5 # Peat core research in Western Siberia: methods applied, regions studied, and future prospects

Agnieszka Halaś[1], Michał Słowiński[1]

[1]Department of Past Landscape Dynamics, Institute of Geography and Spatial Organization, Polish Academy of Sciences, Warsaw, Poland

10 *Correspondence*: Agnieszka Halaś (aj.halas@twarda.pan.pl)

Abstract.

Peatlands are natural archives that preserve information not only about their own development but also about past environmental conditions in surrounding landscapes. This study presents a comprehensive review of palaeoecological research based on peat cores from the Western Siberian Lowland (WSL). We compiled and georeferenced 654 peat cores and

15 documented the application of 26 palaeoecological proxies, including chronological, physical, chemical, and biological indicators, resulting in the creation of the Western Siberian Peat Core Database (WSPC). The database synthesizes information from 156 publications spanning 1953-2025 and captures both the temporal and methodological evolution of peatland studies in the region, highlighting a clear shift from early single-proxy, low resolution investigations to modern multi-proxy high-resolution studies. Spatial analysis reveals high peat core density along major rivers and in the Great Vasyugan Mire, while

20 remote northern continuous permafrost regions remain underrepresented. Temporal coverage indicates that most cores capture Holocene peatland dynamics, with the longest records in non-permafrost and isolated permafrost zones, extending into the Late Glacial (~15,600 cal. yr BP). The database underscores the dominant role of fundamental physical and chemical proxies, while highlighting the selective application of biological proxies and the limited use of specialized chemical analyses. In addition, the study identifies key research challenges in Western Siberia, including narrow seasonal windows for fieldwork,

25 permafrost, limited transport infrastructure, permit requirements, and geopolitical barriers, which collectively constrain peatland sampling. The WSPC database represents the most extensive compilation of peat-core-based palaeoecological data for this region, offering critical guidance for targeted sampling and future research to address spatial, temporal, and proxy-specific gaps in the study of Western Siberian peatlands.

1 Introduction

30 Peatlands are one of the most important terrestrial ecosystems in the world, acting as significant carbon sinks, regulating hydrology, and providing unique habitats for diverse species. Covering only about 3% of the land surface, they store roughly one-third of the world's soil carbon, highlighting their critical role in the global carbon cycle (Scharlemann et al., 2014; Xu et al., 2018). One of the largest peatland complexes in the world is found in Western Siberian Lowland (WSL), with almost 600 000 km^2 of peatlands and 70.2 Pg of carbon stored (Sheng et al., 2004). The scale and ecological significance of the WSL

35 make it a key region for understanding past and future peatland dynamics, particularly under ongoing climate change.

Peatlands across the WSL began accumulating almost simultaneously around 11,000-10,000 years BP, as postglacial environmental conditions became favourable for peat formation, with only a few sites showing evidence of earlier initiation (Alexandrov et al., 2016; Kremenetski et al., 2003). Spanning the entire Holocene and extending over an exceptionally large geographical area, these peatlands form excellent archives that record not only their own developmental history but also past

40 environmental and climatic changes in their surrounding landscapes. With the use of diverse palaeoecological proxies, peatlands allow the reconstruction of past hydrological conditions, vegetation dynamics, fire activity, and carbon accumulation patterns, providing a detailed insight into Holocene environmental history (Chambers and Charman, 2004).

Comprehensive syntheses by Kremenetski et al. (2003) and Solomeshch (2005), who consolidated the extensive Russian-language literature and documented the legacy of scientific work in the WSL, provide the historical context for early exploration and peatland research. As summarized by them, the scientific study of Western Siberian peatlands began in the early 20th century, initially through government botanical and pedological surveys in the southern WSL (Dranitsyn, 1914; Gordiagin, 1901; Zhilinsky, 1907), with more detailed investigations followed in the 1920s (Baryshnikov, 1929; Bronzov, 1930). During the 1930s, botanical expeditions to the Yamal and Gydan peninsulas generated the first scientific descriptions of arctic peatlands in the northern WSL (Gorodkov, 1932; Govorukhin, 1933). These early investigations, largely carried out along river valleys and exposed natural outcrops, formed the foundation for later palaeoecological research and represent a major legacy of early Russian scientists.

The discovery of significant oil reserves in the 1950s triggered a wave of intensive peatland exploration aimed at assessing peat thickness, distribution, and suitability for infrastructure development. Exploration of the WSL have historically been difficult due to harsh climatic conditions, vast distances, and complex topography. Despite these challenges, the West Siberian Peat Exploratory Expedition (Glavtorffond RSFSR, 1956) produced the first large-scale estimates of peat stocks for the region, with similar work carried out in the Middle Taiga zone in a following decade (Lapshina and Zarov, 2023). During the 1960s and 1970s, systematic surveys mapped the spatial distribution of peatlands and documented peat thickness, hydrology and vegetation cover (Ivanov and Novikov, 1976; Liss and Berezina, 1981; Neustadt, 1971). Important cartographic products, including Geoltorfrazvedka's peatland maps (Map of West Siberian wetlands, 1970, 1996) and Romanova's latitudinal zonation of Eurasian peatlands (Ivanov and Novikov, 1976), remain central references. This period also marked the beginning of modern paleoecology in the WSL, with the first radiocarbon dates (Liss and Kulikova, 1967; Neustadt, 1967) and the earliest pollen-dated peat stratigraphies (Glebov et al., 1974; Levkovskaya et al., 1970; Volkov et al., 1973). Evolution of paleoreconstruction methods started in the 1970s when more precise approach, including the method of retrospective ecological peat analysis with higher sampling resolution started to be implemented (Lapshina and Zarov, 2023; L'vov, 1974).

From the 1980s onward, research expanded into peatland ecology, carbon storage, and long-term accumulation dynamics (Botch et al., 1995; Botch and Masing, 1983; Neustadt, M.I., 1984). The first integrative, internationally accessible synthesis appeared in Kremenetski et al. (2003), who reviewed WSL peatland zonation, carbon stocks, and late-Quaternary development, highlighting major gaps in knowledge and the need to integrate the extensive Russian-language legacy. Solomeshch (2005) further refined understanding of WSL peatland ecology and provided an updated overview of their structure, distribution, and environmental significance. Together, these works emphasize the long-standing contributions of Russian scientists and underscore the global importance of the WSL for paleoclimate reconstruction and carbon-cycle research.

Despite the wealth of studies, much of the palaeoecological research in the WSL remains dispersed across numerous publications, often in older Russian-language journals or books. The variety of proxies, peatland types, and sampling locations complicates efforts to form a complete picture of the region's long-term ecological changes. Additionally, access to detailed site-level information, including peat core locations, stratigraphic data, and the specific proxies analysed, is limited, hindering cross-site comparisons and meta-analyses. These challenges underscore the need for a structured and accessible resource that consolidates existing information, providing a clear overview of what has been studied and where gaps in knowledge remain.

The goal of this review is to synthesize and organize existing palaeoecological research across the WSL by developing the Western Siberian Peat Core Database (WSPC). This database compiles information on peat core locations, the palaeoecological proxies analysed, and the original source references, providing a harmonized inventory of research in this globally significant peatland region. Beyond cataloguing peat cores and proxies, this synthesis addresses key questions about the development of peatland research in the WSL. How has the suite of palaeoecological proxies evolved over time, from early single-proxy studies

to modern multi-proxy approaches? Where are the main spatial gaps in peat core coverage across vegetation and permafrost
85 zones, and how have logistical constraints shaped sampling locations? Which proxies remain rarely used, where are these
methods under-represented, and what are the implications for reconstructing peatland hydrology, fire regimes, and geochemical
conditions at a regional scale? By framing the database around these questions, our review not only documents past research
but also highlights priorities and strategies for future studies. Rather than serving as a tool for quantitative analysis, the WSPC
database provides a comprehensive overview of what has been studied to date. By consolidating dispersed and often difficult-
90 to-access data, the database facilitates identification of sites with comparable proxy records, helps researchers locate relevant
datasets, and supports strategic planning of future fieldwork. Ultimately, the WSPC database aims to enhance accessibility,
transparency, and coordination in Western Siberian peatland research.

2 Study region

The geographical extent of the study region considered in this review follows the boundary of the Western Siberian Lowland
95 (WSL) defined by Sheng et al. (2004). The natural boundaries of the region are marked by the Ural Mountains in the west, the
Yenisey River in the east, the Altai Mountains and Kazakh steppes in the south, and the Kara Sea in the north (Fig. 1). The
study region stretches from 60-93°E to 52-73°N and covers the area of approximately 3 000 000 km². The WSL is the flattest
and lowest major physiographic region of Russia, characterized by an extensive plain that gently slopes northward and lies
between 0 and 300 m a.s.l (Solomeshch, 2005). Geologically, the lowland is underlain by a young tectonic plate covered by
100 thick sedimentary sequence that increases from around 3 km in the south to 11 km in the north (Kurakova, 2024). This
succession consists of alternating continental and marine deposits and is capped by 200–250 m of Quaternary sediments,
primarily clays, sands, and loams (Kremenetski et al., 2003; Kurakova, 2024). The topography of the WSL contributes to the
occurrence of a clear latitudinal distribution of climatic zones and vegetation. According to the Köppen-Geiger climate
classification, most of the WSL has a subarctic climate (Dfc), with mean annual air temperatures ranging from -11.5°C in the
105 Gyda Peninsula to 1 to -1°C in the south, and annual precipitation between 390 and 600 mm (Beck et al., 2018; Solomeshch,
2005; Trofimova and Balybina, 2014). Vegetation mirrors this latitudinal pattern, transitioning from arctic tundra in the north
through the extensive zone of boreal forest (taiga), to a narrow belt of temperate broadleaf and mixed forests, and ultimately
temperate grasslands and shrublands in the far south (Olson et al., 2001). The characteristic feature of this region is presence
of permafrost, which developed mostly in Late Pleistocene (Duchkov, 2006). Currently, permafrost extends southward to about
110 60°N, with continuous permafrost on the Yamal and Gyda Peninsulas reaching up to ~67°N and ranging in thickness from 100
to over 500 m, whereas further south the permafrost becomes discontinuous, sporadic, isolated, and finally absent in the
southernmost WSL (Solomeshch, 2005). The combination of flat terrain and fine-grained, poorly drained sediments promotes
extensive waterlogging and widespread peatland development (Kirpotin et al., 2009). As a consequence, nearly 50% of the
WSL is covered by wetland ecosystems. Peatlands occupy 592,440 km² (20%) of this area, with the largest peatland complex
115 in the world, the Great Vasyugan Mire, covering 6.78 million hectares (Sheng et al., 2004; Vaganov et al., 2005). Most of the
region lies within the Ob' River watershed, with smaller northern sectors draining to the Nadym, Pur, and Taz rivers, and
limited areas contributing to the left-bank tributaries of the Yenisey. The region is also rich in lakes, mostly shallow systems
less than 1 km² in area and 2–5 m deep, mainly formed due to the thawing of permafrost (Kirpotin et al., 2009; Polishchuk et
al., 2017). In the forest-swamp zone, basins can contain up to 40–50% lake coverage, whereas lake density declines toward
120 the southeast, though extensive marsh systems continue to regulate water tables and surface hydrology (Kurakova, 2024).
Despite its vast area, population density is low, especially in the northern sector where extensive peatland landscapes remain
sparsely populated. However, since the mid-1960s, the region has undergone intensive oil and gas development, particularly
in the mid- and lower Ob River basin. Consequently, although large areas of the northern Lowland remain relatively
undisturbed, industrial activity and land-use change across West Siberia have imposed substantial pressures on peatlands,
125 altering their structure, hydrology, and ecological dynamics (Solomeshch, 2005).

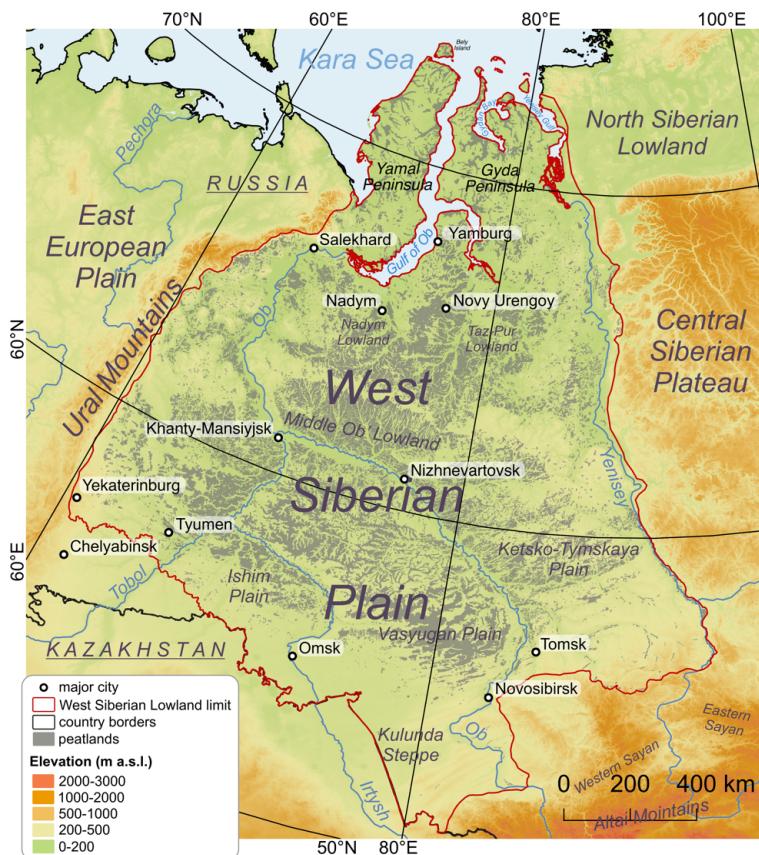



Figure 1. Topographic map of Western Siberian Lowland (WSL) with the extent of peatlands based on Sheng et al (2004), main rivers, selected cities, and main geographic units and geographical extent of study area considered in this literature review. Elevation source: © DLR e.V. 2010-2014 and © Airbus Defence and Space GmbH 2014-2018 provided under COPERNICUS by the European Union and ESA; all rights reserved.

