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Review Article

Multi-proxy palaeoecological studies from peatlands: a comprehensive review of recent advances and future developments

Mariusz Lamentowicz [a,*], Luke Andrews [b], Sambor Czerwiński [c], Katarzyna Marcisz [a]

[a] Climate Change Ecology Research Unit, Adam Mickiewicz University, Poznań, Poland
[b] School of Biological and Environmental Sciences, Liverpool John Moores University, Liverpool, UK
[c] Department of Geomorphology and Quaternary Geology, University of Gdańsk, Gdańsk, Poland

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ABSTRACT

Multi-proxy approaches in palaeoecological studies have gained prominence due to their ability to provide comprehensive insights into palaeoenvironmental changes. This method enhances the complexity and richness of environmental reconstructions by integrating various proxies, such as testate amoebae, pollen, plant macrofossils, charcoal, and stable isotopes. While synthesising these records can be challenging, due both to their complexity and varying journal guidelines for publication, it remains essential for a more precise understanding of past ecosystems. Multi-proxy studies are invaluable for cross-referencing local to extra-local data with proxies from nearby areas, thus validating palaeoclimatic records and minimising speculative conclusions. The approach reveals significant human impacts on ecosystems, particularly peatlands, serving as natural archives for historical environmental and anthropogenic activities. Integrating diverse methodologies from ecology, palaeoecology, archaeology, and history with high-resolution palaeoecological data offers profound insights into settlement patterns, economic development, and historical demography. Despite the challenges of handling extensive datasets, advanced statistical methods enable meaningful interpretations while maintaining the integrity of the data. Historical records enrich the understanding of human and climatic impacts upon a range of peatland ecosystems. By reconstructing long-term changes in food webs through peat records, researchers can gain a deeper understanding of past ecosystem structures and functions, thereby paving the way for future ecological advances. Though underutilised in archaeological and historical contexts, this interdisciplinary approach has significant potential across various academic fields, emphasising the importance of integrating comprehensive datasets to approach complex ecological questions and inform ecological restoration. This review presents the potential of high-resolution, multi-proxy studies of peatlands, shows examples of such studies and summarises best practices and key considerations for conducting such research.

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* Corresponding author.
E-mail address: mariuszl@amu.edu.pl (M. Lamentowicz).

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1. Introduction

Terrestrial ecosystems are diverse and complex (Bardgett and van der Putten, 2014; Wardle, 2002). Understanding their changing dynamics in space and time is a challenge for scientists seeking to better understand how past global and local changes have influenced ecosystem functioning over long periods (Bellard et al., 2012; Kissling et al., 2012; Legendre and Legendre, 1998; Oliver et al., 2015). This complexity increases across the ecosystem-to-biome scales. Therefore, research of environmental processes at the global scale can be exceptionally challenging (Ellis, 2015; Gonzalez et al., 2020; Migliavacca et al., 2021). This challenge is intensified by combining various datasets and methodologies from several sub-disciplines. For example, ecosystem modelling at microbial and landscape scales is complex, computationally demanding and requires a sophisticated methodology (Basquill and Leroux, 2023; Halpern et al., 2023; Sutherland et al., 2013; Sytiuk et al., 2022). Global changes may be identified by synthesising and extrapolating local studies; however, much of the ecological detail may be lost in the process (Zhang et al., 2022). Despite many of these global-focused syntheses being widely recognised, the details contained within these original studies are still highly relevant, adding important context and detail in identifying patterns over long (decadal to millennial) temporal scales - a focus of palaeoecology (Birks and Birks, 1980).

Most contemporary ecological studies are relatively short, typically measuring process changes for < 5 years in line with research grant resources (Hernandez-Almeida et al., 2017; Jassey et al., 2018; Mieczan and Tarkowska-Kukuryk, 2017). This limits our observations to changes that occur within these timescales. Observational studies exceeding decades may better understand ecological processes over extended periods (Birks, 2019; Brussel and Brewer, 2021; Seddon et al., 2014; Willis et al., 2010) but long-term (>10 years) experimental peatland studies are rare (Andrews et al., 2021; Kolka et al., 2024; Lamentowicz et al., 2016) and maintaining these sites requires a significant, continuous investment of time and money. Project managers often must develop new justifications for continuing experiments and observations every few years to secure funding. Even with long-term experiments operating at the sub-decadal scale, it is essential to understand past site-specific land-use changes occurring over centennial to millennial timescales, enabling the examination of the origins and histories of these ecosystems, which may affect their status at the present. Despite the shared objective of exploring complex ecological networks across space and time, studies comparing ecosystem functioning between modern data and palaeoecological reconstructions are scarce (Andrews et al., 2021).

There are considerable differences between ecological and palaeoecological approaches in understanding modern and past communities (Birks and Birks, 1980). Contemporary studies can examine all possible environmental variables and living organisms in the soil, but palaeoecological approaches rely on the remains of taxa preserved after death (named biotic proxies) (Warner, 1990a, 1990b). Taphonomic issues, such as differential effects of peat accumulation and decomposition, can result in the degradation of many ecologically sensitive organisms in the fossil record (Berglund, 1986). Hence, a contrast between modern and fossil taxa communities makes comparing these assemblages challenging (Birks and Birks, 1980). Despite this, palaeoecological approaches provide scientists with the unique capacity to quantitatively reconstruct past long-term ecosystem changes on centennial to millennial timescales, far exceeding the duration of even the longest ecological studies (Nogue et al., 2017; Rull, 2014; Rull, 2010; Woodward et al., 2014).

Among the different archives available to palaeoecologists, peatlands are exceptional ecosystems. Peatlands store organic matter as they accumulate vertically over time, as the accumulation rate of plant material exceeds that of decay in their waterlogged soils (Chambers and Charman, 2004; Succow and Joosten, 2001). As they grow, they preserve a record of their botanical, geochemical and physical conditions at the time of deposition, tracing a record of past changes that can be used to describe past environments (Charman, 2002; Rydin and Jeglum, 2013). Furthermore, peat offers optimal conditions for preserving biotic material, including testate amoebae, plant macroremains, pollen, non-pollen palynomorphs, and other environmentally sensitive organisms and their remains (Barber, 1993; Tobolski, 2000). Cultural remnants, such as archaeological artefacts, are also preserved (Gearey and Fyfe, 2016). Some of these remains (referred to as 'proxies') are deposited in situ and serve as indicators of local conditions (autochthonous) (Chambers et al., 2012). In contrast, other proxies are transported from the surrounding area, providing a record of change over a broader scale (allochthonous) (Williams et al., 2011). Abiotic proxies related to geochemistry or physical analysis of the peat can be used to calculate input rates of atmospheric dust or pollution, or carbon accumulation rates through time (Fiałkiewicz-Kozieł et al., 2020; Li et al., 2023a). Together, these biotic and abiotic proxies can be used in unison to construct a detailed record of local and extra-local changes for a site through time (Warner, 1990a, 1990b). In recent years, the number of proxies used in peatland palaeoecological studies has increased, providing a more comprehensive understanding of past ecosystem changes and enabling the reconstruction of complex ecological structures (Hilfinger and Paulsson, 2011). Earlier, much of the palaeoecological research conducted on peatlands was based upon a single proxy;; those studies focused on one group of organisms to reconstruct environmental changes over time (Godwin, 1945). However, contemporary studies show that using a single proxy is insufficient for reconstructing past ecosystems and understanding the drivers of these changes, as peatland development is a complex process (Connor et al., 2018). The value of the multi-proxy approaches was also mentioned in the context of various scientific questions considering lakes (Birks and Birks, 2006; Birks, 2019) or related to the broader scale of climate change (Lotter, 2003; Mann, 2002). To date, a review describing the potential of the multi-proxy approach in palaeoecological studies of peatlands is still lacking.

Peat is composed of $>$ 40% organic material, primarily formed

within waterlogged environments (peatlands - bogs or fens) (Kulczyński, 1949; Sjörs, 1948; Succow and Joosten, 2001). Peat grows under wet, anaerobic conditions that slow decomposition and allow organic matter to build up over time (Clymo et al., 1998; Rydin and Jeglum, 2013; Succow and Jeschke, 1990). While peatlands have a worldwide distribution, most are concentrated in the Northern Hemisphere (Stiftung, 2023). Despite being widespread, peatlands represent only around 3 % of global land cover (Xu et al., 2018), however they store a disproportionately large reservoir of soil carbon, estimated at around 500 billion tonnes (Gorham, 1991; Yu et al., 2011; Yu, 2012). Unfortunately, peatlands are threatened by human disturbances, including drainage, burning, and anthropogenic climate change (Harenda et al., 2018; Tanneberger et al., 2021; Turetsky et al., 2015). Over time, this has resulted in the degradation or loss of peatlands (Rawlins and Morris, 2010), and a weakening or reversal of their carbon sink function (Joosten, 2024).

The future response of peatlands to the combined pressures of climatic, environmental and anthropogenic change remains highly uncertain (Loisel et al., 2021). Palaeoecological studies, which offer insights into long-term ecosystem dynamics and past environmental change (Seddon et al., 2014), are a valuable method to better understand how peatlands will respond to the future earlier-mentioned environmental change in the long term (Gallego-Sala et al., 2018). Unlike experimental studies, which provide detailed but relatively short-term (typically 2-5 years) perspectives on peatland responses to simulated changes such as climate warming (Buttler et al., 2023; Lamentowicz et al., 2016; Mulot et al., 2015), archives from peat cores can reconstruct environmental, botanical and sedimentary changes over a few years to several millennia (Charman, 2002).

The application of high-resolution, multi-proxy approaches enhances palaeoecological research. These involve analysing biotic data (e.g., pollen, plant macrofossils) and abiotic (e.g., soil physical properties,

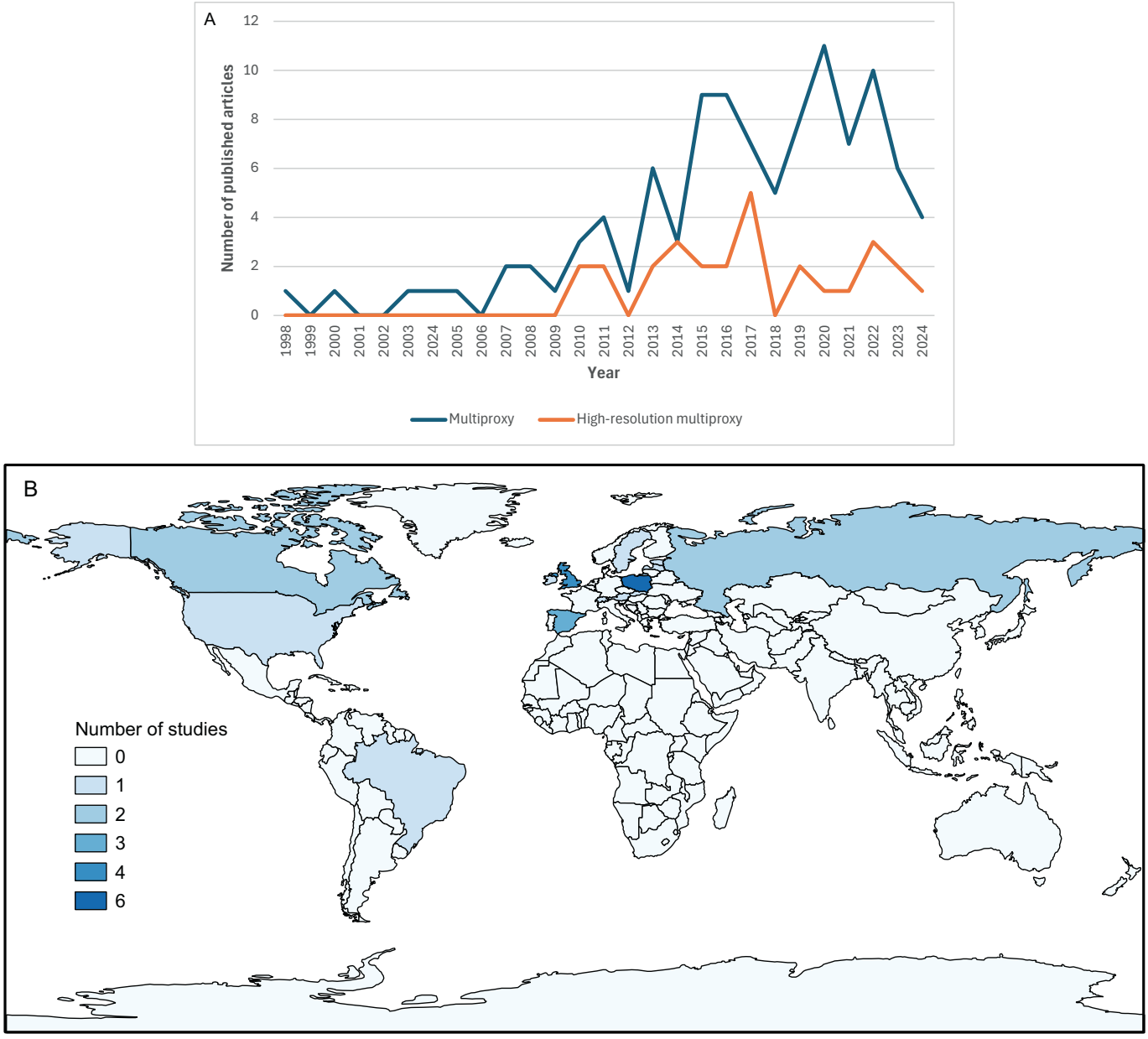


Fig. 1. A) Number of papers published available vs publication year on SCOPUS; containing the following in the title, abstract, or keywords: BLUE: 'peat' OR 'peatland' AND 'multi-proxy' OR 'multi-proxy' AND 'palaeoecology' OR 'paleoecology' ORANGE: 'peat' OR 'peatland' AND 'multi-proxy' OR 'multi-proxy' AND 'palaeoecology' OR 'paleoecology' AND 'high-resolution' OR 'high AND resolution'; B) Geographical heatmaps showing the number of multi-proxy, high-resolution peatland studies identified in the SCOPUS search for each country.

geochemistry) at fine temporal scales (Birks and Birks, 2006; Birks, 2019). This review focuses on high-resolution, multi-proxy studies of peatlands, summarising best practices and key considerations when conducting such research. In the context of this review, 'high-resolution' refers to sampling at appropriately dense intervals, enabling precise environmental reconstructions, although the term may also refer to the temporal resolution achieved (Birks, 2019). 'Multi-proxy' studies incorporate a combination of different palaeoecological proxies, either biotic (e.g., pollen and spores, testate amoebae), abiotic (e.g., isotopes, geochemistry), or a combination of both, to create more accurate and detailed reconstructions of past environmental conditions than is possible using just one proxy (Birks, 1995).

This review addresses the following topics:

1) The potential of high-resolution multi-proxy peatland palaeoecology for reconstructing past environmental changes.
2) The power of high-resolution analyses for syntheses that bridge the gap between palaeoecology, history and archaeology.
3) Present and future advances in multi-proxy peatland studies with implications for nature conservation and ecological restoration.

2. Multi-proxy studies in the literature

We conducted two literature searches in the Scopus database to assess the prevalence of palaeoecological records that incorporate both a high-resolution and multi-proxy approach. The first search targeted the terms 'peat' OR 'peatland' AND 'multi-proxy' OR 'multi-proxy' AND 'palaeoecology' OR 'paleoecology', while the second included 'peat' OR 'peatland' AND 'multi-proxy' OR 'multi-proxy' AND 'palaeoecology' OR 'paleoecology' AND 'high-resolution' OR 'high AND resolution'. These terms were searched across titles, abstracts, and keywords of peer-reviewed journal articles and the results from both searches were compared.

The first search identified 103 studies dated from 1998 to 2024. The second search, which specifically included the term "high-resolution," identified only 28 studies published between 2010 and 2024 (Figure 1), one of which was excluded because it was not a palaeoecological study. These findings suggest that only a few (27 % here) of peatland multi-proxy palaeoecological studies explicitly identify themselves as being "high-resolution". However, we recognise that many more published studies likely fall into both categories but were not identified by our search due to limitations of the terms used. Nevertheless, our sample provides a representative overview of recent research trends in peatland multi-proxy palaeoecology over the past 24 years, as shown in Figure 1A. However, we acknowledge that a significant number of studies may have been overlooked from this search, particularly from tropical, subtropical and global south, where no studies were identified in our search, despite the existence of many (e.g.: Fitchett, 2015; Fitchett et al., 2017; Hapsari et al., 2017; 2018; Björck et al., 2012; Githumbi et al., 2018).

The studies identified through our search span various geographical locations and periods, shedding light on changes in vegetation dynamics, climate variability, and human activities over time. Several studies focus on human impacts throughout the Holocene, particularly changes occurring due to agriculture, peat harvesting and deforestation, with notable examples from Ireland (Roland et al., 2015), Estonia (Łuców et al., 2022), and Poland (Lamentowicz et al., 2019b). Other studies (Feurdean et al., 2021; Schellekens et al., 2014) investigate the history of wildfires and their links to climate change and human activity. In contrast, studies by Lestienne et al. (2023) and Gałka et al. (2021a) focus on vegetation changes and forest development in Slovakia and Latvia in response to long-term climate dynamics.

The density of studies varies across regions, with most studies focused on European sites, particularly in Poland and the UK, as well as countries such as Switzerland, Austria, Estonia, Romania, Latvia, and Slovakia. Canada has the highest representation outside of Europe, followed by a few studies from Siberia, Brazil, and Andorra (Figure 1B). Despite these, tropical and Southern Hemisphere peatlands are noticeably underrepresented, partially due to their relatively low extent compared with Northern Hemisphere peatlands (van Bellen and Larivière, 2020).

The studies vary significantly in their sampling resolution, with intervals ranging from 1 cm to 5 cm. However, in some cases, greater distances between samples were seen for individual proxies - e.g., biotic proxies may be sampled at 1 cm intervals. At the same time, geochemical analyses may require more material, requiring thicker peat slices (5 cm

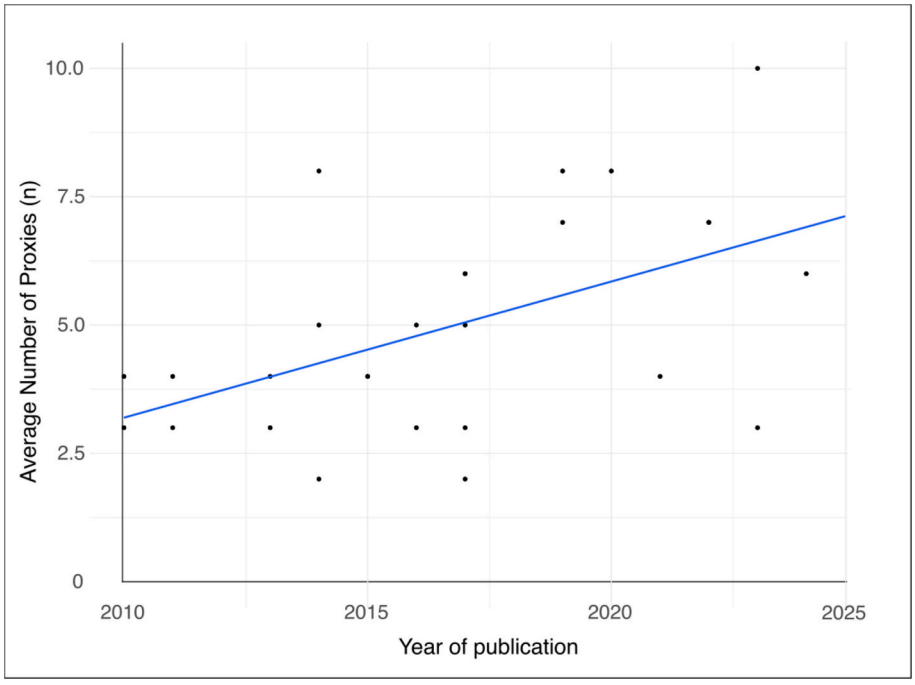


Fig. 2. Number of proxies analysed in each study from SCOPUS search vs. publication year.

or more). The highest resolution sampling was typically used by studies focusing on specific, relatively short-term climate events such as the 5.2 ka event (Roland et al., 2015). Some studies (although none detected by our Scopus search) use intervals of less than 0.5 cm (Amesbury et al., 2011; Lamentowicz et al., 2010) although this sampling strategy is very rare.

Selecting appropriate proxies for palaeoecological reconstructions is a crucial step. These proxies, biological (e.g., pollen, testate amoebae) or abiotic (e.g., stable isotopes, geochemistry) - are chosen based on the specific research question. Given the resource-intensive nature of palaeoecological studies, careful consideration is necessary to ensure that the data collected is appropriate and meaningful. On average, the studies in our dataset used five different proxies in combination, varying from two to ten. There is a slight trend towards increasing proxy numbers in more recent publications, suggesting that the value of multi-proxy palaeoecology is becoming more recognised or simply reflecting changing research trends (Figure 2).

The most commonly used proxy was pollen, which was applied in all but three of the studies. Plant macrofossils were the second most frequently used proxy (n=20), often used alongside pollen to provide local insights that complement regional pollen signals (Birks and Birks, 2000). The third most common proxy was testate amoebae analysis (n=16). Other frequently applied proxies include bulk peat properties such as C/N ratios, loss on ignition (LOI), and bulk density. However, these were typically combined to reconstruct apparent carbon accumulation rates rather than environmental changes. Geochemical analyses (e.g., X-ray Fluorescence - XRF) and colorimetric peat humification assessments were less common. At the same time, some studies incorporated proxies that are rarely used in peatland palaeoecology, such as diatoms and molluscs (Gałka et al., 2021a; Łuców et al., 2022). Stable isotopes—especially ^{13}C and ^{15}N—are also regularly applied, with other isotopic proxies (e.g., ^{18}O, Neodymium) used in select studies, depending again upon the research question (Marcisz et al., 2023a).

3. Significance of high-resolution sampling and chronology

An essential condition for the multi-proxy inferences is an appropriate sampling strategy resulting from the objective of performing high-resolution analyses or the nature of sediments that necessitate a high-resolution testing strategy (Blaauw and Mauquoy, 2012; De Vleeschouwer et al., 2010; Shotyk and Noernberg, 2020). Thus, high-resolution studies in palaeoecology aim to reduce the uncertainty linked to missing data by focusing on specific time intervals. These studies achieve high precision by analysing samples at the finest possible resolution and applying radiocarbon or other dating methods to the sediment profile (Goslar et al., 2009; Kamenik et al., 2009; Marcisz et al., 2015). This approach enables accurate reconstructions of past environmental changes and facilitates precise correlations between palaeoecological, archaeological, and historical findings. However, in the past most of the high-resolution records were focused upon climatic changes, e.g. studies resulting from the Millennium Project (Gagen et al., 2006).

Nevertheless, several studies in Switzerland and the UK have applied high-resolution approaches, often achieving annual resolution in their subsampling level (Amesbury et al., 2011). In the case of a core from the Swiss Alps (Lamentowicz et al., 2010), layers of frozen peat were cut from a core using a precision device (named – Damocles) designed by Greifswald University (Joosten and De Klerk, 2007). However, despite considerable effort, those exciting studies did not meet the methodological limit required to directly comparebetween peatland proxies and instrumental meteorological records (Lamentowicz et al., 2010; Amesbury et al., 2011).

High sampling resolution might result in different temporal resolution throughout a core, depending on downcore variation in peat accumulation rates- floating mats might grow 1 cm/year, in contrast to thick Holocene peat profiles where 1 mm/year is considered rapid accumulation. Hence, in several contributions (Aaby, 1986; Berglund, 1986; Birks and Birks, 1980), the authors advise to adapt sampling strategies to specific scientific questions. However, in most studies, continuous 1-cm sampling is considered sufficient for comparisons with historical events and dendrochronology (Bąk et al., 2024; Cedro and Lamentowicz, 2011; Cedro and Lamentowicz, 2008; Edvardsson et al., 2012). This resolution also provides sufficient resolution to spot relatively short events related to human impact, e.g., drainage, acidification, deforestation or afforestation (Karpińska-Kołaczek et al., 2022). However, high sampling resolution does not always imply high temporal resolution, depending on the varying peat accumulation rates, which vary both between different sites, within a site, and within individual cores. It should also be stressed that the peat subsampling should aim to be consistent with sampling depths and peat slice thicknesses, as differences in sampling resolution between proxies makes proxy comparison, statistical analyses and age-depth modelling more demanding (Lamentowicz et al., 2009; Marcisz et al., 2021).

The quality of the age-depth model also depends upon the peat accumulation rate. The number of radiocarbon dates per core/study varies significantly between studies, often (but not always) reflecting the core depth or the number of cores analysed. For example, Lamentowicz et al. (2020a) used 44 radiocarbon samples throughout a 4-meter peat sequence, while Roland et al. (2015) used 35 dates across three x 4 m cores. In contrast, van der Knaap et al. (2011) dated a 1 m peat core with 29 samples, providing a comprehensive age resolution for dating and age-depth modelling. In the Jaczno peatland Marcisz et al. (2020b) 20 dates were applied for 4 metres of core, spanning 1500 years, while Bąk et al. (2024) dated a 1 m core with 10 dates spanning 300 years. Given that an accurate and detailed chronology is fundamental to palaeoecology, it is unlikely that any studies would limit the number of ^{14}C dates used for reasons other than funding allocation, with the desired age-depth model resolution depending primarily on the scientific question being investigated and the depth of time required. Consequently, peatlands with rapid peat accumulation usually provide the best time scale quality, averaging ~1 metre for 1000 years, which may be regarded as the reliable standard for identifying human impact or climate-related signals connected to palaeohydrological stability. For rapidly growing peatlands, the dating strategy may be different as fewer radiocarbon dates might be required to achieve the exact age resolution as would be required for compacted and decomposed peat; however, this largely depends on the specific research question being addressed.

