.5	5834	0	0	0	0	0	0	0	0	7	0	0	0	1	0	1	0	0
384.5	6000	0	0	0	0	0	0	0	0	10	0	2	0	0	0	0	0	0
394.5	6165	0	0	0	0	0	0	0	0	3	0	2	0	0	0	0	0	0
404.5	6331	0	0	0	0	0	0	0	0	7	0	0	0	0	0	1	0	0
414.5	6497	0	1	0	0	0	1	0	0	17	0	1	0	0	0	2	0	0
424.5	6662	0	0	0	0	0	0	0	0	9	0	0	0	0	2	7	0	0
434.5	6828	0	0	1	0	1	0	0	0	15	0	1	0	0	4	16	0	0
444.5	6937	2	1	0	0	0	0	0	0	11	0	2	0	2	0	10	0	0
454.5	6988	3	3	0	0	0	0	0	0	5	0	2	0	0	0	8	0	0
464.5	7039	0	0	0	0	0	0	0	0	6	1	3	0	0	0	8	0	0
474.5	7090	0	0	0	0	0	0	0	0	8	0	1	0	0	0	7	0	0
484.5	7141	1	1	0	0	0	0	0	0	3	1	7	0	0	0	0	0	0
494.5	7192	0	2	0	1	1	0	0	0	3	0	4	0	0	0	7	0	1
504.5	7243	1	0	0	0	0	0	0	0	3	0	4	0	0	0	4	0	0
514.5	7294	0	1	0	0	1	0	0	0	2	0	1	0	0	0	3	0	1
524.5	7380	0	0	0	0	0	0	0	0	2	0	1	0	0	0	4	0	0
534.5	7519	0	0	1	0	1	0	0	0	2	0	2	0	0	0	4	0	0
544.5	7657	0	2	0	0	0	0	0	0	7	0	4	0	0	0	6	0	0
554.5	7795	0	1	0	0	0	0	0	1	5	0	12	0	0	1	4	0	0
564.5	7933	0	0	0	0	0	0	0	0	3	0	6	0	0	3	3	0	1
570.5	8016	0	7	0	0	0	0	1	0	12	0	3	0	0	1	3	0	0
574.5	8072	2	1	0	0	1	0	0	0	10	0	7	0	0	1	10	0	0
577.5	8113	1	2	0	0	0	0	0	1	10	0	7	0	0	0	4	0	0
580.5	8147	1	4	0	0	0	0	0	0	17	0	3	0	0	0	2	0	0
584.5	8186	0	1	0	0	0	0	0	0	8	0	10	0	0	0	4	0	0
587.5	8216	0	2	0	0	0	0	0	0	15	0	0	0	0	0	2	0	0
590.5	8246	0	3	0	0	0	0	0	0	5	0	1	0	0	0	1	0	0
594.5	8285	2	1	0	0	0	0	0	0	12	0	2	0	0	0	6	0	0
596.5	8305	4	4	0	0	0	0	0	0	15	0	1	0	0	0	2	0	0
599.5	8334	2	3	0	0	0	0	0	0	32	0	6	0	0	0	4	0	0
604.5	8384	1	1	0	0	0	0	0	1	15	0	5	0	0	0	6	0	0
614.5	8522	0	0	0	0	0	0	0	0	20	0	1	0	0	0	2	0	0

Table 7.6 (continue)

Sample depth (cm)	Sample age (a BP)	Apiaceae	*Artemisia*	Asteraceae subfam. Asteroideae	Asteraceae subfam. Cichorioideae	Brassicaceae	Cannabaceae	Caryophyllaceae	Chenopodiaceae	Cyperaceae	Lamiaceae	Poaceae	*Secale*	Polygonaceae	Ranunculaceae	Rosaceae	*Potentilla*	Oher herbs
		H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
624.5	8720	0	0	0	0	0	0	0	1	35	0	10	0	0	0	2	0	0
634.5	8918	0	4	0	0	0	0	0	0	9	0	10	0	0	0	1	0	0
644.5	9116	0	7	0	0	0	0	0	0	30	0	46	0	0	0	3	0	0
654.5	9314	1	3	1	0	0	0	0	2	6	0	24	0	0	1	1	0	0
664.5	9512	0	1	0	0	0	0	0	1	14	1	29	0	0	0	3	0	0
674.5	9710	1	2	1	0	0	0	0	0	9	1	11	0	0	0	4	0	0
684.5	9878	0	0	1	0	0	0	0	1	9	0	18	0	0	0	1	0	0
694.5	9975	0	5	0	1	0	0	0	0	7	0	15	0	0	1	3	0	0
704.5	10071	0	3	0	0	0	0	0	2	10	0	14	0	0	0	4	0	0
714.5	10168	0	2	0	0	0	0	0	0	9	0	15	0	0	1	1	0	0
724	10259	0	5	0	0	0	0	0	2	8	0	18	0	0	1	3	0	0
734	10356	0	4	0	0	0	0	0	2	6	0	21	0	0	0	4	0	0
744	10453	0	0	0	0	0	0	0	1	8	0	11	0	0	0	4	0	0
754	10549	0	2	0	0	0	0	0	3	43	0	15	0	0	1	2	0	0
764	10646	0	3	1	1	0	0	0	4	7	0	9	0	0	0	4	0	0
774	10742	0	6	0	0	0	0	0	1	3	0	9	0	0	0	1	0	1
784	10839	0	4	0	0	0	0	0	1	1	0	2	0	0	0	0	0	0
794	10935	0	2	0	0	0	0	0	0	7	0	3	0	0	1	1	0	0
804	11032	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
814	11129	0	5	0	0	0	0	0	2	3	0	9	0	0	0	8	0	0
824	11225	0	5	0	0	0	0	0	3	5	0	4	0	0	0	3	0	0
834	11322	0	1	0	0	0	0	0	0	4	0	4	0	0	0	2	0	0
844	11418	0	2	0	0	0	0	0	5	1	0	7	0	0	1	1	0	0
854	11515	1	4	0	0	0	0	0	4	17	0	5	0	0	0	3	0	0
864	11611	0	6	0	0	0	0	0	2	9	0	0	0	0	0	1	0	0
874	11708	0	18	0	0	1	0	0	13	25	0	2	0	0	2	2	0	0
884	11805	0	12	1	0	0	0	1	10	13	0	12	0	0	0	2	0	0

Table 7.7: Results of pollen-based vegetation (biome) reconstruction from the RZ19 sediment core, including core depth (cm), age (a BP), conifers - broadleaved pollen ratio, affinity scores of regional biomes and landscape openness, and dominant biome.