2.1 Peatland extent mapping

Estimates of peatland extent in Western Siberia have varied considerably over time due to differences in mapping methods, definitions, and data availability. Early studies reported smaller areas; for example, Neustadt (1971) as a first estimated peatland extent to 325,380 km², later Tiuremnov (1976) 341,000 km², and Efremov and Efremova (2001) 464,000 km², illustrating the progressive refinement of peatland inventories. Sheng et al. (2004) provided a more detailed assessment, estimating 592,440 km² of peatlands with a total carbon pool of 70.2 Pg C, based on a comprehensive GIS-based inventory combining decades of Geoltorfrazvedka field surveys, Russian wetland maps, satellite imagery, and extensive digitized peat depth and carbon data (Fig. 2a). Modern global products, such as the Global Peatland Map 2.0 (GPM2.0), classify regions as peat-dominated or peat-in-soil-mosaic at a 1×1 km resolution by integrating multiple regional and national datasets using proxy mapping, satellite classification, and expert judgement (Greifswald Mire Centre, 2022). The available version of GPM uses a peat depth threshold of ≥10 cm to account for climate-relevant peat carbon, rather than the conventional agricultural threshold of ≥30 cm, which increases Russia's estimated peatland area 2.6 times (UNEP, 2022). While GPM provides consistent and updated coverage, its ≥10 cm threshold overestimates the area of peatlands that are relevant for palaeoecological reconstruction. This overestimation is particularly visible in the continuous permafrost zone, where it shows nearly continuous peatland coverage; as well as along the western border and in the eastern parts of the region, including the Yenisey valley and the Ketsko-Tymskaya Plain (Fig. 2b). Therefore, for this review, the regional map created by Sheng et al. (2004) remains the most reliable source for WSL peatlands. Although many peat cores in the database are located outside the extent defined by

Sheng et al. (2004), and GPM likely has higher overall accuracy, its methodological approach makes it unsuitable for studies

150   requiring peatlands above the ≥30 cm threshold typically used in palaeoecology.

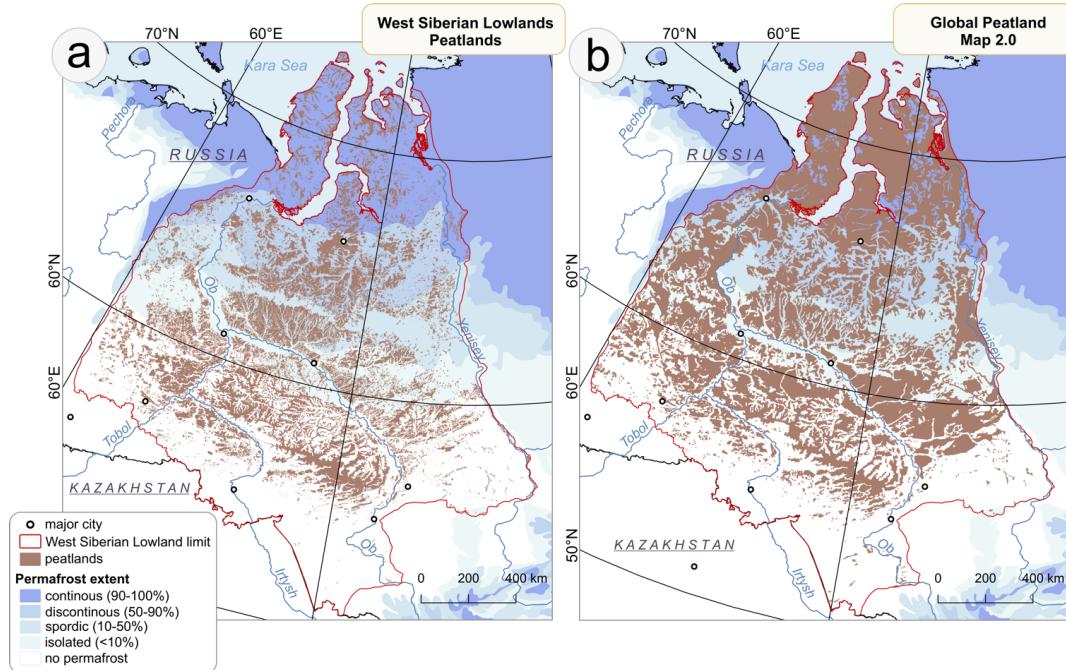



Figure 2. Spatial distribution of peatlands in the Western Siberian Lowlands: (a) regional map by Sheng et al. (2004); (b) Global Peatland Map 2.0 (Greifswald Mire Centre, 2022) with peat depth threshold ≥10 cm.

3 Methods and materials

3.1 Literature selection

155

This literature selection was based on two online databases of scientific papers: Google Scholar and Scopus, using the keywords "*Western Siberia*" AND "*reconstruction*" AND "*peatland*". The initial results were screened manually to identify relevant studies. We applied specific inclusion and exclusion criteria to select studies further used in this review:

- Publication type: only published articles and books were considered.
160
- Time span: studies published up to May 2025 were included.
- Language: only publications in English or Russian were considered.
- Temporal coverage: only stratigraphic peat cores or peat cross-sections were included, with a focus on Holocene records.
- Geographical extent: only studies in which at least one peat core was located within the borders of the Western Siberian
165
Lowland (Fig. 1), as defined by Sheng et al. (2004) were included (Sheng, 2016).
- Core location: studies were included if they reported precise or approximate coring coordinates, or if approximate locations could be estimated from maps provided in the original publication. Studies lacking sufficient locational information were excluded.
- Coring material: only peat sediments (peat cores or peat cross-sections) were included. If the type of sediment could
170
not be clearly determined, the core was excluded.
- Study type: eligible studies presented original palaeoecological data derived from peat cores, or meta-analyses synthesizing data from a defined set of peat core studies. Review articles and books that only summarized previously

published data without referencing specific peat cores were excluded. We also excluded studies based solely on modelling or simulations not directly grounded in empirical peat core data.

175 • Minimum information required: to be eligible, peat cores had to provide at least one source of palaeoecological information (proxy), regardless of whether chronology was available (e.g., palynology, charcoal analysis, loss-on-ignition or bulk density). In addition, cores were also considered if they contained only chronological information or only basal depth data.

3.2 Data extraction and database creation

180 After compiling a database of relevant studies, we developed the Western Siberian Peat Core Database (WSPC) by extracting information on individual cores from each publication. For every peat core, we recorded the following required information: location and core name. Whenever available, we also collected supplementary details, including coring date, dating method, number of dated levels, temporal span of the record, sampling resolution, applied proxies, and basal depth. In total, 26 different proxies were identified (Supplementary Table S1). To avoid duplication, we cross-checked all entries to identify peat cores

185 reported in multiple publications. We first compared core names and reported coordinates (or approximate locations when exact coordinates were unavailable). When cores shared identical or nearly identical locations and had the same ages, lab numbers, basal depths, reference or any unique metadata that could be compared, we treated them as the same record. In cases where the same core was described across multiple publications, we merged the information into a single record. The ages of the records were obtained from the original publications, expressed in calibrated radiocarbon years (cal. yr BP) where available.

190 For 27 sites with only uncalibrated ages, calibration was conducted in R Statistical Software (R Core Team, 2022) using the *bchron* package (Haslett and Parnell, 2008) and the IntCal20 calibration curve (Reimer et al., 2020) (Supplementary Table S2). Peat cores were identified as basal (representing the complete peat sequence down to the mineral substrate) when such information was provided in the source publication, or when it could be inferred from the stratigraphic diagrams. In the WSPC database, each peat core was assigned a unique Core ID in the format WS_X (e.g., WS_1, WS_2, WS_3). Cores were numbered

195 sequentially according to their geographic position, starting from the southernmost site and progressing northwards. In addition to the assigned Core IDs, we retained the original core names as reported in the source publications and databases to facilitate easier identification and cross-referencing. Each core includes also references to the original source from which the authors of this database obtained it, as well as information about the publication of the initial core source, if such details were provided in the reviewed publication.

200 **3.3 Spatial analysis and data visualization**

3.3.1 GIS data preparation and spatial datasets

To visualize and analyse the spatial distribution of peat cores, a shapefile (SHP) layer was created for WSPC database. All sites were georeferenced and compiled into a unified GIS layer using QGIS 3.16.2 software (QGIS Development Team, 2025). The extent of the study region, as well as all subsequent spatial analyses, followed the Western Siberian Lowland boundary as

205 described by Sheng et al. (2004). Given the vast extent of the study region and clustering of coring sites, peat core density was assessed by dividing the area into 50 × 50 km grid cells. The number of cores within each cell was calculated using the *join attributes by location (summary)* tool (geometric predicate: *contains*) in QGIS. Besides the attributes obtained from the original publications, each peat core record was supplemented with information on its location within specific vegetation, permafrost, and peatland zones using the same tool in QGIS. Spatial data about vegetation zones were obtained from the map of terrestrial

210 ecoregions by Olson et al. (2001), while permafrost extent was derived from the circum-Arctic map of permafrost and ground-ice conditions by Brown et al. (2002). The spatial extent of peatland zones was based on the map of major peatland zones originally published by Ivanov and Novikov (1976) and reproduced in Kremenetski et al. (2003). This map was georeferenced and digitized for use in this study.

3.3.2 Temporal coverage analysis and permafrost-related grouping

To analyse the percentage of peat cores covering each time interval, we assumed that the age of the record represents the period from the time of sampling back to the oldest dated level, although in some cases (particularly in the northern part of the study area) this may not have been the case. The same assumption was used to analyse the temporal coverage of individual proxies across Western Siberia. Given the substantial influence of permafrost on sampling and data availability, peat cores were classified into three groups corresponding to different permafrost zones: (1) non-permafrost and isolated permafrost, (2) sporadic and discontinuous permafrost, and (3) continuous permafrost.

3.3.3 Scoring system and spatial visualization of proxy representation

For evaluating peat core datasets, we developed a quantitative scoring system to assess the quality and informational value of each peat core record. Proxies were grouped into three categories (biological, physical, and chemical) and each proxy was assigned an individual weight reflecting its relative contribution to environmental reconstructions (Supplementary Table S3). In addition to proxy-specific weights, we also applied an additional weighting step when integrating proxy information into the final scores. For each proxy group (biological, physical, and chemical), the total sum of all proxy weights from a given group was multiplied by a factor of 4 to emphasize the contribution of group-level proxy richness. When calculating the overall proxy score, the total sum of all proxies across groups was instead multiplied by 5, giving greater influence to records that include a broad suite of proxy types. Each record was also evaluated based on (1) the presence of a chronology, (2) total record length, and (3) the number of proxy types available. These components were scaled to 0–1 and combined with the weighted proxy information to generate four aggregated scores (*combined_bio*, *combined_phys*, *combined_chem*, and *combined_all*) (Table S4). Higher scores indicate records with greater chronological control, longer temporal coverage, and richer multiproxy data. All calculations were performed in R Statistical Software (R Core Team, 2022) using the *dplyr* package (Wickham et al., 2023) for data manipulation. Spatial patterns of combined scores were visualized using QGIS. We applied the Heatmap (Kernel Density Estimation, KDE) tool to each dataset, using a 30 km radius and a pixel size of 100×100 m. The KDE was weighted by the combined scores of all proxies as well as separately for the biological, chemical, and physical proxy groups. The resulting density maps provide a spatially smoothed representation of proxy distribution and highlight both well-sampled regions and areas with insufficient proxy coverage.

3.3.4 Literature-based data extraction and figure assembly

For the literature analysis, if the full text of publication was unavailable, information on the language and proxies used was inferred from the available title, abstract, or bibliographic data accessible to the authors. All plots and diagrams were prepared in R Statistical Software (R Core Team, 2022) using *ggplot2* (Wickham, 2016) and *ggbreak* (Xu et al., 2021) packages, and final figures were assembled in CorelDRAW Graphic Suite 2021.

4 Results and Discussion

4.1 Peat core studies in Western Siberian Lowland – literature analysis

4.1.1 Source publications overview

The database was compiled from a total of 156 publications published between 1953 and 2025, which were classified into two categories. The first group *primary sources* included 99 publications identified through an extensive literature review, from which data were directly obtained and used to build the database. The second group *secondary sources* included 57 original publications that were not directly accessible, but were cited within the primary publications used for data extraction. For each core, references are provided both to the publication from which the data were obtained (primary source) and, where available, to the original source publication cited therein (secondary source). The WSPC database is based on 82 English-language, 73

Russian-language, and one German-language publications. The authors had direct access to 79 of the English-language and 20 of the Russian-language sources.

255 The publications used in the compilation of the database contained information on varying numbers of peat cores. The majority of studies (82%) presented data from one to five cores, typically providing reconstructions at the local or regional scale. Another 13% of the publications included results from six to fifty cores. These studies analysed various regions within the Western Siberian Lowland (WSL), often along transects across peatlands, or incorporated WSL data as part of larger datasets. Only eight publications contained datasets with more than fifty peat cores. These studies generally focused on large-scale

260 syntheses addressing specific research questions at the global scale (such as carbon accumulation) or provided a more detailed analysis of the Western Siberia, and include Kremenetski et al. (2003), Sheng et al. (2004), Smith et al. (2004, 2012), MacDonald et al. (2006), Loisel et al. (2014), Hugelius et al. (2020), and Lapshina and Zarov (2023).

Based on conducted literature review, it was observed that between 1950 and 1990, the number of peat core studies in Western Siberia increased notably, with most results published in Russian-language journals or books and only a limited number

265 appearing in English (Fig. 2a). This pattern reflects the early growth of peat research during the Soviet period and the dominance of domestic Soviet research activity, as the region remained largely inaccessible to the international scientific community. After 1990, this trend shifted, as the number of English-language publications increased rapidly, reflecting the collapse of the USSR and the onset of international collaboration. The decade 2010–2020 saw the highest number of publications, reflecting not only regional research dynamics but also the broader global growth in scientific output. Although

270 the decade 2020–2030 is only halfway through, 28 papers on this topic have already been published. While this trend may suggest that the current decade will produce the highest number of publications, ongoing geopolitical tensions, limited accessibility of some areas, and difficulties in collaborating with Russian scientists may slow down further research activity.