Some studies examining changes occurring during the last two centuries have also used ^{210}Pb dating, occasionally supported by ^{137}Cs to assess more recent layers (Aquino-López et al., 2020; Cwanek et al., 2025). Other dating methods used include tephrochronology, which involves the identification of ash layers from volcanic eruptions (Blaauw et al., 2007; Davies, 2015; Swindles et al., 2011) and the use of spheroidal carbonaceous particles (SCPs) (Charman and Garnett, 2005; Swindles et al., 2015b), which are produced by the incomplete combustion of fossil fuels and can be used to identify anthropogenic activity (Parry et al., 2013; Yang et al., 2001). Using multiple dating methods-including tephrochronology- in unison has multiple advantages, providing an opportunity for a more precise age-depth modelling through the cross calibration and integration of various independent dating methods (Cwanek et al., 2025; Watson et al., 2017).

Establishing the absolute chronology of peat is the first and most crucial step in palaeoecological research (Blaauw and Christen, 2005; Hajdas, 2008). Chronologies based on less than three dates per millennium are usually impractical for precise historical data comparisons (Blaauw et al., 2018). A much higher quality time scale is created when there is one radiocarbon date per 100 years. The more dates, the better, provided the profile is complete and does not contain hiatuses (breaks in sediment accumulation)). In the case of peat profiles and also non-laminated lake sediments, the most common dating method is the ^{14}C carbon method, especially the AMS technique, which allows the dating of tiny fragments of organic origin with high precision. Hence, we can date moss stems, seeds or pieces of the epidermis of plants. In addition,

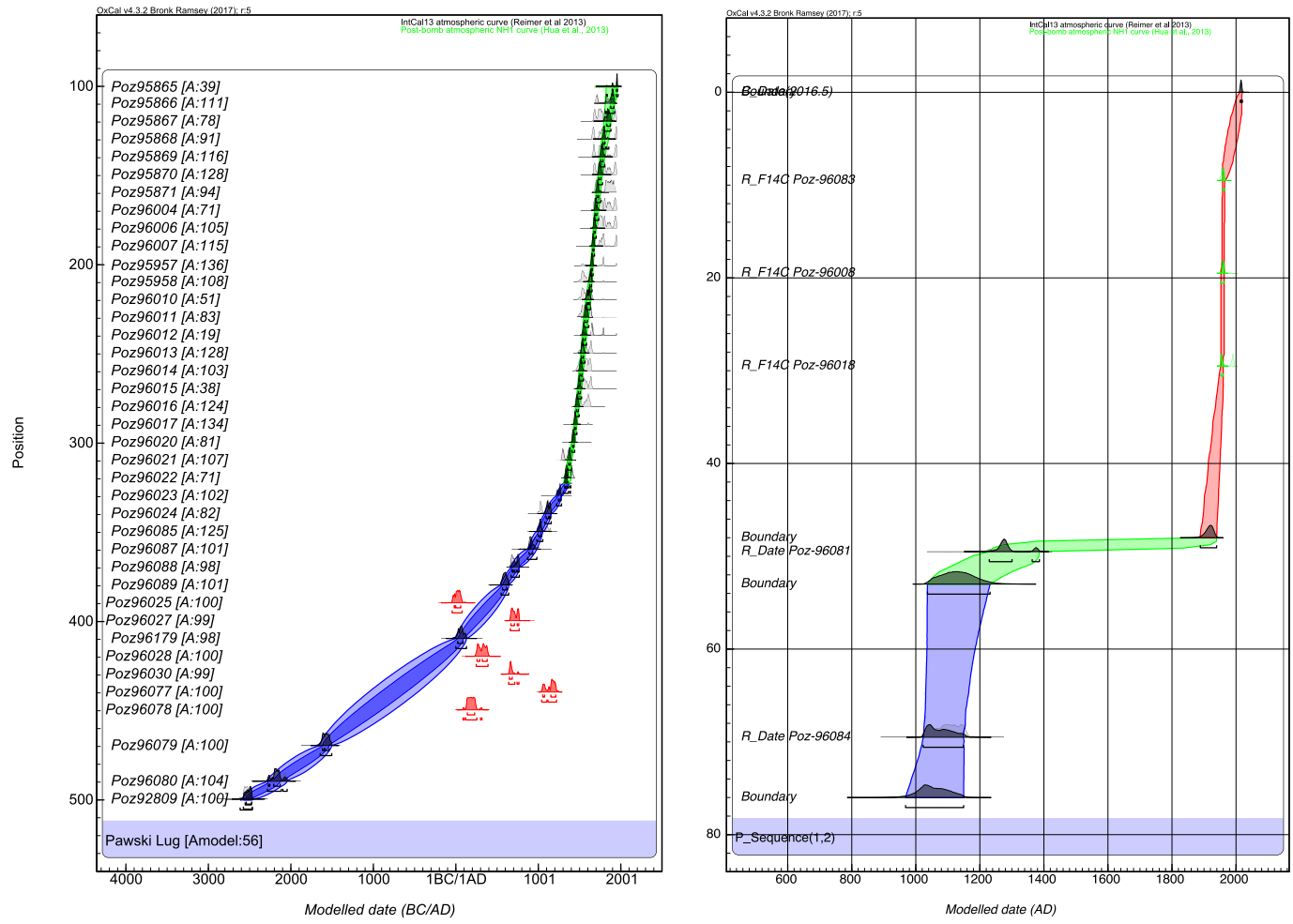


Fig. 3. Age–depth models from Pawski Ług peatland (W Poland). A) Radiocarbon outliers (in red) reflect sediment mixing in an early-stage wetland, likely formed under shallow water with a floating mat. This illustrates a case of "good and bad dates" within one profile: the lower, scattered cloud of ages is too inconsistent to support a robust timescale, whereas the upper, coherent part provides a high-quality chronology suitable for archaeological and historical comparison and it was used in for the multi-proxy study covering the last 1500 years (Lamentowicz et al., 2020). B) Unpublished short core from another part of Pawski Ług peatland, with dense radiocarbon dating, highlights a different perspective, revealing a hiatus and abrupt events likely linked to anthropogenic disturbance. Increased radiocarbon dating resolution in ombrotrophic peat profiles allows the detection of short-lived disturbances that remain invisible in low-resolution chronologies. By applying dense ^{14}C dating, (Kołaczek et al., 2019) revealed hiatuses, sediment mixing, and anthropogenic impacts that interrupt otherwise continuous peat accumulation. This highlights the importance of high-resolution chronologies for accurately reconstructing past environmental change.

the dates from each profile are typically subjected to statistical processing to produce continuous chronologies for cores with only a few dated layers. In most cases in the last decades, Bayesian age-depth modelling has been the preferred method (Blaauw et al., 2018). This technique enables the statistically accurate estimation of a likely calendar age range for sections between two dates, thereby constructing a time scale for the episode of interest. Age-depth models can be made using various software - the most popular are OxCal (Bronk Ramsey, 2001), or rbacon (Blaauw and Christen, 2011) which operates in the statistical environment R (Team R Core, 2024). Determining the age and chronological uncertainty of each sample 'slice' in the examined profile significantly increases the chronological control of a study. The studies have shown that Bayesian modelling using as many dates as possible are essential to obtaining high-quality radiocarbon chronologies (Yeloff et al., 2006). This also applies to the ^{210}Pb lead isotope dating that may improve age modelling based on radiocarbon dates, especially for the last 120 years (maximum range of this method). However, ^{14}C post-bomb dates can provide more precise results and better agreement (Davies et al., 2018; Goslar et al., 2005; Goodsite et al., 2001; Turetsky et al., 2004). The quality of the age-depth model usually depends on continuous non-disturbed peat accumulation. A recent development has been the integration of ^{210}Pb modelling along with ^{14}C and other dating methods within the same modelling framework, removing the need for the remodelling of ^{210}Pb dates (Aquino-López et al., 2018; Cwanek et al., 2025).

An example of a semi-reliable model is the profile from Pawski Ług (Lamentowicz et al., 2020b), where peat accumulated under unstable conditions first and then, after final terrestrialisation, the situation changed (Figure 3A). The stable stage is characterised by a high-quality Bayesian age-depth model that was finally used for the multi-proxy study (Fig. 2 in Lamentowicz et al. (2020b). This core is a prominent example of the problematic section (possessing a high number of outliers). The upper part is reliable and stratigraphically consistent, and it provides an age-depth model robust enough to explore the historical events related to land use. Another short core (Figure 3B) extracted from the peatland margin showed a considerable disturbance and a hiatus, revealing weaknesses of the chronology and potential problems with the interpretations.

The use of other dating methods (e.g. SCPs and tephrochronology) can provide supplemental age horizons based upon comparison with events of a known date, such as volcanic eruptions or changes in industrial emissions and are occasionally used to validate ^{210}Pb

chronologies and further refine age-depth models in peatland palaeoecological studies (Claire et al., 2019; Parry et al., 2013). A relevant example comes from studies conducted in Polish peatlands, where age-depth models built based on ^{14}C and/or ^{210}Pb dating for a multi-proxy high-resolution reconstructions by Marcisz et al. (2015) were been improved by Watson et al. (2017) following the discovery of tephra horizons. However, currently, no age-depth modelling framework can account for the imprecise taphonomy of these methods, owing to the movement of tephra or SCPs in a peat profile following deposition. A study by Kołaczek et al. (2019) demonstrates that increasing the resolution of radiocarbon dating in ombrotrophic peat profiles can fundamentally improve our understanding of peatland chronologies. Traditionally, age–depth models based on widely spaced ^{14}C dates provided robust long-term trends but often smoothed over short-lived phases of instability. By applying a dense series of radiocarbon measurements, the authors showed that previously undetected disturbance periods—such as sediment mixing, hiatuses, or abrupt anthropogenic impacts—can be identified within peat stratigraphy.

4. The value of proxies

Various proxies possess different potentials, but when applied separately, they provide only a small portion of the story about the past changes on the local or regional scale. Here, we describe the most often applied proxies from the peat profiles to show their indicative values and connected challenges in various studies.

4.1. Pollen and spores

Pollen analysis is one of the most widely used techniques in palaeoecology. It allows the reconstruction of vegetation changes using the proportions of individual pollen taxa and plant spores in the analysed layers of the sediment and peat profile (Berglund and Ralska-Jasiewiczowa, 1986; Seppä, 2013). The results obtained from this analysis in palaeoecological studies are crucial for identifying and estimating past human economic activity (such as agricultural development and deforestation) in the vicinity of the study site and on a more regional scale (Behre and Kucan, 1986; Gaillard, 2013). The most critical indicators for detecting past human impacts and related environmental changes are the pollen of cultivated plants and species associated with human economic activities, such as those from ruderal habitats, pastures, or weeds (Gaillard, 2013). Identifying woodland clearings caused by increased human activity is also essential; this is typically indicated by a decrease in arboreal pollen coinciding with a rise in species indicative of ruderal or pastoral farming (Berglund et al., 1991; Gaillard, 2013; Wacnik et al., 2016).

The taxonomic identification of pollen depends on several factors, as summarised by Deza-Araujo et al. (2022). It is crucial to identify individual pollen grains as accurately as possible, mainly those associated with human activities, as this influences the interpretation of the data. Low taxonomic resolution can lead to overestimating human impact on environmental changes, inaccurately suggesting a more significant anthropogenic role than occurred (Deza-Araujo et al., 2022). Other problems may be caused by plants' diverse pollen production (Birks et al., 2016). Like any palaeoecological analysis, pollen analysis also has other deficiencies that arise from the properties of the natural archive and should be considered when interpreting the results. In the case of peatlands, some of these relate to pollen transport in its layers, as well as potential hiatuses, which can be overlooked in situations where the dating resolution is low (Clymo and MacKay, 1987).

The movement of pollen can be both upward and downward, and the extent of movement can be substantial over time, potentially blurring the original deposition boundaries of pollen grains (Clymo and MacKay, 1987). However, peat samples for pollen analysis typically contain pollen grains of mixed ages, making the value of any analysis dependent on the temporal resolution required and the period represented (Davidson et al., 1999). Hiatuses result from removing or destroying a section of peat from the record, often due to disturbance (e.g., fire, peat harvesting) and can be problematic if the period of interest is lost. They are frequently difficult to identify from peat stratigraphy in the field unless there is a clear boundary in the core, but their recognition is usually possible after radiocarbon dating. Pollen (and other organic matter) finds ideal conditions for preservation in an acidic and moist environment and is therefore well-suited for preservation in peat. However, pollen is susceptible to dessication which may affect preservation, and in many situations leads to a deterioration of its physical properties which can consequently prevent identification of grains (Twiddle and Bunting, 2010).

Despite its limitations, pollen analysis remains a fundamental method for understanding long-term vegetation changes concerning climate change (and for reconstructing past climates solely on pollen) (Birks and Berglund, 2018). This method has recently been used to reveal short-term environmental changes resulting from human activities, often measured over decades. While this method is relatively cheap, sample preparation can be time-consuming and involves harsh chemicals (Faegri et al., 2000). Furthermore, all stages of the method, from identification through analysis to data interpretation, require a great deal of training and expertise. Following the high-resolution sampling method, each core is cut into fragments, typically between 1 and as little as 0.2 cm thick. A sample for palynological analysis is taken from each of these slices. Continuous sampling at this resolution is essential for understanding short-term vegetation changes (sometimes at a sub-decadal resolution) associated with past societal reactions to particular historical turmoil caused by, e.g. wars or disease epidemics (Czerwiński et al., 2021; Yeloff et al., 2007). On the other hand, it enables the identification of short-term economic shifts, which can substantiate archaeological/historical findings, particularly where data are limited (Dreibrodt and Wiethold, 2015). For instance, palynology can detect rapid economic declines or validate/refute the utilisation of natural resources (e.g., selective logging of trees) in a specific region (Czerwiński et al., 2021). Notably, high or continuous sampling for the pollen analysis reduces the likelihood of a suck-in and smear error (Baillie, 1991). This involves, among other things, assuming a connection between concurrent changes (Baillie, 1991; Blaauw et al., 2007; Hughes and Dumayne-Peaty, 2002; Lisa et al., 1995). As the distance between samples increases, the chances of overlooking short-term natural phenomena preserved in thin sediment and peat layers also rise. Combined with chronologies derived from low-resolution dating, this can result in the incorrect attribution of vegetation changes (e.g. deforestation, agriculture development) to historical events. For example, by integrating high-resolution pollen data with archaeological and historical evidence, human activity was precisely dated, enabling a detailed assessment of its environmental impact in Greater Poland during the Medieval Period (Czerwiński et al., 2021; Izdebski et al., 2025, 2024).

4.2. Non-pollen palynomorphs

A significant role in identifying human presence is the analysis of non-pollen palynomorphs (NPPs) usually performed in parallel with pollen analysis. For now, more than 1800 NPP types represent different environments and, thus, comprise a heterogeneous group of microfossils, including algae, cyanobacteria, protists, fungi, plants, and invertebrates (Marret et al., 2021; Miola, 2012; Shumilovskikh et al., 2021; van Geel, 1978). Unlike pollen, typically sourced from the broader landscape, NPPs usually represent taxa that lived and died *in situ*. This means they can provide indicators of environmental conditions near the coring site, complementing pollen analyses. Different NPP types can reflect various environmental factors and may be a significant proxy for different ecological or archaeological aspects and interactions in the past. They can inform about local terrestrialisation, erosion processes, hydrological conditions, presence of hosts (in the case of parasites),

animal diets, grazing activities and fire activity (Basumatary and McDonald, 2017; Brinkkemper and van Haaster, 2012; Karpinska-Kolaczek et al., 2013; Kołaczek et al., 2020a; Latałowa et al., 2013; Marret et al., 2021; Shumilovskikh et al., 2021; van Geel et al., 2011; van Geel and Aptroot, 2006).

However, their most common use is to provide direct/indirect evidence of human environmental impacts. For example, coprophilous fungi (found on faeces) provide rare insights into the changing characteristics of pastoral practices or the presence of herbivores over time for a given location. Increased exploitation of catchments of lakes and peatlands, as well as peatlands for pastoral purposes, may be reflected by increased counts of coprophilous fungi. In addition to livestock, parasites such as roundworm (*Ascaris* sp.) or whipworm (*Trichuris* sp.) can indicate the presence of human settlement in the catchment (van Geel et al., 1983). NPPs can also help identify hydrological changes (draining peatlands for crop/grazing sites) or more intensive human management affecting the environment. Eutrophication of lakes or woodland clearing by fire can be visible in the record of cyanobacteria and pyrophilous fungi, respectively (Latałowa et al., 2019; van Geel et al., 1994). Generally, with increasing research using NPPs, their potential and indicative value will grow in research regarding human activity and other fields of palaeoecological studies.

Identification of NPPs is based on images published in the available literature and database (Miola, 2012; Shumilovskikh et al., 2021); however, some groups still need better descriptions, and the ecological preferences of many NPPs need better understanding to ease the interpretation. The most significant drawbacks of NPP analysis are preservation issues and the lack of known indicative values for many NPPs. The first relates to the delicate structures of some NPPs (e.g. thin walls) that do not preserve well, limiting available information (van Geel and Aptroot, 2006). The second is primarily due to problems with the taxonomic affinity, although some unidentified NPPs work well as ecological indicators. Unfortunately, the earlier disregard for NPPs and sometimes lack of systematic recording, together with their selective identification (e.g. interest in coprophilous fungi only), does not help to solve the latter problem. However, despite this, NPPs are a multifaceted, valuable tool for palaeoenvironmental reconstruction, even though their identification and interpretation of results require additional time and expertise.

4.3. Plant macrofossils

Plant macrofossils (henceforth 'plant macros') are widely used in archaeobotanical research and palaeoecology (Birks, 2007; Grosse-Brauckmann, 1986). In the former, they can be used to answer questions about past vegetation, development of agriculture and plant components in the human diet over time, and much more (Birks, 2017; Kennett et al., 2010). In studies of peat cores, they can be used to identify changes in the botanical composition of the peat, 'bog surface wetness' and even trophic status (Blundell et al., 2008; Czerwiński et al., 2021; Galka et al., 2017; Gałka et al., 2022b; Gałka and Apolinarska, 2014; Mauquoy and van Geel, 2007; Ronkainen et al., 2014; Sillasoo et al., 2011; Väliranta et al., 2007, 2015). Because peat is composed almost entirely of botanical remains, plant macrofossil analysis is analogous to recording the stratigraphy of geological profiles, with plant succession events often reflecting key stages in peatland development (Hájková et al., 2012; Loisel and Bunsen, 2020). Such phases are usually associated with changes in the character of the vegetation growing on the peat surface at the time of deposition (e.g., peat initiation, ombrophication, eutrophication) (Barber, 1993). In addition, the analysis of plant macroremains can provide information on the presence of individual plant species near the coring site (Chambers et al., 2012). Still, we also receive information about environmental transformations reflected in the change in the botanical composition of individual samples. Plant macroremains can also be a quantitative proxy of various variables (Barber and Charman, 2003; Birks, 2017). They have been used to build training sets, allowing the relationship between contemporary plant communities and an environmental gradient to be applied to fossil remains, resulting in a quantitative reconstruction of the environmental variable in question (Šímová et al., 2025; Väliranta et al., 2012). However, despite their sensitivity to hydrologic changes, they are not as commonly used as other proxies for quantitative palaeoecological reconstructions from peatlands. Plant macrofossil analysis is, similarly to others proxies, often complex and time-consuming. Plant identification is usually conducted using a microscope, with identifications typically made based upon comparisons between fossil material and modern reference collections. In addition, taxonomic keys and detailed guides for identifying plants are necessary, although many are out of print or difficult to aquire (Berger, 1970; Berggren, 1968; Dickson, 1986; Grosse-Brauckmann, 1986; Katz et al., 1977; Katz et al., 1965; Lévesque et al., 1988; Mauquoy and Hughes, 2010; Mauquoy and van Geel, 2007). While this method allows for a higher taxonomic resolution than many other proxies, including pollen, identifying remains to a genus or species level can be difficult, owing to the differential preservation of diagnostic tissues and remains. For example, graminoids can be particularly difficult to identify, especially if only roots are preserved. Mosses may be more straightforward in identification provided diagnostic features are preserved. Unfortunately, the number of scientists using plant macrofossils has decreased in recent years despite the high demand for high-resolution research from peatlands and the need for more studies that exploit the quantitative potential of plant macrofossils.

4.4. Testate amoebae

Another method used in high-resolution palaeoecological studies is the analysis of subfossil testate amoebae. Testate amoebae are a polyphyletic group of unicellular protists that produce a shell (Beyens and Meisterfeld, 2001; Meisterfeld, 2001a, 2001b). They occur in most terrestrial environments but are particularly common in various types of soil and wetlands, including mosses and lakes (Bonnet, 1974; Tolonen, 1986; Tolonen et al., 1992). Significant advances have been made over the last twenty years in studying the genetic variation of this group, including the identification of many new taxa (Duckert et al., 2018; Lara et al., 2015; Reczuga et al., 2015; Singer et al., 2015; Taylor et al., 2025) and significant reshuffling of these taxa on the tree of life has taken place in recent years (Adl et al., 2019; Adl et al., 2012; Kosakyan et al., 2025; Kosakyan et al., 2016). Testate amoebae possess species-specific, decay-resistant shells that can be preserved in sediments and, later on, extracted and identified (Charman et al., 2000; Mitchell et al., 2007; Warner and Charman, 1994). As individual species often possess well-defined hydrological and trophic preferences, transfer functions can be applied as a proxy of past hydrological (depth-to-water table) and trophy (pH) changes in peatlands. Palaeoecological transfer function is a quantitative model that relates modern biological assemblages (species composition, usually microfossils like pollen, diatoms, chironomids, or testate amoebae) to measured environmental variables, and which can then be applied to fossil assemblages to infer past values of those environmental variables (Birks, 1998; Birks, 1995). Hence, thanks to modern calibration data sets developed for many regions of the world, e.g. Poland, Europe, the USA and Asia (Amesbury et al., 2018; Amesbury et al., 2016; Halaś et al., 2023; Lamentowicz et al., 2010; Qin et al., 2021; Qin et al., 2013), it is possible to reconstruct past hydrological changes in peatlands quantitatively. This is of great importance for interpreting the impact of climate change on human activity in the past. For. For example, it allows us to determine the so-called "dry" or "humid" climate phases, which can be related to contemporary environmental, climatic, anthropogenic and/or economic impacts in the studied areas. Hydrological reconstructions based on testate amoebae are robust because microorganisms react much faster to the environmental changes than plants (Beyens and Meisterfeld, 2001; Foissner, 1997; Warner, 1990a, 1990b). Therefore, it is possible to gain fairly accurate quantitative measures of past water table depths using testate

amoebae.

Most testate amoeba-inferred hydrological reconstructions have focused on studying climate impacts or local hydrological changes. These studies gained interesting results by comparing testate amoeba-derived data with other proxies studied from peatlands. Most investigations regarded (1) climatic controls over the development of peatlands (Blundell and Barber, 2005; Charman et al., 1999; Swindles et al., 2007), (2) reconstruction of past hydrological changes to define peatlands' reaction to local and/or extra-local disturbance (Caseldine and Gearey, 2005; Lamentowicz and Obremska, 2010; Marcisz et al., 2019; Payne, 2010), (3) recognition of the responses of peatland ecosystems to anthropogenic pressure (Fiałkiewicz-Kozieł et al., 2023; Fiałkiewicz-Kozieł et al., 2015), (4) identification of the relationships between testate amoeba communities and other components of peatland ecosystems, e.g., vegetation change (Gałka et al., 2022b) or carbon storage capacities (Karpińska-Kołaczek et al., 2024), (5) reconstruction of rates of acidification processes (Bąk et al., 2024; Karpińska-Kołaczek et al., 2022), or (6) catastrophic events (Payne, 2011). However, testate amoebae have also been used in archaeological and historical research providing data on the past relationships between peatland hydrology and trophy in relation land-use changes, for example, (1) first land-use change signal by local populations (Kajukało et al., 2016; Lamentowicz et al., 2019b), (2) modifications introduced by local policymakers (Bąk et al., 2024; Lamentowicz et al., 2020b), (3) establishment of drainage (Marcisz et al., 2015; Wochal et al., 2025), and (4) other severe peatland degradation (Kołaczek et al., 2018).

Over the last decade, the functional approach has been used to testate amoebae and obtain more information on species' responses to environmental changes. The first papers published in 2015 opened a new avenue for multi-proxy environmental reconstructions using testate amoebae (Fournier et al., 2015; Lamentowicz et al., 2015). Since then, functional traits have been used for testate amoebae in many peatland studies, and their usefulness has been recognised and well established (Brown et al., 2023; Marcisz et al., 2021; Marcisz et al., 2020a; Zhang et al., 2020). Functional traits provide all sorts of additional information about environmental changes, including (1) information on shading and openness of the site, presence of mixotrophic species; (Lamentowicz et al., 2020a; Marcisz et al., 2020b; Marcisz et al., 2019); (2) identification of drying and water table disturbance (Lamentowicz et al., 2015; Marcisz et al., 2016), (3) increased mineral inputs into the peatland (Marcisz et al., 2021) or (4) changes in food web structure (Lamentowicz et al., 2015). Moreover, the trait approach has been used to prepare a functional traits-based transfer function, where functional information has been used to obtain depth-to-water table reconstructions (van Bellen et al., 2017).

4.5. Charcoal

Fire is another crucial element that highly influences various ecosystems worldwide (He et al., 2019). Regardless of its natural or anthropogenic origin, fire significantly changes the functioning of ecosystems (including peatlands), triggering vegetation change, modifying hydrological regimes, surface runoff and soil chemical properties (Whitlock and Tinner, 2010). Fires in the landscape scale can have various characteristics depending on the ecosystem type, vegetation structure, climate, management strategies and environmental history. Fires are often described by several parameters regarding their behaviour, such as fire severity, intensity, area, and pattern (Keeley, 2009; Keeley and Pausas, 2019) and can be characterised by various fire behaviour and impact, e.g., crown vs ground fires or local vs extra-local fires. In palaeoecology, analysis of charcoal accumulated in peat and other sediments (e.g., lake sediments and soil) helps to reconstruct past fire activity (Conedera et al., 2009; Tinner and Hu, 2003; Whitlock and Larsen, 2001). There are several approaches one can use to reconstruct long-term fire regime changes, however, it is often impossible to gain direct and realistic metrics of specific fire parameters, such as intensity or severity; moreover, it is essential to take into account taphonomic processes and preservation biases that may have an influence on palaeofire interpretations from palaeoecological archives (Vachula et al., 2022).