Sample depth (cm)	Sample age (a BP)	Conifers – Broadleaved pollen ratio	Tundra/TUND	Cold deciduous forest/CLDE	Taiga/TAIG	Cool coniferous forest/COCO	Cool mixed forest/ COMX	Cold steppe/STEP	Dominant biome	Landscape openness
2.5	−53	27	2.38	13.48	16.88	16.88	16.88	0.00	TAIG	14.50
12.5	56	16	4.33	14.58	17.42	17.42	17.42	0.67	TAIG	13.09
22.5	150	36	4.59	14.47	17.35	17.35	17.35	0.86	TAIG	12.75
32.5	291	33	5.33	14.91	18.31	18.31	18.31	0.51	TAIG	12.99
42.5	386	17	7.58	14.03	15.87	15.87	15.87	4.94	TAIG	8.29
52.5	480	21	6.30	14.57	16.96	16.96	16.96	1.22	TAIG	10.66
57.5	521	37	8.57	12.45	15.29	15.29	15.29	4.36	TAIG	6.72
67.5	636	46	8.38	12.71	15.07	15.07	15.07	1.86	TAIG	6.69
72.5	710	56	4.86	14.05	17.01	17.01	17.01	2.51	TAIG	12.15
82.5	915	44	4.23	13.69	16.69	16.69	16.69	5.11	TAIG	11.58
92.5	1044	29	5.24	16.48	19.60	19.60	19.60	2.29	TAIG	14.36
102.5	1143	−3	5.67	15.82	19.15	19.15	19.53	0.89	COMX	13.86
112.5	1255	37	6.18	14.41	18.10	18.10	18.10	1.24	TAIG	11.93
122.5	1326	32	7.59	14.53	18.19	18.19	18.19	3.47	TAIG	10.60
132.5	1421	13	6.23	12.25	16.15	16.15	16.15	4.68	TAIG	9.92
142.5	1530	24	7.06	13.19	16.95	16.95	16.95	3.58	TAIG	9.89
152.5	1622	13	5.94	15.20	19.24	19.24	19.24	1.98	TAIG	13.30
162.5	1722	41	4.30	12.77	17.07	17.55	17.55	3.21	COCO	13.24

Table 7.7 (continue)

Sample depth (cm)	Sample age (a BP)	Conifers – Broadleaved pollen ratio	Tundra/TUND	Cold deciduous forest/CLDE	Taiga/TAIG	Cool coniferous forest/COCO	Cool mixed forest/ COMX	Cold steppe/STEP	Dominant biome	Landscape openness
172.5	1831	13	6.27	12.59	16.67	17.08	17.08	3.96	COCO	10.81
182.5	1986	15	4.98	12.07	16.44	16.44	16.44	3.80	TAIG	11.47
192.5	2087	44	2.83	10.26	15.36	15.36	15.36	3.42	TAIG	11.94
201.5	2196	34	3.95	11.61	16.28	16.28	16.28	3.35	TAIG	12.33
213.5	2375	34	6.12	10.86	16.42	16.69	16.69	3.99	COCO	10.57
223.0	2464	49	5.09	9.80	16.21	16.21	16.21	3.27	TAIG	11.12
234.5	2597	36	5.47	11.13	16.49	17.19	17.19	3.50	COCO	11.72
244.5	2676	23	4.76	11.94	16.80	18.87	18.87	1.95	COCO	14.11
254.5	2765	4	6.32	11.99	16.03	16.69	16.69	2.85	COCO	10.37
264.5	3005	32	5.97	12.11	16.69	16.69	16.69	2.41	TAIG	10.73
274.5	3240	52	7.38	10.59	15.62	15.62	15.62	3.45	TAIG	8.24
284.5	3619	52	5.07	11.82	16.91	16.91	16.91	0.00	TAIG	11.84
294.5	3850	49	6.32	9.84	14.89	14.89	14.89	1.88	TAIG	8.57
304.5	4073	77	2.07	10.74	17.09	17.09	17.09	0.00	TAIG	15.02
314.5	4263	74	2.54	11.07	16.12	16.12	16.12	2.11	TAIG	13.59
324.5	4403	81	2.10	11.48	16.17	16.17	16.17	0.76	TAIG	14.08
334.5	4817	60	4.75	12.35	17.00	17.00	17.00	0.61	TAIG	12.25
344.5	4894	46	4.82	13.35	17.88	18.27	18.27	1.74	COCO	13.44
354.5	5355	75	4.54	10.71	16.09	16.09	16.09	0.12	TAIG	11.55
364.5	5512	72	4.01	9.80	14.78	14.78	14.78	2.32	TAIG	10.76
374.5	5642	58	7.17	14.18	18.35	18.35	18.35	0.62	TAIG	11.17
384.5	5803	59	5.87	11.95	16.79	17.94	17.94	0.43	COCO	12.07
394.5	5949	46	4.61	11.80	16.87	16.87	16.87	0.73	TAIG	12.26
404.5	6374	40	5.21	12.74	16.91	17.31	17.31	0.40	COCO	12.10
414.5	6539	10	4.96	14.00	17.29	18.55	19.32	1.37	COMX	14.35
424.5	6670	39	2.68	13.30	17.14	19.34	19.34	2.41	COCO	16.66
434.5	6774	−4	2.21	14.50	17.86	18.33	18.33	3.25	COCO	15.07
444.5	6879	−14	4.12	13.57	16.89	19.49	19.49	4.78	COCO	14.71
454.5	6926	27	3.00	14.13	17.73	19.25	19.25	3.08	COCO	16.17
464.5	7001	10	5.70	14.05	17.80	20.70	20.70	3.44	COCO	15.01
474.5	7081	52	2.93	13.96	17.34	18.67	18.67	1.48	COCO	15.74
484.5	7150	19	4.53	15.70	18.76	20.68	20.68	1.43	COCO	16.14
494.5	7218	52	2.85	12.59	17.39	17.85	17.85	2.83	COCO	15.00
504.5	7271	39	2.73	14.78	17.20	17.20	17.20	2.30	TAIG	14.48
514.5	7345	43	0.31	14.81	17.73	17.73	17.73	0.63	TAIG	17.10
524.5	7429	56	0.83	14.28	16.95	16.95	16.95	0.68	TAIG	16.12
534.5	7534	−29	3.88	16.30	17.67	18.76	18.76	1.58	COCO	14.88
544.5	7683	47	2.23	14.32	16.91	17.87	17.87	1.65	COCO	15.64
554.5	7790	6	3.04	15.52	16.41	17.30	17.30	2.35	COCO	14.27
564.5	7942	−30	2.86	16.03	16.38	17.90	18.25	2.49	COMX	15.39
570.5	8001	−19	3.37	15.70	16.64	17.45	17.45	1.93	COCO	14.08
574.5	8042	−10	4.90	16.24	16.89	17.23	17.23	3.22	COCO	12.33
577.5	8078	−33	3.77	15.88	16.71	18.22	18.22	1.25	COCO	14.45
580.5	8118	−38	4.35	16.26	16.26	17.36	17.36	1.18	COCO	13.00
584.5	8152	−14	5.47	16.77	17.66	18.18	18.18	2.17	COCO	12.71
587.5	8191	−14	4.12	16.42	16.42	16.51	16.51	0.17	COCO	12.39
590.5	8241	−25	3.31	16.41	16.89	17.58	17.58	0.48	COCO	14.27
594.5	8279	−7	3.36	15.57	15.77	16.54	16.54	1.47	COCO	13.18
596.5	8308	2	4.88	15.94	16.11	17.94	17.94	1.66	COCO	13.06
599.5	8353	13	5.44	14.95	14.95	15.31	15.31	1.03	COCO	9.88
604.5	8396	−6	5.68	16.15	16.79	17.74	17.74	2.14	COCO	12.05
614.5	8512	10	3.63	15.66	16.62	16.88	16.88	0.26	COCO	13.25
624.5	8636	3	7.73	15.12	15.70	16.64	16.64	1.75	COCO	8.92
634.5	8757	−6	4.22	14.19	14.83	16.10	16.10	2.43	COCO	11.88
644.5	8979	−1	9.34	13.26	13.67	13.84	13.84	3.02	COCO	4.50
654.5	9206	−12	5.77	13.33	13.83	13.83	13.83	2.84	TAIG	8.06
664.5	9376	−7	7.37	13.82	13.82	13.82	13.82	3.04	CLDE	6.45
674.5	9536	−19	4.35	13.43	13.71	13.71	13.71	2.73	TAIG	9.36
684.5	9740	10	5.65	13.92	14.22	14.22	14.22	2.19	TAIG	8.58