4.1.2 Evolution of proxy use in Western Siberian studies

Based on the use of proxies, two distinct periods can be identified in Western Siberian studies: an early stage (1950–2000),

275 characterized by single-proxy studies, and the modern period (after 2000), marked by increasing integration of biological, physical, and chemical indicators (Fig. 2b). A major step forward in peatland research was the implementation of radiocarbon dating, developed in the 1940s (Olsson, 2009). Since the 1960s, it has become increasingly important in paleoenvironmental studies and remains the most widely applied chronological tool in research on Western Siberia (Kremenetski et al., 2003). Whereas earlier studies often reported results solely based on depth, radiocarbon dating is now used almost universally. Basal

280 depth was an important physical parameter not only from a scientific perspective but also from an economic one. The discovery of oil in the 1950s initiated intensive studies of Western Siberian peatlands, as information on peat thickness was essential for constructing roads and infrastructure required for oil exploration (Kremenetski et al., 2003). Early decades were dominated by classic palynological studies. Pollen was the first biological proxy applied in this region and has maintained its importance to the present day. However, although pollen analysis is widely used, it primarily provides information about the vegetation and

285 environment surrounding the peatland rather than the peatland itself. Growing interest in peatland development led to the increasing use of plant macrofossil analysis, which began to be applied from the 1980s onward. After 2000 more proxies started to be implemented in research on Western Siberia. New biological proxies, such as testate amoebae and micro- and macrocharcoal, were introduced, providing valuable tools for reconstructing changes in peatland hydrology and fire activity at different spatial scales. More laboratory analyses aimed at obtaining more precise data on the physical and chemical

290 properties of peat began to be applied (e.g., bulk density, pH, ash content), along with newly developed technologies introduced over the past decade (e.g., XRF, FTIR). Peat and carbon accumulation were already studied in research conducted before 2000; however, their frequency had increased noticeably since then. The increased variety of applied proxies over the past 25 years, on one hand reflects the development of new research methods, and on the other, a growing awareness of the importance of these ecosystems and the desire to better understand their history.

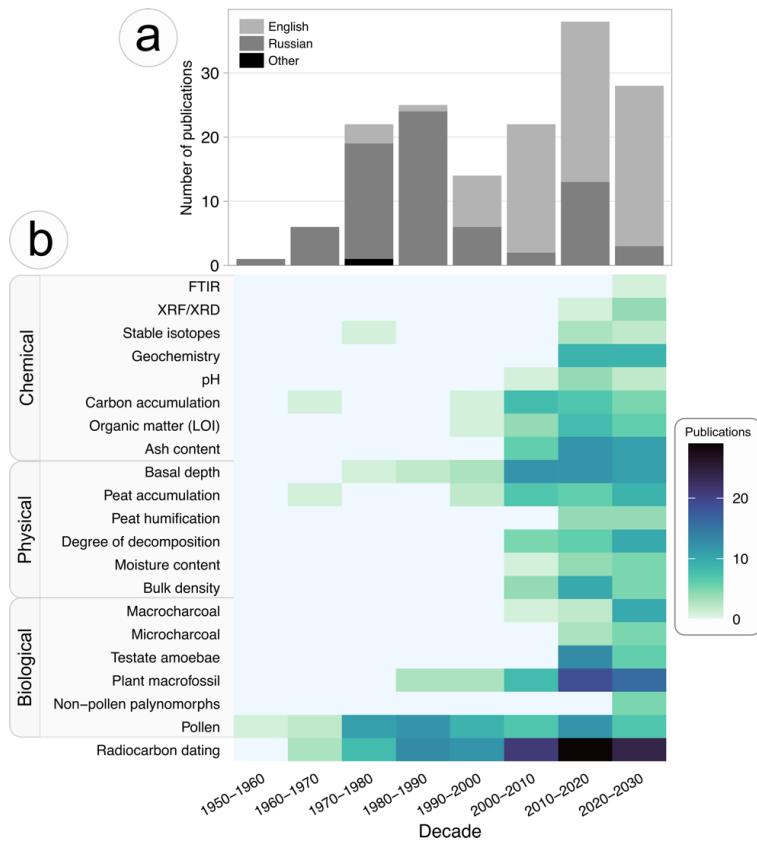



Figure 3. Temporal patterns in research output and methodological approaches: (a) trends in the number of publications in Russian and English per decade; (b) frequency of selected proxies used in studies across decades.

4.2 Western Siberian Peat Core Database

4.2.1 General information and spatial distribution

The Western Siberian Peat Core Database (WSPC) includes information on the locations and applied palaeoecological proxies of 654 peat cores or peat cross-sections collected from the Western Siberian Lowland (WSL) (Fig. 3a). The spatial distribution of cores highlights the considerable challenges associated with conducting research in the peatlands of Western Siberia. Their vast extent, the widespread presence of permafrost, and limited transport accessibility largely determine the areas where sediment sampling is logistically feasible. Notably, 47% of all peat cores (306 out of 654) included in the WSPC database were collected within a 100 km buffer zone of the major rivers: Ob, Yenisey, Irtysh, and Tobol, with hight density of cores in the Middle Ob' Lowland (Fig. 3b). A distinct concentration of collected cores is observed in the Great Vasyugan Mire (west of Tomsk), which represents the largest contiguous peatland in the world (Fig. 3c) (Kirpotin et al., 2009). Various parts of this extensive complex have been the focus of numerous previous studies (e.g.: Blyakharchuk et al., 2019; Lapshina and Zarov, 2023; Rudmin et al., 2018; Syso and Peregon, 2009) due to the absence of permafrost and the proximity to major cities facilitating field work organisation. Another distinct concentration of peat cores is observed in the central part of the study region, between the Ob and Yenisey rivers, where numerous cores were collected during extensive Russian-American field campaigns conducted between 1999 and 2001 (Sheng et al., 2004; Smith et al., 2000). Although the railway network in Western Siberia is relatively sparse, a major line crosses this area, connecting Tyumen with Novy Urengoy, Nadym, and Yamburg, thereby facilitating logistical access to this part of the region. Peatlands in the northern part of the WSL have been studied mostly on the Yamal Peninsula, with a few coring sites on the Gyda Peninsula, mainly along the shore of the Gydan Bay. The

northernmost core in the database was located on Bely Island (73,34190°N, 70,12760°E) and southernmost on Dolgon'koye swamp (53,21250°N, 84,40720°E).

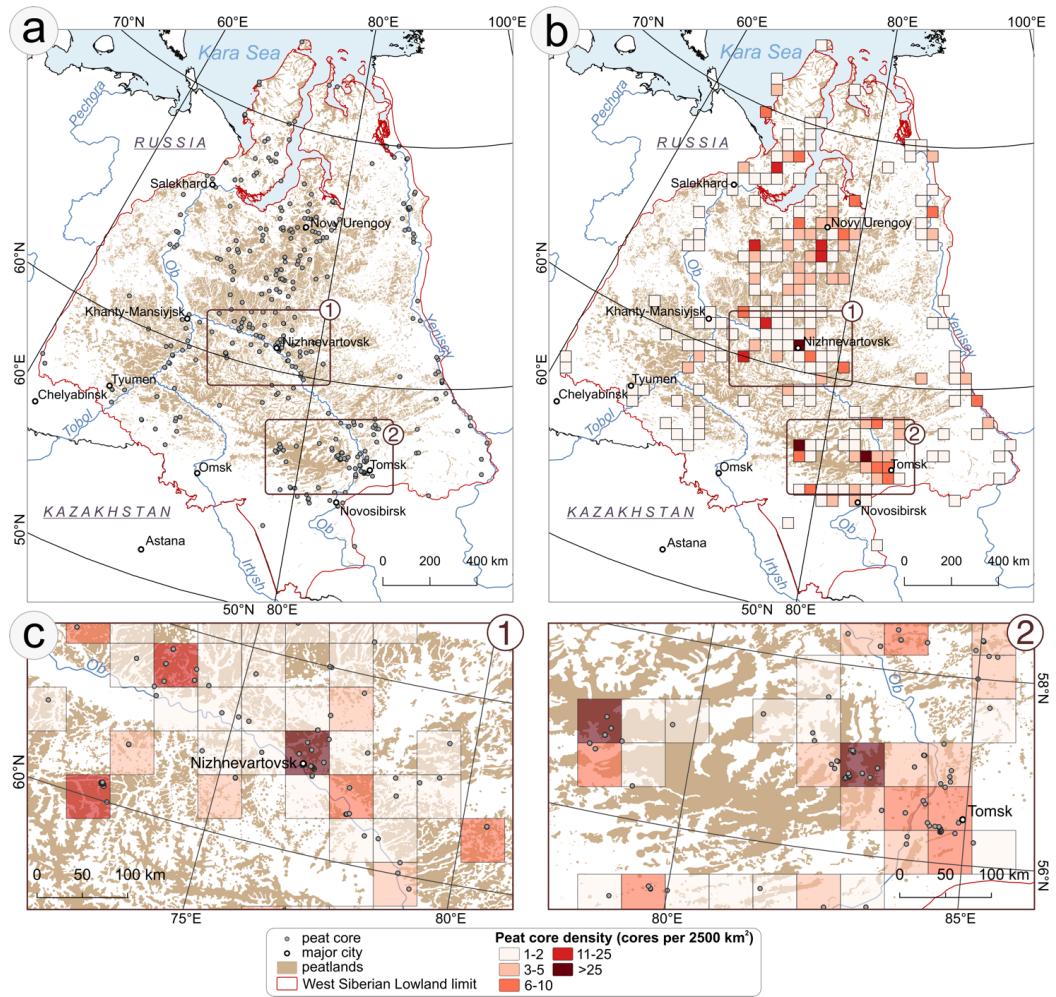



Figure 4. Distribution of peat cores in Western Siberian Peat Core Database: (a) spatial distribution of peat cores in Western Siberia, (b)
320 peat core density (number of cores per 2500 km²), (c) the zoomed maps of two regions within the Western Siberian Lowland: (1) peatland complexes in the Middle Ob' Lowland near Nizhnevartovsk, and (2) the eastern part of the Great Vasyugan Mire. Maps include peatlands extent based on Sheng et al. (2004).

The WSPC database includes peat cores, representing a broad range of environmental settings across the region. Peatlands in Western Siberia occupy all major permafrost zones and vegetation types, although their spatial extent and sampling intensity
325 vary in some cases. (Fig. 4a, 4c). Peatlands are most extensive in the non-permafrost zone, which covers 41.5% of the total peatland area, followed by the discontinuous (18.6%), sporadic (14.1%), isolated (13.9%), and continuous (11.9%) permafrost zones. In general, the number of peat cores reflects the relative area of peatlands in each zone. The two permafrost zones with the largest peatland areas also have the highest numbers of peat cores: the non-permafrost zone (278 cores, 42.5% of the total) and the discontinuous permafrost zone (132 cores, 20.2%). The number of peat cores in the isolated (94 cores, 14.4%) and
330 continuous (101 cores, 15.4%) permafrost zones also corresponds closely to the proportion of peatland area in these zones. The main exception is the sporadic permafrost zone, which contains the third-largest share of peatland area (14.1%) but is relatively underrepresented, accounting for only 7.5% of all peat cores in the database.

Across vegetation types, the majority of Western Siberian peatlands are associated with boreal forests/taiga (78.9%), followed by tundra (13.7%), temperate broadleaf and mixed forests (6.1%), and temperate grasslands and shrublands (1.3%). The distribution of peat cores reflects this pattern: cores from peatlands in boreal forests dominate the dataset (405 cores, 61.9%), followed by tundra sites (118 cores, 18.0%), while mixed forests (92 cores, 14.1%) and shrubland peatlands (39 cores, 6.0%) are considerably less represented by peat cores in the database.

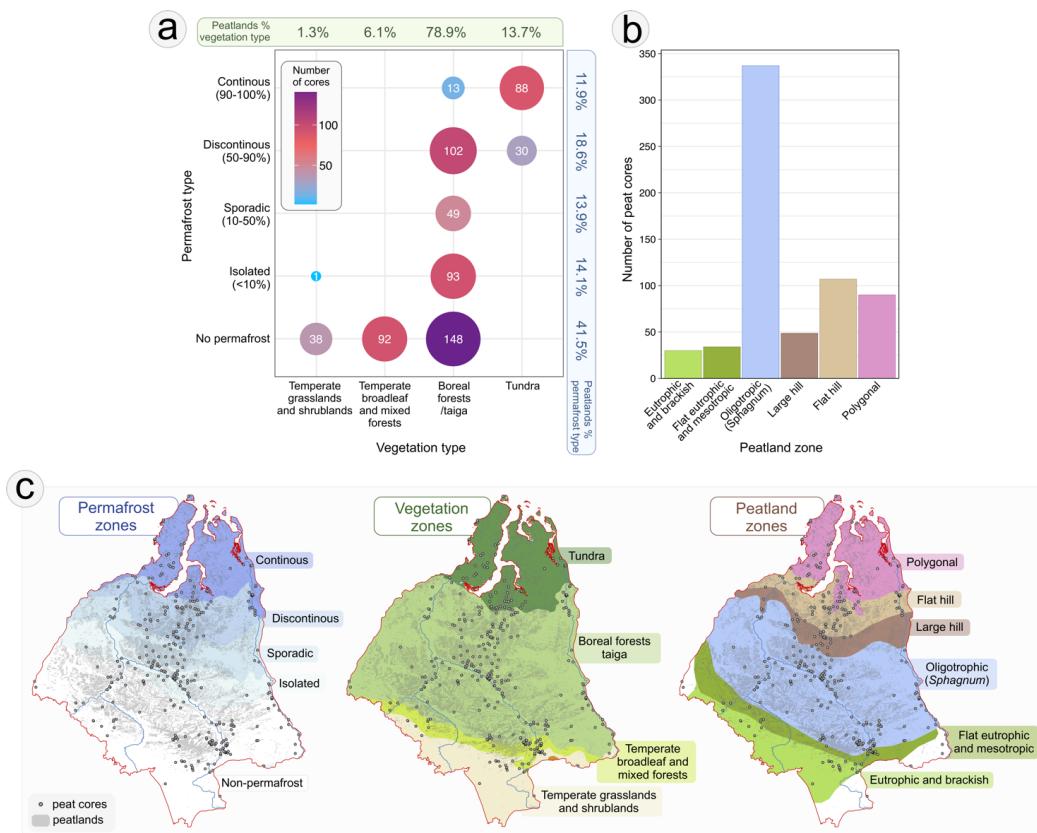



Figure 5. Distribution of peat cores in the Western Siberian Peat Core Database by permafrost, vegetation, and peatland type; (a) number of peat cores within each permafrost zone and vegetation type, with percentages of peatlands occurring in each category; (b) number of peat cores by major peatland zones; (c) spatial distribution of peat cores in relation to permafrost zone, vegetation type and peatland type. Vegetation zones are based on Olson et al. (2001), permafrost extent on Brown et al. (2002), major peatland zones on Kremenetski et al. (2003) (after Ivanov and Novikov, 1976), and peatland extent on Sheng et al. (2004).