The most commonly used methods for reconstructing fire activity are simple charcoal sums from sediment samples, presented as charcoal concentrations (particles/cm^3) and charcoal accumulation rates (particles/cm^2/year). Such data are often used for performing statistical reconstructions of fire regime changes, which include fire return interval and calculations of the number of significant fire events with statistical tools such as CharAnalysis (Higuera et al., 2010), statistical models (Adolf et al., 2018) or dedicated R packages (Blarquez et al., 2014; Finsinger and Bonnici, 2022). Additional information can be gained by identification of the type of fuel burnt in the past through the analysis of the morphology of individual charcoal pieces (leaf, graminoids, wood) or their dimensions/area (area or length-width ratio) (Colombaroli et al., 2014; Feurdean et al., 2023; Marcisz et al., 2019; Umbanhowar and Mcgrath, 1998). Size classes of charcoal can be used to identify local vs extra-local fires; however, available charcoal dispersal patterns have been studied using lakes as model environments, not peatlands (Adolf et al., 2018; Vachula and Rehn, 2022; Vachula, 2018).

It is essential to mention that several new methods were developed over the last decades to improve past fire interpretations. These focus on various approaches to reconstruct fire intensity using 1) charcoal reflectance (Hudspith et al., 2015; McParland et al., 2009), 2) Raman spectroscopy developed specifically for peat sediments based upon a peatland vegetation reference data set (Marcisz et al., 2025; Mauquoy et al., 2020; Theurer et al., 2024; Theurer et al., 2022; Theurer et al., 2021), or 3) Fourier Transform Infrared spectroscopy (FT-IR) (Constantine and Mooney, 2022; Costa et al., 2018; Gosling et al., 2019). These new approaches to palaeofire reconstructions will broaden future interpretations of wildfire impact on the environment.

4.6 Geochemistry, dust and carbon accumulation rates

To fully understand how peatland dynamics are impacted under anthropogenic or climatic pressures, it is essential to examine how changes in the physical properties of the peat (e.g., bulk density, carbon accumulation and degree of decomposition) occur alongside changes in biotic proxies and environmental conditions. This allows for a clearer picture of how shifts in reconstructed variables (e.g., water table levels from testate amoebae or botanical succession) may affect measured variables (e.g., carbon content, accumulation, or humification), providing a comprehensive view of peatland responses to environmental changes (Loisel and Garneau, 2010; Payne et al., 2016).

A commonly used method to assess decomposition in a peat core is to determine the degree of humification. Peat humification provides insight into the decomposition processes of peat during its time in the acrotelm (the oxic layer above the water table), where decay is faster, before it is incorporated into the catotelm (the anaerobic layer below the water table), where decomposition rates are nearly negligible (Clymo, 1984). Humification is often evaluated visually or by examining peat colour and texture, for example, some studies adopt scales such as the von Post scale (Grover and Baldock, 2013), which classifies peat from light, undecomposed material to dark, highly decomposed peat; however the majority of studies use semi-quantitative colorimetric methods involving the chemical extraction of humic acids, followed by optical absorption techniques (colorimetry) (Aaby and Tauber, 1975; de Jong et al., 2010). This method has the advantage of being a relatively simple, fast and non-resource intensive method for determining peat humification. However, the influence of changes in the botanical composition of the peat upon alkali-extracted compounds may override any climatic signal that might exist (Overbeck, 1947; Yeloff and Mauquoy, 2006), as may other factors such as wildfire and anthropogenic disturbance (Payne and Blackford, 2005; Zaccone et al., 2014).

Humification is one of the most frequently used proxies for climate-

driven decomposition in peatland studies (de Jong et al., 2010). Peat humification reflects the extent of peat decomposition in the acrotelm, the oxic layer above the water table, before its incorporation into the permanently saturated catotelm, where decay rates are generally much slower (Blackford and Chambers, 1995; Chambers et al., 2012; Chambers et al., 2011; Clymo, 1984). Humic acids concentrate in peat as by-products of organic matter decay and are dark brown. Darkly coloured peat is assumed to indicate high degrees of humification, indicating dry or warm conditions resulting from faster decomposition or more time spent in the acrotelm (de Jong et al., 2010). By chemically extracting humic acids from peat, their concentrations can be determined from the optical absorption of the resulting solution using colorimetric procedures (light spectroscopy) (Aaby, 1976; Blackford and Chambers, 1995).

Other methods are commonly used, including C:N ratios. Peat C:N ratios (calculated from total C and N % throughout a core, measured using elemental analysers) are influenced by biogeochemical cycling processes, where C is preferentially lost following decomposition relative to N, which is largely retained in peat (Leifeld et al., 2020; Malmer and Holm, 1984). In healthy peatland ecosystems, where the water table is higher, decomposition rates are slower, more C is retained resulting in larger C:N ratio values (Kuhry and Vitt, 1996; Leifeld et al., 2020). As with colorimetric peat humification measurements, C:N ratios can be influenced by the botanical composition of the peat (Biester et al., 2014; Hornibrook et al., 2000)

While some studies show strong correlations between humification and climate proxies, others have found weak associations. For instance, Borgmark and Schoning (2006) observed a discrepancy between colorimetric humification records and reconstructed water levels, with decomposition preceding drier conditions, suggesting older peat being re-decomposed. Similarly, Payne and Blackford (2005) found little coherence between humification and water table reconstructions in Alaska. Further research, such as Zaccone et al. (2018), has identified spectroscopic methods, such as hydrogen-carbon (H:C) ratios, that may provide more robust assessments of humification variability downcore, avoiding chemical dissolution artefacts that affect the reliability of the colorimetric approach. Careful comparison with multiple proxies may offer insights into the drivers' underlying changes in humification records over time. However, this may also result in an erroneous interpretation, especially if the results are directly compared with proxies that are not truly independent of humification.

Decomposition proxies are rarely tested experimentally. While some studies have found good correlations between proxies and decomposition indices or instrumental climate records (Blackford and Chambers, 1991; Tfaily et al., 2014), others have not (Blundell and Barber, 2005; Mauquoy et al., 2002). (Borgmark and Schoning, 2006) compared humification and C/N records with reconstructed water levels from two Swedish peat bogs and correlated these records with meteorological data. They found that C/N ratios and humification indices were strongly correlated and exhibited similar trends between sites, but that correlations between these decomposition proxies and reconstructed water table depths were weak. Increased decomposition appeared to precede drier climatic conditions, reflecting renewed decomposition of previously deposited, older peat. Payne and Blackford (2009) compared humification records with testate amoebae-inferred water table depth reconstructions from multiple cores from southeast Alaska, finding little correlation between sites or proxies. Zaccone et al. (2018) tested several physical, chemical, and spectroscopic approaches from nine peatlands across four continents to identify the most effective methods for determining humification. They found that C/N ratios correlated poorly with most other proxies and that the supply of inorganic wind-blown material was mainly responsible for variations in loss on ignition. Spectroscopic indices (including alkali-extracted humic acids) showed good correlations between sites. Zaccone et al. (2018) recommended the ratios of hydrogen and carbon (H/C) as the proxy most representative of peat humification, whilst being cost-effective and removing the need for chemical dissolution that may introduce artefacts. Understanding whether these proxies preserve palaeoenvironmental decay signals relevant to past climate changes is fundamental to their continued use in peatland studies and essential for their use in climate model testing (Swindles et al., 2012).

Dry bulk density refers to the mass of dried peat per unit volume in a peat sample and is typically expressed in grams per cubic centimetre (g/cm^3). In peatland palaeoecological studies, it is typically measured by measuring the wet volume of peat slices taken throughout the peat column, drying and weighing the samples, and dividing the dry-weight by the wet volume to produce a record of changes in bulk density downcore, reflective of changes in compaction and pore-space (Chambers et al., 2011). Changes in bulk density can reflect shifts in vegetation, hydrology, and decomposition and are an essential variable for calculating peat accumulation rates, carbon storage, and decomposition, alongside organic matter content, C and other elemental content determinations, in addition to age-depth model derived changes in peat accumulation rates (Beilman et al., 2009; Heinemeyer et al., 2018). A decrease in bulk density may signal increased plant productivity and/or reduced decomposition due to more waterlogged conditions, resulting in less compacted, 'spongier' peat with more pore-space for water. In comparison, an increase suggests drier conditions causing increased rates of decomposition and increased compaction, with reduced hydrological permeability (Gnatowski et al., 2010; Menberu et al., 2021).

Stable isotope analysis was used to reconstruct abiotic variables, including precipitation and temperature. Stable isotopes of ^{18}O and ^{13}C extracted from the cellulose of *Sphagnum* stems and branches were tested as climatic proxies (Daley et al., 2010; Jonathan et al., 2009; Kaislahti Tillman et al., 2010a; Lamentowicz et al., 2011; van der Knaap et al., 2011); however, because of the different fractionation processes in the various species, the interpretation becomes challenging (Loader et al., 2007). This analysis was also applied to the bulk peat, which might be even more difficult to obtain robust palaeoclimatic data (Lamentowicz et al., 2015).

Integrating inorganic geochemistry in palaeoecological studies has enabled a more profound understanding of past environmental processes. For instance, studies have used elemental records to reconstruct past volcanic activity, ocean storminess, and industrial pollution (Kylander et al., 2005; Le Roux et al., 2005). The use of X-ray fluorescence core scanning (XRF-cs) has revolutionised peatland research, providing rapid, non-destructive multi-elemental profiling with high resolution, making it a powerful tool in modern palaeoecological studies (Longman et al., 2019).

Key components of peat inorganic geochemistry include major elements (e.g., calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na) which are typically derived either from the parent plant material, precipitation, groundwater, aeolian deposition or pollution (Longman et al., 2019; William, 1988). In addition, trace elements such as iron (Fe), phosphorus (P), sulphur (S) and aluminium (Al) may reflect pedogenic processes in the peat, such as oxidation, nutrient availability, and human activity, such as agricultural run-off (Longman et al., 2021). Finally, heavy metals (e.g., mercury (Hg), lead (Pb), cadmium (Cd) and copper (Cu) are often used to track anthropogenic pollution through time (Li et al., 2025, 2023a, 2023b; Mighall et al., 2017). The uses of specific elemental concentrations in peat are reviewed in detail by (Kaislahti Tillman et al., 2010b; Longman et al., 2019).

Geochemical analyses of the peat were used to infer past environmental pollution. Different elements were also used to reconstruct plutonium (Pu) fallout related to nuclear tests (Fiałkiewicz-Kozieł et al., 2025; Fiałkiewicz-Kozieł et al., 2016). Recently, those data were used to determine the onset of the Anthropocene (Fiałkiewicz-Kozieł et al., 2023; Summerhayes et al., 2024; Waters et al., 2023; Williams et al., 2024; Zalasiewicz et al., 2023). An interesting example of proxy is neodymium (Nd), which was used to reconstruct air circulation (Le Roux et al., 2023) and local land use changes (Bąk et al., 2025; Marcisz et al., 2023a, 2023b). Another example of the use of peat geochemistry is work on the history of lead pollution (Shotyk et al., 1998; Shotyk et al., 1996;

Weiss et al., 1999). Geochemistry has also been applied in the case of calcium-rich spring fens, to reconstruct past environmental changes (Almendinger and Leete, 1998; Galka et al., 2017; Mazurek et al., 2014; Dobrowolski et al., 2019; Dobrowolski et al., 2016; Dobrowolski et al., 2012). A further interesting example is the analysis of aeolian dust as a proxy of air circulation (Ireland et al., 2014; Kylander et al., 2016; Le Roux et al., 2023; Pratte et al., 2017; Vanneste et al., 2015; von Scheffer et al., 2023) or local land-use changes resulting from deforestation (De Vleeschouwer et al., 2009b).

4.6. Biomarkers

The use of organic geochemistry, termed 'biomarkers', is a valuable approach for the reconstruction of climatic and environmental changes in peatlands (Kuder and Kruge, 1998). Biomarkers are the molecular remains of materials generated from biological sources or processes and are often abundant and well preserved within peatland stratigraphic profiles (Naafs et al., 2019). This type of analysis enables the characterisation of the organic chemistry of bulk peat samples, whereby concentrations of specific molecules or groups of compounds can be associated with their sources—such as particular plant types, microbial activity, or diagenetic transformations of the peat itself (Pancost et al., 2003).

The range of different biomarkers detected is often interpreted using indices or ratios based on an understanding of the processes by which they accumulate within peatland environments. A multitude of molecular biomarkers have been applied in peatland studies; for a comprehensive review, see Naafs et al. (2019). Branched glycerol dialkyl glycerol tetraethers (brGDGTs) have been applied to reconstruct climatic and hydrological changes (Naafs et al., 2019; Weijers et al., 2006); stereochemical degradation of hopanes (Inglis et al., 2025; Inglis et al., 2019; Inglis et al., 2018) and the presence of anaerobic and aerobic microbial lipids have been used as proxies for peat humification, linked to changing water table depth (Jeelani et al., 2025). Faecal sterols have been employed to detect anthropogenic activities and grazing (Davies et al., 2022), and polycyclic aromatic hydrocarbons (PAHs), alongside levoglucosan, have been used to reconstruct burn histories (Kong et al., 2021). Biomarkers can also be used to reconstruct mean annual temperature via the MBT/CBT indices (Weijers et al., 2006), or peatland wetness using the BIT index (Hopmans et al., 2004). The value of biomarkers may also be enhanced when used in conjunction with stable isotopes. Compound-specific isotope analysis (CSIA) can provide unique insights into changes in ecosystem functioning that would be supplemented by a multi-proxy framework. For instance, Richard et al. (2011) in a study covering four bogs across a range of European climate zones, quantified past methanogenesis from peat using the presence and $\delta^{13}C$ signatures of lipids derived from Archaea, which could be compared with changing botanical, climatic and environmental changes if this method were employed as part of a multi-proxy framework.

Biomarkers can also provide source-specific information that is often difficult or impossible to obtain from other palaeoecological proxies. For example, the resistant nature of aliphatic hydrocarbons such as n-alkanes, whose dominant chain lengths differ between Sphagnum and non-*Sphagnum* species, allows for quantitative assessment of plant abundance changes under conditions where plant (or other biological proxy) remains are not well preserved (Nott et al., 2000). This has made their application particularly valuable where peat is often well-humified or even lignified, limiting the preservation of biological proxies (Inglis et al., 2015; Naafs et al., 2019). Although this restricts their co-application with many morphological proxies in these contexts, the analysis of multiple biomarker types within a single core allows for the application of a 'multi-biomarker' framework, with the same benefits as for multi-proxy studies (Inglis et al., 2022; Naafs et al., 2019).

As with other proxies, the integration of biomarkers into multi-proxy studies can help to corroborate or refine signals of environmental change and human impacts. There are several examples of the use of biomarkers in multi-proxy palaeoecological peatland studies: Thomas et al. (2023) used pollen, plant macrofossils and lipid biomarkers to reconstruct Holocene vegetation changes from a site in Beerberg, central Germany, enhancing the resolution of local vegetation changes from this record. Zheng et al. (2009) compared n-alkane biomarkers with pollen from peat samples from southern China, finding that the regional record provided by the pollen analysis contrasted with the localised signal of n-alkanes, and that n-alkanes were more sensitive to climatic changes than pollen. Despite the lack of correspondence between the two methods, the two proxies provided complementary data, allowing for the reconstruction of both local and regional patterns of climatic change. Faecal sterols have been used to confirm the presence of humans or livestock, which previously could only be inferred qualitatively using NPPs, such as coprophilous fungi. For example, Davies et al. (2022) examined six peat cores from the UK for pollen, fungal spores and faecal lipid biomarkers, comparing these with historical sheep density data from the area. They found that faecal sterols offered species-specific confirmation of increases in herd pressure, while only high-intensity grazing periods were identifiable from the palynological records.

While biomarkers are not necessarily expected to reflect changes in pollen, which are typically transported over large distances, n-alkane records do not always yield results consistent with plant macrofossil records either Pancost et al. (2002), suggesting that environmental or diagenetic factors within peatland environments may exert greater influence upon these than is assumed (Naafs et al., 2019). In contrast, Nichols et al. (2006) found that n-alkane indices showed strong correlations between testate amoeba inferred water table depth and humification from a single core from a North American peatland, suggesting that n-alkanes can provide reliable estimations of hydrological or botanical changes complemented by other methods, in some cases.

Despite their many strengths, biomarker analyses have limitations. Preservation biases, especially under variable redox conditions, can influence biomarker diagenesis and complicate their interpretation over long timescales. However, the preferential degradation of plant macromolecules such as polysaccharides and lignin can still provide insights into water table fluctuations and associated biogeochemical responses (Judith and Peter, 2011). Furthermore, while the source specificity of some compounds is high, others remain poorly constrained, particularly in transitional or heterogeneous environments, or where quantitative calibration is limited by the availability of modern datasets and the influence of regional variability. A key challenge in comparing biomarker data with other proxies is the limited understanding of the differences in temporal relationships among them, particularly the lags between environmental changes and biomarker responses, which in some cases can be on the order of several decades (Naafs et al., 2019). While such lags may offer important insights into ecological responses to disturbance or climatic change, in other cases, they may introduce uncertainties or signal misalignments that necessitate cautious interpretation.

The biological or environmental processes affecting biomarker concentrations, ratios, and indices in peatlands are complex and not always well understood, particularly across peat with different site histories (Jeelani et al., 2025). Fractionation, along with the possibility that some indicators derive from a wide range of sources, including both above and below ground plant material and microbial contributions, may introduce ambiguity into the signals (Naafs et al., 2019). Where traditional proxies are preserved, comparison with biomarkers may provide insights into the drivers of environmental change and the reliability of the biomarker signals. For example, the Carbon Preference Index (CPI), based on long-chain n-alkanes, has been used to infer past peat humification rates and temperature in peatlands. While CPI values in modern samples correlate with mean annual air temperatures (Naafs et al., 2019), analysis of core samples from a UK peatland alongside plant macrofossils, testate amoebae, and humification measures revealed little correspondence between the proxies. In that study, a lack of a clear downcore trend in CPI indicative of humification led Naafs et al. (2019)

to conclude that CPI more likely reflects vegetation change and is only partly driven by climate.

Despite their limitations, biomarkers remain a beneficial and underutilised tool in multi-proxy studies of peatland palaeoecology. They can provide a unique source of information on environmental and biogenic changes, many of which are difficult or impossible to reconstruct using traditional palaeoecological methods, especially in cases where traditional proxies are not well preserved. When used in combination with other proxies, biomarkers may allow for a more nuanced, detailed and robust environmental reconstruction. However, care should be taken in their interpretation, and their integration within a multi-proxy palaeoecological framework may assist with this.

4.7. Environmental DNA (eDNA)

High-throughput DNA metabarcoding methods show promise for advancing peatland palaeoecological studies via the analysis of environmental DNA (eDNA) stored within stratigraphic records. eDNA provides objective, scalable, and potentially more taxonomically rich insights into past biodiversity than is often achievable using traditional proxies such as pollen and plant macrofossils (Epp et al., 2012; Garcés-Pastor et al., 2019; Gould et al., 2010).

Despite its promise, few studies have yet to apply eDNA in a multi-proxy palaeoecological framework. Still, those that have done so show that eDNA can provide a complementary insight in addition to expanding the number of identified taxa (Fracasso et al., 2022; Parducci et al., 2015). However, comparison between eDNA and proxies of changing palaeobotanical diversity, such as plant macrofossils and pollen, does not always overlap and provides conflicting lines of evidence. For example, Parducci et al. (2015) observed stronger correspondence between eDNA and pollen relative to plant macrofossils in peat records from Finland and Russia, suggesting that a broad landscape-level eDNA dominates in peat records. Each proxy identified unique taxa, and there was relatively little overlap between the three proxies, indicating both the value of incorporating eDNA as part of a multi-proxy framework as well as the potential for misinterpreting the eDNA signal without first acknowledging the source of the eDNA within peat stratigraphic records. As with all proxies, eDNA is not without interpretative challenges, with DNA potentially deriving from local and distant sources, as well as from both ancient and contemporary sources. eDNA signals from peat may be dominated by abundant taxa such as Sphagnaceae or Cyperaceae, which may obscure the presence of less common taxa (Fracasso et al., 2022). Understanding the taphonomy of eDNA in peat, particularly in tropical systems that have received less attention, remains an important area for future research (Dommain et al., 2020). This may be better elucidated within a multi-proxy framework.

The improved taxonomic resolution possible by eDNA studies is arguably the greatest 'selling-point' for its incorporation within a multi-proxy framework. However, although eDNA can identify taxa that other proxies cannot, gaps in barcoding reference databases and primer biases may limit the taxonomic resolution possible by this method (Garcés-Pastor et al., 2019). The eDNA methodology is also relatively complicated, resource-intensive and remains expensive, and is therefore typically applied at low temporal resolution throughout peatland stratigraphic reconstructions relative to other proxies (Garcés-Pastor et al., 2019). However, recent advances in sequencing technologies and more complete barcoding databases are starting to resolve these limitations. Fracasso et al. (2022) demonstrated the potential of higher-resolution sampling in a 2500-year alpine peat record in combination with a suite of other proxies (although the sampling resolution would be considered low compared with other studies). Despite these limitations, eDNA revealed shifts in vegetation as well as invertebrate and microbial fauna that are not evident from other proxies; however, signal dominance by a few species would have limited the usefulness of eDNA had it been used alone.

In summary, eDNA is an emerging tool in peatland palaeoecology that has the potential to increase taxonomic coverage in future studies (Birks and Birks, 2016). However, interpretive issues relating to taphonomy should be resolved before the method is routinely adopted. These have begun to be addressed by comparative studies incorporating eDNA and traditional proxies. There is still undiscovered potential in the peat eDNA research where palaeoecology meets archaeology, considering land-use changes, plagues, or past human genomes (Özdoğan et al., 2024).

4.8. Apparent Rates of Carbon Accumulation

The Apparent Rate of Carbon Accumulation (aCAR) is a valuable measure for understanding changes in the rate of atmospheric carbon accumulation by peatlands over time (Abdalla et al., 2016 10; Blodau, 2002; Clymo et al., 1998; Gorham, 1991). aCAR is calculated based on measurements of bulk density, organic matter, and organic carbon content, and the amount of carbon content is divided by the age-depth model-derived accumulation rate for each peat slice (Beilman et al., 2009; Frolking et al., 2014; Yu et al., 2009). However, it should be noted that aCAR is not a standard variable included in multi-proxy studies worldwide, and several limitations can lead to misinterpretation of the data (Young et al., 2019). aCAR is calculated based on measurements of bulk density, organic matter and organic carbon content, and the amount of carbon content is divided by the age-depth model-derived accumulation rate for each peat slice. CAR was applied to many local and global studies exploring carbon accumulation rates in different temporal scales (Fiałkiewicz-Kozieł et al., 2014; Frolking et al., 2010; Gallego-Sala et al., 2018; Karpińska-Kołaczek et al., 2024; Loisel and Garneau, 2010; Loisel and Yu, 2013a). Such studies help demonstrate the significant carbon storage capacity (Loisel et al., 2014; Turetsky et al., 2004; van Bellen et al., 2020; Young et al., 2019; Yu, 2006; Yu et al., 2014; Yu et al., 2010) in highlighting differences in carbon accumulation throughout the Holocene due to regional differences, climatic changes or anthropogenic activity (Beaulne et al., 2021; Longman et al., 2021). However, it should be noted that aCAR is not a standard variable included in multi-proxy studies worldwide, even though the laboratory procedures to obtain such data are neither complicated nor time-consuming.

4.9. Less commonly used proxies

Several palaeoecological proxies which have seen wide usage in limnological studies include chironomids, molluscs, cladocerans, insect remains and diatoms, which are infrequently used in peatland studies (Cao et al., 2019; Carballeira and Pontevedra-Pombal, 2020; Gałka et al., 2021a; Leppänen et al., 2018; Płóciennik et al., 2011, 2020; Schafstall et al., 2024; Słowiński et al., 2016). This is typically due to the relatively low abundance or poor preservation potential for these remains in peatlands compared to lake sediments, where their use is more associated. However, these proxies have been applied successfully in a few specific peatland studies, mainly alkaline fens and spring fens (Apolinarska et al., 2024; Horsak, 2011; Łuców et al., 2022). The application of such methods is rare, but they should be applied, when possible, to answer particular research question. However, in the case of chironomids or cladocerans, which are often well preserved and abundant in peat records and have found application as particularly sensitive proxies for temperature, their lack of use may reflect the time required to learn and analyse these biotic remains compared to the use of other, similar proxies, or a limited understanding of their ecosystem dynamics within peatlands in comparison with better established proxies (e.g., pollen or plant macrofossils).

5. The importance of the multi-proxy palaeoecological data

Multi-proxy palaeoecological studies have become much more common in the past two decades, as it was realised that increasing the

number of proxies can give a more detailed and richer view of palaeoenvironmental changes over time (Birks, 2019; Lotter, 2003). However, as the number of proxies increases and our understanding deepens, synthesising these records has become more complex (Birks and Birks, 2006). Journal guidelines may also hinder the publication of multi-proxy records or seriously reduce the detail that can be communicated within the main body of a manuscript. Additionally, the demand for simple, easily interpretable figures often conflicts with the palaeoecological practice of providing detailed and complex stratigraphic plots, which can be a barrier to non-specialists, usually requiring specific taxonomic and ecological expertise to interpret. While studies incorporating multiple proxies remain valuable, focusing on the sampling resolution necessary to answer a particular research question or hypothesis can limit the need to analyse each proxy at high resolution, allowing researchers to focus on the essential proxies (Chambers et al., 2012). In some cases, addressing palaeoclimatic questions can be challenging with the majority of proxies, as the results may instead reflect local changes related to human impact (Kołaczek et al., 2020b; Kołaczek et al., 2018).

While one proxy applied to a core (e.g., plant macrofossils) can provide an essential environmental reconstruction for a site or study, the data become more complex when additional proxies (for example, testate amoebae) are added (Bąk et al., 2024; Gałka et al., 2022b; Šímová et al., 2025). When we apply the another proxy, such as geochemistry (e.g. stable isotopes or XRF data), the detailed picture of the past increases in new dimensions, although interpretation also becomes progressively more complex (De Vleeschouwer et al., 2009b; Fiałkiewicz-Kozieł et al., 2016; Galka et al., 2017; Słowiński et al., 2022; van der Knaap et al., 2011).