Table 7.7 (continue)

Sample depth (cm)	Sample age (a BP)	Conifers – Broadleaved pollen ratio	Tundra/TUND	Cold deciduous forest/CLDE	Taiga/TAIG	Cool coniferous forest/COCO	Cool mixed forest/ COMX	Cold steppe/STEP	Dominant biome	Landscape openness
694.5	9836	20	5.84	13.73	13.73	14.32	14.32	2.75	COCO	8.49
704.5	9947	15	5.96	13.47	13.47	14.26	14.26	2.69	COCO	8.31
714.5	10060	29	6.77	13.80	13.80	13.80	13.80	2.28	CLDE	7.03
724.0	10163	19	7.00	13.75	14.06	14.37	14.37	2.76	COCO	7.37
734.0	10270	30	5.76	13.36	13.36	13.36	13.36	3.35	CLDE	7.61
744.0	10373	50	6.34	13.63	13.63	13.63	13.63	2.04	CLDE	7.30
754.0	10461	56	7.15	13.15	13.15	13.15	13.15	1.17	CLDE	6.00
764.0	10571	29	6.00	13.94	13.94	13.94	13.94	2.95	CLDE	7.95
774.0	10672	23	6.30	13.75	13.75	13.75	13.75	2.36	CLDE	7.45
784.0	10813	62	3.95	13.63	14.58	14.58	14.58	1.84	TAIG	10.63
794.0	10902	54	6.46	12.00	12.00	12.00	12.00	2.44	CLDE	5.55
804.0	11053	52	6.49	12.31	12.81	12.81	12.81	0.99	TAIG	6.31
814.0	11137	−21	8.72	10.68	11.94	11.94	11.94	5.32	TAIG	3.22
824.0	11249	32	8.16	13.32	14.03	14.03	14.03	4.64	TAIG	5.86
834.0	11337	3	8.71	14.36	14.72	15.45	15.45	2.67	COCO	6.74
844.0	11432	4	9.36	11.33	12.42	13.47	13.47	4.69	COCO	4.10
854.0	11530	−12	12.82	9.85	10.51	10.51	10.51	4.66	TUND	−2.30
864.0	11615	2	14.36	9.19	9.19	9.19	9.19	3.86	TUND	−5.17
874.0	11700	1	12.88	7.09	7.09	7.09	7.09	11.82	TUND	−5.80
884.0	11800	5	12.84	6.44	7.22	7.22	7.22	13.21	STEP	−6.00

7.2.3 Lake Kotokel

The results of the palynological analysis of 104 samples from the Lake Kotokel (KTK19-II) core (Chapter 4) are detailed in three tables. Table 7.8 lists the sample core depth (cm), sample age (a BP), pollen concentration (CONC, grains/cm^3), and counts of trees (T) and shrubs (S) taxa. Table 7.9 provides the pollen analysis results for herbs (H) taxa. Table 7.10 presents the biome reconstruction results, including the affinity scores for regional biomes and landscape openness, dominant biome, and charcoal particle counts in three size groups (>100 µm, 50–100 µm, and 10–50 µm).

Table 7.8: Results of the palynological analysis from the KTK19-II sediment core, including sample core depth (cm), age (a BP), pollen concentration (CONC, grains/cm^3), and counts of tree (T) and shrubs (S) taxa.

Sample depth (cm)	Sample age (a BP)	Pollen CONC (grains/cm^3)	*Abies*	*Picea*	*Pinus sibirica* type	*Pinus sylvestris* type	*Larix*	*Betula* sect. *Albae* type	*Ulmus*	*Alnus fruticosa* type	*Betula* sect. *Nanae/Fruticosae* type	*Ephedra*	Ericales	*Salix*
			T	T	T	T	T	T	T	S	S	S	S	S
6.6	103	91291	9	2	11	215	7	188	0	15	2	0	0	0
12.2	274	101762	0	3	2	192	1	136	0	34	3	0	0	0
17.8	450	100302	1	1	2	252	0	123	0	12	2	0	0	0
29	793	75399	10	1	12	275	8	157	0	13	2	0	0	1
40.2	1127	59202	0	0	0	281	1	120	0	22	0	0	0	0
51.4	1498	89962	6	0	1	175	3	186	0	14	1	0	0	4
62.6	1822	89194	1	2	1	280	1	136	0	12	0	0	0	1
73.8	2184	82640	3	0	8	286	9	120	0	8	1	0	0	3

Table 7.8 (continue)