Based on major peatland zones, polygonal peatlands, which dominate north of 67°N and are associated with continuous permafrost and tundra vegetation, are represented by 90 cores (13.8%) in the database (Fig. 4b, 4c). Flat hill and large hill peatlands, which occur predominantly within the discontinuous permafrost zone and are associated with taiga vegetation between 61–67°N, account for 107 (16.4%) and 49 (7.5%) cores, respectively. Oligotrophic (*Sphagnum*-dominated) peatlands, concentrated between 56–61°N and typically associated with boreal forest/taiga areas exhibiting either non-permafrost, isolated or sporadic permafrost, represent the most frequent peatland type in WSL and are represented by the largest group of 337 cores (51.5%). The two southernmost peatland zones, where permafrost is absent and temperate vegetation types predominate, are the least represented in the dataset. Flat eutrophic and mesotrophic peatlands, occurring in a narrow belt from 55–58°N in the east and up to 60°N in the west, include 34 cores (5.2%), while eutrophic and brackish peatlands, located south

of 55°N, form the smallest group, with 30 cores (4.6%). Additionally, 7 cores (1.0%) are outside the extent of the defined peatland zones.

4.2.2 Variation in the number of proxies per core

The WSPC database documents the application of 26 palaeoecological proxies in Western Siberian peat cores, grouped into four categories: biological, physical, chemical and chronological (Fig. 5b, Table S1). Peat cores in the database differ substantially in the number of applied proxies, ranging from only one to a maximum of 12 per core (Fig. 5a, Fig. 6a). Fewer than 5% of all cores include only a single proxy, most commonly basal depth or sediment age; in some cases, they include only pollen or plant macrofossil data. For cores containing only biological proxies, this may be explained by the extraction of data from more recent, method-focused publications (e.g. palynology), whereas broader and potentially more comprehensive information may have been reported in earlier sources that were inaccessible for the authors of this database. Cores analysed using two proxies constitute the largest group in the database, representing 50.1% of all records. The most frequent combinations include basal depth or age paired with either pollen or carbon accumulation data. Peat cores containing data from three to six proxies typically include several biological proxies combined with age or basal depth information, and in some cases supplemented with peat property measurements (e.g. peat or carbon accumulation, or organic matter content). The second most common proxy count is seven (13.5%). Within this group, two distinct core types can be distinguished: (1) cores that resemble the 3–6 proxy category but incorporate more biological proxies, and (2) cores that lack biological proxies but provide more extensive data on the physical and chemical properties of peat. Cores containing eight or more proxies represent multi-proxy analyses, integrating biological, physical, and chemical data along with sediment dating, and thus provide the most comprehensive information on the history of the studied peatlands. Only 9.8% of all cores include this number of proxies, while just 1.2% contain ten or more. The spatial distribution of peat cores with a given number of proxies is also evident (Fig. 6a). High concentrations of well-studied peatlands occur along major rivers, particularly the Ob (Mukhrino, Sredne Vasyuganskoe, Samara, and Bakchar) and the Yenisey (Igarka). Given its large size and ecological significance, the Great Vasyugan Mire also contains numerous peat cores with a high number of proxies, reflecting its long-term use as a key site for multi-proxy palaeoecological research. Another cluster of cores analysed with multiple proxies is observed in the central part of the study region, between the Ob and Yenisey rivers. These cores were mostly collected during Russian-American field campaigns and include detailed physical and chemical analyses of peat, as well as cores described in single-core studies, such as the Khanymei peatland.

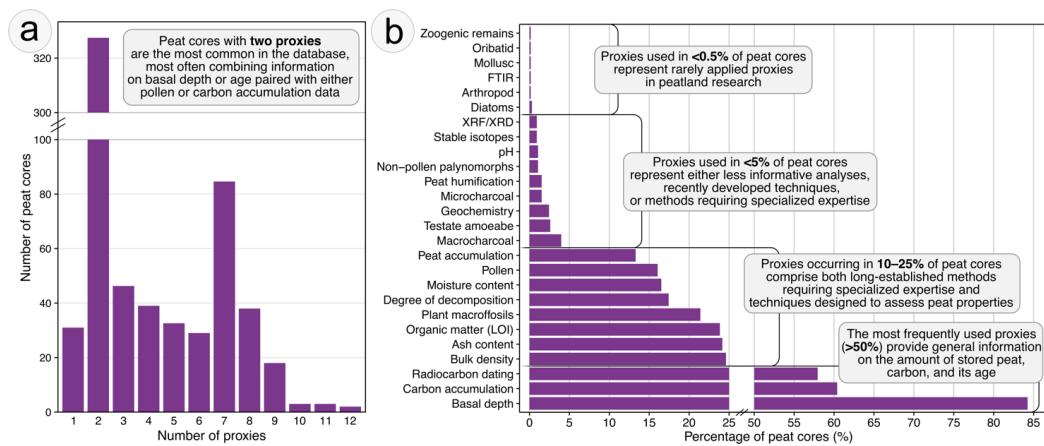



Figure 6. Summary of palaeoecological proxies applied in peat cores in the Western Siberian Peat Core Database; (a) number of proxies used and corresponding number of peat cores, (b) frequency (%) of use of individual proxies across the peat cores.

4.2.3 Relative use of different proxy and their regional patterns

In the WSPC database, a total of 26 palaeoecological proxies has been applied to peat cores from Western Siberia; however,
385   their use varies significantly, both in quantitative frequency and in spatial distribution across the study area (Fig. 6b, 7, S1).

Chronological proxies

Chronological proxies are essential for reconstructing peatland development over time and were applied in 58.0% of all peat cores. Radiocarbon dating is by far the most frequently used method in the region, enabling age-depth modelling and temporal correlation of palaeoecological data (Chambers and Charman, 2004). The resolution of dating varies considerably between
390   cores: some cores were dated only at the basal level, whereas others include several dated horizons. This variability often reflects financial constraints, as multipoint dating remains relatively expensive. Nevertheless, in recent decades researchers have increasingly adopted multi-level dating within individual cores to achieve more robust reconstructions and to facilitate comparison with climate-change records (e.g. Feurdean et al., 2019; Lamentowicz et al., 2015; Leonova et al., 2022; Novenko et al., 2023). Due to its widespread application, the spatial distribution of this proxy is relatively uniform, and it is represented
395   in peat cores across most of Western Siberia (Fig. S1c).

Physical proxies

Physical proxies, which provide information on peat properties and stratigraphy, are frequently applied in the database. Basal depth is by far the most common proxy, present in 84.3% of cores (Fig. 5b). Such a large number of basal depth measurements is primarily due to the fact that this parameter is relatively easy to obtain in the field and usually does not require specialist
400   expertise (Parry et al., 2014). Many basal depth data were collected during geological prospecting campaigns or as part of detailed investigations of the development of individual peatland complexes (Kremenetski et al., 2003; Lapshina and Zarov, 2023). This widespread use reflects both its fundamental importance for peatland development studies and its relevance as an economically significant parameter (Fig. S1a). Another important physical proxy useful e.g. for carbon content calculations is bulk density, reported in 24.6% of cores, mostly from the central part between the Ob and Yenisey rivers and from the Vasyugan
405   Plain (Fig. S1d). Degree of decomposition and peat humification are both analyses that indicate the intensity of decay processes; however, the methods differ (Biester et al., 2014). Peat humification is an older technique and is rarely used (1.5% of cores), whereas the degree of decomposition, usually assessed via the von Post scale – a traditional Russian field method – is much more common in Western Siberian cores (17.3%). Their occurrence within the study area is characterized by a clear concentration in the south, on the Vasyugan Plain, while in the remaining regions the proxy is represented only in a small
410   number of sites (Fig. S1h, S1p). Moisture or water content, a proxy useful for interpreting decomposition processes or nutrient mobility (Rydin et al., 2006), was applied in 16.5% of all cores, and its spatial distribution is similar to that of bulk density (Fig. S1i). Peat accumulation is an important proxy that not only provides information about peatland development but can also indirectly inform about past climate variability (Swindles et al., 2025). It was used in 13.3% of the cores, which are distributed across the study region, with more sites located on the Vasyugan Plain (Fig. S1k). The form in which this
415   information is reported varies depending on analytical resolution, sometimes it is a single value for the entire core, and its accuracy increases with increasing resolution.

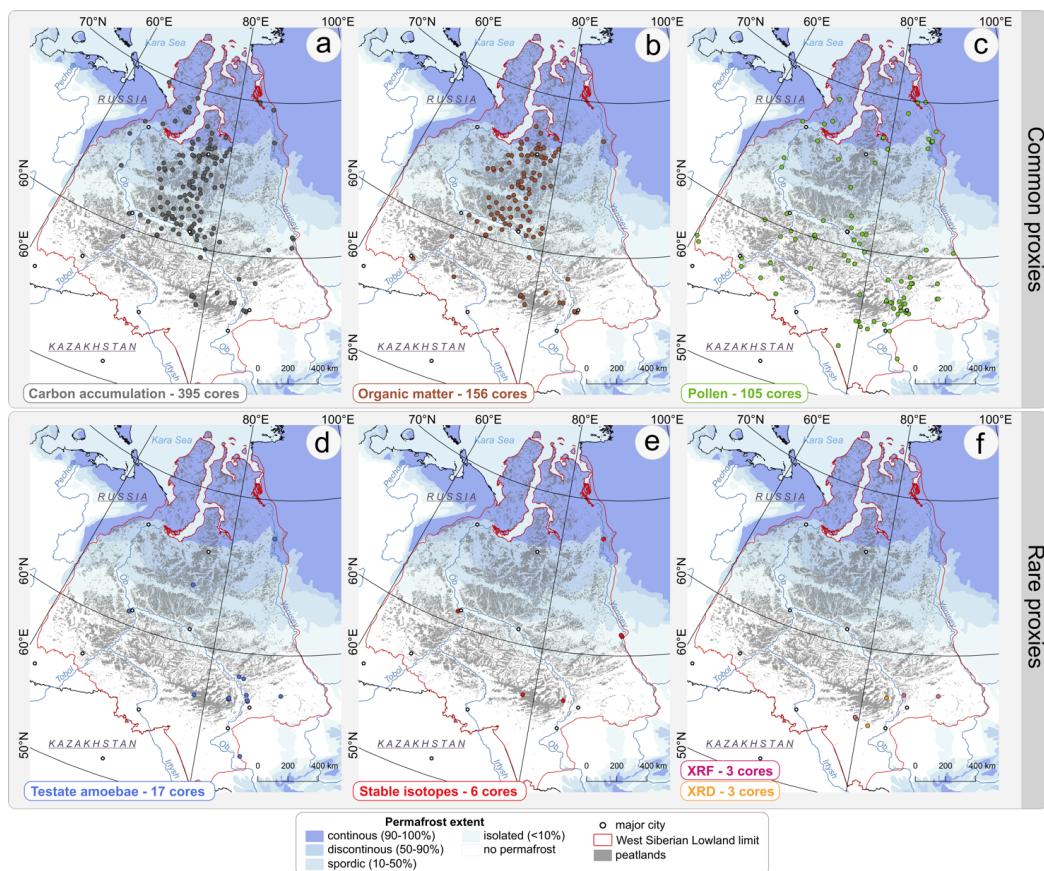



Figure 7. Spatial distribution of peat cores included in the Western Siberian Peat Core Database with records of selected proxies. Commonly used palaeoecological proxies are shown in panels a-c (a – carbon accumulation; b – organic matter; c – pollen), while rarely applied proxies are presented in panels d-f (d – testate amoebae; e – stable isotopes; f – XRF/XRD). Numbers indicate the total count of cores containing each proxy. Maps include peatlands extent based on Sheng et al. (2004) and permafrost extent based on Brown et al. (2002).

Chemical proxies

Chemical properties of accumulated peat in Western Siberia have also been frequently analysed in peat cores. The most commonly used chemical proxy is carbon accumulation, applied in 60.4% of all studied cores (Fig. 5b). This proxy provides valuable information about the total amount of stored carbon in the peat and about long-term changes in peatland carbon sink strength (Charman et al., 2015). Western Siberia is recognized as a global carbon hotspot; therefore, many studies focus on carbon budgets and accumulation patterns, which explains the widespread use of this proxy. This proxy has been applied to cores collected in river valleys and on the Yamal Peninsula; however, its use is still dominated by sites from both the central part of the study region and the peatlands of the Vasyugan Plain (Fig. 7a). Organic matter and ash content, typically measured via loss-on-ignition (LOI), are also commonly analysed in Western Siberian peat cores, appearing in 24.0% and 23.9% of peat cores, respectively. These simple and low-cost methods are widely used in paleoecology and provide information about peat composition and the input of inorganic material (Chambers and Charman, 2004; Tolonen, 1984). Their spatial distribution is very similar and resembles the distribution pattern of bulk density (Fig. 7b, S1e). Other chemical proxies included in this database: geochemistry, pH, stable isotopes, XRF or XRD and FTIR have been rarely applied in Western Siberian peat cores. Data on pH, which reflects peat acidity, are more characteristic of modern ecological surveys than of palaeoecological studies. Consequently, this proxy was used in only 1.1% of all cores, exclusively in non-permafrost peatlands in the southern part of the region (Fig. S1r). Traditional geochemical analyses (2.4%), stable isotopes (0.9%), XRF/XRD (0.9%), and FTIR (0.2%)

all require specialised expertise and laboratory infrastructure, which until recently were not widely accessible. Geochemical
440   analyses and XRF/XRD are different methods for determining the elemental composition of peat; geochemistry has become
increasingly popular in recent years, whereas XRF and XRD, traditionally used in lake sediment studies, have only recently
begun to be applied to peat (Longman et al., 2019; Shotyk, 1988). Geochemical analyses have been conducted in several
peatlands south of 64°N, while XRF/XRD has been used primarily in peatlands near Tomsk in the south-eastern part of the
study area (Fig. 7f, S1n). Stable isotopes in peat provide valuable insights into past environmental and climatic conditions;
445   however, they are costly and require specialized isotope facilities (McClymont et al., 2010). Such data are scattered across
Western Siberia and are typically collected from cores analysed in extensive studies that integrate multiple other proxies
(Feurdean et al., 2019; Startsev et al., 2022) (Fig. 7e).