Moreover, the detail in the local signal may consequently be lost when searching for answers to questions of global scope and significance (currently favoured by publishers and often more frequently cited) using a set of proxies, even though the original local data remain highly valuable. However, the peatland palaeoclimatic records can be independently validated through the multi-proxy-multi-archive approach – e.g. simultaneous research on peatland and lake archive records located in the close vicinity. Such an example is the study of Pleskot et al. (2020) where chironomid-based temperature records from a lake were compared with testate amoebae-based quantitative water table reconstruction from a nearby Baltic raised bog to test hypotheses relating to the wetness-temperature relationships during the last 4000 years (Lamentowicz et al., 2015). Their findings indicated that during the previous 2500 years, climate cooling periods were associated with higher water levels in the bog. Another example comes from the Romanian Carpathians, where the peat record was also compared to a nearby pond (Diaconu et al., 2017), or another comparison of speleothems vs a peat profile in northwest Scotland (Charman et al., 2001).

It should also be noted that multi-proxy contributions often look less attractive as they provide a more realistic look at the data that calibrate themselves, without allowing a high degree of speculation, thus limiting the occurrence of "geo-fantasy", which is the situation where interpretations are not connected with reality and limitation of proxies and beyond published data. Such an approach might provoke a weakening of the main message with a high degree of speculation, triggering the impression that global-scale research is finally based on one core.

Figure 4 presents examples of syntheses derived from the pure, visual comparisons of quantitative reconstructions based on testate amoebae, pollen, plant macrofossils, charcoal, and stable isotopes to structural equation models (SEM) that test hypotheses regarding the environmental drivers. Determining which ecological variables influence change becomes progressively challenging the more variables are included, emphasising the need to establish these relationships. This can be tested through various numerical approaches, ranging from simple linear correlations between proxies to SEM. However, it is possible to utilise graphics and statistics to explore the past multidimensional peatland environment reliably. Each proxy provides a subsequent multivariate package composed of species or abiotic elements that accumulate in large datasets that are challenging to explore (Birks, 1998).

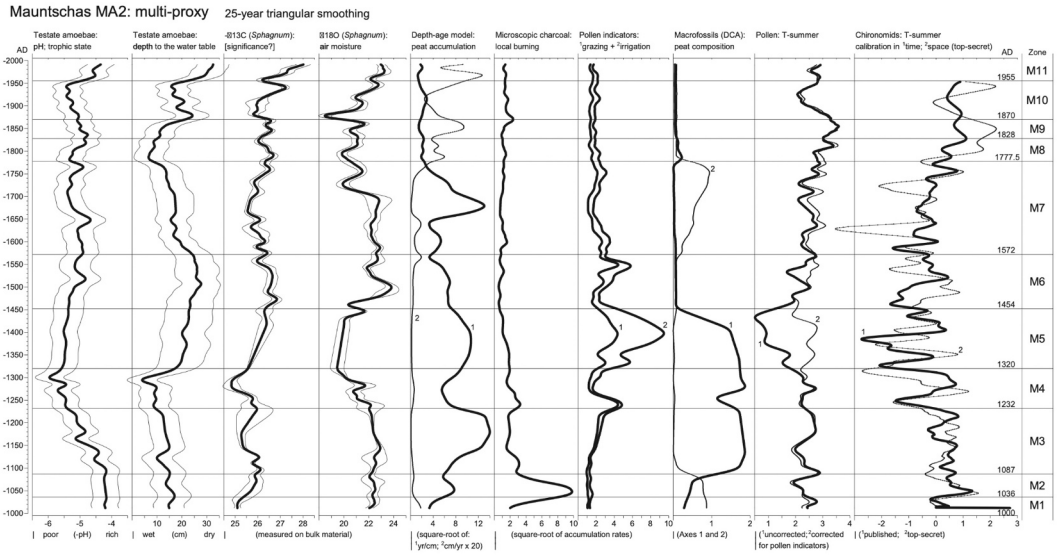
In many peatland palaeoecological contributions, interpretation is mainly based on subjective visual examination of the graphical output – proxies over time. It is challenging, but several approaches exist for presenting data from many proxies. Simple synthesis figures showing the chosen species from each proxy, presented in one figure, are standard (Lamentowicz et al., 2013). For instance, testate amoebae and plant macrofossils are proxies for local peatland hydrology and potential climatic drivers. In this case, we can rely solely on the taxonomic composition or quantitative reconstruction using the calibration data set to perform the transfer function. Water table depth (WTD) or depth to the water table (DWT) measured in cm emerges as the pivotal variable, subsequently used to correlate it with potential past climate changes (Charman, 2007; Charman et al., 2006; Gauthier et al., 2019; Šímová et al., 2025; Väliranta et al., 2012).

Proxies from the peat are complementary, explaining past environmental changes. Plant macros provide insights into past local vegetation changes, while pollen offers information about local and regional vegetation. Furthermore, charcoal is a proxy of the fire regime, and NPPs provide information about hydrology and human impact. Microcharcoal informs about larger spatial scales, while macrocharcoal is a proxy of the local fire activity. Consequently, multi-proxy analysis offers substantial potential for various scenarios and opportunities to construct alternative hypotheses in the complex multidimensional palaeoecological space. Simultaneously, some drivers, such as human activity, often become more evident to avoid, for instance, climatic speculations. Ultimately, synthesising numerous proxies (preferably at high resolution) emerges as a potent source of information regarding the past dynamics of peatland ecosystems. A reliable example is the research tracking changes in permafrost peatlands where plant macrofossil data and testate amoebae are prerequisites to understand local vegetation transformation and permafrost subsidence (Gałka et al., 2017; Sim et al., 2021). However, multi-proxy data for the permafrost are rare and often based on one core (Słowiński et al., 2022).

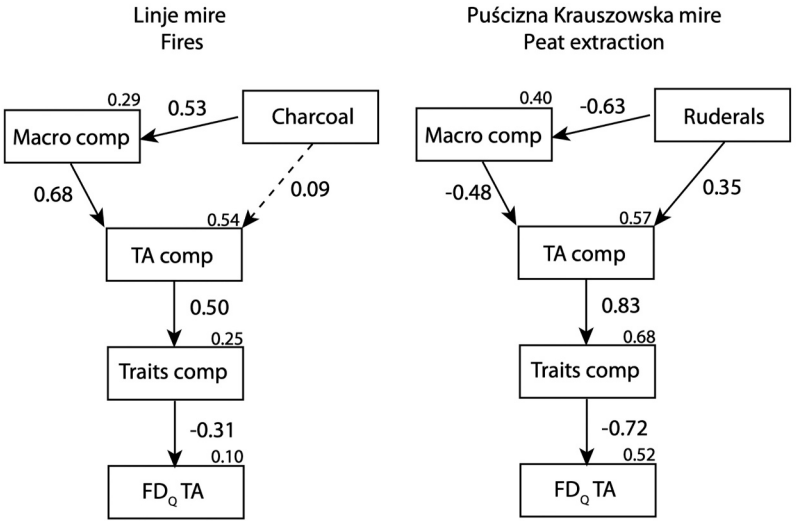
Studies based only on one proxy (e.g., testate amoebae) might provide an illusory palaeoclimatic signal that might eventually be related to land use, especially when the last 2000 years are in focus. The autogenic land-use change drivers are underestimated and might be challenging to separate from the valid palaeoclimatic signal. This is particularly true when proxies for anthropogenic activity, such as pollen, are not included (Andrews et al., 2021; Blundell and Langdon, 2023). In peatlands, local biotic proxies allow a glimpse of the preserved local food web within a system (Bysouth and Finkelstein, 2021; Gilbert et al., 1998). As a result, it is often striking how intensely the local peatland ecosystem change responds to the external landscape transformation by humans (Bunting and Warner, 1998; Gałka et al., 2021b). An example is the Głęboczek peatland in N Poland, which recorded a clear environmental impact associated with archaeological evidence for changes in cultures and past societies over the last 6500 years (Lamentowicz et al., 2019b) – multi-proxy data provide a consistent story of land-use generated wetland transformations. Another example of an unquestionably sharp human impact signal can be seen from the following sites: Kazanie (Czerwiński et al., 2021), Okoniny (Bąk et al., 2024) in Poland, and the Cambusurich Wood forest hollow in Scotland (Everard et al., 2024). Multi-proxy perspectives advise that the impact of land-use change on peatlands in the last 2000 years has been underestimated, and even extensive ombrotrophic peatlands (assumed to be relatively stable) were highly sensitive to local deforestation and, in consequence, dust input from the opened soils in the medieval period (De Vleeschouwer et al., 2009b).

Multi-proxy studies provide a more profound understanding of ecosystems' dynamics over long temporal scales. We should not perceive modern ecology and palaeoecology as distinct entities but rather view palaeoecology as an integral part of the temporal progression in ecology and evolution (Rull, 2010). Because of this division, while ecosystem-

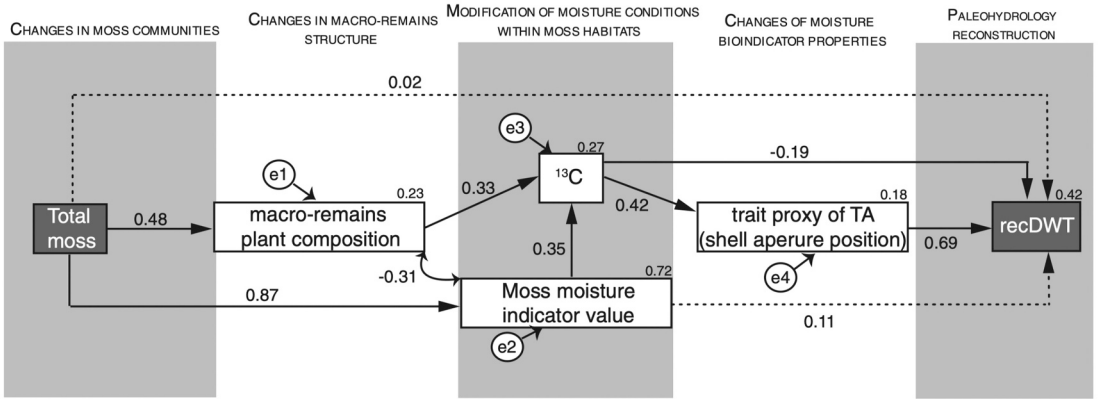
A



B



C



(caption on next page)

Fig. 4. Examples of syntheses in the context of multiple proxies: A) Mauntschas (Switzerland) (Knaap et al., 2011): Summary curves of proxies. Reconstructions of pH and depth to the water table (DWT) are shown with their bootstrap error intervals (thin lines). Thin lines flanking $\delta^{18}O$ and $\delta^{13}C$ measurements indicate 1σ standard deviations of two measurements per level. The depth–age model provides peat accumulation rates (cm yr^{-1}) and their inverse (yr cm^{-1}). Charcoal represents microscopic charcoal in pollen slides; accumulation rates are expressed as particles mm^{-2} yr^{-1}. The pollen indicators "grazing" and "irrigation" summarise curves shown in Fig. 3; accumulation rates are grains mm^{-2} yr^{-1}. DCA axes 1 and 2 of macrofossils track changes in peat composition. The pollen-based reconstruction of mean April–November temperatures follows Kamenik et al. (2009 #4297); the thin line is corrected for irrigation indicators. The chironomid-based temperature reconstruction (far right) is based on a nearby lake (Larocque-Tobler et al., 2010).; B) Structural Equation Models (SEM) for multi-proxy data sets from Linje and Puścizna Krauszowska (Poland) (Marcisz et al., 2016): SEMs showing the effect of environmental disturbances on testate amoeba functional diversity (FDQ). Solid lines represent significant paths ($P < 0.05$), dashed lines represent non-significant paths ($P > 0.05$). Squared multiple correlations (R^2) for predicted (dependent) variables are shown at the top of each box. TA comp = testate amoebae species composition (PCA axis 1); Macro comp = plant macrofossil composition (PCA axis 1); Traits comp = testate amoebae trait composition (PCoA axis 1). These three are synthetic variables (see Methods). Models include macroscopic charcoal influx (proxy for local fire) and ruderals (proxy for direct human impact) as disturbance indicators; C) SEM for a multi-proxy data set from Bagno Kusowo (Poland) (Lamentowicz et al., 2015): Structural equation model of relationships among macrofossils, moss traits, testate amoeba traits, and water-table depth ($\chi^2 = 5.81$, $P = 0.33$, CFI = 0.99, RMSEA = 0.03, SRMR = 0.03). Solid arrows show significant relationships (pathways) between variables; dotted arrows indicate non-significant relationships. Numbers next to arrows are standardised parameter estimates. Circles (e1–e4) indicate error terms; double-headed arrows indicate significant correlations between error terms. Squared multiple correlations (R^2) for the dependent variables are given within their respective boxes. Abbreviations: recDWT = reconstructed water-table depth; TA = testate amoebae; CWM = community-weighted mean; Total moss = total abundance of mosses in plant macrofossils.

based approaches to nature conservation are evident, their application to long-term scales remains uncertain. This is primarily due to the limited understanding of ecosystem dynamics at local scales. The distribution and thickness of peatland records are becoming more well known, as are their histories of developmental change and human disturbance. Palaeoecological approaches offer a convenient way to examine the trajectories of change and the underlying causes of these changes over time. By employing these approaches, we can validate existing ecological descriptions and gain insights into the timing and characteristics of any deviations from normal conditions. Moreover, when integrated with contemporary monitoring and modelling techniques, palaeoecological insights can provide an early warning signal of potential future changes (Finlayson et al., 2015).

However, we still lack a comprehensive understanding of pre-disturbance baselines for protected ecosystems. For instance, it is evident that European forests have undergone significant modifications and no longer possess a pristine state (Czerwiński et al., 2022; Kaplan et al., 2009). Despite our common perception of peatlands as partially pristine, it is still unclear whether they underwent significant changes during the medieval period, coinciding with deforestation and intensified soil exploitation. Multiple proxies bring us closer to understanding the current state of these ecosystems, which can often be surprising. For example, in the last millennium, many peatlands originated alongside land-use change-induced shallowing lakes (Bąk et al., 2024; Karpińska-Kołaczek et al., 2022; Lamentowicz et al., 2020b). Consequently, for instance in Europe the current state of most peatlands is a result of human interventions that took place over a century ago (Tanneberger et al., 2021), which have been forgotten due to 'generational amnesia' and for which there are often no modern analogues remaining (Finlayson et al., 2015). The transient nature of peatlands, in addition to their resilience to disturbance and their limits, can often only be understood using detailed palaeoecological studies.

Peatlands' global importance in the carbon cycle is increasingly recognised, yet they are still not adequately protected (Austin et al., 2025). In this context, palaeoecological multi-proxy studies might strengthen conservation approaches (Birks, 2012). Multi-proxy palaeoecological data provide essential awareness for the protection of peatlands (Marcisz et al., 2022) and new insights into conservation targets (Chambers et al., 2017; McCarroll et al., 2016a, 2016b). Environmental monitoring and historical data are often fragmentary. In contrast, multi-proxy palaeoecological data offer a comprehensive view of changing baselines, such as the history of drainage, vegetation change, hydrology, hydrochemistry, pollution, deforestation, afforestation, eutrophication, and acidification (Booth et al., 2004; Charman, 2002; Fiałkiewicz-Kozieł et al., 2016). A study (using testate amoebae and plant macrofossils) focused on the last 2000 years revealed that a critical hydrological threshold for ecosystem transitions (expressed as the water table depth) is approximately 12 cm (Lamentowicz et al., 2019a). This value is essential for the effective growth of healthy ombrotrophic peatlands, as demonstrated by other palaeoecological studies (Swindles et al., 2025) and modern greenhouse gas emissions (Evans et al., 2021; Jurasinski and Günther, 2016). This highlights the synergy between multi-proxy palaeoecological data and contemporary ecological and instrumental data in identifying hydrological tipping points within peatland ecosystems. Considering the importance of such data, each protected peatland should be analysed using multi-proxy palaeoecological approaches as a critical reference for any nature protection approaches. Studying the history of the peatland is the best way to understand the changing ecosystem and its relative stability over the last centuries or millennia, for which there is often little to no written record.

Moreover, multi-proxy palaeoecological data provide robust data on the effects of peatland restoration. The re-establishment of peat accumulation is visible in the peat profiles after restoration practices. Multi-proxy palaeoecological data provide a vital perspective before and after investment. Some studies that have done this apply only one proxy (Swindles et al., 2016a), while not much work has been done on freshly rewetted peatlands (Łuców et al., 2022). While several publications underline the potential of the palaeoecology for ecological restoration of peatlands (Blundell and Holden, 2015; Chambers et al., 2017; McCarroll et al., 2016a, b; Ramdzan et al., 2023), few studies have undertaken this task. The multi-proxy palaeoecological data raise pertinent questions regarding the protection of ecosystems, mainly when long-term data are often absent. It poses challenges in distinguishing natural succession pathways from anthropogenically induced changes in the past. Furthermore, it necessitates the determination of the direction of restoration, for example, if palaeoecological evidence suggests that the protected ecosystem itself resulted from a large-scale anthropogenic degradation (Wochal et al., 2025). Multi-proxy palaeoecological data-based long-term look at the past peatland dynamics is a valuable reference for the long-term peatland restoration perspective that is often predicted to take decades or centuries (Zak and McInnes, 2022).

6. Proxy limitations and synergies

All proxies may offer a comprehensive picture of the past environment and possess synergistic possibilities, contingent upon the scientific inquiry at hand. Given resource constraints and the scarcity of experts (see section 8 for details), it is exceptionally uncommon for all feasible proxies to be synthesised within a single study.

All proxies preserved in peat possess their specific potential. The principal emerging feature is the ability to reconstruct environmental variables and, ultimately, the structure of past ecosystems (that is, the primary aim of palaeoecology). Usually, separated proxies are not effective in explaining the broader context of past environmental change. In reality, through one proxy one obtains a fragment of the

Table 1
Table 1. Overview of commonly used palaeoecological proxies, including their significance, type of data, inference potential, strengths, weaknesses, and possible multi-proxy synergies.

N	Proxy	Significance	Type of data used	Inference	Strenghts	Weaknesses	Best multi-proxy synergies
1	pollen	high	counts; genus or species level identification	local and regional vegetation, land-use change	detection of human impact and climate change	mostly qualitative; time-consuming analysis	TA, plant macros, NPPs, charcoal
2	plant macrofossils	high	counts, proportion data; genus or species level identification; functional traits	local vegetation; peat composition	validating the local signal in pollen analysis	mostly qualitative	pollen, TA, charcoal
3	testate amoebae (TA)	high	counts; genus or species level identification; functional traits	hydrology, trophy	quantitative	ongoing dynamic changes in taxonomic identification of taxa and species may disrupt data interpretation and comparison of odl and new studies; mostly used in bogs and poor fens while there is a scarcity of data for fens	pollen, plant macros
4	biomarkers	high	Lipid compounds (n-alkanes, GDGTs, sterols, PAHs, lignin phenols, faecal sterols)	temperatures, vegation types	quantitative	low taxonomic resolution	plant macros, pollen
5	geochemistry	high	Bulk C, N, S; C/N ratio; XRF (Si, Ti, Ca, Fe, Mn, Br, Pb, Hg, etc.); LOI	decomposition, air circulation, local land-use change	quantitative	focus on physical processes limiting the cause of signal - e.g. global vs local changes	pollen, plant macros
6	stable isotopes	medium	$\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, δD (bulk, compound-specific, Sphagnum cellulose, biomarkers)	hydrology	proxy of wetness change	mostly qualitative, challenging interpretation	plant macros
7	non-pollen palynomorphs (NPPs)	low	counts; group, type, genus or (rarely) species level identification	human impact, decomposition, hydrology	some of the NPP types are proved to be sensitive to human impact and hydrology	mostly qualitative, challenging interpretation and taxonomy; most of the NPPs are not identified to species level and their response to environmental factors is not clearly defined	plant macros, TA, pollen, charcoal
8	charcoal	medium	counts, accumulation rates, concentrations, morphological types, size classes, new advances to reconstruct fire regime parameters (e.g., fire intensity)	past fire activity	identification of local and extra-local fire events, identification of hiatuses	no established methods for quantitative measures for fire regime changes; various approaches used for fire reconstructions with no consistency/standarization in approach to define charcoal size classes, source area, morphologcal type classification etc. across different case studies; most methodology defined for lake studies	plant macros, TA, pollen, NPPs
9	Loss on ignition (LOI), bulk density and peat accumulation rates	high	mm/year; %	rates of peat accumulation over time; water content, organic matter content, bulk density	gives an overview/ estimate of accumulation processes over time; analysis is quick to perform	not precise measurements, especially in the accrotelm level	plant macros, TA, pollen, charcoal
11	carbon accumulation rates	high	$gC/m^2/year$	rates of carbon accumulation over time	gives an overview/ estimate of carbon accumulation over time; analysis is quick to perform	not precise measurements, especially in the accrotelm level	plant macros, TA, pollen, charcoal

story, and so using multiple proxies offers a more complete picture of environmental changes, and allows for the validation of interpretations as well as other proxies. Moreover, the value of proxies becomes more evident when analysed together from the same horizons of the peat core. The fundamentals of each proxy's potential and value have been described in several publications (Berglund, 1986; Birks and Birks, 1980). We summarised strengths, weaknesses and other important information of most commonly used proxies in peatland palaeoecology in Table 1.

Oftentimes, biotic proxies, such as plant macrofossils and pollen, are employed together to infer past vegetation alterations associated with climate or human influence. Occasionally, stable isotopes or other geochemical or molecular proxies have been applied in tandem with biotic proxies, although such high-resolution studies are less common (Gałka et al., 2022a; Kołaczek et al., 2018). Notably, pollen and testate amoebae serve as proxies that can unequivocally indicate human impact and palaeohydrological disturbances, through pollen anthropogenic indicators and quantitative palaeohydrology measured in centimetres of water depth, respectively. However, most proxies are qualitative or semi-quantitative at best, and the strength of the inference is enhanced when multiple proxies are explored collectively, thereby increasing data complexity. It is also worth mentioning tha single-proxy studies are often linked to the tradition and limitations of communication among experts, who tend to remain within their comfort zones. Despite its substantial potential and the great number of studies applying a multi-proxy framework, the power of multiple proxies has not been

sufficiently exploited to date and there remain many advancements and improvements to be made.

Historical pollution or dust investigations predominantly employ geochemistry (De Vleeschouwer et al., 2009b; Li et al., 2020; von Scheffer et al., 2023), while inquiries into human impact utilize pollen and charcoal as primary data sources within the context of archaeological research. There is an excellent potential for geochemistry and biotic proxies to be employed in resolving questions about local land-use change, deforestations and soil erosion on ecosystems (De Vleeschouwer et al., 2009a; De Vleeschouwer et al., 2009b) (Le Roux et al., 2012). Peatland development and hydrological research often employs employ testate amoebae and plant macrofossils (Booth et al., 2004; Gałka et al., 2014; Väliranta et al., 2012) (Lamentowicz et al., 2019a). At the same time, NPPs can contribute to the enrichment of paleohydrological inferences, particularly in terms of water table fluctuations, across diverse peatland types (Kołaczek et al., 2025, 2020a). Notably, there is a strong potential of geochemical proxies, testate amoebae, and pollen to reconstruct the drivers of land-use transformation, industrial pollution and peat carbon accumulation rates.

Over the past two decades, pollen and testate amoeba records have demonstrated a strong agreement in high-resolution multi-proxy context, shedding light on human impacts on forests and, consequently, wetlands (Bąk et al., 2024; Booth et al., 2004; Connor et al., 2018; Gałka et al., 2014; Gauthier et al., 2019). These studies revealed that the pollen-testate amoebae fitness enabled them to avoid climatic traps in interpretations connected mainly with the land-use change. Consequently, palynological data, supported by NPPs and testate amoebae, provide novel insights into water table fluctuations, suggesting that local deforestation and other disturbances, rather than climate change, may be the primary driver of these fluctuations in peatland palaeoecological records, particularly in recent years (Lamentowicz et al., 2020b; Karpińska-Kołaczek et al., 2022). This proxy composition safeguards against the aforementioned „geo-fantasy" and potential false paleoclimatic interpretations related to testate amoebae interpreted in isolation.

Biomarkers hold significant potential for identifying previously unknown phenomena, particularly in scenarios characterised by exceptionally high rates of peat decomposition (Jeelani et al., 2025), as demonstrated in the case of lake sediments (Brown et al., 2021). Furthermore, biomarkers can be effectively utilized in conjunction with testate amoebae or plant macrofossils to validate testate amoeba-based hydrological reconstructions. Such a proxy combination offers a more comprehensive understanding of the peatland's development and the role of microbes in peat growth and decomposition within the context of past environmental changes.

Notably, eDNA, together with pollen and plant macrofossil data, would provide a novel context associated with vegetation change in interdisciplinary studies (Schwörer et al., 2022). Human-related eDNA may also prove highly beneficial for a deeper understanding of various environmental conditions, including human migration patterns or epidemics, as seen in lakes (Bramanti et al., 2021; Capo et al., 2023; Izdebski et al., 2022). Biomarker, eDNA supported by classical proxy data are anticipated to undergo rigorous testing in the future, particularly in high-resolution studies, within the framework of precisely defined scientific questions.

The future challenge should focus on connecting all possible proxies to select the strongest and most significant signals of past changes in peatlands. From the theory we know about the division between biotic and abiotic proxies, however, we need to trigger a new understanding of mult-proxy potential using multivariate statistics and artificial intelligence to go beyond the experts' comfort zone.