Sample depth (cm)	Sample age (a BP)	Pollen CONC (grains/cm^3)	*Abies*	*Picea*	*Pinus sibirica* type	*Pinus sylvestris* type	*Larix*	*Betula* sect. *Albae* type	*Ulmus*	*Alnus fruticosa* type	*Betula* sect. *Nanae/Fruticosae* type	*Ephedra*	Ericales	*Salix*
			T	T	T	T	T	T	T	S	S	S	S	S
85	2515	188610	0	4	1	282	0	109	0	5	1	0	0	1
96.2	2811	132466	3	0	3	267	1	102	0	6	0	0	0	0
107.4	3013	172349	2	3	1	280	2	136	0	10	0	0	0	0
118.6	3205	177654	3	2	2	258	1	226	0	18	1	0	0	1
129.8	3407	187912	0	2	0	237	4	174	0	10	3	0	0	3
141	3603	183579	8	3	21	247	4	208	0	16	1	0	0	1
152.2	3805	339609	1	1	1	356	0	135	0	6	0	0	0	3
163.4	3999	142082	5	0	2	273	4	141	0	2	0	0	0	0
174.6	4200	358916	0	1	2	282	2	147	0	6	1	0	0	0
185.8	4408	147919	4	1	4	251	2	139	0	3	2	0	0	1
197	4608	244664	4	4	7	211	5	151	0	4	1	0	0	0
208.2	4807	170607	6	0	6	216	3	188	0	5	3	0	0	2
219.4	4948	190505	3	1	7	258	2	172	0	4	2	0	0	1
230.6	5047	175344	4	3	3	262	5	212	0	2	0	0	0	1
241.8	5154	219467	1	6	2	199	1	164	0	3	0	0	0	0
253	5255	211751	5	1	3	222	2	221	0	3	4	0	0	0
264.2	5360	184478	0	4	3	234	0	136	0	4	3	0	0	1
275.4	5467	181268	8	4	2	273	2	188	0	1	1	0	0	0
286.6	5570	194571	0	3	0	233	0	210	0	6	0	0	0	1
297.8	5677	191303	0	2	6	285	0	156	0	1	2	1	0	1
309	5773	245555	0	3	0	135	4	253	0	6	3	0	0	2
320.2	5867	226119	0	2	2	181	5	229	0	4	2	0	0	2
331.4	6134	350672	0	0	0	30	3	329	0	2	0	0	0	0
342.6	6430	270153	1	4	4	57	4	341	0	1	1	0	0	3
353.8	6723	320183	2	0	4	26	5	372	0	4	4	0	0	1
365	7028	262806	2	2	3	35	2	463	0	3	8	0	0	0
376.2	7316	221053	2	7	1	19	4	418	0	6	11	0	0	1
387.4	7619	325344	5	4	1	16	1	400	0	6	10	0	0	3
398.6	7894	236145	0	7	2	11	0	356	0	3	3	0	0	1
410	8184	368432	5	3	1	13	0	537	0	3	7	0	0	3
420	8395	193056	2	7	4	16	3	379	0	5	11	0	0	2
430	8606	271955	2	9	0	3	3	403	0	0	12	1	0	1
440	8817	233048	6	13	0	5	0	320	0	4	7	1	0	0
450	9036	196161	1	10	0	3	1	370	0	1	9	0	0	2
460	9254	180883	5	20	5	9	1	380	1	0	4	0	1	1
470	9467	305592	5	11	8	15	2	395	0	5	8	1	0	2
480	9691	173179	11	17	0	18	4	295	0	4	7	0	0	1
490	9907	192690	10	7	2	3	1	367	0	2	12	1	0	1
500	10118	213919	4	16	4	12	4	304	0	5	5	0	0	3
510	10328	226591	11	4	4	3	1	345	2	5	9	2	0	4
519	10567	121395	0	67	1	2	2	215	0	8	18	1	0	3
529	10879	199009	1	14	1	5	1	315	0	4	22	1	0	3
539	11197	97658	0	42	0	9	2	260	0	9	27	2	0	1
550	11536	150692	0	6	0	2	6	363	0	3	8	1	0	1
566	12040	144556	0	19	0	0	0	324	0	103	15	0	0	14
572	12218	150996	0	33	0	0	0	270	0	116	16	0	0	8
578	12383	86194	0	54	0	2	0	219	0	74	15	1	1	4
584	12639	130987	0	24	0	0	0	260	0	146	14	0	0	6
591	12900	56419	0	41	0	0	0	216	0	94	23	0	0	1
597	13134	148733	0	29	0	1	0	237	0	150	3	0	0	7
604	13420	101931	0	39	0	2	0	161	0	147	10	0	0	6
610	13662	108990	0	116	0	0	1	185	0	59	27	0	0	15
617	13940	79410	0	47	0	1	0	139	0	17	18	0	0	26
623	14169	109373	0	27	0	0	2	246	0	45	6	0	0	19
629	14385	82961	0	6	0	3	0	174	0	32	2	1	2	35
635	14564	76760	0	2	0	0	0	205	0	24	6	1	0	27

Table 7.8 (continue)

Sample depth (cm)	Sample age (a BP)	Pollen CONC (grains/cm^3)	*Abies*	*Picea*	*Pinus sibirica* type	*Pinus sylvestris* type	*Larix*	*Betula* sect. *Albae* type	*Ulmus*	*Alnus fruticosa* type	*Betula* sect. *Nanae/Fruticosae* type	*Ephedra*	Ericales	*Salix*
			T	T	T	T	T	T	T	S	S	S	S	S
641	14736	37407	0	3	0	0	0	170	0	20	11	1	0	35
647	14917	103783	0	1	0	0	0	206	0	18	2	1	0	32
653	15085	56735	0	0	0	0	0	184	0	18	14	0	0	23
659	15254	57773	0	1	0	0	0	186	0	5	10	0	0	53
665	15425	64756	0	0	0	0	0	115	0	7	18	0	0	43
671	15590	36954	0	0	0	0	0	126	0	11	4	0	0	45
677	15766	55365	0	9	0	1	0	156	0	19	13	1	0	26
683	16043	36553	0	0	0	1	0	131	0	6	10	0	0	12
689	16349	35498	0	0	0	0	0	85	0	5	7	0	0	8
695	16662	34944	0	0	1	0	0	76	0	3	9	0	0	13
701	16979	20532	0	0	0	0	0	55	0	4	15	0	0	6
707	17325	24493	0	0	0	1	0	48	0	2	11	0	0	4
713	17661	26651	0	0	0	0	0	63	0	3	6	0	0	4
719	17996	25203	0	0	0	1	0	38	0	1	3	0	0	5
725	18318	15711	0	0	0	1	0	21	0	3	4	0	0	2
731	18623	19969	0	0	0	0	0	14	0	1	3	0	0	7
737	18924	33463	0	0	0	0	0	20	0	1	5	0	0	3
743	19267	16263	0	1	0	1	0	12	0	1	1	0	0	6
765	20601	15882	0	1	0	3	0	7	0	5	1	0	0	8
777	21186	16620	0	0	0	0	0	5	0	1	1	0	0	2
789	21728	12048	0	3	0	0	0	17	0	4	0	0	1	5
801	22252	12107	0	1	0	0	0	6	0	1	2	0	0	3
813	22802	19629	0	2	0	0	0	16	0	5	1	0	1	2
825	23201	20501	0	0	0	0	0	12	0	7	5	0	1	5
837	23511	13955	0	0	0	1	0	10	0	3	0	0	0	2
849	23824	16360	0	0	0	0	0	9	0	3	1	0	0	3
861	24145	16231	0	0	0	1	0	5	0	2	0	0	0	2
873	24447	14970	0	0	0	0	0	8	0	4	2	0	0	1
885	24741	26646	0	0	0	1	0	19	0	4	0	0	0	3
897	25027	14696	0	0	0	0	0	11	0	2	1	0	0	1
909	25314	20648	0	0	0	0	0	19	0	4	0	0	1	9
921	25591	24190	0	1	0	0	0	15	0	10	0	0	0	2
933	26040	23187	0	0	0	0	0	10	0	2	2	0	0	2
954	27289	17380	0	0	0	1	0	16	0	3	0	0	1	9
966	27899	17126	0	0	0	0	0	18	0	15	0	0	0	3
978	28559	26839	0	0	0	1	0	17	0	8	5	0	0	5
990	29203	22630	0	0	0	1	0	27	0	6	9	0	0	10
1002	29757	28390	0	0	0	1	0	12	0	3	6	0	0	7
1014	30227	29686	0	0	0	0	0	18	0	15	2	0	2	7
1026	30683	28238	0	0	0	0	0	40	0	6	11	0	0	2