Biological proxies

The group of palaeoecological proxies that has been the least frequently applied in Western Siberian peat cores are biological
450   proxies (Fig. 5b). They rely on the identification of remains of organisms preserved in peat and are therefore highly dependent
on preservation conditions. Additionally, they are usually time-consuming and require specialist expertise. The most frequently
used biological proxy, applied in 21.3% of all cores, is plant macrofossils (referred to as "botanical composition" in older
publications), which reflect local peatland vegetation and are essential for reconstructing peatland development and hydrology
(Birks and Birks, 2000). However, the level of analytical detail varies between studies. In some cores, particularly in older
455   works, the data are limited to reporting dominant *Sphagnum* species or other major plant groups, often at a low sampling
resolution of 10 or 25 cm. In contrast, more recent studies tend to use higher-resolution sampling and more detailed
identifications, frequently including subfossil vegetative fragments and carpological remains (e.g.: Halaś et al., 2025; Novenko
et al., 2022). Peat cores with plant macrofossil data are spread across Western Siberia, with a higher concentration on Vasyugan
Plain and in the area near Tomsk (Fig. S1g). Pollen is an excellent proxy for reconstructing past regional vegetation and
460   landscape-scale ecological changes (Mander and Punyasena, 2018). Owing to its long-established use in palaeoecological
studies, it was introduced very early in Western Siberian research. To date, 16.1% of all cores in the database contain pollen
data. These cores cover the majority of Western Siberia, with their highest frequency occurring in areas where core density is
greatest (Fig. 7c). Non-pollen palynomorphs (NPPs) are additional microfossils that can be identified during standard
palynological analysis (Shumilovskikh et al., 2021). Because Quaternary palynologists historically did not focus on these other
465   palynomorphs, their identification is challenging, and their systematic documentation only began in the late 1970s, their use
in Western Siberian cores has remained limited. Although the scientific community has increasingly recognized the potential
of this proxy to reflect local ecological conditions and it is now being applied at more sites (Feurdean et al., 2022; Halaś et al.,
2025), only 1.1% of all cores currently include NPP data, and these come from only a few locations in the WSL (Fig. S1q).
Peatlands are also valuable archives of past fire activity, with charcoal commonly used as a proxy for this purpose. Depending
470   on the intended spatial scale of fire reconstruction, different charcoal size fractions are analysed: macrocharcoal for local fires
and microcharcoal for regional fire activity (Conedera et al., 2009). Both types are present in the WSL, although at low
frequency. Macrocharcoal has been used more often, occurring in 4.0% of all cores, whereas microcharcoal appears in only
1.5%. There is no clear spatial pattern in their use; instead, they are found sporadically in isolated cores across the study area
(Fig. S1l, S1o). A lack of fire-history research in Western Siberia (and in Russia more broadly) was also noted by Pupysheva
475   and Blyakharchuk (2023). They emphasized that fire proxies are relatively new to this region and highlighted the importance
of expanding fire-history studies across this territory. Hydrology is one of the most important environmental variables
controlling the condition of peatland (Rydin et al., 2013), and testate amoebae are a well-established proxy for reconstructing
past hydrology of these ecosystems (Charman, 2001). Although their widespread use in palaeoecological research began
roughly 40 years ago (Mitchell, 2025), their application in Western Siberian peat cores remains very limited, appearing in only
480   about 2.6% of all studied cores. Testate amoebae have been used primarily in non-permafrost peatlands in the southern part of

the WSL, while in other types of permafrost peatlands they have been applied only sporadically (Fig. 7d). Less frequently used biological proxies include arthropods, molluscs, oribatid mites, diatoms, and zoogenic remains, each recorded in less than 0.3% of cores. Although these proxies can offer valuable insights into local environmental conditions, their preservation in peat is generally poor, and they are more characteristic of lake sediment studies. As a result, they are rarely applied in peatland

485   research. This pattern is also evident in Western Siberia, where their use in peat cores is limited to only a few isolated cases (Fig. S1u, S1w-S1z).

Overall, the WSPC database demonstrates a strong focus on fundamental physical and chemical proxies, particularly basal depth, carbon accumulation, and organic matter content, reflecting the importance of these variables in peatland palaeoecology. Biological proxies are applied more selectively, often depending on the research question, while more specialized proxies such

490   as geochemistry, stable isotopes, or FTIR are rarely used. This distribution highlights both the breadth of multi-proxy approaches in Western Siberian peatlands and the gaps in underrepresented proxy types, particularly in biological and specialized chemical analyses.

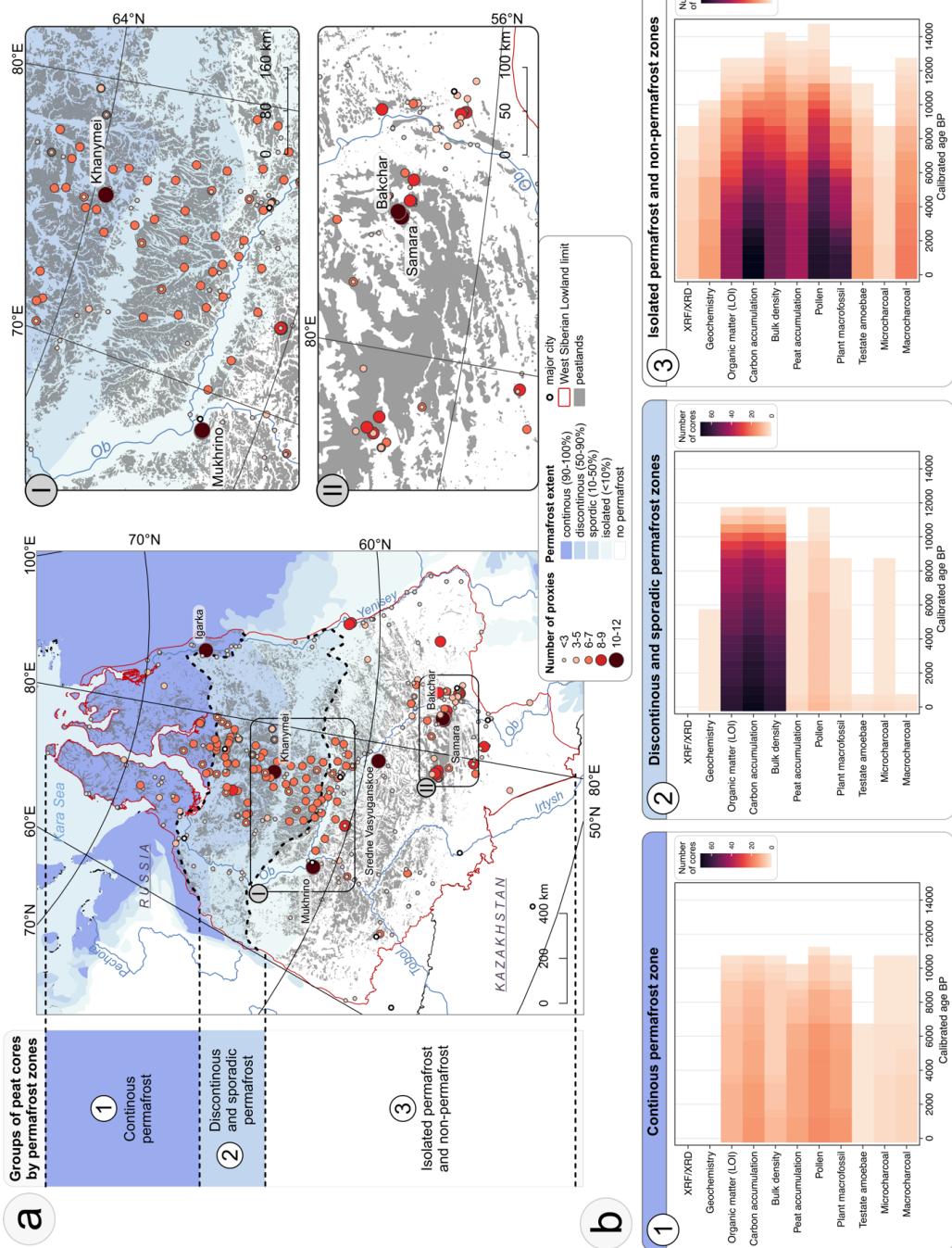



Figure 8. Palaeoecological proxies used in peat cores in the Western Siberian Peat Core Database: (a) spatial distribution of peat cores categorized by the number of proxies analysed, with names of peatlands (cores) with the greatest number of proxies, permafrost zones based on Brown et al. (2002), and peatland extent based on Sheng et al. (2004); (b) heatmaps of the temporal coverage of individual proxies within three groups of cores distinguished by permafrost zone: (1) the continuous permafrost zone, (2) the discontinuous and sporadic permafrost zones, and (3) the isolated permafrost and non-permafrost zones. Colour intensity reflects the number of cores contributing data within 500-year intervals.

Heatmaps were prepared only based on cores with established chronologies.

4.2.4 Age structure of peat cores and temporal coverage of proxies

The database includes three types of peat cores: (1) full-length sequences that extend from the basal mineral substrate to the sampling date and thus capture the complete peat accumulation history; (2) upper-only sequences that begin at the modern

505   peat surface but do not reach the basal layer, typically resulting from targeted sampling strategies such as upper-core ecological reconstructions or from logistical constraints, particularly in permafrost regions; and (3) cores that may or may not reach the basal mineral substrate but are distinguished by the absence of the youngest peat layer due to climate-driven cessation of peat accumulation, a pattern most commonly observed in polygonal peatlands in the northern part of the region. The temporal distribution of peat core ages, summarised in 300-year intervals, shows a highly uneven pattern, revealing several distinct

510   phases across the time span up to ~16,000 cal. yr BP (Fig. 9b). Since the majority of cores in the WSCP database were published after 1950 and type-3 cores are relatively rare, we assumed for this analysis that each peat core represents continuous data from 1950 to the deepest dated layer.

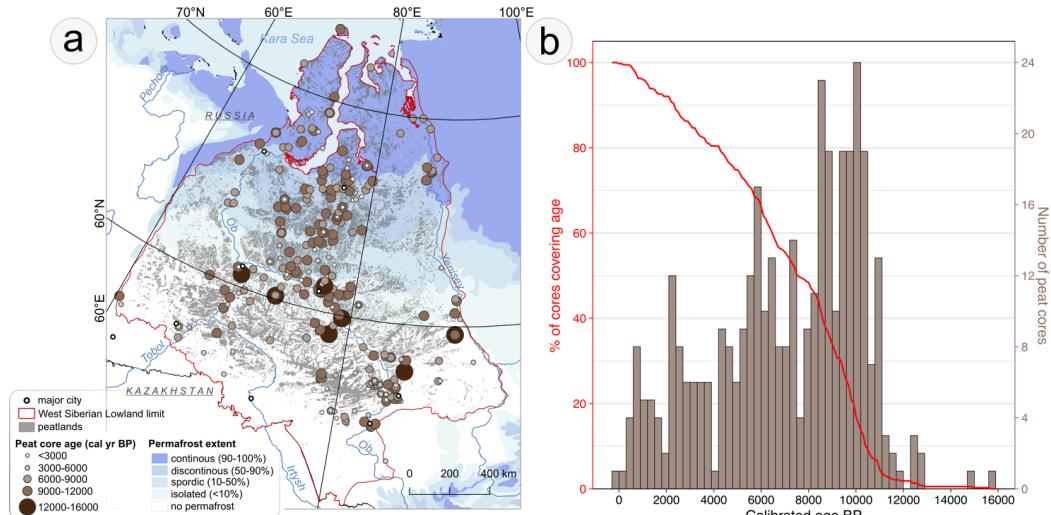



Figure 9. Age distribution of peat cores in the Western Siberian Peat Core Database: (a) spatial distribution of peat cores with calibrated

515   ages (cal. yr BP) of basal or dated bottom levels across Western Siberia; (b) histogram of the number of peat cores within 300-year age intervals, representing the temporal coverage and length of palaeoecological records in the database, and percentage of peat cores in the WSPC database covering age.
Map and plot created only based on cores with established chronologies.

Peat cores covering only the near-modern period (0-2,000 cal. yr BP) are quite rare in the database, usually less than 5 cores

520   per 300-year interval (Fig. 9b). There is an increase in the number of cores that cover longer periods of the Late Holocene up to 4,000 cal. yr BP, with 6-12 cores per interval. Cores covering the Middle Holocene (~4,000-8,000 cal. yr BP) form the second most frequent group, averaging 10 cores per interval. The highest representation is observed for cores spanning ~8,000–11,000 cal. yr BP, with nearly half of all chronologically established cores reaching this period. Beyond ~11,500 cal. yr BP, the number of cores declines sharply, with only individual cores reaching into the Late Glacial. The oldest peat core in the

525   WSPC database dates to 15,623 cal. yr BP (core WSL_246) and is located near the Yenisey River within a present-day non-permafrost region. Peat cores older than 11,500 cal. yr BP are exclusively situated south of 62°N, where current ground conditions correspond to non-permafrost or isolated permafrost zones, and all of these oldest records are located within 100 km of major river channels (Fig. 9a). The lack of records from this period is consistent with limited peatland development in WSL during the Late Glacial, when conditions were generally unfavourable for peat accumulation (Alexandrov et al., 2016;

530 Velichko et al., 2011). In terms of coverage, ~80% of cores extend over the last 4,000 cal. yr BP, ~50% reach 8,000 cal. yr BP, and only ~5% cover 11,000 cal. yr BP.

Because the database includes both basal-depth and upper-only cores, these data cannot be interpreted as direct records of peatland initiation and serve as a basis for analysis spatial peatland development in WSL. Instead, it reflects the age extent of available peat profiles. Despite this limitation, the broad temporal pattern – many cores spanning the early Holocene and very 535 few extending into the Late Glacial – broadly aligns with regional peatland development phases described for this region (Kremenetski et al., 2003).