7. Challenges of Southern Hemisphere peatland studies

Southern Hemisphere peatlands possess a great potential for reconstructing past climate changes. They also hold an intriguing signal of the human impact related to the indigenous people, as well as the arrival of Europeans and the subsequent land transformation. Considering central and southern America there is several studies from Patagonia which focus on the palaeohydrological change (Daley et al., 2012), air circulation (Vanneste et al., 2015) or precipitation (Daley et al., 2012), vegetation succession, carbon accumulation rates (Loisel and Bunsen, 2020; Loisel and Yu, 2013b). Among them, there are several multi-proxy studies (Borromei et al., 2010; Pendall et al., 2001) using NPPs, plant macros and stable isotopes to reconstruct past climate changes or geochemistry, aiming to answer how the westerlies have varied over time in the Atlantic sector of the Southern Ocean) (Björck et al., 2012; Loisel et al., 2023). Several studies have applied single proxies in Amazonia (Swindles et al., 2016b; Winton et al., 2025). A strong example of a multi-proxy study in this hemisphere is the study of Swindles et al. (2018) that reconstructed long-term ecohydrological controls on carbon accumulation in an Amazonian peat dome using plant macrofossils and a testate amoebae calibration data set (Swindles et al., 2014). A recent review synthesises palaeoecological studies from south-western and north-eastern Amazonia (Wang and Behling, 2025), highlighting that distinct regional drivers, including river dynamics, sea-level fluctuations, geomorphological settings, and human activity shape peat formation and carbon accumulation. The study underscores the importance of multi-proxy approaches for unravelling the complex and regionally diverse mechanisms underlying tropical peatland development, with significant implications for climate modelling and conservation planning.

Another location that needs attention is the Southern Ocean islands. The studies are primarily focused on the past climate and fires to explore human impact. Most published studies use a single proxy and are focused on the invasive plants on Galapagos Island (van Leeuwen et al., 2008), carbon accumulation on the Falklands (Payne et al., 2019). The Falkland Islands also possess a significant multi-proxy study focused on past fire activity (Mauquoy et al., 2020). Another reliable examples come from Crozet Islands (Van der Putten et al., 2008), Kergulen Islands (Van der Putten et al., 2015) and South Georgia (Van der Putten et al., 2004); all mentioned studies used plant macros, pollen and geochemistry to infer climate change in the Holocene.

Africa has an evident gap in terms of multi-proxy peatland studies, despite having excellent potential for palaeoecological inferences. On the African continent, extensive peatlands are a feature of the central Congo River basin, where they cover a considerable land area estimated at 146,000 km^2 (Page, 2024). Recent studies have shown great potential in Congo peatlands as a source of data on past environmental changes (Dargie et al., 2017), example is research of Garcin et al. (2022) that used pollen, biomarkers, charcoal, Menges et al. (2025) using geochemistry and stable isotopes, Dargie et al. (2017), and Hawthorne et al. (2023) that analysed pollen, biomarkers, radiocarbon dating, and charcoal to explore peat initiation. Another example from Africa comes from the south of the continent, e.g. Miller et al. (2019) explored Mfabeni peatland, KwaZulu-Natal, analysing $\delta^{13}C/\delta D$ of n-alkanes showing vegetation (C_3/C_4 balance) in an attempt to reconstruct climate change over the last 32 cal ka BP. Another study from Vankervelsvlei peatland (Strobel et al., 2024) is a multi-proxy study using oxygen isotopes from hemicellulose-derived sugars and hydrogen isotopes from leaf wax-derived n-alkanes to reconstruct hydroclimatic variability through time.

Several peatland palaeoecological records from South-East Asia include multiple proxies; however, the existing gap is evident in this region, especially in the context of the high-resolution data. The examples from the area come from Sumatra (Biagioni et al., 2015) with testate amoebae and palynological data to reconstruct ecosystem-climate interactions. The subsequent two studies, a review on the application of palaeoecological and geochemical proxies in the context of tropical peatland degradation and restoration by (Ramdzan et al., 2022) and an original study from Borneo (Ramdzan et al., 2023) applied geochemistry, pollen, charcoal and testate amoebae, aiming to reconstruct peatland development with implications for ecosystem restoration. Furthermore, it should be noted that there are several multi-proxy

studies from New Zealand focused on climate change and climate (Fewster et al., 2025; McGlone and Wilmshurst, 1999; Wilmshurst et al., 2003) utilising pollen, testate amoebae, humification and NPPs, aiming to reconstruct vegetation change, peatlands development, palaeohydrology and climate change.

Despite advancements in Holocene peatland paleoecology in the Southern Hemisphere, significant gaps persist in both spatial and methodological coverage. Multi-proxy studies are disproportionately concentrated in select regions such as southern Patagonia, while vast areas, particularly in southern Africa, the tropical Andes, and maritime Southeast Asia, remain underrepresented or unexplored. Many existing studies heavily rely on pollen and charcoal, with fewer incorporating hydrological indicators such as testate amoebae, biomarkers, or geochemistry. Temporal resolution is often low, hindering the ability to identify rapid environmental events or anthropogenic disturbances. Furthermore, integrating palaeoecological data with archaeological or historical records remains rare, constraining our understanding of coupled human-environment interactions. Addressing these gaps necessitates more geographically diverse fieldwork, broader proxy integration, and interdisciplinary collaboration with local researchers to fully comprehend the complexity of Southern Hemisphere peatland histories.

8. The constraints of high-resolution multi-proxy peatland studies

Even though a high-resolution multi-proxy approach brings numerous advantages in palaeoecological peatland research, significantly broadening our understanding of past ecosystem dynamics, limitations still exist in performing such studies. This is evident through our literature search – the number of high-resolution multi-proxy studies increases, but there is no uniform standard for the method to be applied. Several reasons are responsible for this: High-resolution multi-proxy studies require a considerable investment in many areas –study materials, resources, costs, time, and expert personnel involved. The large amount of study material (peat core or monolith) is crucial, as a large sub-sample from each peat layer is required for multi-proxy analyses, which are often destructive and require 1-5cm3 of peat material at a time. It may be challenging to obtain enough material, especially from deeper peat layers.

High costs are mainly associated with to the use of expensive resources (such as specialised machinery, e.g.: mXRF core scanners) and costly fundamental analyses such as ^{14}C and ^{210}Pb dating that provide the basis for reconstructions and interpretations (e.g., the lack of a radiocarbon facility in Southern America increases the costs of radiocarbon dating for researchers from this region). A higher number of samples extends the analysis time, delays the publication of results, and often increases costs for the personnel involved. The specialised personnel may also be hard to find, due to a shortage of specialists in a specific area (e.g., plant macrofossil analysts) or the need for extended analysis time (which is often scarce for researchers, especially those employed on short-term contracts). Each of these obstacles must be overcome to perform high-resolution multi-proxy palaeoecology; however, the many benefits highlighted in this review indicate that additional time and effort may be worthwhile. The geographical coverage of peat deposits, which have been investigated using a multi-proxy approach, is currently limited. This constraint is related to the limited access to regions and the lack of scientific teams in particular parts of the world (Fig. 1B).

9. Future perspectives

9.1. Synthesising multiple proxies with historical and archaeological studies

Peatland palaeoecological research holds significant potential for advancing socio-ecological breakthroughs, settlement patterns, economic development, and historical demography (Czerwiński et al., 2021; Degroot et al., 2021; Izdebski et al., 2025). While much research in high-resolution palaeoecology has been conducted independently of historical studies, collecting information and linking it to previously established reference studies is still feasible. Simultaneously, it is crucial to establish new research sites to maximise the possibilities of interdisciplinary syntheses. These sources, such as inventories of goods typical of large landowners (e.g., the king or ecclesiastical institutions), were prevalent in the sixteenth century and recorded sources of income related to livestock farming, primarily the land area in the hands of peasants. The development of farms and the establishment of latifundial bureaucracy enabled the study of dominant crop types on manor farms, harvest yields, and animal numbers (Haldon et al., 2018). Tax sources, particularly those from the sixteenth century, provided valuable data on land size in hereditary use by peasants or proto-industrial devices that required forest resource exploitation ((e.g., forges, breweries)). In subsequent centuries, tax sources recorded smoke (houses), indirectly indicating population density (Czerwiński et al., 2019; Izdebski et al., 2022; Słowiński et al., 2021).

Peatlands are diverse, influenced by the specificity of the accumulation environment, which may impact the continuity of event recordings in a specific site. Furthermore, various peatlands, theoretically similar, may either better or worse reflect, for instance, climate signals (e.g., the Jaczno peatland; (Marcisz et al., 2020b) or anthropogenic signals, e.g., the Głęboczek peatland; (Lamentowicz et al., 2019b). Consequently, a complementary data set enhances the probability of acquiring crucial information regarding the human impact on nature and the impact of climate on human populations. The more critical issues concerning the integration of palaeoecology and historical geography, environmental history, and economic history are related to the impact of settlement and agriculture on nature over the past thousands of years, as well as the impact of climate on economic activity, considering demographic growth (Czerwiński et al., 2021; Kołaczek et al., 2025; Niebieszczański et al., 2021). Human impact on the environment is also a fundamental area of research, but several questions arise regarding the intensity/scale of human activity in the past (Albert et al., 2021; Sjögren and Lamentowicz, 2008). For example, it is essential to address questions such as how land-use changes in historical times have affected forest areas (Jaroszewicz et al., 2019; Latałowa et al., 2015), how the gradual opening of the landscape may, in turn, have affected peatland ecosystems (Ireland and Booth, 2012), and how past environmental changes have influenced current land-use patterns, social patterns, and natural ecosystems. Furthermore, big questions related to the delimitation of the Anthropocene (Fiałkiewicz-Kozieł et al., 2023) and catastrophic industrial pollution events (Fiałkiewicz-Kozieł et al., 2015) can be explored using multiple proxies from the peat.

The presence and economic activity of humans in the last millennium have left evident traces in peatlands (Gallego-Sala et al., 2018). We can utilise these natural archives to advance our understanding of economic development by integrating multiple proxies with historical geography. This approach often directly relates to environmental changes (Barber, 1993). One definition of palaeoecology states that this discipline explores past ecosystem changes (Birks and Birks, 1980). The multi-proxy approach (utilising biotic and abiotic proxies) in peatland research aligns with the simultaneously complex objective of handling multivariate data. We must construct a new framework for multi-proxy reconstructions that reveal past change trends to obtain high-quality data related to archaeological, historical, and instrumental data. Applying multiple proxies may be a prerequisite for future palaeoecological research. It will undoubtedly enhance the inference quality and precision of detecting short events, such as historical data like ecological crises, violent conflicts, wars or short-term climatic fluctuations (Czerwiński et al., 2021; Izdebski et al., 2025). Still, the prerequisite is the high-resolution approach (Figure 5). We can only achieve satisfying timescales by increasing the subsampling and dating resolution. This

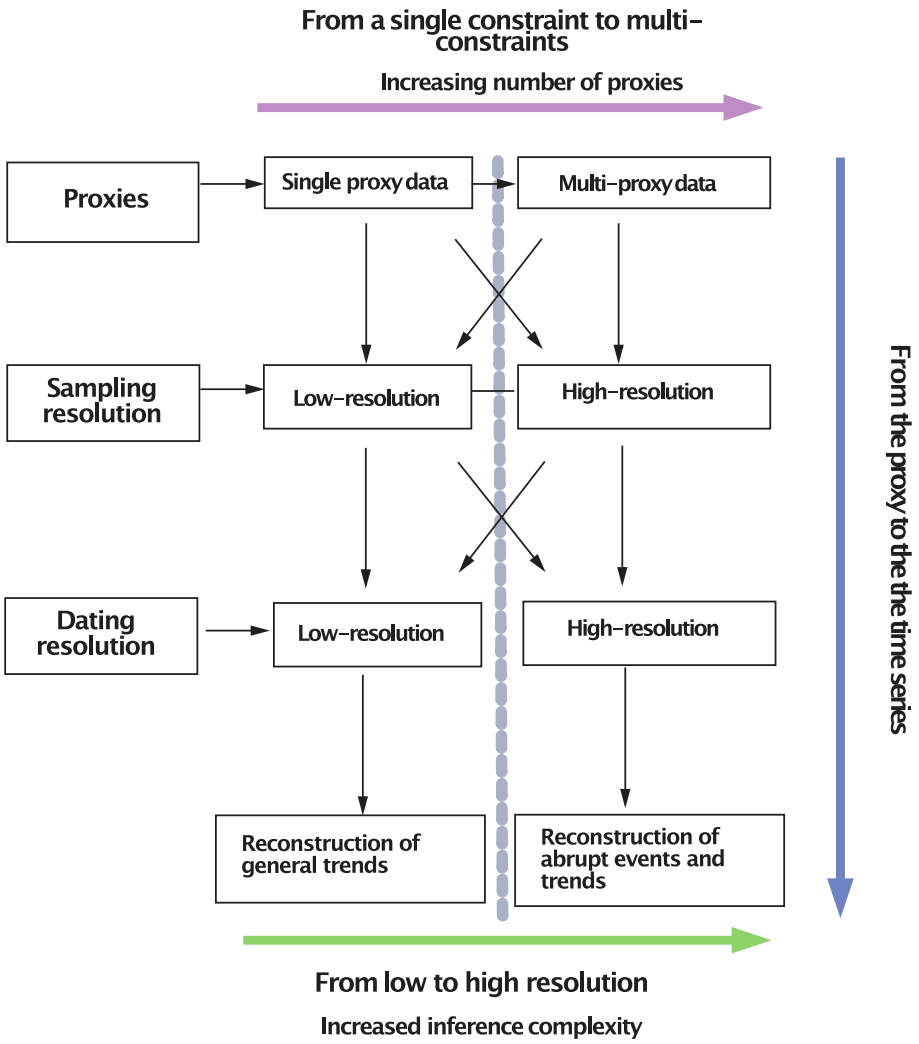


Fig. 5. Conceptual framework illustrating the progression from low-resolution, single-proxy approaches to high-resolution, multi-proxy studies. Low-resolution, single-proxy data typically allow only the reconstruction of broad, long-term trends, while high-resolution, multi-proxy datasets enable the detection of both general patterns and short-lived, abrupt events. The transition from single to multiple constraints, combined with finer temporal resolution, increases the analytical power of palaeoenvironmental reconstructions but also raises the complexity of inference. Improved dating resolution, together with multi-proxy integration, strengthens the reliability of timescales and enhances the capacity to disentangle climatic, ecological, and anthropogenic signals.

approach allows for the reconstruction of short-term archaeological and historical processes, as well as the identification of abrupt events such as tornadoes, megafires, or permafrost collapse in the peat record (Büntgen and Esper, 2024; Łuców et al., 2021; Swindles et al., 2015a; van Geel et al., 2014). It is particularly valuable in contexts where the subsidence and hydrology of permafrost peatlands are challenging to interpret (Halaś et al., 2025).

Considering the uncertainties revealed through palaeoecological studies, it is imperative to exercise meticulous care in interpreting each proxy and its implications (Jackson, 2012). While single biotic or abiotic proxies may seem appealing for providing a universal explanation of past environmental changes, ranging from climate (e.g., air circulation) to well-established anthropogenic impacts, it is crucial to acknowledge alternative hypotheses, including local and autogenic changes. Through cautious and in-depth discussions, we can arrive at more reliable conclusions that avoid the misrepresentation of the spectacular environment-peatland inferences - 'geo-fantasies'. Comprehensive examinations of challenging and complex multi-proxy data enable us to scrutinise the potential human or climate impacts. Two decades ago, palaeoclimate was the primary focus of palaeoecological investigations, primarily aimed at tracking and verifying past references for ongoing global warming (PAGES, 2019). Emerging research areas now connect peatland palaeoecology with history and archaeology (Izdebski et al., 2022). Numerous newly developed research approaches, such as consilience (Izdebski et al., 2016) or archaeoecology (Crabtree and Dunne, 2022), underscore the necessity of studying past human impacts on the environment holistically. This entails integrating diverse research methods through collaborative efforts involving experts from various disciplines, including ecology, palaeoecology, archaeology, and history. Consequently, in recent times, palaeoecological data have garnered widespread interest from archaeologists, who have a longstanding tradition of collaboration with palaeoenvironmental scientists (Bryant and Holloway, 1983) and historians (Haldon et al., 2018; Izdebski et al., 2024, 2022).

The work of (Izdebski et al., 2025) is an example of a multi-archive lake study based on pollen data and historical sources goes much beyond a standard palaeoenvironmental reconstruction, revealing complex social-ecological intensification relating to various cultural, economic, religious, and social networks supporting political expansion. This research shows the strength of interdisciplinary cooperation. However, there is still much potential in integrating other proxies to obtain the peatland ecosystem changes triggered by the economic and political processes (Bąk et al., 2024).

9.2. Integrating modern techniques in multi-proxy peatland studies

Reconstructing past environments in space and time needs novel numerical techniques for exploring multidimensional data. Building global data to gain a better understanding of big data helps to exploit the complexity of studies focused on multiple proxies. Incorporating ecological and process-based models significantly enhances the interpretation of peatland palaeo-records; such studies are the next step in the better understanding of peatlands' development under different levels of disturbance. An interesting case is the study of Frolking et al. (2010) that explored the simulation model with the peat core against the ant macrofossil composition in time in the context of climate change and nutrients and acidity. Further avenue is related to the application of the multi-proxy data in the Earth system models. Considering the meaning of the peat carbon for the climate change, this gap should be urgently considered in future modelling benchmark global carbon cycle models against Holocene peat-carbon dynamics (Loisel et al., 2021). This type of modelling can improve predictions of the climate impacts on peatland ecosystems and carbon fluxes. However, there are still challenges remaining as the models simplify reality, while including many proxies might be limited by the data availability and dating uncertainties. The growing databases like Neotoma (Booth, 2025; Williams et al., 2018) might help in the future to achieve better modelling results.

Traditional interpretation (visually comparing proxy curves or applying basic statistical correlations) can be subjective. It may overlook complex, multivariate patterns in the complex multivariate data (Barel et al., 2023; Jassey et al., 2022). Using advanced numerical methods, such as machine learning, may advance our understanding of the multi-proxy data. An interesting example is the study from Kyrgyzstan where an innovative approach was used that combines the novel dimension reduction technique Uniform Manifold Approximation and Projection (UMAP) and time series analysis to identify and characterise Holocene environmental phases and phase boundaries in a sediment core (Schroeter et al., 2020). As a result, subtle changes were identified in the record that could not be identified by traditional methods and particularly not by qualitative means. This kind of computational tools enhances the sensitivity of the interpretation process. Another step is applying network analysis to study past ecological communities and their interactions, using palaeoecological data (Jeraj et al., 2006). There are several examples from palaeontology that addressed mass extinctions (Muscente et al., 2018) or de-extinction candidate species (Wood et al., 2017). Such an approach, which is common in modern ecological studies (Kurtz et al., 2015; Sole and Montoya, 2001), enables the indirect identification of relationships between ecological communities to explore ecosystem structure and its response to different disturbances like human impact and climate change. As a result, it might be possible to infer past food webs (Gilbert et al., 1998) and their long-term changes (Adl et al., 2011). There are perspectives for the future that the new generation multi-proxy studies will reveal a novel look at the past of peatland ecosystems, while the eDNA might provide a broader picture of the microbial communities, for example, in the context of carbon balance (Wyatt et al., 2021).

There is a growing body of studies on peatlands using remote sensing techniques, including high-resolution LiDAR (Light Detection and Ranging), multispectral/hyperspectral imaging, and satellite observations (Crichton et al., 2025; Harris et al., 2005; Lees et al., 2018). LIDAR and vegetation mapping techniques help with understanding modern vegetation as well as hydrology, providing essential information for the multi-proxy coring context. Furthermore, there is still unexplored potential related to global processes, such as the spread of fires and droughts, and integrating with multiple proxies sampled at high resolution. Although the challenge remains in the availability of such material. One of the examples is the work of Bąk et al. (2024) using remote sensing analysis in conjunction with hyperspectral, lidar and thermal airborne data, which provided information about the current condition of the peatland vegetation. With the application of spectral indices and the analysis of land surface temperature, spatial variations in peatland drying trends have been identified. The data were synthesised in the context of the pine monocultures introduced 200 years ago that affected peatland development in Northern Poland. By integrating such spatial datasets with palaeoecological data, researchers can upscale site-specific paleo findings to the landscape or region. An emergent need is for the continuous monitoring of peatland ecosystems considering vegetation succession and wetness changes (Giese et al., 2025). The palaeoecological and remote sensing data still await being well-integrated, especially in the context of global climate change impact on pristine peatlands or peatlands restoration planning and monitoring. Multi-proxy data (especially plant macrofossils, testate amoebae and NPPs) integrated with the remote sensing would effectively show peatland rewetting effects through the synthesis of various spatial and temporal perspectives (Lamentowicz et al., 2025). This would trigger collaboration between palaeoecologists and remote sensing specialists, and it moves peatland research toward a more holistic understanding, connecting past dynamics to present landscape ecology and aiding conservation management with knowledge of long-term trajectories. Furthermore, using the techniques mentioned above, palaeoecological multi-proxy data in nature conservation and restoration provide compelling evidence that offers perspectives on past ecosystem dynamics in allogenic and autogenic contexts (Finsinger et al., 2024). A further advancement lies in integrating multi-proxy long-term data with experimental approaches to manipulate environmental variables that are quantitatively reconstructed by proxies (Lamentowicz et al., 2016; Andrews et al., 2021). The next level of understanding is to reconstruct long-term food web changes using peat records with methods applied to the modern ecosystems (Gilbert et al., 1998; Jassey et al., 2013; Wyatt et al., 2021). Progress in understanding past ecosystem structures and their functioning in relation to climate and human interventions might be a solid objective in the following decades. This becomes realistic considering a growing understanding of the identification of proxies, taxonomy, and ecology of peatland-dwelling taxa. Furthermore, a stronger international interdisciplinary cooperation of scientists building extensive databases makes this new perspective feasible. Moreover, combining AI with the palaeoecological studies might be extremely helpful in the decision-making process in nature conservation (Berger-Tal et al., 2024).

10. Conclusions

The multi-proxy approach offers a detailed and enriched view of palaeoenvironmental changes over time, aiding in the synthesis of various proxies like testate amoebae, pollen, plant macrofossils, charcoal, and stable isotopes to reconstruct past environments. Despite the complexity of synthesising multiple proxy records and potential challenges posed by journal guidelines, such an approach validates peatland palaeoclimatic records by comparing local data with proxies from nearby locations. This helps us to avoid speculative climatic interpretations and emphasises the significant impacts of human activities on ecosystems, particularly peatlands. Peatlands serve as natural archives, preserving evidence of past environmental and human activities that enable researchers to reconstruct historical ecosystems and human impacts. Integrating diverse research methods, including an interdisciplinary approach across ecology, palaeoecology, archaeology, and history, and linking high-resolution palaeoecological research with historical data provide insights into settlement patterns, economic development, and historical demography. Challenges in analysing large datasets are addressed by employing advanced statistical methods to derive meaningful interpretations, while careful proxy selection and interpretation simplify analyses without compromising the richness of data. For example, historical records provide valuable information on land ownership, resource exploitation, and population density, enhancing the understanding of the human impact on nature and the influence of climate on human populations. By reconstructing long-term

changes in food webs using peat records, one aims to understand past ecosystem structures and their functioning, thus paving the way for future ecological breakthroughs. The comprehensive integration of multi-proxy data enhances understanding of the interactions between climate, human populations, and the environment, offering substantial potential for constructing alternative hypotheses in the complex multi-dimensional palaeoecological space. While the focus has usually been on multi-proxy palaeoclimatic inferences in the last decades, the archaeological and historical context has still been poorly studied. This approach's potential lies on the frontiers of various disciplines like geography, history, and archaeology, as well as in integrating peat records with other archives such as lake sediments, tree rings, speleothems, and marine sediments. We can only get closer to the truth by extending our comfort zone to approach the complex multivariate data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

References

Aaby, B., 1976. Cyclic climatic variations in climate over the past 5,500 yr reflected in raised bogs. Nature 263, 281–284. https://doi.org/10.1038/263281a0.

Aaby, B., 1986. Palaeoecological studies of mires. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons Ltd., pp. 145–163

Aaby, B., Tauber, H., 1975. Rates of peat formation in relation to degree of humification of local environment, as shown by studies of raised bog in Denmark. Boreas 4, 1–17.

Abdalla, M., Hastings, A., Truu, J., Espenberg, M., Mander, Ü., Smith, P., 2016. 10. Emissions of methane from northern peatlands: a review of management impacts and implications for future management options. Ecol. Evol. 6, 7080–7102. https://doi.org/10.1002/ece3.2469.

Adl, S., Girard, V., Breton, G., Lak, M., Maharning, A., Mills, A., Perrichot, V., Trionnaire, M., Vullo, R., Neraudeau, D., 2011. Reconstructing the soil food web of a 100 million-year-old forest: The case of the mid-Cretaceous fossils in the amber of Charentes (SW France). Soil Biol. Biochem. 43, 726–735. https://doi.org/10.1016/j.soilbio.2010.12.003.

Adl, S.M., Simpson, A.G., Lane, C.E., Lukes, J., Bass, D., Bowser, S.S., Brown, M.W., Burki, F., Dunthorn, M., Hampl, V., Heiss, A., Hoppenrath, M., Lara, E., le Gall, L., Lynn, D.H., McManus, H., Mitchell, E.A., Mozley-Stanridge, S.E., Parfrey, L.W., Pawlowski, J., Rueckert, S., Shadwick, L., Schoch, C.L., Smirnov, A., Spiegel, F.W., 2012. The revised classification of eukaryotes. J. Eukaryot. Microbiol. 59, 429–514. https://doi.org/10.1111/j.1550-7408.2012.00644.x.

Adl, S.M., Bass, D., Lane, C.E., Lukeš, J., Schoch, C.L., Smirnov, A., Agatha, S., Berney, C., Brown, M.W., Burki, F., Cárdenas, P., Čepička, I., Chistyakova, L., Del Campo, J., Dunthorn, M., Edvardsen, B., Eglit, Y., Guillou, L., Hampl, V., Heiss, A.A., Hoppenrath, M., James, T.Y., Karnkowska, A., Karpov, S., Kim, E., Kolisko, M., Kudryavtsev, A., Lahr, D.J.G., Lara, E., Le Gall, L., Lynn, D.H., Mann, D.G., Massana, R., Mitchell, E.A.D., Morrow, C., Park, J.S., Pawlowski, J.W., Powell, M.J., Richter, D.J., Rueckert, S., Shadwick, L., Shimano, S., Spiegel, F.W., Torruella, G., Youssef, N., Zlatogursky, V., Zhang, Q., 2019. Revisions to the Classification, Nomenclature, and Diversity of Eukaryotes. J. Eukaryot. Microbiol. 66, 4–119. https://doi.org/10.1111/jeu.12691.