Table 7.9: Results of the palynological analysis from the KTK19-II sediment core, including sample core depth (cm), age (a BP), and counts of herbs (H) taxa.

Sample depth (cm)	Sample age (a BP)	Apiaceae	*Artemisia*	Asteraceae subfam. Asteroideae	Asteraceae subfam. Cichorioideae	Brassicaceae	Caryophyllaceae	Chenopodiaceae	Cyperaceae	Poaceae	Polygonaceae	Ranunculaceae	*Thalictrum*	Rosaceae	Rubiaceae	Saxifragaceae	Valerianaceae	Other herbs
		H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
6.6	103	0	14	0	0	0	0	2	2	1	0	0	0	0	0	0	0	0
12.2	274	0	25	0	0	0	0	1	6	13	0	2	0	1	0	0	0	0
17.8	450	0	17	0	0	0	0	2	1	9	0	1	0	0	0	0	0	0
29	793	1	20	0	0	0	0	0	6	3	0	0	0	0	0	0	0	0

Table 7.9 (continue)

Sample depth (cm)	Sample age (a BP)	Apiaceae	*Artemisia*	Asteraceae subfam. Asteroideae	Asteraceae subfam. Cichorioideae	Brassicaceae	Caryophyllaceae	Chenopodiaceae	Cyperaceae	Poaceae	Polygonaceae	Ranunculaceae	*Thalictrum*	Rosaceae	Rubiaceae	Saxifragaceae	Valerianaceae	Other herbs
		H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
40.2	1127	0	12	0	0	0	0	2	4	5	0	0	0	1	0	0	0	0
51.4	1498	1	35	0	0	0	0	8	4	7	0	0	3	3	1	0	0	0
62.6	1822	0	22	0	0	0	0	1	3	8	0	0	2	0	1	0	0	0
73.8	2184	0	21	0	0	0	0	3	0	5	0	0	2	2	1	0	0	0
85	2515	0	20	0	0	0	3	0	2	6	0	0	1	0	1	0	0	0
96.2	2811	0	28	0	1	0	0	3	2	1	0	0	3	3	1	0	0	0
107.4	3013	3	10	0	0	0	1	2	5	12	0	0	0	1	1	0	0	0
118.6	3205	0	29	1	0	0	0	6	6	7	0	0	1	1	1	0	0	0
129.8	3407	0	19	2	0	0	0	2	1	7	0	0	0	0	1	0	0	0
141	3603	0	23	0	0	3	0	1	3	3	0	0	1	1	1	0	0	0
152.2	3805	0	26	1	0	0	0	4	3	7	0	0	0	1	1	0	0	0
163.4	3999	0	25	1	0	0	0	1	2	5	0	0	1	1	1	0	0	1
174.6	4200	0	24	0	0	0	0	3	3	6	0	0	0	0	1	0	0	0
185.8	4408	0	14	0	0	0	0	2	6	4	0	0	4	4	1	0	0	0
197	4608	0	22	0	0	0	0	5	2	9	0	0	0	0	1	0	0	0
208.2	4807	0	14	0	0	0	0	2	1	7	0	0	3	3	1	0	0	0
219.4	4948	0	31	0	0	0	0	1	8	10	0	1	2	0	1	0	0	0
230.6	5047	0	36	0	0	0	0	7	6	3	0	0	1	1	1	0	0	0
241.8	5154	0	30	0	0	0	0	2	5	9	0	0	0	0	1	0	0	0
253	5255	0	21	0	0	0	0	4	7	12	0	0	4	4	1	0	0	1
264.2	5360	0	34	0	0	0	0	0	5	5	0	0	0	0	1	0	0	0
275.4	5467	0	28	0	0	0	0	5	5	3	0	0	7	7	1	0	0	0
286.6	5570	0	35	1	0	0	0	3	2	10	0	0	1	0	1	0	0	0
297.8	5677	0	12	0	0	0	0	2	11	6	0	0	4	4	1	0	0	0
309	5773	0	34	0	0	0	0	6	10	10	0	0	2	0	1	0	0	0
320.2	5867	0	15	0	0	0	0	1	5	1	0	0	1	1	1	0	0	0
331.4	6134	1	29	0	0	0	0	4	12	5	0	0	2	0	1	0	0	0
342.6	6430	0	32	0	0	0	2	4	4	8	0	0	5	5	1	0	0	0
353.8	6723	0	33	0	0	0	0	2	7	5	0	1	3	1	1	0	0	0
365	7028	0	42	0	0	0	0	4	8	10	0	0	3	3	1	0	0	0
376.2	7316	0	42	0	0	0	0	0	6	13	0	0	1	0	1	0	0	0
387.4	7619	0	45	0	0	0	0	2	2	6	0	0	2	2	1	0	0	0
398.6	7894	0	33	1	0	0	0	5	6	8	0	0	7	2	1	0	0	0
410	8184	0	52	0	0	0	0	3	3	4	0	1	6	7	1	0	0	0
420	8395	0	35	1	0	0	0	5	0	9	0	0	3	3	1	0	0	0
430	8606	0	24	1	0	0	0	4	7	6	0	0	1	1	1	0	0	0
440	8817	0	53	1	1	0	0	5	8	9	0	0	2	1	1	0	0	0
450	9036	0	34	0	0	0	1	4	11	4	0	0	5	5	1	0	0	0
460	9254	0	23	0	0	0	0	2	5	6	0	0	2	1	1	0	0	0
470	9467	1	63	0	0	0	0	9	18	7	0	0	6	6	1	0	0	0
480	9691	1	53	1	0	0	0	5	5	7	0	0	6	1	1	0	0	0
490	9907	1	63	3	0	0	1	15	8	11	0	0	5	5	1	0	0	0
500	10118	0	45	0	0	0	0	6	17	10	0	1	6	0	1	0	0	0
510	10328	1	110	0	0	0	0	15	12	7	0	1	13	14	1	0	0	0
519	10567	0	47	0	0	0	0	6	19	8	0	2	9	1	1	0	0	0
529	10879	0	83	1	0	0	0	8	15	6	0	0	6	6	1	0	0	0
539	11197	1	54	2	0	0	1	13	15	11	0	0	8	2	1	0	0	0
550	11536	1	100	0	0	1	0	8	17	8	0	1	15	16	1	0	0	0
566	12040	0	41	1	0	0	0	3	22	13	0	0	7	7	1	0	0	0
572	12218	1	29	0	0	0	1	2	34	20	0	0	6	6	1	0	0	0
578	12383	0	24	0	0	0	0	2	27	21	0	4	1	0	1	0	0	0
584	12639	1	56	1	0	0	0	4	12	21	0	0	8	8	1	0	0	0
591	12900	0	38	0	0	0	0	0	22	15	0	2	2	0	1	0	0	0
597	13134	1	46	0	0	0	0	2	13	19	0	1	3	4	1	0	0	0
604	13420	0	30	0	1	0	0	5	22	26	0	0	6	1	1	1	0	0
610	13662	1	77	1	0	0	0	7	26	29	0	1	20	21	1	0	0	0