Temporal coverage of selected proxies varies across permafrost zones, reflecting differences in peat core density, maximum peat age in each zone, and the overall frequency of proxy application (Fig. 8b). The longest peat records occur in isolated and non-permafrost zones, where the majority of studied proxies have been applied, and where most of them provide the greatest 540 temporal coverage, with some extending to almost 15,000 cal. yr BP. In other permafrost zones less proxies have been used, in sporadic and discontinuous permafrost zones proxies' coverage span up to 11,500 cal. yr BP, whereas in continuous permafrost zone, maximum temporal coverage reaches ~11,000 cal. yr BP. Temporal coverage of proxies also depends on the number of cores available for each time interval, which directly affects the completeness and spatial representativeness of the data. When only a few cores provide information for a given variable, such as peat accumulation, the insights are limited and 545 largely local, whereas larger numbers of cores allow for more comprehensive and regionally representative interpretations.

Isolated and non-permafrost zones
The peat cores from isolated and non-permafrost zone provide the earliest and most continuous proxy coverage of all three regions, with several proxies extend into the Late Glacial, providing broader and more detailed insights into the regional peatland history (Fig. 8b). Pollen data for this region are present from ~15,000 cal. yr BP, making it the oldest palaeoecological 550 proxy across all regions and providing a continuous record of vegetation composition and broader regional ecological transitions from the Late Glacial through the Holocene. Although the earliest period is represented by only a few sites, the number of cores grows rapidly after 11,000 cal. yr BP, reaching more than 60 cores in the recent period. Thus, this region offers the highest-resolution, most spatially extensive vegetation reconstructions from peatlands in Western Siberia. Peat-property proxies, including organic matter and bulk density, as well as peat and carbon accumulation extend to ~14,000 and 555 12,000 cal. yr BP, earlier than in any other region. Their steady increase to dozens of cores through the Holocene offers robust reconstruction of substrate evolution, decomposition dynamics, carbon accumulation rates, and peat accumulation phases. Macrofossils data are available until ~12,000 cal. yr BP and reach over 60 cores in the Late Holocene, enabling high-resolution reconstructions of local plant assemblages, peatland microtopography, and fen-bog transitions. Hydrological reconstructions through testate amoebae extend to ~11,000 cal. yr BP and increase to 14 cores, supporting long-term and spatially extensive 560 water-table reconstructions. Geochemical and XRF/XRD records are present from ~10,000-8,500 cal. yr BP, capturing changes in mineral influx, ash content, and geochemical environment. These datasets are largely only available in this part of Western Siberia; although representation increases through time, they still allow only spatially restricted interpretations. Fire proxies vary in temporal coverage. Macrocharcoal is recorded from ~12,500 cal. yr BP, with moderate representation after 8,500 cal. yr BP, providing the deepest temporal perspective on local fire history across Western Siberia. Microcharcoal, which can 565 inform on regional fire dynamics, is traceable to ~8,500 cal. yr BP but remains very sparse.

Sporadic and discontinuous permafrost zones
The temporal coverage in the discontinuous and sporadic permafrost zones differs markedly from the previous region. Here, a few proxies dominate, providing long-term data across the Holocene, while others are absent or offer temporally and spatially restricted information. Organic matter, carbon accumulation, and bulk density data are available until ~11,500 cal. yr BP, and

570 their representation increases sharply through the Early Holocene, remaining exceptionally high (>60 cores) throughout the Mid- and Late Holocene. This suggests that this zone provides the strongest quantitative foundation for Holocene carbon-accumulation reconstructions among all permafrost regions. In contrast, peat accumulation data extend only to ~9,500 cal. yr BP and are available from a very limited number of cores. While these data add a quantitative dimension to vegetation productivity, low representation restricts their use to localized reconstructions rather than regional-scale trends. Pollen data,

575 similar to bulk density, are present from ~11,500 cal. yr BP but remain sparse until the Mid-Holocene. Only from ~7,000 cal. yr BP onward does pollen coverage expand to 7–9 cores per interval, allowing spatially broader vegetation reconstructions. Macrofossil and microcharcoal data extend to ~8,500 cal. yr BP but remain rare, providing long-term yet localized records of plant communities, peatland-surface conditions, and regional fire history. Geochemical information obtained from traditional geochemical analyses is limited to a single site but extends back to ~6,000 cal. yr BP, whereas XRF/XRD data are unavailable

580 for peatlands located in sporadic and discontinuous permafrost zones. Hydrological records through testate amoebae are largely absent, appearing only within the last 500 years, which restricts water-table reconstructions to the very recent past. A similar pattern is observed in macrocharcoal data; information on local fire activity, in contrast to the southern region of WSL, is almost entirely absent for peatlands in this region.

Continuous permafrost zone

585 Proxy data in the continuous permafrost zone are available up to ~11,000 cal. yr BP, with pollen providing the longest and most continuous environmental record. Most other proxies are present until ~10,500–10,000 cal. yr BP, and in all cases, representation peaks around 6,500 cal. yr BP, though it remains relatively low compared to the other regions. These datasets allow reconstruction of peatland vegetation changes, substrate development, and peat and carbon accumulation dynamics across almost the entire Holocene; however, spatial coverage is limited due to the low number of cores. Hydrological

590 information from testate-amoebae extends to ~7,000 cal. yr BP but is available from only a single site, making water table reconstructions largely site-specific. Fire proxies (micro- and macrocharcoal) are present through the Holocene but remain sparse, restricting fire history interpretations to localized events and preventing robust regional-scale reconstructions. Geochemical information, derived from traditional analyses or XRF/XRD, is absent for peatlands in the continuous permafrost zone.

595 In summary, there is a clear regional variation in the temporal coverage of selected proxies. The longest and most continuous records are found in isolated and non-permafrost zones, reflecting both the early initiation of peatlands in this region and the relatively easy accessibility for research due to the absence or spare presence of permafrost. In discontinuous and sporadic permafrost zones, only a few proxies provide long-term, spatially extensive coverage, primarily for basic peat and carbon properties, while other biological and geochemical proxies remain sparse. In continuous permafrost zones, many proxies

600 extend into the early Holocene, but the low number of cores limits spatial representativeness, meaning that long-term reconstructions of ecological dynamics are largely site-specific.

5 Challenges and future directions in Western Siberian paleoenvironmental research

Fieldwork in Western Siberian peatlands is associated with persistent and interrelated logistical, environmental, and political constraints, which together contribute to the underrepresentation of some areas in paleoenvironmental research. First,

605 environmental conditions complicate fieldwork. In northern areas, permafrost dictates when and how sampling can occur. Winter freeze improves travel across bog surfaces but makes coring extremely difficult due to frozen sediments. In summer, the thawed active layer allows proper coring, yet saturated, unstable ground often makes sites inaccessible. This narrow and seasonally contradictory operational window limits the number of reachable localities. This also contributes to limited
accessibility, many parts of Western Siberia lacks roads or rail connections, and many sites can only be reached by navigable

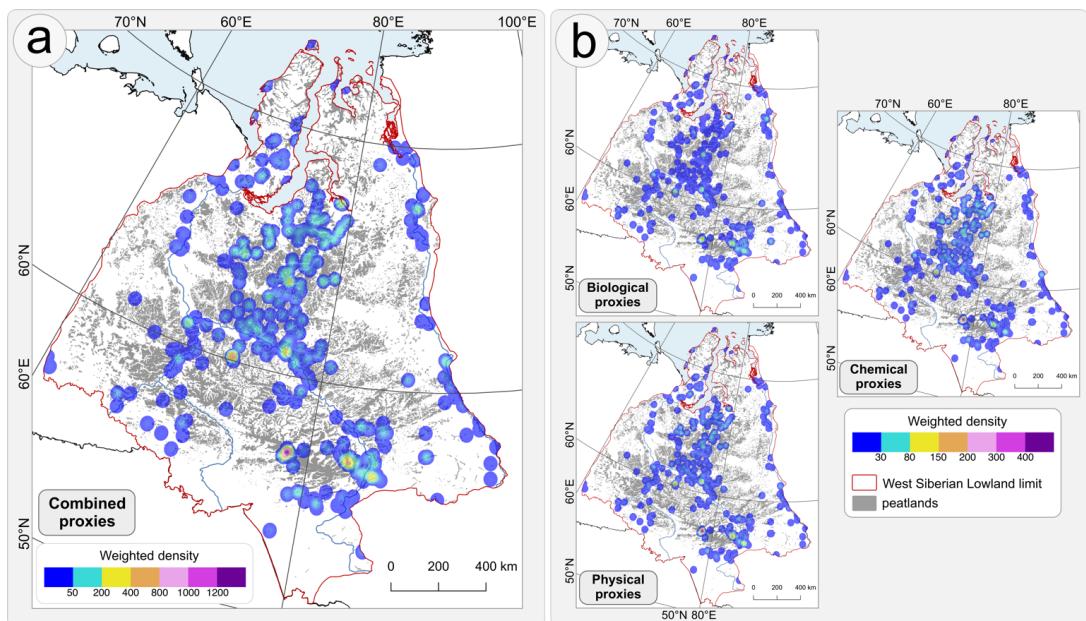
610   waterways, helicopter or specialized off-road vehicles. This greatly increases costs and restricts the spatial extent of sampling, leaving remote peatlands poorly studied. Additional logistical and political constraints, including permit requirements, transport coordination, and recent geopolitical restrictions further reduce access to certain regions (Schuur et al., 2024). As a result, some parts of Western Siberia, particularly remote and permafrost-affected zones, remain underrepresented in palaeoecological research simply because they are exceptionally difficult to reach and sample (Fig. 10a).

615

Figure 10. Spatial representation of peatland areas in Western Siberia sampled by peat cores and their relative contribution of information: (a) heatmap of combined scores of all proxy types, and (b) heatmaps of proxy group scores (biological, chemical, and physical). Heatmaps were generated using Kernel Density Estimation, with a 30 km radius, assuming each core represents the surrounding of 30 km, and weighted by the combined or group-specific scores to depict relative data density. Peat core scoring was based on both chronology and proxies.

620   These limitations are especially critical given the global climatic importance of Western Siberian peatlands. The WSL stores one of the largest peat carbon pools on Earth (Hugelius et al., 2020; Kremenetski et al., 2003; Sheng et al., 2004) and acts both as a long-term carbon sink and a major methane source (Kirpotin et al., 2009; MacDonald et al., 2006; Smith et al., 2004), while ongoing climate change drives complex, regionally variable shifts in ecosystem functioning (Halaś et al., 2025; Zhang et al., 2022). In the context of global soil carbon and peatland assessments (Scharlemann et al., 2014), reducing spatial and

625   methodological gaps in this region is therefore essential for both local process understanding and improved global C–CH₄ budgets.

Looking ahead, the patterns revealed by the WSPC database suggest clear priorities. Continuous and sporadic permafrost zones, especially beyond major river corridors and well-studied complexes such as the Great Vasyugan Mire, should be key targets for new coring campaigns (Fig. 10a). In addition, some areas that appear well covered in terms of core numbers are

630   represented mainly by low-resolution, single-proxy records based on older methods; where detailed reconstructions of hydrology, fire regimes or carbon dynamics are needed, such sites should be revisited or re-analysed using modern, high-resolution multi-proxy approaches. Future work would benefit from wider use of underrepresented biological proxies (e.g. testate amoebae, macro- and microcharcoal, non-pollen palynomorphs) and advanced geochemical and isotopic analyses, particularly in permafrost-affected peatlands (Fig. 10b).

635   At the same time, overcoming logistical and political barriers will require new collaboration and field strategies, including closer partnerships with regional institutions and local communities, greater use of remote sensing and existing infrastructure to pre-select coring sites, and flexible multi-site expeditions using lighter, easily deployable equipment. Aligning such practical solutions with the spatial and methodological gaps highlighted by the WSPC database will allow future research in Western Siberia to move beyond opportunistic sampling towards systematically planned, hypothesis-driven studies that better capture

640   the diversity and dynamics of WSL peatlands.

6 Database limitations

- **Incomplete coverage of literature sources** – The database is based on a literature review of available repositories, which may be missing some publications. The authors acknowledge that not all studies presenting peat core data from the region were identified or accessible.

645

- **Limited access to Russian-language literature published before 1990** – Most pre-1990 Russian-language publications were not available in open-access repositories. As a result, some original sources could not be obtained, limiting the ability to gather comprehensive information on peat cores and proxy usage. Consequently, certain proxies may have been applied earlier or more frequently than indicated by this database.

- **Uncertainty related to incomplete reporting in key studies** – Some works provided aggregated descriptions of coring

650   efforts without reporting exact locations of individual cores. For example, Lapshina & Zarov (2023) described 355 sampling cores along hypsometric profiles, yet precise coordinates were not provided, allowing only 76 cores to be included. It remains possible that many of these cores overlap with records included in other compilations (e.g., Hugelius et al., 2020), but this could not be verified.

- **Ambiguity in classification of basal cores** – In most cases the oldest core from a study site represents a basal core;

655   however, some publications did not clearly specify whether a core reached the mineral substrate. This ambiguity may introduce minor uncertainty into the interpretation of basal depths included in the database.

- **Existence of unpublished data** – Some peat cores are known to exist (e.g., from reports, institutional archives, or personal communications), but lack published stratigraphic or proxy data. These could not be incorporated into the database.

660

- **Variable spatial precision of reported core locations** – Many older or regionally published studies provide only approximate locations (e.g., mire name or nearest settlement) rather than precise coordinates. As a result, included cores differ in spatial accuracy.

- **Dependence on secondary sources for inaccessible studies** – When original publications, particularly older Russian-language works, were unavailable, information was obtained from secondary citations in later papers. This reliance on

665   indirect sources may introduce errors. For example, Liss and Berezina (1981) published stratigraphic diagrams with several dated levels within single cores, but in later studies these levels were misinterpreted as separate basal cores. Such discrepancies highlight the risk of propagating mistakes when direct access to original materials is not possible.

- **Potential duplication or omission of cores** – Some cores appear repeatedly across multiple publications, yet lack of precise metadata sometimes prevented determining whether two references referred to the same core. This introduces

670   a small risk of either under- or over-counting cores.

Data availability

The data are available on the Zenodo platform at the following link: https://doi.org/10.5281/zenodo.17866098 (Halaś and Słowiński, 2025). We plan to expand this database in the future by providing a submission form that will allow researchers to contribute additional peat cores, either from new studies or from existing collections not yet included in the database.