Adolf, C., Wunderle, S., Colombaroli, D., Weber, H., Gobet, E., Heiri, O., van Leeuwen, J. F.N., Bigler, C., Connor, S.E., Gałka, M., La Mantia, T., Makhortykh, S., Svitavská-Svobodová, H., Vannière, B., Tinner, W., 2018. The sedimentary and remote-sensing reflection of biomass burning in Europe. Glob. Ecol. Biogeogr. 27, 199–212. https://doi.org/10.1111/geb.12682.

Albert, B.M., Innes, J.B., Blackford, J.J., 2021. Multi-profile fine-resolution palynology of Late Mesolithic to Bronze Age peat at Cat Stones. The Holocene, Rishworth Moor, Central Pennines, UK. https://doi.org/10.1177/0959683620972768.

Almendinger, J.E., Leete, J.H., 1998. Peat characteristics and groundwater geochemistry of calcareous fens in the Minnesota River Basin, U.S.A. Biogeochemistry 43, 17–41.

Amesbury, M.J., Barber, K.E., Hughes, P.D.M., 2011. The methodological basis for fine-resolution, multi-proxy reconstructions of ombrotrophic peat bog surface wetness. Boreas 40, 161–174.

Amesbury, M.J., Swindles, G.T., Bobrov, A., Charman, D.J., Holden, J., Lamentowicz, M., Mallon, G., Mazei, Y., Mitchell, E.A.D., Payne, R.J., Roland, T.P., Turner, T.E., Warner, B.G., 2016. Development of a new pan-European testate amoeba transfer function for reconstructing peatland palaeohydrology. Quat. Sci. Rev. 152, 132–151. https://doi.org/10.1016/j.quascirev.2016.09.024.

Amesbury, M.J., Booth, R.K., Roland, T.P., Bunbury, J., Clifford, M.J., Charman, D.J., Elliot, S., Finkelstein, S., Garneau, M., Hughes, P.D.M., Lamarre, A., Loisel, J., Mackay, H., Magnan, G., Markel, E.R., Mitchell, E.A.D., Payne, R.J., Pelletier, N., Roe, H., Sullivan, M.E., Swindles, G.T., Talbot, J., van Bellen, S., Warner, B.G., 2018. Towards a Holarctic synthesis of peatland testate amoeba ecology: Development of a new continental-scale palaeohydrological transfer function for North America and comparison to European data. Quat. Sci. Rev. 201, 483–500. https://doi.org/10.1016/j.quascirev.2018.10.034.

Andrews, L.O., Rowson, J.G., Caporn, S.J.M., Dise, N.B., Barton, E., Garrett, E., Roland Gehrels, W., Gehrels, M., Kay, M., Payne, R.J., 2021. Plant community responses to experimental climate manipulation in a Welsh ombrotrophic peatland and their palaeoenvironmental context. Glob. Chang. Biol. https://doi.org/10.1111/gcb.16003.

Apolinarska, K., Kiełczewski, R., Pleskot, K., Marzec, M., Aunina, L., Michalska, D., Siepak, M., Kowalczyk, C., Gałka, M., 2024. The decline of tufa deposition in an alkaline fen ecosystem in East-Central Europe and its impact on biotic assemblages: Insights from monitoring and paleoecological data. Sci. Total Environ. 912, 169408. https://doi.org/10.1016/j.scitotenv.2023.169408.

Aquino-López, M.A., Blaauw, M., Christen, J.A., Sanderson, N.K., 2018. Bayesian Analysis of 210Pb Dating. J. Agric. Biol. Environ. Stat. 23, 317–333. https://doi.org/10.1007/s13253-018-0328-7.

Aquino-López, M.A., Sanderson, N.K., Blaauw, M., Sanchez-Cabeza, J.-A., Ruiz-Fernandez, A.C., Aquino-López, J.A.C.M.A., Sanderson, N.K., Blaauw, M., Sanchez-Cabeza, J.-A., Ruiz-Fernandez, A.C., Christen, J.A., 2020. A simulation study to compare 210Pb dating data analyses. arXiv 2012.06819v1.

Austin, K.G., Elsen, P.R., Coronado, E.N.H., DeGemmis, A., Gallego-Sala, A.V., Harris, L., Kretser, H.E., Melton, J.R., Murdiyarso, D., Sasmito, S.D., Swails, E., Wijaya, A., Winton, R.S., Zarin, D., 2025. Mismatch Between Global Importance of Peatlands and the Extent of Their Protection. Conserv. Lett. 18, 0. doi: https://doi.org/10.1111/conl.13080.

Baillie, M.G.L., 1991. Suck in and smear: two related chronological problems for the 90s. J. Theoretical Archaeol. 2, 12–16.

Bąk, M., Lamentowicz, M., Kołaczek, P., Wochal, D., Matulewski, P., Kopeć, D., Wietecha, M., Jaster, D., Marcisz, K., 2024. Assessing the impact of forest management and climate on a peatland under Scots pine monoculture using a multidisciplinary approach. Biogeosciences 21, 5143–5172. https://doi.org/10.5194/bg-21-5143-2024.

Bąk, M., Lamentowicz, M., Kołaczek, P., Wochal, D., Jakubowicz, M., Andrews, L., Marcisz, K., 2025. Twentieth-century ecological disasters in central European monoculture pine plantations led to critical transitions in peatlands. Biogeosciences 22, 3843–3866. https://doi.org/10.5194/bg-22-3843-2025.

Barber, K., 1993. Peatlands as scientific archives of past biodiversity. Biodivers. Conserv. 2, 474–489.

Barber, K., Charman, D., 2003. Holocene palaeoclimate records from peatlands. In: Mackay, A., Battarbee, R.W., Birks, H.H., Oldfield, F. (Eds.), Global Change in the Holocene. Arnold, London, pp. 210–226.

Bardgett, R.D., van der Putten, W.H., 2014. Belowground biodiversity and ecosystem functioning. Nature 515, 505–511. https://doi.org/10.1038/nature13855.

Barel, J.M., Petchey, O.L., Ghaffouli, A., Jassey, V.E.J., 2023. Uncovering microbial food webs using machine learning. Soil Biol. Biochem. 186, 109174. https://doi.org/10.1016/j.soilbio.2023.109174.

Basquill, S.P., Leroux, S.J., 2023. Predicting ecosystem pattern across landscapes. Oikos. https://doi.org/10.1111/oik.09873.

Basumatary, S., McDonald, H., 2017. Coprophilous fungi from dung of the Greater One-Horned Rhino in Kaziranga National Park, India and its implication to paleoherbivory and paleoecology. Quat. Res. 88, 14–22. https://doi.org/10.1017/qua.2017.34.

Beaulne, J., Garneau, M., Magnan, G., Boucher, É., 2021. Peat deposits store more carbon than trees in forested peatlands of the boreal biome. Sci. Rep. 11, 2657. https://doi.org/10.1038/s41598-021-82004-x.

Behre, K.-E., Kucan, 1986. The reflection of archaeologically known settlements in pollen diagrams of varying distances. Examples from the siedlungskammer Flögeln, NW Germany. In: Behre, K.-E. (Ed.), Athropogenic Indicators in Pollen Diagrams. A.A. Balkema, Rotterdam/Boston, pp. 95–113jo.

Beilman, D.W., MacDonald, G.M., Smith, L.C., Reimer, P.J., 2009. Carbon accumulation in peatlands of West Siberia over the last 2000 years. Glob. Biogeochem. Cycles 23. https://doi.org/10.1029/2007gb003112.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., Courchamp, F., 2012. Impacts of climate change on the future of biodiversity. Ecol. Lett. https://doi.org/10.1111/j.1461-0248.2011.01736.x.

Berger, H., 1970. Atlas of seeds and fruits of North-European plant species (Sweden, Norway, Denmark, East Fennoscandia and Iceland) with morphological descriptions. In: Part 3, Salicaceae - Cruciferae. Swedish Natural Science Research Council, Stockholm.

Berger-Tal, O., Wong, B.B.M., Adams, C.A., Blumstein, D.T., Candolin, U., Gibson, M.J., Greggor, A.L., Lagisz, M., Macura, B., Price, C.J., Putman, B.J., Snijders, L., Nakagawa, S., 2024. Leveraging AI to improve evidence synthesis in conservation. Trends Ecol. Evol. 39, 548–557. https://doi.org/10.1016/j.tree.2024.04.007.

Berggren, G., 1968. Atlas of seeds and fruits of North-European plant species (Sweden, Norway, Denmark, East Fennoscandia and Iceland) with morphological descriptions. In: Part 2, *Cyperaceae*. Swedish Natural Science Research Council, Stockholm.
Berglund, B.E., 1986. Handbook of Holocene Palaeoecology and Palaeohydrology, p. 869.
Berglund, B.E., Ralska-Jasiewiczowa, M., 1986. Pollen analysis and pollen diagrams. In: Berglund, B.E. (Ed.), Handbook of Holocene Paleoecology and Paleohydrology. Wiley & Sons Ltd., Chichester-Toronto, pp. 455–484.
Berglund, B.E., Malmer, N., Persson, T., 1991. Landscape-ecological aspects of long-term changes in the Ystad area. The cultural landscape during 6000 years in southern Sweden 405–424.
Beyens, L., Meisterfeld, R., 2001. Protozoa: Testate Amoebae, in: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestial, Algal and Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, pp. 121–153.
Biagioni, S., Krashevska, V., Achnopha, Y., Saad, A., Sabiham, S., Behling, H., 2015. 8000 years of vegetation dynamics and environmental changes of a unique inland peat ecosystem of the Jambi Province in Central Sumatra, Indonesia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 440, 813–829. https://doi.org/10.1016/j.palaeo.2015.09.048.
Biester, H., Knorr, K.H., Schellekens, J., Basler, A., Hermanns, Y.M., 2014. Comparison of different methods to determine the degree of peat decomposition in peat bogs. Biogeosciences 11, 2691–2707. https://doi.org/10.5194/bg-11-2691-2014.
Birks, H.J.B., 1995. Quantitative Palaeoenvironmental Reconstructions. In: Maddy, D., Brew, J.S. (Eds.), Statistical Modelling of Quaternary Science Data. Quaternary Research Associacion, Cambridge, pp. 161–254.
Birks, H.J.B., 1998. Numerical tools in palaeolimnology - Progress, potentialities, and problems. J. Paleolimnol. 20, 307–332.
Birks, H.H., 2007. Plant macrofossil introduction. In: Encyclopedia of Quaternary Science. Elsevier, pp. 2266–2288. https://doi.org/10.1016/b0-44-452747-8/00215-5.
Birks, H.J.B., 2012. Ecological palaeoecology and conservation biology: controversies, challenges, and compromises. Int. J. Biodiv. Sc. Ecosyst. Serv. Manag. 8, 292–304. https://doi.org/10.1080/21513732.2012.701667.
Birks, H.H., 2017. Plant macrofossil introduction. In: Reference Module in Earth Systems and Environmental Sciences. Elsevier. https://doi.org/10.1016/b978-0-12-409548-9.10499-3.
Birks, H.J.B., 2019. Contributions of Quaternary botany to modern ecology and biogeography. Plant Ecol. Diversity 12, 189–385. https://doi.org/10.1080/17550874.2019.1646831.
Birks, H.J.B., Berglund, B.E., 2018. One hundred years of Quaternary pollen analysis 1916–2016. Veg. Hist. Archaeobotany 27, 271–309. https://doi.org/10.1007/s00334-017-0630-2.
Birks, H.J.B., Birks, H.H., 1980. Quaternary palaeoecology. Arnold, London.
Birks, H.J.B., Birks, H.H., 2000. Future uses of pollen analysis must include plant macrofossils. J. Biogeogr. 27, 31–35.
Birks, H.H., Birks, H.J.B., 2006. Multi-proxy studies in palaeolimnology. Veget. Hist. Archaeobot. 15, 235–251. https://doi.org/10.1007/s00334-006-0066-6.
Birks, H.J.B., Birks, H.H., 2016. How have studies of ancient DNA from sediments contributed to the reconstruction of Quaternary floras? New Phytol. 209, 499–506. https://doi.org/10.1111/nph.13657.
Birks, H.J.B., Felde, V.A., Bjune, A.E., Grytnes, J.-A., Seppä, H., Giesecke, T., 2016. Does pollen-assemblage richness reflect floristic richness? A review of recent developments and future challenges. Rev. Palaeobot. Palynol. 228, 1–25. https://doi.org/10.1016/j.revpalbo.2015.12.011.
Björck, S., Rundgren, M., Ljung, K., Unkel, I., Wallin, Å., 2012. Multi-proxy analyses of a peat bog on Isla de los Estados, easternmost Tierra del Fuego: a unique record of the variable Southern Hemisphere Westerlies since the last deglaciation. Quat. Sci. Rev. 42, 1–14. https://doi.org/10.1016/j.quascirev.2012.03.015.
Blaauw, M., Christen, J.A., 2005. Radiocarbon peat chronologies and environmental change. Appl. Stat. 54.
Blaauw, M., Christen, J.A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Anal. 6, 457–474.
Blaauw, M., Mauquoy, D., 2012. Signal and variability within a Holocene peat bog - Chronological uncertainties of pollen, macrofossil and fungal proxies. Rev. Palaeobot. Palynol. 186, 5–15. https://doi.org/10.1016/j.revpalbo.2012.06.005.
Blaauw, M., Bakker, R., Andrés Christen, J., Hall, V.A., van der Plicht, J., 2007. A Bayesian framework for age modeling of radiocarbon-dated peat deposits: Case studies from the Netherlands. Radiocarbon 49, 357–367.
Blaauw, M., Christen, J.A., Bennett, K.D., Reimer, P.J., 2018. Double the dates and go for Bayes — Impacts of model choice, dating density and quality on chronologies. Quat. Sci. Rev. 188, 58–66. https://doi.org/10.1016/j.quascirev.2018.03.032.
Blackford, J.J., Chambers, F.M., 1991. Proxy records of climate from blanket mires: evidence for a Dark Age (1400 BP) climatic deterioration in the British Isles. The Holocene 1, 63–67. https://doi.org/10.1177/095968369100100108.
Blackford, J.J., Chambers, F.M., 1995. Proxy climate record for the last 1000 years from Irish blanket peat and a possible link to solar variability. Earth Planet. Sci. Lett. 133, 145–150.
Blarquez, O., Vannière, B., Marlon, J.R., Daniau, A.-L., Power, M.J., Brewer, S., Bartlein, P.J., 2014. paleofire: An R package to analyse sedimentary charcoal records from the Global Charcoal Database to reconstruct past biomass burning. Comput. Geosci. 72, 255–261. https://doi.org/10.1016/j.cageo.2014.07.020.
Blodau, C., 2002. Carbon cycling in peatlands A review of processes and controls. Environ. Rev. 10, 111–134. https://doi.org/10.1139/a02-004.
Blundell, A., Barber, K., 2005. A 2800-year palaeoclimatic record from Tore Hill Moss, Strathspey, Scotland: the need for a multi-proxy approach to peat-based climate reconstructions. Quat. Sci. Rev. 24, 1261–1277.
Blundell, A., Holden, J., 2015. Using palaeoecology to support blanket peatland management. Ecol. Indic. 49, 110–120. https://doi.org/10.1016/j.ecolind.2014.10.006.
Blundell, A.C., Langdon, P.G., 2023. A 3000-year multi-proxy palaeoclimate record from Killorn Moss, Stirlingshire. Scotland, Mires and Peat, p. 29.
Blundell, A., Charman, D.J., Barber, K., 2008. Multi-proxy late Holocene peat records from Ireland: towards a regional palaeoclimate curve. J. Quat. Sci. 23, 59–71.
Bonnet, L., 1974. Les Thécamoebiens. In: Quelques Aspects de La Faune Des Mousses. Annales du centre régional de recherche et de documentation pédagogiques de Clermont-Ferrand, Clermont-Ferrand, France, pp. 21–30.
Booth, R., 2025. Testate amoebae as paleoenvironmental indicators in peatlands: calibration-dataset synthesis and assessment of modern analogues using the Neotoma Paleoecology Database. Quat. Sci. Rev. https://doi.org/10.1016/j.quascirev.2025.109491.
Booth, R.K., Jackson, S.T., Gray, C.E.D., 2004. Paleoecology and high-resolution paleohydrology of a kettle peatland in upper Michigan. Quat. Res. 61, 1–13.
Borgmark, A., Schoning, K., 2006. A comparative study of peat proxies from two eastern central Swedish bogs and their relation to meteorological data. J. Quat. Sci. 21, 109–114.
Borromei, A.M., Coronato, A., Franzén, L.G., Ponce, J.F., Sáez, J.A.L., Maidana, N., Rabassa, J., Candel, M.S., 2010. Multi-proxy record of Holocene paleoenvironmental change, Tierra del Fuego, Argentina. Palaeogeogr. Palaeoclimatol. Palaeoecol. 286, 1–16. https://doi.org/10.1016/j.palaeo.2009.11.033.
Bramanti, B., Wu, Y., Yang, R., Cui, Y., Stenseth, N.C., 2021. Assessing the origins of the European Plagues following the Black Death: A synthesis of genomic, historical, and ecological information. Proc. Natl. Acad. Sci. USA 118, e2101940118. https://doi.org/10.1073/pnas.2101940118.
Brinkkemper, O., van Haaster, H., 2012. Eggs of intestinal parasites whipworm (Trichuris) and mawworm (Ascaris): Non-pollen palynomorphs in archaeological samples. Rev. Palaeobot. Palynol. 186, 16–21. https://doi.org/10.1016/j.revpalbo.2012.07.003.
Bronk Ramsey, C., 2001. Development of the Radiocarbon Program OxCal. Radiocarbon 43, 355–363.
Brown, A.G., Van Hardenbroek, M., Fonville, T., Davies, K., Mackay, H., Murray, E., Head, K., Barratt, P., McCormick, F., Ficetola, G.F., Gielly, L., Henderson, A.C.G., Crone, A., Cavers, G., Langdon, P.G., Whitehouse, N.J., Pirrie, D., Alsos, I.G., 2021. Ancient DNA, lipid biomarkers and palaeoecological evidence reveals construction and life on early medieval lake settlements. Sci. Rep. 11, 11807. https://doi.org/10.1038/s41598-021-91057-x.
Brown, K.A., Bunting, M.J., Carvalho, F., de Bello, F., Mander, L., Marcisz, K., Mottl, O., Reitalu, T., Svenning, J., 2023. Trait-based approaches as ecological time machines: Developing tools for reconstructing long-term variation in ecosystems. Funct. Ecol. 37, 2552–2569. https://doi.org/10.1111/1365-2435.14415.
Brussel, T., Brewer, S.C., 2021. Functional Paleoecology and the Pollen-Plant Functional Trait Linkage. Front. Ecol. Evol. 8. https://doi.org/10.3389/fevo.2020.564609.
Bryant, V.M., Holloway, R.G., 1983. The role of palynology in archaeology. In: Advances in Archaeological Method and Theory. Elsevier, pp. 191–224. https://doi.org/10.1016/b978-0-12-003106-1.50010-9.
Büntgen, U., Esper, J., 2024. The need for high-resolution paleoclimate research. Dialogues Climate Change 0. https://doi.org/10.1177/29768659241305959.
Bunting, M.J., Warner, B.G., 1998. Hydroseral development in southern Ontario: Patterns and controls. J. Biogeogr. 25, 3–18.
Buttler, A., Bragazza, L., Laggoun-Défarge, F., Gogo, S., Toussaint, M.-L., Lamentowicz, M., Chojnicki, B.H., Słowiński, M., Słowińska, S., Zielińska, M., Reczuga, M., Barabach, J., Marcisz, K., Lamentowicz, Ł., Harenda, K., Lapshina, E., Gilbert, D., Schlaepfer, R., Jassey, V.E.J., 2023. Ericoid shrub encroachment shifts aboveground-belowground linkages in three peatlands across Europe and Western Siberia. Glob. Chang. Biol. 29, 6772–6793. https://doi.org/10.1111/gcb.16904.
Bysouth, D., Finkelstein, S.A., 2021. Linking testate amoeba assemblages to paleohydrology and ecosystem function in Holocene peat records from the Hudson Bay Lowlands. The Holocene, Ontario, Canada. https://doi.org/10.1177/09596836209727922.
Cao, X., Tian, F., Li, F., Gaillard, M.-J., Rudaya, N., Xu, Q., Herzschuh, U., 2019. Pollen-based quantitative land-cover reconstruction for northern Asia covering the last 40 ka cal BP. Clim. Past 15, 1503–1536. doi: https://doi.org/10.5194/cp-15-1503-2019.
Capo, E., Barouillet, C., Smol, J.P. (Eds.), 2023. Tracking Environmental Change Using Lake Sediments. Volume 6: Sedimentary DNA. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-031-43799-1.
Carballeira, R., Pontevedra-Pombal, X., 2020. Diatoms in Paleoenvironmental Studies of Peatlands. Quaternary 3, 10. https://doi.org/10.3390/quat3020010.
Caseldine, C., Gearey, B., 2005. A multi-proxy approach to reconstructing surface wetness changes and prehistoric bog bursts in a raised mire system at Derryville Bog, 15. Holocene, Co. Tipperary, Ireland, pp. 585–601. https://doi.org/10.1191/0959683605hl833rp.
Cedro, A., Lamentowicz, M., 2008. Last hundred years dendroecology of Scots pine Pinus sylvestris L. on a raised bog in northern Poland: human impact and hydrological changes. Balt. For. 14, 26–33.
Cedro, A., Lamentowicz, M., 2011. Contrasting responses to environmental changes by pine (Pinus sylvestris L.) growing on peat and mineral soil: An example from a Polish Baltic bog. Dendrochronologia 29, 211–217. https://doi.org/10.1016/j.dendro.2010.12.004.