Table 7.9 (continue)

Sample depth (cm)	Sample age (a BP)	Apiaceae	*Artemisia*	Asteraceae subfam. Asteroideae	Asteraceae subfam. Cichorioideae	Brassicaceae	Caryophyllaceae	Chenopodiaceae	Cyperaceae	Poaceae	Polygonaceae	Ranunculaceae	*Thalictrum*	Rosaceae	Rubiaceae	Saxifragaceae	Valerianaceae	Other herbs
		H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	H	
617	13940	2	85	0	0	0	2	8	28	33	0	0	32	2	1	1	0	0
623	14169	0	113	2	0	0	0	9	22	27	0	0	39	39	1	0	0	0
629	14385	0	101	5	1	0	1	5	17	32	0	2	27	1	1	0	0	0
635	14564	2	138	4	0	0	2	5	17	28	0	1	33	34	1	0	0	0
641	14736	0	119	2	0	1	1	7	35	17	0	1	24	4	1	0	0	0
647	14917	0	120	0	0	0	0	10	11	21	0	0	15	15	1	0	0	0
653	15085	1	123	3	0	0	1	13	11	29	1	3	11	7	1	0	0	0
659	15254	2	149	2	0	0	2	12	10	29	0	1	5	6	1	0	0	0
665	15425	1	157	3	1	0	0	5	18	42	0	1	6	3	1	0	0	0
671	15590	0	121	2	0	0	2	14	30	65	0	2	2	4	1	0	0	0
677	15766	7	107	0	0	2	3	7	15	49	4	3	11	1	1	0	0	0
683	16043	3	156	3	0	0	1	9	61	84	0	5	3	8	1	0	0	0
689	16349	2	164	5	6	0	3	4	47	111	4	2	9	0	1	0	0	0
695	16662	0	178	1	0	0	3	10	44	92	0	0	3	3	1	0	0	0
701	16979	1	129	5	0	5	11	10	65	78	0	7	8	8	1	0	0	0
707	17325	8	196	5	0	1	7	13	55	97	0	0	5	5	1	0	0	0
713	17661	3	196	4	1	2	8	14	66	105	0	7	5	5	1	0	0	0
719	17996	9	192	5	0	0	10	7	58	116	0	1	5	6	1	0	0	0
725	18318	1	171	3	5	4	17	5	45	119	1	6	9	0	1	0	0	0
731	18623	4	236	1	0	3	3	8	34	112	0	0	11	11	1	0	0	0
737	18924	4	217	2	2	0	4	13	35	91	1	11	9	1	1	0	0	0
743	19267	1	215	4	0	0	8	8	46	133	0	3	8	11	1	0	0	0
765	20601	4	224	2	0	0	8	4	38	134	1	11	9	1	1	0	2	1
777	21186	2	220	4	11	2	6	6	27	129	0	0	5	2	1	0	0	0
789	21728	6	177	5	10	7	7	7	54	118	0	6	13	1	1	0	0	0
801	22252	6	161	8	9	4	7	7	50	146	2	4	7	0	1	1	0	0
813	22802	5	143	7	0	3	5	5	75	134	0	14	5	1	1	1	0	0
825	23201	3	209	3	10	0	4	7	41	109	0	2	8	3	1	0	0	0
837	23511	4	250	5	6	0	7	8	30	122	0	23	6	7	1	0	0	1
849	23824	5	219	4	6	0	7	4	24	113	0	15	8	4	1	0	0	0
861	24145	8	199	5	8	0	5	11	16	94	1	52	9	2	1	0	0	0
873	24447	5	211	7	3	0	5	4	21	114	1	19	5	5	1	0	0	0
885	24741	8	185	11	13	1	11	2	54	115	0	4	4	0	1	0	0	0
897	25027	5	176	8	6	0	5	6	36	127	0	23	5	6	1	0	0	0
909	25314	6	181	9	8	3	8	8	44	109	0	23	2	1	1	0	0	0
921	25591	7	215	2	6	1	4	2	48	93	1	19	9	2	1	0	0	0
933	26040	6	219	6	3	0	7	5	19	111	1	11	2	4	1	0	0	0
954	27289	3	235	5	10	0	5	6	40	136	0	6	6	1	1	0	0	0
966	27899	7	132	4	5	4	7	6	72	129	5	1	18	7	1	0	0	0
978	28559	7	199	2	4	3	10	9	37	122	0	5	4	4	1	0	0	0
990	29203	6	156	4	2	1	7	10	46	109	1	11	7	4	1	0	0	0
1002	29757	6	157	4	2	0	10	11	59	129	2	10	6	1	1	0	0	0
1014	30227	1	161	4	0	0	4	11	72	117	0	9	6	0	1	0	0	0
1026	30683	1	105	8	1	2	4	6	83	146	0	10	3	6	1	0	0	0

Table 7.10: Results of the biome reconstruction from the KTK19-II sediment core, including sample core depth (cm), age (a BP), affinity scores of regional biomes and landscape openness, dominant biome, and charcoal particle counts in three size groups (>100 µm, 50–100 µm, 10–50 µm).