675

Conclusions

The Western Siberian Peat Core Database (WSPC) provides a harmonized and georeferenced dataset of peat cores that greatly advances the capacity for regional analyses of Holocene environmental change in the Western Siberian Lowland (WSL). The literature review demonstrates a clear progression in Western Siberian peatland research, from early single-proxy and low-

680 resolution studies to modern multi-proxy approaches with higher chronological and analytical precision. Increasing attention to peatland hydrology, fire history, and carbon accumulation reflects both methodological developments and a growing recognition of the crucial ecological and climatic importance of WSL peatlands. The WSPC database integrates information from 654 georeferenced peat cores or cross-sections reported in 156 publications (1953–2025), documenting 26 palaeoecological proxies across biological, physical, chemical, and chronological categories. Spatial analyses reveal a

685 concentration of sampling along major rivers (Ob, Yenisey, Irtysh, Tobol) and in the Great Vasyugan Mire, reflecting both the extent of peatlands and relative accessibility. Most cores originate from non-permafrost and discontinuous permafrost zones, whereas continuous permafrost regions remain sparsely sampled. Temporal coverage varies substantially: ~80% of cores span the last 4,000 years, ~50% extend to 8,000 years, and only a limited number reach the Late Glacial (~15,600 cal. yr BP), with the longest and most continuous records found in non-permafrost and isolated permafrost zones. Overall, the dataset shows a

690 strong dominance of fundamental physical and chemical proxies, particularly basal depth, carbon accumulation, and organic matter content, which underscores their central role in peatland palaeoecology. Biological proxies such as plant macrofossils, pollen, and testate amoebae are applied more selectively and largely depend on specific research goals, while specialized chemical proxies (e.g., geochemistry, FTIR, XRF, stable isotopes) remain infrequently used. This distribution highlights both the breadth of existing multi-proxy approaches and the clear gaps in the application of biological and advanced geochemical

695 methods. Collectively, this database provides an essential foundation for large-scale reconstructions of Holocene peatland development, hydrology, fire regimes, and carbon dynamics, while clearly identifying spatial and proxy-specific gaps. Several limitations must be acknowledged, including incomplete access to older or Russian-language literature, ambiguous reporting of basal cores, variable spatial precision of core locations, reliance on secondary sources, and the existence of unpublished or inaccessible core data. These factors introduce minor uncertainties and may lead to under- or overrepresentation of some cores

700 or proxies. Despite these constraints, the WSPC database constitutes a valuable and robust resource for regional and pan-WSL palaeoenvironmental research. It highlights key spatial, temporal, and methodological gaps and provides clear guidance for future research priorities, particularly in under-sampled northern regions, underrepresented proxy types, and logistical strategies needed to overcome the persistent challenges of fieldwork in Western Siberia.

Author contribution

705 AH designed the research, conducted the literature review, compiled the database, and wrote the original draft of the manuscript. MS contributed to the research design, supervised the project, revised the manuscript, and contributed to the writing.

Competing interests

The contact author has declared that none of the authors has any competing interests.

710 **Acknowledgements**

This study was funded by the National Science Centre in Poland (no. 2019/35/O/ST10/02903).

References

Alexandrov, G. A., Brovkin, V. A., and Kleinen, T.: The influence of climate on peatland extent in Western Siberia since the
715 Last Glacial Maximum, Sci. Rep., 6, 24784, https://doi.org/10.1038/srep24784, 2016.

Baryshnikov, M. K.: Carex-Hypnum Bogs of the West Vasuganye, Moscow, 37 pp., 1929.

Beck, H. E., Zimmermann, N. E., McVicar, T. R., Vergopolan, N., Berg, A., and Wood, E. F.: Present and future Köppen-
Geiger climate classification maps at 1-km resolution, Sci. Data, 5, 180214, https://doi.org/10.1038/sdata.2018.214, 2018.

Biester, H., Knorr, K.-H., Schellekens, J., Basler, A., and Hermanns, Y.-M.: Comparison of different methods to determine
720 the degree of peat decomposition in peat bogs, Biogeosciences, 11, 2691–2707, https://doi.org/10.5194/bg-11-2691-2014,
2014.

Birks, H. H. and Birks, H. J. B.: Future Uses of Pollen Analysis Must Include Plant Macrofossils, J. Biogeogr., 27, 31–35,
2000.

Blyakharchuk, T. A., Kurina, I. V., and Pologova, N. N.: Late Holocene dynamics of vegetation cover and climate humidity
725 in the southeastern sector of the West Siberian Plain based on palynological and rhizopod studies of peat deposits, Bull.
Tomsk State Univ. Biol., 164–189, 2019.

Botch, M. S. and Masing, V. V.: Mire ecosystems in the USSR, in: Mires: Swamp, Bog, Fen and Moor, Elsevier Science,
New York, 95–152, 1983.

Botch, M. S., Kobak, K. I., Vinson, T. S., and Kolchugina, T. P.: Carbon pools and accumulation in peatlands of the former
730 Soviet Union, Glob. Biogeochem. Cycles, 9, 37–46, https://doi.org/10.1029/94GB03156, 1995.

Bronzov, A. Y.: Raised bogs of the Narymski Krai (Vasugan basin), Proc. Peat Inst., 3, 1–100, 1930.

Brown, J., Ferrians, O., Heginbottom, J. A., and Melnikov, E.: Circum-Arctic Map of Permafrost and Ground-Ice Conditions
(2), https://doi.org/10.7265/SKBG-KF16, 2002.

Chambers, F. M. and Charman, D. J.: Holocene environmental change: contributions from the peatland archive, The
735 Holocene, 14, 1–6, https://doi.org/10.1191/0959683604hl684ed, 2004.

Charman, D.: Biostratigraphic and palaeoenvironmental applications of testate amoebae, Quat. Sci. Rev., 20, 1753–1764,
https://doi.org/10.1016/S0277-3791(01)00036-1, 2001.

Charman, D. J., Amesbury, M. J., Hinchliffe, W., Hughes, P. D. M., Mallon, G., Blake, W. H., Daley, T. J., Gallego-Sala, A.
V., and Mauquoy, D.: Drivers of Holocene peatland carbon accumulation across a climate gradient in northeastern North
740 America, Quat. Sci. Rev., 121, 110–119, https://doi.org/10.1016/j.quascirev.2015.05.012, 2015.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A. F., and Krebs, P.: Reconstructing past fire regimes: methods,
applications, and relevance to fire management and conservation, Quat. Sci. Rev., 28, 555–576,
https://doi.org/10.1016/j.quascirev.2008.11.005, 2009.

Dranitsyn, D. A.: Secondary podzols and the shift in the podzol zone in the northern part of the Ob'-Irtysh watershed, Proc.
745 Dokuchaev Soil Comm., 2, 33–93, 1914.

Duchkov, A. D.: Characteristics of permafrost in Siberia, in: Advances in the Geological Storage of Carbon Dioxide,
Dordrecht, 81–91, https://doi.org/10.1007/1-4020-4471-2_08, 2006.

Efremov, S. P. and Efremova, T. T.: Present stocks of peat and organic carbon in bog ecosystems of west Siberia, in: Carbon
Storage and Atmospheric Exchange by West Siberian Peatlands, Utrecht Univ., Utrecht, Netherlands, 73–78, 2001.

750 Feurdean, A., Gałka, M., Florescu, G., Diaconu, A.-C., Tanţău, I., Kirpotin, S., and Hutchinson, S. M.: 2000 years of variability in hydroclimate and carbon accumulation in western Siberia and the relationship with large-scale atmospheric circulation: A multi-proxy peat record, Quat. Sci. Rev., 226, 105948, https://doi.org/10.1016/j.quascirev.2019.105948, 2019.

Feurdean, A., Diaconu, A. C., Pfeiffer, M., Gałka, M., Hutchinson, S. M., Butiseaca, G., Gorina, N., Tonkov, S., Niamir, A., Tantau, I., Zhang, H., and Kirpotin, S.: Holocene wildfire regimes in western Siberia: interaction between peatland moisture
755 conditions and the composition of plant functional types, Clim Past, 18, 1255–1274, https://doi.org/10.5194/cp-18-1255-2022, 2022.

Glavtorffond RSFSR: Peat Deposits in Western Siberia, Glavtorffond RSFSR, Moscow, 1956.

Glebov, F. Z., Toleyko, L. S., Starikov, E. V., and Zhidovlenko, V. A.: Palynology and 14C dating of a peat bog from the Aleksandrovsk district of Tomskregion (middle taiga sub-belt), in: Types of the USSR Bogs and Principles of their
760 Classification, Nauka, Leningrad, 194–199, 1974.

Gordiagin, A. Y.: Data to know about soils and vegetation of West Siberia, Proc. Nat. Soc. Kazan Univ., 34, 222, 1901.

Gorodkov, B. N.: Permafrost in the Northern Area, Leningrad, 109 pp., 1932.

Govorukhin, V. S.: Vegetation of the summer pasture area of reindeer, Zemlevedenie, 35, 68–92, 1933.

Greifswald Mire Centre: Global Peatland Map 2.0. Underlying dataset of the UNEP Global Peatland Assessment - The State
765 of the World's Peatlands: Evidence for action toward the conservation, restoration, and sustainable management of peatlands, Global Peatlands Initiative, 2022.

Halaś, A. and Słowiński, M.: Western Siberian Peat Core Database (WSPC), https://doi.org/10.5281/zenodo.17866098, 2025.

Halaś, A., Lamentowicz, M., Obremska, M., Łucόw, D., and Słowiński, M.: Peatland development reconstruction and complex biological responses to permafrost thawing in Western Siberia, Biogeosciences, 22, 4797–4822,
770 https://doi.org/10.5194/bg-22-4797-2025, 2025.

Haslett, J. and Parnell, A. C.: A simple monotone process with application to radiocarbon-dated depth chronologies, J. R. Stat. Soc. Ser. C Appl. Stat., 57, 399–418, 2008.

Hugelius, G., Loisel, J., Chadburn, S., Jackson, R. B., Jones, M., MacDonald, G., Marushchak, M., Olefeldt, D., Packalen, M., Siewert, M. B., Treat, C., Turetsky, M., Voigt, C., and Yu, Z.: Large stocks of peatland carbon and nitrogen are
775 vulnerable to permafrost thaw, Proc. Natl. Acad. Sci., 117, 20438–20446, https://doi.org/10.1073/pnas.1916387117, 2020.

Ivanov, K. E. and Novikov, S. M.: Bogs of West Siberia, their structure and hydrology, Gidrometeoizdat, Leningrad, 447 pp., 1976.

Kirpotin, S. N., Berezin, A., Bazanov, V., Polishchuk, Y., Vorobiov, S., Mironycheva-Tokoreva, N., Kosykh, N., Volkova, I., Dupre, B., Pokrovsky, O., Kouraev, A., Zakharova, E., Shirokova, L., Mognard, N., Biancamaria, S., Viers, J., and
780 Kolmakova, M.: Western Siberia wetlands as indicator and regulator of climate change on the global scale, Int. J. Environ. Stud., 66, 409–421, https://doi.org/10.1080/00207230902753056, 2009.

Kremenetski, K. V., Velichko, A. A., Borisova, O. K., MacDonald, G. M., Smith, L. C., Frey, K. E., and Orlova, L. A.: Peatlands of the Western Siberian lowlands: current knowledge on zonation, carbon content and Late Quaternary history, Quat. Sci. Rev., 22, 703–723, https://doi.org/10.1016/S0277-3791(02)00196-8, 2003.

785 Kurakova, A. A.: Landscape-Hydrological Zoning of the Flat Areas of Western Siberia and Its Application in the Analysis of River Bank Erosion, Geogr. Nat. Resour., 45, 397–409, https://doi.org/10.1134/S1875372824700720, 2024.

Lamentowicz, M., Słowiński, M., Marcisz, K., Zielińska, M., Kaliszan, K., Lapshina, E., Gilbert, D., Buttler, A., Fiałkiewicz-Kozieł, B., Jassey, V. E. J., Laggoun-Defarge, F., and Kołaczek, P.: Hydrological dynamics and fire history of the last 1300 years in western Siberia reconstructed from a high-resolution, ombrotrophic peat archive, Quat. Res., 84, 312–
790 325, https://doi.org/10.1016/j.yqres.2015.09.002, 2015.

Lapshina, E. D. and Zarov, E. A.: Stratigraphy of peat deposits and mire development in the southernpart of the forest zone of Western Siberia in Holocene., Environ. Dyn. Glob. Clim. Change, 14, 70–101, https://doi.org/10.18822/edgcc568688, 2023.

Leonova, G. A., Maltsev, A. E., Preis, Yu. I., Miroshnichenko, L. V., Shavekin, A. S., and Rubanov, M. V.: Biogeochemical
795 Features of Holocene Sediments in Oligotrophic Bogs of the Baraba Forest Steppe, Geochem. Int., 60, 183–202, https://doi.org/10.1134/S0016702922020069, 2022.

Levkovskaya, G. M., Kind, N. V., Zavelsky, F. C., and Forova, V. S.: Absolute age of peat bogs of the Igarka City region and the division of the West Siberia Holocene, Bull. Comm. Quat. Stud., 37, 94–101, 1970.

Liss, O. L. and Berezina, N.: Bogs of the West Siberian Lowland, Moscow University publishing, Moscow, 206 pp., 1981.

800 Liss, O. L. and Kulikova, G. G.: About the regional classification of bogs in Tomsk region, Vestn. Mosk. Univ., 4, 87–91, 1967.

Loisel, J., Yu, Z., Beilman, D. W., Camill, P., Alm, J., Amesbury, M. J., Anderson, D., Andersson, S., Bochicchio, C., Barber, K., Belyea, L. R., Bunbury, J., Chambers, F. M., Charman, D. J., De Vleeschouwer, F., Fiałkiewicz-Kozieł, B., Finkelstein, S. A., Gałka, M., Garneau, M., Hammarlund, D., Hinchcliffe, W., Holmquist, J., Hughes, P., Jones, M. C., Klein, E. S.,
805 Kokfelt, U., Korhola, A., Kuhry, P., Lamarre, A., Lamentowicz, M., Large, D., Lavoie, M., MacDonald, G., Magnan, G., Mäkilä, M., Mallon, G., Mathijssen, P., Mauquoy, D., McCarroll, J., Moore, T. R., Nichols, J., O'Reilly, B., Oksanen, P., Packalen, M., Peteet, D., Richard, P. J., Robinson, S., Ronkainen, T., Rundgren, M., Sannel, A. B. K., Tarnocai, C., Thom, T., Tuittila, E.-S., Turetsky, M., Väliranta, M., van der Linden, M., van Geel, B., van Bellen, S., Vitt, D., Zhao, Y., and Zhou, W.: A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation, The
810 Holocene, 24, 1028–1042, https://doi.org/10.1177/0959683614538073, 2014.