Chambers, F.M., Charman, D.J., 2004. Holocene environmental change: contributions from the peatland archive. The Holocene 14, 1–6. https://doi.org/10.1191/0959683604hl684ed.
Chambers, F.M., Beilman, D.W., Yu, Z., 2011. Methods for determining peat humification and for quantifying peat bulk density, organic matter and carbon content for palaeostudies of climate and peatland carbon dynamics. Mires Peat 7.
Chambers, F.M., Booth, R.K., De Vleeschouwer, F., Lamentowicz, M., Le Roux, G., Mauquoy, D., Nichols, J.E., van Geel, B., 2012. Development and refinement of proxy-climate indicators from peats. Quat. Int. 268, 21–33. https://doi.org/10.1016/j.quaint.2011.04.039.
Chambers, F., Crowle, A., Daniell, J., Mauquoy, D., McCarroll, J., Sanderson, N., Thom, T., Toms, P., Webb, J., 2017. Ascertaining the nature and timing of mire degradation: using palaeoecology to assist future conservation management in Northern England. AIMS Environ. Sci. 4, 54–82. https://doi.org/10.3934/environsci.2017.1.54.
Charman, D., 2002. Peatlands and Environmental Change. Wiley, Chichester.
Charman, D.J., 2007. Summer water deficit variability controls on peatland water-table changes: implications for Holocene palaeoclimate reconstructions. The Holocene 17, 217–227.
Charman, D.J., Garnett, M.H., 2005. Chronologies for Recent Peat Deposits Using Wiggle–matched Radiocarbon Ages: Problems with Old Carbon Contamination. Radiocarbon 47, 135–145. https://doi.org/10.1017/S0033822200052255.
Charman, D.J., Hendon, D., Packman, S., 1999. Multi-proxy surface wetness records from replicate cores on an ombrotrophic mire: implications for Holocene palaeoclimate records. J. Quat. Sci. 14, 451–463.
Charman, D.J., Hendon, D., Woodland, W.A., 2000. The identification of testate amoebae (Protozoa: Rhizopoda) in peats. Technical Guide No. 9. Quaternary Research Association, London.
Charman, D.J., Caseldine, C., Baker, A., Gearey, B., Hatton, J., Proctor, C., 2001. Paleohydrological records from peat profiles and speleothems in Sutherland, northwest Scotland. Quat. Res. 55, 223–234.
Charman, D.J., Blundell, A., Chiverrell, R.C., Hendon, D., Langdon, P.G., 2006. Compilation of non-annually resolved Holocene proxy climate records: stacked Holocene peatland palaeo-water table reconstructions from northern Britain. Quat. Sci. Rev. 25, 336–350.
Claire, L.C., Graeme, T.S., Elizabeth, J.W., Ivan, P.S., Mariusz, G., Angela, G.-S., Werner, B., 2019. Evaluating tephrochronology in the permafrost peatlands of northern Sweden. Quat. Geochronol. 50, 16–28. https://doi.org/10.1016/j.quageo.2018.11.001.
Clymo, R.S., 1984. The limits to peat bog growth. Philosophical Transactions of the Royal Society of London. Biol. Sci. 303, 605–654.
Clymo, R.S., MacKay, D.M., 1987. Upwash and downwash of pollen and spores in the unsaturated layer of *Sphagnum*-dominated peat. New Phytol. 105, 175–183.
Clymo, R.S., Turunen, J., Tolonen, K., 1998. Carbon accumulation in peatlands. Oikos 81, 368–388.
Colombaroli, D., Ssemmanda, I., Gelorini, V., Verschuren, D., 2014. Contrasting long-term records of biomass burning in wet and dry savannas of equatorial East Africa. Glob. Chang. Biol. 20, 2903–2914. https://doi.org/10.1111/gcb.12583.
Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A.F., Krebs, P., 2009. 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.
Connor, S.E., Colombaroli, D., Confortini, F., Gobet, E., Ilyashuk, B.P., Ilyashuk, E.A., van Leeuwen, J.F.N., Lamentowicz, M., van der Knaap, W.O., Malysheva, E., Marchetto, A., Margalitadze, N., Mazei, Y., Mitchell, E.A.D., Payne, R.J., Ammann, B., 2018. Long-term population dynamics: Theory and reality in a peatland ecosystem. J. Ecol. 106, 333–346. https://doi.org/10.1111/1365-2745.12865.
Constantine, M., Mooney, S., 2022. Widely used charcoal analysis method in paleo studies involving NaOCl results in loss of charcoal formed below 400°C. The Holocene 32, 1358–1362. https://doi.org/10.1177/09596836211041740.
Costa, L.R., Trugilho, P.F., Hein, P.R.G., 2018. Evaluation and classification of eucalypt charcoal quality by near infrared spectroscopy. Biomass Bioenergy 112, 85–92. https://doi.org/10.1016/j.biombioe.2018.02.017.
Crabtree, S.A., Dunne, J.A., 2022. Towards a science of archaeoecology. Trends Ecol. Evol. S0169-5347 (22), 00174. https://doi.org/10.1016/j.tree.2022.07.010.
Crichton, K.A., Anderson, K., Fewster, R.E., Charman, D.J., Garneau, M., Väliranta, M., Mleczko, M., Handley, J.N., Hodson, S., Parker, R.E., Swindles, G.T., Blaauw, M., Gallego-Sala, A.V., 2025. Satellite data indicates recent Arctic peatland expansion with warming. Commun. Earth Environ. 6, 461. https://doi.org/10.1038/s43247-025-02375-1.
Cwanek, A., Aquino-Lopez, M.A., Kołaczek, P., Lamentowicz, M., Fiałkiewicz-Kozieł, B., Gałka, M., Słowiński, M., Łucław, D., Marcisz, K., Obremska, M., Czerwiński, S., Łokas, E., 2025. Strengthening potential of recent peat dating. J. Environ. Radioact. 282, 107594. https://doi.org/10.1016/j.jenvrad.2024.107594.
Czerwiński, S., Guzowski, P., Karpińska-Kołaczek, M., Lamentowicz, M., Gałka, M., Kołaczek, P., Izdebski, A., Poniat, R., 2019. Znaczenie wspólnych badań historycznych i paleoekologicznych nad wpływem człowieka na środowisko. Przykład ze stanowiska Kazanie we wschodniej Wielkopolsce. Studia Geohistorica 56. https://doi.org/10.12775/sg.2019.04.
Czerwiński, S., Guzowski, P., Lamentowicz, M., Gałka, M., Karpińska-Kołaczek, M., Poniat, R., Łokas, E., Diaconu, A.-C., Schwarzer, J., Miecznik, M., Kołaczek, P., 2021. Environmental implications of past socioeconomic events in Greater Poland during the last 1200 years. Synthesis of paleoecological and historical data. Quat. Sci. Rev. 259, 106902. https://doi.org/10.1016/j.quascirev.2021.106902.
Czerwiński, S., Marcisz, K., Wacnik, A., Lamentowicz, M., 2022. Synthesis of palaeoecological data from the Polish Lowlands suggests heterogeneous patterns of old-growth forest loss after the Migration Period. Sci. Rep. 12. https://doi.org/10.1038/s41598-022-12241-1.
Daley, T.J., Barber, K.E., Street-Perrott, F.A., Loader, N.J., Marshall, J.D., Crowley, S.F., Fisher, E.H., 2010. Holocene climate variability revealed by oxygen isotope analysis of Sphagnum cellulose from Walton Moss, northern England. Quat. Sci. Rev. 29, 1590–1601.
Daley, T.J., Mauquoy, D., Chambers, F.M., Street-Perrott, F.A., Hughes, P.D.M., Loader, N.J., Roland, T.P., van Bellen, S., Garcia-Meneses, P., Lewin, S., 2012. Investigating late Holocene variations in hydroclimate and the stable isotope composition of precipitation using southern South American peatlands: an hypothesis. Clim. Past 8, 1457–1471. https://doi.org/10.5194/cp-8-1457-2012.
Dargie, G.C., et al., 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature 542, 86–90. https://doi.org/10.1038/nature21048.
Davidson, D.A., Carter, S., Boag, B., Long, D., Tipping, R., Tyler, A., 1999. Analysis of pollen in soils: processes of incorporation and redistribution of pollen in five soil profile types. Soil Biol. Biochem. 31, 643–653.
Davies, S.M., 2015. Cryptotephras: the revolution in correlation and precision dating. J. Quat. Sci. 30, 114–130. https://doi.org/10.1002/jqs.2766.
Davies, L.J., Appleby, P., Jensen, B.J.L., Magnan, G., Mullan-Boudreau, G., Noernberg, T., Shannon, B., Shotyk, W., van Bellen, S., Zaccone, C., Froese, D.G., 2018. High-resolution age modelling of peat bogs from northern Alberta, Canada, using pre- and post-bomb 14 C, 210 Pb and historical cryptotephra. Quat. Geochronol. 47, 138–162. https://doi.org/10.1016/j.quageo.2018.04.008.
Davies, A.L., Harrault, L., Milek, K., McClymont, E.L., Dallimer, M., Hamilton, A., Warburton, J., 2022. A multi-proxy approach to long-term herbivore grazing dynamics in peatlands based on pollen, coprophilous fungi and faecal biomarkers. Palaeogeogr. Palaeoclimatol. Palaeoecol. 598, 111032. https://doi.org/10.1016/j.palaeo.2022.111032.
de Jong, R., Blaauw, M., Chambers, F.M., Christensen, T.R., De Vleeschouwer, F., Finsinger, W., Fronzek, S., Johansson, M., Kokfelt, U., Lamentowicz, M., LeRoux, G., Mitchell, E.A.D., Mauquoy, D., Nichols, J.E., Samaritani, E., van Geel, B., 2010. Climate and peatlands. In: Dodson, J. (Ed.), Changing Climates, Earth Systems and Society. Series: International Year of Planet Earth. Springer, Heidelberg, pp. 85–121. https://doi.org/10.1007/978-90-481-8716-4 5.
De Vleeschouwer, F., Chambers, F.M., Swindles, G.T., 2010. Coring and sub-sampling of peatlands for palaeoenvironmental research. Mires Peat 7, 1–10.
Degroot, D., Anchukaitis, K., Bauch, M., Burnham, J., Carnegy, F., Cui, J., de Luna, K., Guzowski, P., Hambrecht, G., Huhtamaa, H., Izdebski, A., Kleemann, K., Moesswilde, E., Neupane, N., Newfield, T., Pei, Q., Xoplaki, E., Zappia, N., 2021. Towards a rigorous understanding of societal responses to climate change. Nature 591, 539–550. https://doi.org/10.1038/s41586-021-03190-2.
Deza-Araujo, M., Morales-Molino, C., Conedera, M., Pezzatti, G.B., Pasta, S., Tinner, W., 2022. Influence of taxonomic resolution on the value of anthropogenic pollen indicators. Veg. Hist. Archaeobotany 31, 67–84. https://doi.org/10.1007/s00334-021-00838-x.
Diaconu, A.-C., Tóth, M., Lamentowicz, M., Heiri, O., Kuske, E., Tanţău, I., Panait, A.-M., Braun, M., Feurdean, A., 2017. How warm? How wet? Hydroclimate reconstruction of the past 7500 years in northern Carpathians, Romania. Palaeogeogr. Palaeoclimatol. Palaeoecol. 482, 1–12. https://doi.org/10.1016/j.palaeo.2017.05.007.
Dickson, J.H., 1986. Bryophyte analysis. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons, pp. 627–643.
Dobrowolski, R., Pidek, I., Alexandrowicz, W., Hałas, S., Pazdur, A., Piotrowska, N., Buczek, A., Urban, D., Melke, J., 2012. Interdisciplinary studies of spring mire deposits from Radzików (South Podlasie Lowland, East Poland) and their significance for palaeoenvironmental reconstructions. Geochronometria 39. https://doi.org/10.2478/s13386-011-0052-3.
Dobrowolski, R., Bałaga, K., Buczek, A., Alexandrowicz, W.P., Mazurek, M., Hałas, S., Piotrowska, N., 2016. Multi-proxy evidence of Holocene climate variability in Volhynia Upland (SE Poland) recorded in spring-fed fen deposits from the Komarów site. The Holocene 26, 1406–1425. https://doi.org/10.1177/0959683616640038.
Dobrowolski, R., Mazurek, M., Osadowski, Z., Alexandrowicz, W.P., Pidek, I.A., Pazdur, A., Piotrowska, N., Drzymulska, D., Urban, D., 2019. Holocene environmental changes in northern Poland recorded in alkaline spring-fed fen deposits – A multi-proxy approach. Quat. Sci. Rev. 219, 236–262. https://doi.org/10.1016/j.quascirev.2019.05.027.
Dommain, R., Andama, M., McDonough, M.M., Prado, N.A., Goldhammer, T., Potts, R., Maldonado, J.E., Nkurunungi, J.B., Campana, M.G., 2020. The Challenges of Reconstructing Tropical Biodiversity With Sedimentary Ancient DNA: A 2200-Year-Long Metagenomic Record From Bwindi Impenetrable Forest, Uganda. Front. Ecol. Evol. 8, 36. https://doi.org/10.3389/fevo.2020.00218.
Dreibrodt, S., Wiethold, J., 2015. Lake Belau and its catchment (northern Germany): A key archive of environmental history in northern central Europe since the onset of agriculture. The Holocene 25, 296–322. https://doi.org/10.1177/0959683614558648.
Duckert, C., Blandenier, Q., Kupferschmid, F.A.L., Kosakyan, A., Mitchell, E.A.D., Lara, E., Singer, D., 2018. En garde! Redefinition of Nebela militaris (Arcellinida, Hyalospheniidae) and erection of Alabasta gen. nov. Eur. J. Protistol. 66, 156–165. https://doi.org/10.1016/j.ejop.2018.08.005.
Edvardsson, J., Linderson, H., Rundgren, M., Hammarlund, D., 2012. Holocene peatland development and hydrological variability inferred from bog-pine dendrochronology and peat stratigraphy - a case study from southern Sweden. J. Quat. Sci. 27, 553–563. https://doi.org/10.1002/jqs.2543.

Ellis, E.C., 2015. Ecology in an anthropogenic biosphere. Ecol. Monogr. 85, 287–331. https://doi.org/10.1890/14-2274.1.
Epp, L.S., Boessenkool, S., Bellemain, E.P., Haile, J., Esposito, A., Riaz, T., Erséus, C., Gusarov, V.I., Edwards, M.E., Johnsen, A., Stenøien, H.K., Hassel, K., Kauserud, H., Yoccoz, N.G., Bråthen, K.A., Willerslev, E., Taberlet, P., Coissac, E., Brochmann, C., 2012. New environmental metabarcodes for analysing soil DNA: potential for studying past and present ecosystems. Mol. Ecol. 21, 1821–1833. https://doi.org/10.1111/j.1365-294X.2012.05537.x.
Evans, C.D., Peacock, M., Baird, A.J., Artz, R.R.E., Burden, A., Callaghan, N., Chapman, P.J., Cooper, H.M., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R.P., Helfter, C., Heppell, C.M., Holden, J., Jones, D.L., Kaduk, J., Levy, P., Matthews, R., McNamara, N.P., Misselbrook, T., Oakley, S., Page, S.E., Rayment, M., Ridley, L.M., Stanley, K.M., Williamson, J.L., Worrall, F., Morrison, R., 2021. Overriding water table control on managed peatland greenhouse gas emissions. Nature 593, 548–552. https://doi.org/10.1038/s41586-021-03523-1.
Everard, A., Schofield, J.E., Mighall, T., Timpany, S., Plunkett, G., 2024. The missing woodland story: Implications of 1700 years of stand-scale change on 'naturalness' and managing remnant broadleaved woodlands. People Nature 0. https://doi.org/10.1002/pan3.10752.
Faegri, K., Iversen, J., Kaland, P.E., Krzywinski, K., 2000. Textbook of Pollen Analysis. Blackburn Press.
Feurdean, A., Diaconu, A.-C., Pfeiffer, M., Gałka, M., Hutchinson, S.M., Butiseaca, G., Gorina, N., Tonkov, S., Niamir, A., Tantau, I., Kirpotin, S., 2021. Holocene wildfire regimes in forested peatlands in western Siberia: interaction between peatland moisture conditions and the composition of plant functional types. https://doi.org/10.5194/cp-2021-125.
Feurdean, A., Vachula, R.S., Hanganu, D., Stobbe, A., Gumnior, M., 2023. Charcoal morphologies and morphometrics of a Eurasian grass-dominated system for robust interpretation of past fuel and fire type. Biogeosciences 20, 5069–5085. https://doi.org/10.5194/bg-20-5069-2023.
Fewster, R.E., Swindles, G.T., Carrivick, J.L., Gałka, M., Roland, T.P., McKeown, M., Sutherland, J.L., Tweed, F., Mullan, D., Graham, C., 2025. Climate warming and deglaciation drive new peat formation in the Southern Alps. Geophysical Research Letters, Aotearoa/New Zealand. https://doi.org/10.1029/2024GL113786.
Fiałkiewicz-Kozieł, B., Smieja-Król, B., Piotrowska, N., Sikorski, J., Gałka, M., 2014. Carbon accumulation rates in two poor fens with different water regimes: Influence of anthropogenic impact and environmental change. The Holocene 24, 1539–1549. https://doi.org/10.1177/0959683614544062.
Fiałkiewicz-Kozieł, B., Smieja-Król, B., Ostrovnaya, T.M., Frontasyeva, M., Siemińska, A., Lamentowicz, M., 2015. Peatland Microbial Communities as Indicators of the Extreme Atmospheric Dust Deposition. Water Air Soil Pollut. 226, 97. https://doi.org/10.1007/s11270-015-2338-1.
Fiałkiewicz-Kozieł, B., Smieja-Król, B., Frontasyeva, M., Słowiński, M., Marcisz, K., Lapshina, E., Gilbert, D., Buttler, A., Jassey, V.E., Kaliszan, K., Laggoun-Défarge, F., Kołaczek, P., Lamentowicz, M., 2016. Anthropogenic- and natural sources of dust in peatland during the Anthropocene. Sci. Rep. 6, 38731. https://doi.org/10.1038/srep38731.
Fiałkiewicz-Kozieł, B., Łokas, E., Gałka, M., Kołaczek, P., De Vleeschouwer, F., Le Roux, G., Smieja-Król, B., 2020. Influence of transboundary transport of trace elements on mountain peat geochemistry (Sudetes, Central Europe). Quat. Sci. Rev. 230, 106162. https://doi.org/10.1016/j.quascirev.2020.106162.
Fiałkiewicz-Kozieł, B., Łokas, E., Smieja-Król, B., Turner, S., De Vleeschouwer, F., Woszczyk, M., Marcisz, K., Gałka, M., Lamentowicz, M., Kołaczek, P., Hajdas, I., Karpińska-Kołaczek, M., Kołtonik, K., Mróz, T., Roberts, S., Rose, N., Krzykawski, T., Boom, A., Yang, H., 2023. The Śnieżka peatland as a candidate Global boundary Stratotype Section and Point for the Anthropocene series. Anthropocene Rev. 10, 288–315. https://doi.org/10.1177/20530196221136425.
Fiałkiewicz-Kozieł, B., Smieja-Król, B., Łokas, E., Cwanek, A., Plado, J., Mróz, T., Wąsowicz, P., Gałka, M., 2025. Synchronizing Pu fallout and inorganic fly ash particles record in Northern Hemisphere peatlands. Sci. Total Environ. 993, 180011. https://doi.org/10.1016/j.scitotenv.2025.180011.
Finlayson, C.M., Clarke, S.J., Davidson, N.C., Gell, P., 2015. Role of palaeoecology in describing the ecological character of wetlands. Mar. Freshw. Res. https://doi.org/10.1071/MF15293.
Finsinger, W., Bonnici, I., 2022. tapas: an R package to perform trend and peaks analysis.
Fitchett, J.M., 2015. *Towards a multi-proxy Holocene palaeoenvironmental and palaeoclimatic reconstruction for Eastern Lesotho* (Doctoral dissertation, University of the Witwatersrand, Faculty of Science, School of Geography, Archaeology & Environmental Studies).
Finsinger, W., Bigler, C., Schwörer, C., Tinner, W., 2024. Rates of palaeoecological change can inform ecosystem restoration. Biogeosciences 21, 1629–1638. https://doi.org/10.5194/bg-21-1629-2024.
Fitchett, J.M., Mackay, A.W., Grab, S.W., Bamford, M.K., 2017. Holocene climatic variability indicated by a multi-proxy record from southern Africa's highest wetland. The Holocene 27 (5), 638–650. https://doi.org/10.1177/0959683616670467.
Foissner, W., 1997. Protozoa as bioindicators in agroecosystems, with emphasis on farming practices, biocides, and biodiversity. Agric. Ecosyst. Environ. 62, 93–103.
Fournier, B., Lara, E., Jassey, V.E.J., Mitchell, E.A.D., 2015. Functional traits as a new approach for interpreting testate amoeba palaeo-records in peatlands and assessing the causes and consequences of past changes in species composition. The Holocene 25, 1375–1383. https://doi.org/10.1177/0959683615585842.
Fracasso, I., Dinella, A., Giammarchi, F., Marinchel, N., Kołaczek, P., Lamentowicz, M., Marcisz, K., Łokas, E., Miecznik, M., Bragazza, L., Girardi, M., Ventura, M., Borruso, L., Tonon, G., Vernesi, C., 2022. Climate and human impacts inferred from a 1500-year multi-proxy record of an alpine peatland in the South-Eastern Alps. Ecol. Indic. 145, 109737. https://doi.org/10.1016/j.ecolind.2022.109737.
Frolking, S., Roulet, N.T., Tuittila, E., Bubier, J.L., Quillet, A., Talbot, J., Richard, P.J.H., 2010. A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation. Earth System Dynamics 1, 1–21. https://doi.org/10.5194/esd-1-1-2010.
Frolking, S., Talbot, J., Subin, Z.M., 2014. Exploring the relationship between peatland net carbon balance and apparent carbon accumulation rate at century to millennial time scales. The Holocene. https://doi.org/10.1177/0959683614538078.
Gagen, M., Hicks, S., McCarroll, D., 2006. The Millennium project: European climate of the last millennium. PAGES News 14, 4.
Gaillard, M.-J., 2013. POLLEN METHODS AND STUDIES Archaeological Applications. In: Encyclopedia of Quaternary Science. Elsevier, pp. 880–904. https://doi.org/10.1016/b978-0-444-53643-3.00182-5.
Gałka, M., Apolinarska, K., 2014. Climate change, vegetation development, and lake level fluctuations in Lake Purwin (NE Poland) during the last 8600 cal. BP based on a high-resolution plant macrofossil record and stable isotope data (δ13C and δ18O). Quat. Int. https://doi.org/10.1016/j.quaint.2013.12.030.
Gałka, M., Tobolski, K., Górska, A., Milecka, K., Fiałkiewicz-Kozieł, B., Lamentowicz, M., 2014. Disentangling the drivers for the development of a Baltic bog during the Little Ice Age in northern Poland. Quat. Int. 328–329, 323–337. https://doi.org/10.1016/j.quaint.2013.02.026.
Gałka, M., Aunina, L., Feurdean, A., Hutchinson, S., Kolaczek, P., Apolinarska, K., 2017. Rich fen development in CE Europe, resilience to climate change and human impact over the last ca. 3500 years. Palaeogeogr. Palaeoclimatol. Palaeoecol. 473, 57–72. https://doi.org/10.1016/j.palaeo.2017.02.030.
Gałka, M., Szal, M., Watson, E.J., Gallego-Sala, A., Amesbury, M.J., Charman, D.J., Roland, T.P., Edward Turner, T., Swindles, G.T., 2017. Vegetation Succession, Carbon Accumulation and Hydrological Change in Subarctic Peatlands, Abisko, Northern Sweden. Permafr. Periglac. Process. 28, 589–604. https://doi.org/10.1002/ppp.1945.
Gałka, M., Feurdean, A., Sim, T.G., Tobolski, K., Aunina, L., Apolinarska, K., 2021a. A multi-proxy long-term ecological investigation into the development of a late Holocene calcareous spring-fed fen ecosystem (Raganu Mire) and boreal forest at the SE Baltic coast (Latvia). Ecol. Indic. 126, 107673. https://doi.org/10.1016/j.ecolind.2021.107673.
Gałka, M., Kołaczek, P., Sim, T.G., Knorr, K., Niedzielski, P., Lewandowska, A., Szczurek, G., 2021b. Palaeoenvironmental conditions and human activity in the vicinity of the Grodzisko fortified settlement (central Europe, Poland) from the late-Neolithic to the Roman period. Geoarchaeology. https://doi.org/10.1002/gea.21896.
Gałka, M., Hölzer, A., Feurdean, A., Loisel, J., Teickner, H., Diaconu, A.-C., Szal, M., Broder, T., Knorr, K.-H., 2022a. Insight into the factors of mountain bog and forest development in the Schwarzwald Mts.: Implications for ecological restoration. Ecol. Indic. 140, 109039.
Gałka, M., Knorr, K.-H., Tobolski, K., Gallego-Sala, A., Kołaczek, P., Lamentowicz, M., Kajukało-Drygalska, K., Marcisz, K., 2022b. How far from a pristine state are the peatlands in the Białowieża Primeval Forest (CE Europe) – Palaeoecological insights on peatland and forest development from multi-proxy studies. Ecol. Indic. 143, 109421. https://doi.org/10.1016/j.ecolind.2022.109421.
Gallego-Sala, A.V., Charman, D.J., Brewer, S., Page, S.E., Prentice, I.C., Friedlingstein, P., Moreton, S., Amesbury, M.J., Beilman, D.W., Björck, S., Blyakharchuk, T., Bochicchio, C., Booth, R.K., Bunbury, J., Camill, P., Carless, D., Chimner, R.A., Clifford, M., Cressey, E., Courtney-Mustaphi, C., De Vleeschouwer, F., de Jong, R., Fialkiewicz-Koziel, B., Finkelstein, S.A., Garneau, M., Githumbi, E., Hribjlan, J., Holmquist, J., Hughes, P.D.M., Jones, C., Jones, M.C., Karofeld, E., Klein, E.S., Kokfelt, U., Korhola, A., Lacourse, T., Le Roux, G., Lamentowicz, M., Large, D., Lavoie, M., Loisel, J., Mackay, H., MacDonald, G.M., Makila, M., Magnan, G., Marchant, R., Marcisz, K., Martínez Cortizas, A., Massa, C., Mathijssen, P., Mauquoy, D., Mighall, T., Mitchell, F.J.G., Moss, P., Nichols, J., Oksanen, P.O., Orme, L., Packalen, M.S., Robinson, S., Roland, T.P., Sanderson, N.K., Sannel, A.B.K., Silva-Sánchez, N., Steinberg, N., Swindles, G.T., Turner, T.E., Uglow, J., Väliranta, M., van Bellen, S., van der Linden, M., van Geel, B., Wang, G., Yu, Z., Zaragoza-Castells, J., Zhao, Y., 2018. Latitudinal limits to the predicted increase of the peatland carbon sink with warming. Nat. Clim. Chang. 8, 907–913. https://doi.org/10.1038/s41558-018-0271-1.
Garcés-Pastor, S., Wangensteen, O.S., Pérez-Haase, A., Pèlachs, A., Pérez-Obiol, R., Cañellas-Boltà, N., Mariani, S., Vegas-Vilarrúbia, T., 2019. DNA metabarcoding reveals modern and past eukaryotic communities in a high-mountain peat bog system. J. Paleolimnol. 62, 425–441. https://doi.org/10.1007/s10933-019-00097-x.
Garcin, Y., Schefuß, E., Dargie, G.C., Hawthorne, D., Lawson, I.T., Sebag, D., Biddulph, G.E., Crezee, B., Bocko, Y.E., Ifo, S.A., Mampouya Wenina, Y.E., Mbemba, M., Ewango, C.E.N., Emba, O., Bola, P., Kanyama Tabu, J., Tyrrell, G., Young, D.M., Gassier, G., Girkin, N.T., Vane, C.H., Adatte, T., Baird, A.J., Boom, A., Gulliver, P., Morris, P.J., Page, S.E., Sjögersten, S., Lewis, S.L., 2022. Hydroclimatic vulnerability of peat carbon in the central Congo Basin. Nature. https://doi.org/10.1038/s41586-022-05389-3.
Gauthier, E., Jassey, V.E.J., Mitchell, E.A.D., Lamentowicz, M., Payne, R., Delarue, F., Laggoun-Defarge, F., Gilbert, D., Richard, H., 2019. From Climatic to Anthropogenic Drivers: A Multi-Proxy Reconstruction of Vegetation and Peatland Development in the French Jura Mountains. Quaternary 2, 38. https://doi.org/10.3390/quat2040038.
Gearey, B., Fyfe, R.M., 2016. Archaeological resources and the protection of cultural services. In: Peatland Restoration and Ecosystem Services. Cambridge, pp. 95–113.
Giese, L., Baumberger, M., Ludwig, M., Schneidereit, H., Sánchez, E., Robroek, B.J.M., Lamentowicz, M., Lehmann, J.R.K., Hölzel, N., Knorr, K.-H., Meyer, H., 2025. Recent trends in moisture conditions across European peatlands. In: Remote Sensing