Sample depth (cm)	Sample age (a BP)	Tundra/TUND	Cold deciduous forest/CLDE	Taiga/TAIG	Cool coniferous forest/COCO	Cold steppe/STEP	Dominant biome	Landscape openness	Charcoal particles >100 µm	Charcoal particles 50–100 µm	Charcoal particles 10–50 µm
6.6	103	1.64	15.40	16.59	16.59	1.58	TAIG	14.95	0	5	131
12.2	274	5.80	12.39	12.85	12.85	3.95	TAIG	7.05	1	3	160
17.8	450	2.80	13.03	13.03	13.03	3.15	CLDE	9.88	1	6	121
29	793	2.56	15.22	16.43	16.43	2.15	TAIG	13.88	1	2	88
40.2	1127	3.51	13.02	13.02	13.02	2.26	CLDE	9.50	0	5	33
51.4	1498	3.88	13.58	14.49	14.49	5.65	TAIG	8.84	2	6	119
62.6	1822	2.90	13.02	13.02	13.02	3.14	CLDE	9.88	2	2	51
73.8	2184	2.21	15.41	15.78	15.78	3.11	TAIG	12.67	1	6	85
85	2515	1.74	12.98	13.62	13.62	3.40	TAIG	10.23	4	6	76
96.2	2811	0.96	13.23	13.69	13.69	3.85	TAIG	9.84	0	4	116
107.4	3013	3.46	13.03	13.41	13.41	3.09	TAIG	9.94	0	7	75
118.6	3205	3.26	13.03	13.21	13.21	3.77	TAIG	9.44	1	7	161
129.8	3407	3.05	14.16	14.16	14.16	2.90	CLDE	11.11	2	6	75
141	3603	2.02	15.16	16.37	16.37	2.38	TAIG	13.99	1	5	98
152.2	3805	2.11	13.20	13.20	13.20	3.44	CLDE	9.77	2	6	53
163.4	3999	0.76	13.71	14.47	14.47	2.97	TAIG	11.50	1	5	85
174.6	4200	2.10	13.16	13.16	13.16	3.36	CLDE	9.80	2	5	75
185.8	4408	1.99	13.72	14.36	14.36	3.55	TAIG	10.81	3	6	91
197	4608	1.94	14.82	16.15	16.15	4.26	TAIG	11.89	2	16	149
208.2	4807	2.17	14.47	15.37	15.37	3.39	TAIG	11.98	2	6	68
219.4	4948	2.81	13.88	14.19	14.19	3.60	TAIG	10.59	2	9	135
230.6	5047	1.00	13.95	14.65	14.65	3.58	TAIG	11.08	4	17	192
241.8	5154	2.56	13.01	13.97	13.97	3.84	TAIG	10.12	3	4	130
253	5255	3.10	13.34	14.03	14.03	4.83	TAIG	9.20	1	4	52
264.2	5360	2.74	13.38	14.04	14.04	3.54	TAIG	10.50	0	11	160
275.4	5467	0.91	13.01	14.50	14.50	4.89	TAIG	9.62	1	3	92
286.6	5570	2.05	13.17	13.47	13.47	4.06	TAIG	9.41	2	5	94
297.8	5677	2.16	14.00	14.00	14.00	3.35	CLDE	10.64	5	9	116
309	5773	3.82	13.24	13.61	13.61	4.76	TAIG	8.85	1	5	95
320.2	5867	1.40	14.17	14.17	14.17	1.68	CLDE	12.49	2	8	80
331.4	6134	2.38	11.91	11.91	11.91	4.05	CLDE	7.86	6	17	209
342.6	6430	2.03	13.35	13.93	13.93	5.65	TAIG	8.28	0	5	101
353.8	6723	2.92	12.44	12.44	12.44	3.67	CLDE	8.77	4	15	140
365	7028	3.04	11.25	11.25	11.25	4.27	CLDE	6.98	4	5	153
376.2	7316	4.24	11.10	12.01	12.01	4.12	TAIG	7.77	1	8	282
387.4	7619	3.18	10.81	12.05	12.05	3.73	TAIG	8.32	1	12	264
398.6	7894	2.89	10.32	11.36	11.36	5.59	TAIG	5.76	4	12	144
410	8184	1.10	10.29	10.81	10.81	4.49	TAIG	6.32	1	9	125
420	8395	3.22	11.38	12.35	12.35	5.16	TAIG	7.19	3	12	108
430	8606	3.27	9.87	11.05	11.05	3.58	TAIG	7.47	1	11	192
440	8817	4.10	9.34	11.85	11.85	5.47	TAIG	6.38	1	15	96
450	9036	3.18	9.32	10.61	10.61	5.36	TAIG	5.25	1	6	229
460	9254	2.24	10.96	13.66	13.66	2.99	TAIG	10.67	2	5	95
470	9467	4.09	10.79	12.62	12.62	6.69	TAIG	5.93	2	4	79
480	9691	3.53	10.71	13.96	13.96	6.61	TAIG	7.35	0	2	49
490	9907	3.64	8.67	10.79	10.79	7.88	TAIG	2.90	4	10	80
500	10118	5.17	11.45	13.85	13.85	6.29	TAIG	7.56	4	11	111
510	10328	4.27	8.89	10.56	10.56	9.45	TAIG	1.11	3	8	133
519	10567	6.91	7.70	11.68	11.68	6.81	TAIG	4.78	0	3	69
529	10879	5.33	9.02	10.55	10.55	7.65	TAIG	2.90	3	5	160
539	11197	6.57	8.70	11.64	11.64	7.38	TAIG	4.27	2	2	37
550	11536	3.73	8.80	9.56	9.56	9.13	TAIG	0.43	1	4	81
566	12040	10.22	8.90	10.59	10.59	5.79	TAIG	0.37	1	4	70

Table 7.10 (continue)