Longman, J., Veres, D., and Wennrich, V.: Utilisation of XRF core scanning on peat and other highly organic sediments, Quat. Int., 514, 85–96, https://doi.org/10.1016/j.quaint.2018.10.015, 2019.

L'vov, Yu. A.: Methodical materials for the typology and classification of the Tomsk Province mires, in: Types of the USSR Bogs and Principles of their Classification, Nauka, Leningrad, 188–194, 1974.

815 MacDonald, G. M., Beilman, D. W., Kremenetski, K. V., Sheng, Y., Smith, L. C., and Velichko, A. A.: Rapid Early Development of Circumarctic Peatlands and Atmospheric CH4 and CO2 Variations, Science, 314, 285–288, https://doi.org/10.1126/science.1131722, 2006.

Mander, L. and Punyasena, S. W.: Fossil Pollen and Spores in Paleoecology, in: Methods in Paleoecology: Reconstructing Cenozoic Terrestrial Environments and Ecological Communities, edited by: Croft, D. A., Su, D. F., and Simpson, S. W.,
820 Springer International Publishing, Cham, 215–234, https://doi.org/10.1007/978-3-319-94265-0_11, 2018.

Map of West Siberian wetlands: Karta bolot Zapadnoi Sibiri, Moscow: Main Administration of Geodesy and Cartography, 1970.

Map of West Siberian wetlands: Karta bolot Zapadnoi Sibiri, Omsk, 1996.

McClymont, E. L., Pendall, E., and Nichols, J.: Stable isotopes and organic geochemistry in peat: Tools to investigate past
825 hydrology, temperature and biogeochemistry, PAGES News, 18, 15–18, https://doi.org/10.22498/pages.18.1.15, 2010.

Mitchell, E. A. D.: A brief history of testate amoebae research and introducing the International Society for Testate Amoeba Research (ISTAR), Acta Protozool., 2024, 1–14, 2025.

Neustadt, M. I.: On absolute age of peat bogs of Western Siberia., Rev. Roum. Biol. Ser. Bot., 12, 181–186, 1967.

Neustadt, M. I.: The world natural phenomenon—Bogs of the West Siberian Lowland, Izv Akad Nauk SSSR, 21–34, 1971.

830 Neustadt, M.I.: Holocene peatland development, in: Late Quaternary Environments of the Soviet Union, University of Minnesota Press, Minneapolis, 201–206, 1984.

Novenko, E., Rudenko, O., Mazei, N., Kupriyanov, D., Andreev, R., Shatunov, A., Kusilman, M., Prokushkin, A., and Olchev, A.: Effects of Climate Change and Fire on the Middle and Late Holocene Forest History in Yenisei Siberia, Forests, 14, 2321, https://doi.org/10.3390/f14122321, 2023.

835 Novenko, E. Y., Mazei, N. G., Kupriyanov, D., Shatunov, A. E., Andreev, R. A., Makarova, E. A., Borodina, K. A., Rudenko, O., Prokushkin, A. S., and Volkova, E. M.: Vegetation changes in Yenisei Siberia over the last 4700 years: new palaeoecological data from Igarka area; Krasnoyarsk Region, Geomorfologiya, 53, 5–6, https://doi.org/10.31857/S0435428122030129, 2022.

Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'amico, J. A.,
840 Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., and Kassem, K. R.: Terrestrial Ecoregions of the World: A New Map of Life on Earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity, BioScience, 51, 933–938, https://doi.org/10.1641/0006-3568(2001)051%255B0933:TEOTWA%255D2.0.CO;2, 2001.

Olsson, I. U.: Radiocarbon Dating History: Early Days, Questions, and Problems Met, Radiocarbon, 51, 1–43,
845 https://doi.org/10.1017/S0033822200033695, 2009.

Parry, L. E., West, L. J., Holden, J., and Chapman, P. J.: Evaluating approaches for estimating peat depth, J. Geophys. Res. Biogeosciences, 119, 567–576, https://doi.org/10.1002/2013JG002411, 2014.

Polishchuk, Y. M., Bogdanov, A. N., Polishchuk, V. Yu., Manasypov, R. M., Shirokova, L. S., Kirpotin, S. N., and Pokrovsky, O. S.: Size Distribution, Surface Coverage, Water, Carbon, and Metal Storage of Thermokarst Lakes in the
850 Permafrost Zone of the Western Siberia Lowland, Water, 9, 228, https://doi.org/10.3390/w9030228, 2017.

Pupysheva, M. A. and Blyakharchuk, T. A.: Fires and their Significance in the Earth's Post-Glacial Period: a Review of Methods, Achievements, Groundwork, Contemp. Probl. Ecol., 16, 303–315, https://doi.org/10.1134/S1995425523030095, 2023.

QGIS Development Team: QGIS Geographic Information System, 2025.

855 R Core Team: R: A language and environment for statistical computing, 2022.

Reimer, P. J., Austin, W. E. N., Bard, E., Bayliss, A., Blackwell, P. G., Ramsey, C. B., Butzin, M., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kromer, B., Manning, S. W., Muscheler, R., Palmer, J. G., Pearson, C., Plicht, J. van der, Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Turney, C. S. M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S. M., Fogtmann-Schulz, A., Friedrich, R.,
860 Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., and Talamo, S.: The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP), Radiocarbon, 62, 725–757, https://doi.org/10.1017/RDC.2020.41, 2020.

Rudmin, M., Ruban, A., Savichev, O., Mazurov, A., Dauletova, A., and Savinova, O.: Authigenic and Detrital Minerals in Peat Environment of Vasyugan Swamp, Western Siberia, Minerals, 8, 500, https://doi.org/10.3390/min8110500, 2018.

865 Rydin, H., Gunnarsson, U., and Sundberg, S.: The Role of Sphagnum in Peatland Development and Persistence, in: Boreal Peatland Ecosystems, edited by: Wieder, R. K. and Vitt, D. H., Springer, Berlin, Heidelberg, 47–65, https://doi.org/10.1007/978-3-540-31913-9_4, 2006.

Rydin, H., Jeglum, J. K., and Bennett, K. D.: The Biology of Peatlands, OUP Oxford, 397 pp., 2013.

Scharlemann, J. P., Tanner, E. V., Hiederer, R., and Kapos, V.: Global soil carbon: understanding and managing the largest
870 terrestrial carbon pool, Carbon Manag., 5, 81–91, https://doi.org/10.4155/cmt.13.77, 2014.

Schuur, E. A. G., Pallandt, M., and Göckede, M.: Russian collaboration loss risks permafrost carbon emissions network, Nat. Clim. Change, 14, 410–411, https://doi.org/10.1038/s41558-024-02001-6, 2024.

Sheng, Y.: West Siberian Lowland Peatland GIS Data Collection, https://doi.org/10.5065/D65T3HM5, 2016.

Sheng, Y., Smith, L. C., MacDonald, G. M., Kremenetski, K. V., Frey, K. E., Velichko, A. A., Lee, M., Beilman, D. W., and
875   Dubinin, P.: A high-resolution GIS-based inventory of the west Siberian peat carbon pool, Glob. Biogeochem. Cycles, 18,
https://doi.org/10.1029/2003GB002190, 2004.

Shotyk, W.: Review of the inorganic geochemistry of peats and peatland waters, Earth-Sci. Rev., 25, 95–176,
https://doi.org/10.1016/0012-8252(88)90067-0, 1988.

Shumilovskikh, L., O'Keefe, J. M. K., and Marret, F.: An overview of the taxonomic groups of non-pollen palynomorphs,
880   Geol. Soc. Lond. Spec. Publ., 511, 13–61, https://doi.org/10.1144/SP511-2020-65, 2021.

Smith, L. C., MacDonald, G., Frey, K. E., Velichko, A. A., Kremenetski, K., Borisova, O. K., Dubinin, P., and Forster, R. R.:
U.S.-Russia venture probes Siberian peatlands' sensitivity to climate, Eos Trans. Am. Geophys. Union, 2000.

Smith, L. C., MacDonald, G. M., Velichko, A. A., Beilman, D. W., Borisova, O. K., Frey, K. E., Kremenetski, K. V., and
Sheng, Y.: Siberian Peatlands a Net Carbon Sink and Global Methane Source Since the Early Holocene, Science, 303, 353–
885   356, https://doi.org/10.1126/science.1090553, 2004.

Smith, L. C., Beilman, David. W., Kremenetski, K. V., Sheng, Y., MacDonald, G. M., Lammers, R. B., Shiklomanov, A. I.,
and Lapshina, E. D.: Influence of permafrost on water storage in West Siberian peatlands revealed from a new database of
soil properties, Permafr. Periglac. Process., 23, 69–79, https://doi.org/10.1002/ppp.735, 2012.

Solomeshch, A. I.: The West Siberian Lowland, in: The World's Largest Wetlands: Ecology and Conservation, edited by:
890   Fraser, L. H. and Keddy, P. A., Cambridge University Press, Cambridge, 11–62,
https://doi.org/10.1017/CBO9780511542091.003, 2005.

Startsev, V., Gorbach, N., Mazur, A., Prokushkin, A., Karpenko, L., and Dymov, A.: Macrocharcoal Signals in Histosols
Reveal Wildfire History of Vast Western Siberian Forest-Peatland Complexes, Plants, 11, 3478,
https://doi.org/10.3390/plants11243478, 2022.

895   Swindles, G. T., Mullan, D. J., Brannigan, N. T., Fewster, R. E., Sim, T. G., Gallego-Sala, A., Blaauw, M., Lamentowicz, M.,
Jassey, V. E. J., Marcisz, K., Green, S. M., Roland, T. P., Loisel, J., Amesbury, M. J., Blundell, A., Chambers, F. M.,
Charman, D. J., Evans, C. R. C., Feurdean, A., Galloway, J. M., Gałka, M., Karofeld, E., Keaveney, E. M., Korhola, A.,
Lamentowicz, Ł., Langdon, P., Mauquoy, D., McKeown, M. M., Mitchell, E. A. D., Plunkett, G., Roe, H. M., Turner, T. E.,
Sillasoo, Ü., Väliranta, M., van der Linden, M., and Warner, B.: Climate and water-table levels regulate peat accumulation
900   rates across Europe, PLOS One, 20, e0327422, https://doi.org/10.1371/journal.pone.0327422, 2025.

Syso, A. I. and Peregon, A. M.: The features of peat-accumulation process at the southern slope of the Great Vasyugan Bog,
Contemp. Probl. Ecol., 2, 124–127, https://doi.org/10.1134/S1995425509020064, 2009.

Tiuremnov, S. N.: Peat Deposits I, Nedra, Moscow, 487 pp., 1976.

Tolonen, K.: Interpretation of changes in the ash content of ombrotrophic peat layers, Bull. - Geol. Soc. Finl., 56, 207–219,
905   https://doi.org/10.17741/bgsf/56.1-2.013, 1984.

Trofimova, I. E. and Balybina, A. S.: Classification of climates and climatic regionalization of the West-Siberian plain,
Geogr. Nat. Resour., 35, 114–122, https://doi.org/10.1134/S1875372814020024, 2014.

UNEP: The State of the World's Peatlands: Evidence for action toward the conservation, restoration, and sustainable
management of peatlands, Global Peatlands Initiative. United Nations Environment Programme, Nairobi, 2022.

910   Vaganov, E. A., Vedrova, E. F., Verkhovets, S. V., Efremov, S. P., Efremova, T. T., Kruglov, V. B., Onuchin, A. A., Sukhinin,
A. I., and Shibistova, O. B.: Forests and swamps of Siberia in the global carbon cycle, Sib. Ecol. J., 4, 631–649, 2005.

Velichko, A. A., Timireva, S. N., Kremenetski, K. V., MacDonald, G. M., and Smith, L. C.: West Siberian Plain as a late
glacial desert, Quat. Int., 237, 45–53, https://doi.org/10.1016/j.quaint.2011.01.013, 2011.

Volkov, V. S., Gurtovaya, Ye. Ye., Firsov, L. V., Panychev, V. A., and Orlova, L. A.: Structure, age and history of
915   development of the Holocene peat-bog near Gorno-Slinkino village on the Irtysh River, in: Pleistotsen Sibiri i smezhnykh
oblastei, Nauka, Moscow, 34–39, 1973.

Wickham, H.: ggplot2: Elegant Graphics for Data Analysis, Springer-Verlag New York, 2016.

Wickham, H., François, R., Henry, L., Müller, K., Vaughan, D., Software, P., and PBC: dplyr: A Grammar of Data
Manipulation, 2023.

920   Xu, J., Morris, P. J., Liu, J., and Holden, J.: PEATMAP: Refining estimates of global peatland distribution based on a meta-
analysis, CATENA, 160, 134–140, https://doi.org/10.1016/j.catena.2017.09.010, 2018.

Xu, S., Chen, M., Feng, T., Zhan, L., Zhou, L., and Yu, G.: Use ggbreak to Effectively Utilize Plotting Space to Deal With
Large Datasets and Outliers, Front. Genet., 12, https://doi.org/10.3389/fgene.2021.774846, 2021.

Zhang, H., Väliranta, M., Swindles, G. T., Aquino-López, M. A., Mullan, D., Tan, N., Amesbury, M., Babeshko, K. V., Bao,
925   K., Bobrov, A., Chernyshov, V., Davies, M. A., Diaconu, A.-C., Feurdean, A., Finkelstein, S. A., Garneau, M., Guo, Z.,
Jones, M. C., Kay, M., Klein, E. S., Lamentowicz, M., Magnan, G., Marcisz, K., Mazei, N., Mazei, Y., Payne, R., Pelletier,
N., Piilo, S. R., Pratte, S., Roland, T., Saldaev, D., Shotyk, W., Sim, T. G., Sloan, T. J., Słowiński, M., Talbot, J., Taylor, L.,
Tsyganov, A. N., Wetterich, S., Xing, W., and Zhao, Y.: Recent climate change has driven divergent hydrological shifts in
high-latitude peatlands, Nat. Commun., 13, 4959, https://doi.org/10.1038/s41467-022-32711-4, 2022.

930   Zhilinsky, I. I.: Description of hydrotechnical works in the area of the Siberian railroad to insure water supply for settlements
in the Ishim steppe and to drain bogs in the Baraba forest-steppe (1895–1904), Saint-Petersburg, 829 pp., 1907.