Sample depth (cm)	Sample age (a BP)	Tundra/TUND	Cold deciduous forest/CLDE	Taiga/TAIG	Cool coniferous forest/COCO	Cold steppe/STEP	Dominant biome	Landscape openness	Charcoal particles >100 µm	Charcoal particles 50–100 µm	Charcoal particles 10–50 µm
572	12218	11.29	7.99	10.35	10.35	5.53	TUND	−0.94	3	4	53
578	12383	10.69	7.56	10.95	10.95	4.86	TAIG	0.27	0	5	40
584	12639	10.30	7.53	9.47	9.47	7.27	TUND	−0.83	2	4	48
591	12900	10.38	6.85	9.77	9.77	4.47	TUND	−0.61	0	1	22
597	13134	9.76	7.67	9.93	9.93	5.49	TAIG	0.17	1	6	98
604	13420	12.18	6.79	9.63	9.63	6.41	TUND	−2.55	1	4	59
610	13662	10.64	7.00	11.39	11.39	9.95	TAIG	0.75	1	6	77
617	13940	11.11	7.89	11.08	11.08	10.72	TUND	−0.03	1	5	87
623	14169	8.77	8.00	10.01	10.01	12.22	STEP	−2.22	1	2	44
629	14385	9.66	9.30	10.21	10.21	11.18	STEP	−0.97	1	5	61
635	14564	8.79	8.33	8.33	8.33	13.25	STEP	−4.92	1	7	84
641	14736	10.56	8.78	9.19	9.19	10.73	STEP	−1.54	1	4	70
647	14917	7.84	9.26	9.26	9.26	11.78	STEP	−2.52	0	2	46
653	15085	9.54	8.56	8.56	8.56	12.51	STEP	−3.95	0	4	38
659	15254	8.93	9.50	9.50	9.50	10.99	STEP	−1.49	3	3	45
665	15425	11.16	8.30	8.30	8.30	11.86	STEP	−3.56	0	2	65
671	15590	11.65	8.54	8.54	8.54	11.43	TUND	−3.10	0	0	26
677	15766	10.87	8.28	9.53	9.53	12.57	STEP	−3.04	1	2	43
683	16043	10.97	6.49	6.49	6.49	13.54	STEP	−7.05	0	1	40
689	16349	11.45	5.34	5.34	5.34	15.22	STEP	−9.88	0	0	18
695	16662	10.88	5.68	5.68	5.68	13.51	STEP	−7.83	0	1	37
701	16979	11.69	4.58	4.58	4.58	17.97	STEP	−13.39	0	0	29
707	17325	9.93	3.77	3.77	3.77	17.02	STEP	−13.25	0	1	34
713	17661	9.87	4.06	4.06	4.06	16.67	STEP	−12.62	0	2	17
719	17996	9.65	3.57	3.57	3.57	17.40	STEP	−13.84	0	1	43
725	18318	9.64	2.13	2.13	2.13	18.60	STEP	−16.47	0	0	26
731	18623	9.05	2.65	2.65	2.65	17.55	STEP	−14.90	0	0	40
737	18924	8.69	2.53	2.53	2.53	17.45	STEP	−14.92	0	0	17
743	19267	9.31	2.35	2.35	2.35	17.84	STEP	−15.49	0	2	47
765	20601	9.94	2.48	2.48	2.48	17.07	STEP	−14.59	1	1	68
777	21186	7.90	0.83	0.83	0.83	17.51	STEP	−16.69	0	1	35
789	21728	9.97	2.62	3.05	3.05	20.07	STEP	−17.02	0	1	39
801	22252	9.63	1.41	1.41	1.41	19.88	STEP	−18.47	0	1	105
813	22802	10.48	1.80	1.80	1.80	17.71	STEP	−15.91	0	1	60
825	23201	10.70	2.33	2.33	2.33	17.52	STEP	−15.19	0	1	59
837	23511	7.69	1.25	1.25	1.25	20.20	STEP	−18.95	0	2	86
849	23824	8.27	1.72	1.72	1.72	19.98	STEP	−18.26	0	2	38
861	24145	6.49	0.83	0.83	0.83	21.71	STEP	−20.88	0	1	31
873	24447	7.99	1.19	1.19	1.19	19.85	STEP	−18.66	1	0	30
885	24741	9.61	2.40	2.40	2.40	18.43	STEP	−16.03	0	3	70
897	25027	8.31	1.46	1.46	1.46	20.75	STEP	−19.29	0	3	27
909	25314	9.96	3.22	3.22	3.22	19.65	STEP	−16.43	1	1	28
921	25591	9.12	1.71	1.71	1.71	17.35	STEP	−15.64	0	2	45
933	26040	7.19	1.39	1.39	1.39	18.99	STEP	−17.60	0	2	65
954	27289	9.56	2.84	2.84	2.84	17.85	STEP	−15.00	0	1	48
966	27899	12.40	2.35	2.35	2.35	19.83	STEP	−17.48	1	1	49
978	28559	10.74	2.62	2.62	2.62	18.61	STEP	−15.99	0	1	40
990	29203	11.91	3.81	3.81	3.81	18.42	STEP	−14.61	0	4	48
1002	29757	11.55	2.58	2.58	2.58	18.17	STEP	−15.58	0	2	96
1014	30227	11.99	2.98	2.98	2.98	16.20	STEP	−13.22	2	1	61
1026	30683	12.44	2.95	2.95	2.95	16.09	STEP	−13.14	2	7	73

7.3 List of publications

Krikunova, A.I., Kostromina, N.A., Savelieva, L.A., Tolstobrov, D.S., Petrov, A.Y., Long, T., Kobe, F., Leipe, C., Tarasov, P.E., 2022. Late- and postglacial vegetation and climate history of the central Kola Peninsula derived from a radiocarbon-dated pollen record of Lake Kamenistoe. Palaeogeography, Palaeoclimatology, Palaeoecology 603, 111191. https://doi.org/10.1016/j.palaeo.2022.111191

Krikunova, A.I., Kostromina, N.A., Savelieva, L.A., Tolstobrov, D.S., Petrov, A.Y., Long, T., Kobe, F., Leipe, C., Tarasov, P.E., 2023. A radiocarbon-dated pollen record and pollen-based vegetation (biome) reconstruction of the last 13,000 years derived from Lake Kamenistoe (Kola Peninsula) [dataset]. PANGAEA, https://doi.org/10.1594/PANGAEA.955707

Krikunova, A.I., Savelieva, L.A., Long, T., Leipe, C., Kobe, F., Kostromina, N.A., Vasilyeva, A.V., Tarasov, P.E., 2024a. Postglacial vegetation and climate change in the Lake Onega region of eastern Fennoscandia derived from a radiocarbon-dated pollen record. Quaternary International 695, 31–44. https://doi.org/10.1016/j.quaint.2024.04.003

Krikunova A.I., Kobe F., Long, T., Leipe, C., Gliwa J., Shchetnikov A.A., Olschewski, P., Hoelzmann, P., Wagner M., Bezrukova, E.V., Tarasov, P.E., 2024b. Vegetation and fire history of the Lake Baikal Region since 32 ka BP reconstructed through microcharcoal and pollen analysis of lake sediment from Cis- and Trans-Baikal. Quaternary Science Reviews 340, 108867. https://doi.org/10.1016/j.quascirev.2024.108867

Krikunova, A.I., Savelieva, L.A., Long, T., Leipe, C., Kobe, F., Kostromina, N.A., Vasilyeva, A.V., Tarasov, P.E., 2024c. The 11,800-year pollen record obtained from Razlomnoe Peat in the Lake Onega region (eastern Fennoscandia) [dataset]. PANGAEA, https://doi.org/10.1594/PANGAEA.971527

Krikunova, A.I., Savelieva, L.A., Long, T., Leipe, C., Kobe, F., Kostromina, N.A., Vasilyeva, A.V., Tarasov, P.E., 2024d. The 11,800-year pollen-based vegetation (biome) reconstruction from Razlomnoe Peat in the Lake Onega region (eastern Fennoscandia) [dataset]. PANGAEA, https://doi.org/10.1594/PANGAEA.971601

7.4 Curriculum vitae

Due to data protection regulations, the curriculum vitae is not included in the online version of this doctoral thesis.

Due to data protection regulations, the curriculum vitae is not included in the online version of this doctoral thesis.

7.5 Declaration

Berlin, December 2024

I hereby declare that I wrote this doctoral thesis on my own and that all used sources are properly acknowledged. This thesis has not been previously submitted to the Freie Universität Berlin or any other institution.

Aleksandra Krikunova