Applications: Society and Environment, 37, 101385. https://doi.org/10.1016/j.rsase.2024.101385.
Gilbert, D., Amblard, C., Bourdier, G., Francez, A.-J., 1998. The microbial loop at the surface of a peatland: Structure, function, and impact of nutrient input. Microb. Ecol. 35, 83–93.
Githumbi, E.N., Courtney Mustaphi, C.J., Yun, K.J., Muiruri, V., Rucina, S.M., Marchant, R., 2018. Late Holocene wetland transgression and 500 years of vegetation and fire variability in the semi-arid Amboseli landscape, southern Kenya. Ambio 47 (6), 682–696. https://doi.org/10.1007/s13280-018-1014-2.
Gnatowski, T., Szatyłowicz, J., Brandyk, T., Kechavarzi, C., 2010. Hydraulic properties of fen peat soils in Poland. Geoderma 154, 188–195.
Godwin, H., 1945. Coastal Peat-Beds of the North Sea Region, as Indices of Land- and Sea-Level Changes. New Phytologist 44, 29–69.
Gonzalez, A., Germain, R.M., Srivastava, D.S., Filotas, E., Dee, L.E., Gravel, D., Thompson, P.L., Isbell, F., Wang, S., Kéfi, S., Montoya, J., Zelnik, Y.R., Loreau, M., 2020. Scaling-up biodiversity-ecosystem functioning research. Ecol. Lett. https://doi.org/10.1111/ele.13456.
Goodsite, M.E., Rom, W., Heinemeier, J., Lange, T., Ooi, S., Appleby, P.G., Shotyk, W., van der Knaap, W.O., Lohse, C., Hansen, T.S., 2001. High-resolution AMS 14C dating of post-bomb peat archives of atmospheric pollutants. Radiocarbon 43, 495–515.
Gorham, E., 1991. Northern peatlands - role in the carbon-cycle and probable responses to climatic warming. Ecol. Appl. 1, 182–195. https://doi.org/10.2307/1941811.
Goslar, T., van der Knaap, W.O., Hicks, S., Andric, M., Czernik, J., Goslar, E., Räsänen, S., Hyötylä, H., 2005. Radiocarbon dating of modern peat profiles: pre- and postbomb 14C variations in the construction of age-depth models. Radiocarbon 47, 115–134.
Goslar, T., Van der Knaap, W.O., Kamenik, C., Van Leeuwen, J.F.N., 2009. Free-shape 14C age–depth modelling of an intensively dated modern peat profile. J. Quat. Sci. 24, 481–499.
Gosling, W.D., Cornelissen, H.L., McMichael, C.N.H., 2019. Reconstructing past fire temperatures from ancient charcoal material. Palaeogeogr. Palaeoclimatol. Palaeoecol. 520, 128–137. https://doi.org/10.1016/j.palaeo.2019.01.029.
Gould, B.A., León, B., Buffen, A.M., Thompson, L.G., 2010. Evidence of a high-Andean, mid-Holocene plant community: An ancient DNA analysis of glacially preserved remains. Am. J. Bot. 97, 1579–1584. https://doi.org/10.3732/ajb.1000058.
Grosse-Brauckmann, G., 1986. Analysis of vegetative plant macrofossils, in: Berglund, B. E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. JohnWiley&Sons, pp. 591–618.
Grover, S.P.P., Baldock, J.A., 2013. The link between peat hydrology and decomposition: Beyond von Post. J. Hydrol. 479, 130–138. https://doi.org/10.1016/j.jhydrol.2012.11.049.
Hajdas, I., 2008. Radiocarbon dating and its applications in Quaternary studies. E& G Quaternary Science Journal 57, 2–24. doi: https://doi.org/10.3285/eg.57.1-2.1.
Hájková, P., Grootjans, A., Lamentowicz, M., Rybníčková, E., Madaras, M., Opravilová, V., Michaelis, D., Hájek, M., Joosten, H., Wołejko, L., 2012. How a Sphagnum fuscum -dominated bog changed into a calcareous fen: the unique Holocene history of a Slovak spring-fed mire. J. Quat. Sci. 27, 233–243. https://doi.org/10.1002/jqs.1534.
Halaś, A., Lamentowicz, M., Łuców, D., Słowiński, M., 2023. Developing a new testate amoeba hydrological transfer function for permafrost peatlands of NW Siberia. Quat. Sci. Rev. 308, 108067. https://doi.org/10.1016/j.quascirev.2023.108067.
Halaś, A., Lamentowicz, M., Obremska, M., Łuców, D., Słowiński, M., 2025. Peatland development reconstruction and complex soil biological responses to permafrost thawing in Western Siberia. Biogeosciences 1–32.
Haldon, J., Mordechai, L., Newfield, T.P., Chase, A.F., Izdebski, A., Guzowski, P., Labuhn, I., Roberts, N., 2018. History meets palaeoscience: Consilience and collaboration in studying past societal responses to environmental change. Proc. Natl. Acad. Sci. USA 115, 3210. https://doi.org/10.1073/pnas.1716912115.
Halpern, B.S., Boettiger, C., Dietze, M.C., Gephart, J.A., Gonzalez, P., Grimm, N.B., Groffman, P.M., Gurevitch, J., Hobbie, S.E., Komatsu, K.J., Kroeker, K.J., Lahr, H.J., Lodge, D.M., Lortie, C.J., Lowndes, J.S.S., Micheli, F., Possingham, H.P., Ruckelshaus, M.H., Scarborough, C., Wood, C.L., Wu, G.C., Aoyama, L., Arroyo, E.E., Bahlai, C.A., Beller, E.E., Blake, R.E., Bork, K.S., Branch, T.A., Brown, N.E.M., Brun, J., Bruna, E.M., Buckley, L.B., Burnett, J.L., Castorani, M.C.N., Cheng, S.H., Cohen, S.C., Couture, J.L., Crowder, L.B., Dee, L.E., Dias, A.S., Diaz-Maroto, I.J., Downs, M.R., Dudney, J.C., Ellis, E.C., Emery, K.A., Eurich, J.G., Ferriss, B.E., Fredston, A., Furukawa, H., Gagné, S.A., Garlick, S.R., Garroway, C.J., Gaynor, K.M., González, A.L., Grames, E.M., Guy-Haim, T., Hackett, E., Hallett, L.M., Harms, T.K., Haulsee, D.E., Haynes, K.J., Hazen, E.L., Jarvis, R.M., Jones, K., Kandlikar, G.S., Kincaid, D.W., Knope, M.L., Koirala, A., Kolasa, J., Kominoski, J.S., Koricheva, J., Lancaster, L.T., Lawlor, J.A., Lowman, H.E., Muller-Karger, F.E., Norman, K.E.A., Nourn, N., O'Hara, C.C., Ou, S.X., Padilla-Gamino, J.L., Pappalardo, P., Peek, R.A., Pelletier, D., Plont, S., Ponisio, L.C., Portales-Reyes, C., Provete, D.B., Raes, E.J., Ramirez-Reyes, C., Ramos, I., Record, S., Richardson, A.J., Salguero-Gómez, R., Satterthwaite, E.V., Schmidt, C., Schwartz, A.J., See, C.R., Shea, B.D., Smith, R.S., Sokol, E.R., Solomon, C.T., Spanbauer, T., Stefanoudis, P.V., Sterner, B.W., Sudbrack, V., Tonkin, J.D., Townes, A.R., Valle, M., Walter, J.A., Wheeler, K.I., Wieder, W.R., Williams, D.R., Winter, M., Winterova, B., Woodall, L.C., Wymore, A. S., Youngflesh, C., 2023. Priorities for synthesis research in ecology and environmental science. Ecosphere 14. https://doi.org/10.1002/ecs2.4342.
Hapsari, K.A., Biagioni, S., Jennerjahn, T.C., Reimer, P.M., Saad, A., Achnopha, Y., Sabiham, S., Behling, H., 2017. Environmental dynamics and carbon accumulation rate of a tropical peatland in Central Sumatra, Indonesia. Quat. Sci. Rev. 169, 173–187. https://doi.org/10.1016/j.quascirev.2017.05.026.
Hapsari, K.A., Biagioni, S., Jennerjahn, T.C., Reimer, P., Saad, A., Sabiham, S., Behling, H., 2018. Resilience of a peatland in Central Sumatra, Indonesia to past anthropogenic disturbance: Improving conservation and restoration designs using palaeoecology. J. Ecol. 106 (6), 2473–2490. https://doi.org/10.1111/1365-2745.13000.
Harenda, K.M., Lamentowicz, M., Samson, M., Chojnicki, B.H., 2018. The Role of Peatlands and Their Carbon Storage Function in the Context of Climate Change. In: Zielinski, T., Sagan, I., Surosz, W. (Eds.), Interdisciplinary Approaches for Sustainable Development Goals: GeoPlanet: Earth and Planetary Sciences. Springer International Publishing, Cham, pp. 169–187. https://doi.org/10.1007/978-3-319-71788-3_12.
Harris, A., Bryant, R.G., Baird, A.J., 2005. Detecting near-surface moisture stress in *Sphagnum* spp. Remote Sens. Environ. 97, 371–381.
Hawthorne, D., Lawson, I.T., Dargie, G.C., Bocko, Y.E., Ifo, S.A., Garcin, Y., Schefuß, E., Hiles, W., Jovani-Sancho, A.J., Tyrrell, G., Biddulph, G.E., Boom, A., Chase, B.M., Gulliver, P., Page, S.E., Roucoux, K.H., Sjögersten, S., Young, D.M., Lewis, S.L., 2023. Genesis and development of an interfluvial peatland in the central Congo Basin since the Late Pleistocene. Quat. Sci. Rev. 305, 107992. https://doi.org/10.1016/j.quascirev.2023.107992.
He, T., Lamont, B.B., Pausas, J.G., 2019. Fire as a key driver of Earth's biodiversity. Biol. Rev. Camb. Philos. Soc. 94, 1983–2010. https://doi.org/10.1111/brv.12544.
Heinemeyer, A., Asena, Q., Burn, W.L., Jones, A.L., 2018. Peatland carbon stocks and burn history: Blanket bog peat core evidence highlights charcoal impacts on peat physical properties and long-term carbon storage. Geo Geogr. Environ. 5, e00063. https://doi.org/10.1002/geo2.63.
Hernandez-Almeida, I., Grosjean, M., Pla-Rabes, S., Filipiak, J., Bonk, A., Tylmann, W., 2017. Influence of inter-annual environmental variability on chrysophyte cyst assemblages: insight from a 2-years sediment trap study in lakes from northern Poland. J. Limnol. 76, 409–423. https://doi.org/10.4081/jlimnol.2017.1604.
Higuera, P.E., Gavin, D.G., Bartlein, P.J., Hallett, D.J., 2010. Peak detection in sediment-charcoal records: Impacts of alternative data analysis methods on fire-history interpretations. Int. J. Wildland Fire 19, 996–1014.
Hilfinger, A., Paulsson, J., 2011. Separating intrinsic from extrinsic fluctuations in dynamic biological systems. Proc. Natl. Acad. Sci. USA 108, 12167–12172. https://doi.org/10.1073/pnas.1018832108.
Hopmans, E.C., Weijers, J.W.H., Schefuß, E., Herfort, L., Sinninghe Damsté, J.S., Schouten, S., 2004. A novel proxy for terrestrial organic matter in sediments based on branched and isoprenoid tetraether lipids. Earth Planet. Sci. Lett. 224, 107–116. https://doi.org/10.1016/j.epsl.2004.05.012.
Hornibrook, E.R., Longstaffe, F.J., Fyfe, W.S., 2000. Factors influencing stable isotope ratios in CH4 and CO2 within subenvironments of freshwater wetlands: implications for delta-signatures of emissions. Isot. Environ. Health Stud. 36, 151–176. https://doi.org/10.1080/10256010008032940.
Horsak, M., 2011. Mollusc assemblages in palaeoecological reconstructions: an investigation of their predictive power using transfer function models. Boreas 40, 459–467. https://doi.org/10.1111/j.1502-3885.2010.00195.x.
Hudspith, V.A., Belcher, C.M., Kelly, R., Hu, F.S., 2015. Charcoal reflectance reveals early holocene boreal deciduous forests burned at high intensities. PLoS One 10, e0120835. https://doi.org/10.1371/journal.pone.0120835.
Hughes, P.D.M., Dumayne-Peaty, L., 2002. Testing theories of mire development using multiple successions at Crymlyn Bog, West Glamorgan, South Wales, UK. J. Ecol. 90, 456–471. https://doi.org/10.1046/j.1365-2745.2002.00677.x.
Inglis, G.N., Collinson, M.E., Riegel, W., Wilde, V., Robson, B.E., Lenz, O.K., Pancost, R. D., 2015. Ecological and biogeochemical change in an early Paleogene peat-forming environment: Linking biomarkers and palynology. Palaeogeogr. Palaeoclimatol. Palaeoecol. 438, 245–255. https://doi.org/10.1016/j.palaeo.2015.08.001.
Inglis, G.N., Naafs, B.D.A., Zheng, Y., McClymont, E.L., Evershed, R.P., Pancost, R.D., 2018. Distributions of geohopanoids in peat: Implications for the use of hopanoid-based proxies in natural archives. Geochim. Cosmochim. Acta 224, 249–261. https://doi.org/10.1016/j.gca.2017.12.029.
Inglis, G.N., Naafs, B.D.A., Zheng, Y., Schellekens, J., Pancost, R.D., 2019. δ13C values of bacterial hopanoids and leaf waxes as tracers for methanotrophy in peatlands. Geochim. Cosmochim. Acta 260, 244–256. https://doi.org/10.1016/j.gca.2019.06.030.
Inglis, G.N., Bhattacharya, T., Hemingway, J.D., Hollingsworth, E.H., Feakins, S.J., Tierney, J.E., 2022. Biomarker Approaches for Reconstructing Terrestrial Environmental Change. Annu. Rev. Earth Planet. Sci. 50, 369–394. https://doi.org/10.1146/annurev-earth-032320-095943.
Inglis, G.N., De Jonge, C., Häggi, C., Feakins, S.J., Guo, J., Dercon, G., Bertassoli Jr., D.J., Akabane, T.K., Bentley, M.R., Beverly, E., Naafs, B.D.A., Pancost, R.D., 2025. Hopanoid distributions differ in mineral soils and peat: a re-evaluation of hopane-based pH proxies. Adv. Geochem. Cosmochem. 1, 0. doi: 10.33063/agc.v1i2.755.
Ireland, A.W., Booth, R.K., 2012. Upland deforestation triggered an ecosystem state-shift in a kettle peatland. J. Ecol. 100, 586–596. https://doi.org/10.1111/j.1365-2745.2012.01961.x.
Ireland, A.W., Clifford, M.U., Booth, R.K., 2014. Widespread dust deposition on North American peatlands coincident with European land-clearance. Veg. Hist. Archaeobotany 1–8. https://doi.org/10.1007/s00334-014-0466-y.
Izdebski, A., Holmgren, K., Weiberg, E., Stocker, S.R., Büntgen, U., Florenzano, A., Gogou, A., Leroy, S.A.G., Luterbacher, J., Martrat, B., Masi, A., Mercuri, A.M., Montagna, P., Sadori, L., Schneider, A., Sicre, M.-A., Triantaphyllou, M., Xoplaki, E., 2016. Realising consilience: How better communication between archaeologists, historians and natural scientists can transform the study of past climate change in the Mediterranean. Quat. Sci. Rev. https://doi.org/10.1016/j.quascirev.2015.10.038.
Izdebski, A., Guzowski, P., Poniat, R., Masci, L., Palli, J., Vignola, C., Bauch, M., Cocozza, C., Fernandes, R., Ljungqvist, F.C., Newfield, T., Seim, A., Abel-Schaad, D., Alba-Sánchez, F., Björkman, L., Brauer, A., Brown, A., Czerwiński, S., Ejarque, A., Fiłoc, M., Florenzano, A., Fredh, E.D., Fyfe, R., Jasiunas, N., Kołaczek, P., Kouli, K., Kozáková, R., Kupryjanowicz, M., Lagerås, P., Lamentowicz, M., Lindbladh, M.,

López-Sáez, J.A., Luelmo-Lautenschlaeger, R., Marcisz, K., Mazier, F., Mensing, S., Mercuri, A.M., Milecka, K., Miras, Y., Noryśkiewicz, A.M., Novenko, E., Obremska, M., Panajiotidis, S., Papadopoulou, M.L., Pędziszewska, A., Pérez-Díaz, S., Piovesan, G., Pluskowski, A., Pokorny, P., Poska, A., Reitalu, T., Rösch, M., Sadori, L., Sá Ferreira, C., Sebag, D., Słowiński, M., Stančikaitė, M., Stivrins, N., Tunno, I., Veski, S., Wacnik, A., Masi, A., 2022. Palaeoecological data indicates land-use changes across Europe linked to spatial heterogeneity in mortality during the Black Death pandemic. Nat. Ecol. Evol. 6, 297–306. https://doi.org/10.1038/s41559-021-01652-4.

Izdebski, A., Bloomfield, K., Eastwood, W.J., Fernandes, R., Fleitmann, D., Guzowski, P., Haldon, J., Ludlow, F., Luterbacher, J., Manning, J.G., Masi, A., Mordechai, L., Newfield, T.P., Stine, A.R., Şenkul, Ç., Xoplaki, E., 2024. The Emergence of Interdisciplinary Environmental History. Collaborative Approaches to the Late Holocene. Annales. Histoire, Sciences Sociales, pp. 1–43. https://doi.org/10.1017/ahsse.2022.21.

Izdebski, A., Czerwiński, S., Jankowiak, M., Danielewski, M., Fiołna, S., Gromig, R., Guzowski, P., Haghipour, N., Hajdas, I., Kołaczek, P., Lamentowicz, M., Marcisz, K., Niebieszczański, J., Sankiewicz, P., Wagner, B., 2025. Unbalanced social-ecological acceleration led to state formation failure in early medieval Poland. Proc. Natl. Acad. Sci. USA 122, e2409056122. https://doi.org/10.1073/pnas.2409056122.

Jackson, S.T., 2012. Representation of flora and vegetation in Quaternary fossil assemblages: known and unknown knowns and unknowns. Quat. Sci. Rev. 49, 1–15. https://doi.org/10.1016/j.quascirev.2012.05.020.

Jaroszewicz, B., Cholewińska, O., Gutowski, J.M., Samojlik, T., Zimny, M., Latałowa, M., 2019. Białowieża Forest—A Relic of the High Naturalness of European Forests. Forests 10, 849. doi: https://doi.org/10.3390/f10100849.

Jassey, V.E., Chiapusio, G., Binet, P., Buttler, A., Laggoun-Defarge, F., Delarue, F., Bernard, N., Mitchell, E.A., Toussaint, M.L., Francez, A.J., Gilbert, D., 2013. Above- and belowground linkages in Sphagnum peatland: climate warming affects plant-microbial interactions. Glob. Chang. Biol. 19, 811–823. https://doi.org/10.1111/gcb.12075.

Jassey, V.E.J., Reczuga, M.K., Zielińska, M., Słowińska, S., Robroek, B.J.M., Mariotte, P., Seppey, C.V.W., Lara, E., Barabach, J., Słowiński, M., Bragazza, L., Chojnicki, B.H., Lamentowicz, M., Mitchell, E.A.D., Buttler, A., 2018. Tipping point in plant-fungal interactions under severe drought causes abrupt rise in peatland ecosystem respiration. Glob. Chang. Biol. 24, 972–986. https://doi.org/10.1111/gcb.13928.

Jassey, V.E.J., Walcker, R., Kardol, P., Geisen, S., Heger, T., Lamentowicz, M., Hamard, S., Lara, E., 2022. Contribution of soil algae to the global carbon cycle. New Phytol. 234, 64–76. https://doi.org/10.1111/nph.17950.

Jeelani, N., Fischer, K., Thomas, C.L., Knorr, K.-H., Lamentowicz, M., Gałka, M., Glatzel, S., 2025. Investigating the impact of peatland degradation: A lipid biomarker analysis. Iscience 28. https://doi.org/10.1016/j.isci.2025.112604.

Jeraj, M., Džeroski, S., Todorovski, L., Debeljak, M., 2006. Application of machine learning methods to palaeoecological data. Ecol. Model. 191, 159–169. https://doi.org/10.1016/j.ecolmodel.2005.08.018.

Jonathan, E.N., Marie, W., Raymond, B., Jon, P., Yongsong, H., 2009. Quantitative assessment of precipitation seasonality and summer surface wetness using ombrotrophic sediments from an Arctic Norwegian peatland. Quat. Res. 72, 443–451. https://doi.org/10.1016/j.yqres.2009.07.007.

Joosten, H., 2024. Peatland Must Be Wet. In: Advance Rewetting, Stop Peat Extraction, in: 3 Degrees More. Advance Rewetting, Stop Peat Extraction. Springer Nature, Switzerland, Cham, pp. 179–203. https://doi.org/10.1007/978-3-031-58144-1_9.

Joosten, H., De Klerk, P., 2007. DAMOCLES: a DAshing MOnolith Cutter for fine sectioning of peats and sediments into LargE Slices. Boreas 36, 76–81. https://doi.org/10.1111/j.1502-3885.2007.tb01182.x.

Judith, S., Peter, B., 2011. n-Alkane distributions as palaeoclimatic proxies in ombrotrophic peat: The role of decomposition and dominant vegetation. Geoderma 164, 112–121. https://doi.org/10.1016/j.geoderma.2011.05.012.

Jurasinski, G., Günther, A., Vytas Huth, Couwenberg, J., Glatzel, S., 2016. Ecosystem services provided by paludiculture, in: Wichtmann, W., Schröder, C., Joosten, H. (Eds.), Paludiculture Productive Use Wet Peatlands.

Kaislahti Tillman, P., Holzkämper, S., Kuhry, P., Sannel, A.B.K., Loader, N.J., Robertson, I., 2010a. Stable carbon and oxygen isotopes in Sphagnum fuscum peat from subarctic Canada: Implications for palaeoclimate studies. Chem. Geol. 270, 216–226.

Kaislahti Tillman, P., Holzkämper, S., Kuhry, P., Sannel, A.B.K., Loader, N.J., Robertson, I., 2010b. Long-term climate variability in continental subarctic Canada: A 6200-year record derived from stable isotopes in peat. Palaeogeogr. Palaeoclimatol. Palaeoecol. 298, 235–246.

Kajukało, K., Fiałkiewicz-Kozieł, B., Gałka, M., Kołaczek, P., Lamentowicz, M., 2016. Abrupt ecological changes in the last 800 years inferred from a mountainous bog using testate amoebae traits and multi-proxy data. Eur. J. Protistol. 55, 165–180. https://doi.org/10.1016/j.ejop.2016.04.003.

Kamenik, C., van der Knaap, W.O., van Leeuwen, J.F.N., Goslar, T., 2009. Pollen/climate calibration based on a near-annual peat sequence from the Swiss Alps. J. Quat. Sci. 24, 529–546.

Kaplan, J.O., Krumhardt, K.M., Zimmermann, N., 2009. The prehistoric and preindustrial deforestation of Europe. Quat. Sci. Rev. 28, 3016–3034. https://doi.org/10.1016/j.quascirev.2009.09.028.

Karpinska-Kolaczek, M., Kolaczek, P., Galka, M., Fialkiewicz-Koziel, B., Marcisz, K., Lamentowicz, M., 2013. Two millennia of environmental changes on ombrotrophic peat bogs in the Orawa-Nowy Targ Depression (southern Poland) inferred from palaeobotanical proxies. Acta Biol. Cracov. Ser. Bot. 55, 49.

Karpińska-Kołaczek, M., Kołaczek, P., Czerwiński, S., Gałka, M., Guzowski, P., Lamentowicz, M., 2022. Anthropocene history of rich fen acidification in W Poland - Causes and indicators of change. Sci. Total Environ. 838, 155785. https://doi.org/10.1016/j.scitotenv.2022.155785.

Karpińska-Kołaczek, M., Kołaczek, P., Marcisz, K., Gałka, M., Kajukało-Drygalska, K., Mauquoy, D., Lamentowicz, M., 2024. Kettle-hole peatlands as carbon hot spots: Unveiling controls of carbon accumulation rates during the last two millennia. CATENA 237, 107764. https://doi.org/10.1016/j.catena.2023.107764.

Katz, N.J., Katz, S.V., Kipiani, M.G., 1965. Atlas opredelitel plodov i semyan vstretchayushchikhsya v chetvertinnykh otuocheniyakh SSSR. Izd, Nauka, Moskva.

Katz, N.J., Katz, S.V., Skobiejeva, E.I., 1977. Atlas rastitielnych ostatkov v torfach. Nedra, Moskva.

Keeley, J.E., 2009. Fire intensity, fire severity and burn severity: a brief review and suggested usage. Int. J. Wildland Fire 18, 116. https://doi.org/10.1071/wf07049.

Keeley, J.E., Pausas, J.G., 2019. Distinguishing disturbance from perturbations in fire-prone ecosystems. Int. J. Wildland Fire 28, 282. https://doi.org/10.1071/wf18203.

Kennett, D.J., Piperno, D.R., Jones, J.G., Neff, H., Voorhies, B., Walsh, M.K., Culleton, B. J., 2010. Pre-pottery farmers on the Pacific coast of southern Mexico. J. Archaeol. Sci. 37, 3401–3411.

Kissling, W.D., Dormann, C.F., Groeneveld, J., Hickler, T., Kühn, I., McInerny, G.J., Montoya, J.M., Römermann, C., Schiffers, K., Schurr, F.M., Singer, A., Svenning, J.-C., Zimmermann, N.E., O'Hara, R.B., 2012. Towards novel approaches to modelling biotic interactions in multispecies assemblages at large spatial extents. J. Biogeogr. 39, 2163–2178. https://doi.org/10.1111/j.1365-2699.2011.02663.x.

Kołaczek, P., Karpińska-Kołaczek, M., Marcisz, K., Gałka, M., Lamentowicz, M., 2018. Palaeohydrology and the human impact on one of the largest raised bogs complex in the Western Carpathians (Central Europe) during the last two millennia. The Holocene 28, 595–608. https://doi.org/10.1177/0959683617735587.

Kołaczek, P., Gałka, M., Lamentowicz, M., Marcisz, K., Kajukało-Drygalska, K., Karpińska-Kołaczek, M., 2019. Increased radiocarbon dating resolution of ombrotrophic peat profiles reveals periods of disturbance which were previously undetected. Quat. Geochronol. 52, 21–28. https://doi.org/10.1016/j.quageo.2019.03.001.

Kołaczek, P., Karpińska-Kołaczek, M., Gałka, M., Miotk-Szpiganowicz, G., Obremska, M., Lamentowicz, M., 2020a. Do the relationships between testate amoebae and fungi reflect the variability of past water table fluctuations in the ombrotrophic peatlands of Central Europe. The Holocene 30, 1186–1195. https://doi.org/10.1177/0959683620913927.

Kołaczek, P., Margielewski, W., Gałka, M., Karpińska-Kołaczek, M., Buczek, K., Lamentowicz, M., Borek, A., Zernitskaya, V., Marcisz, K., 2020b. Towards the understanding the impact of fire on the lower montane forest in the Polish Western Carpathians during the Holocene. Quat. Sci. Rev. 229, 106137. https://doi.org/10.1016/j.quascirev.2019.106137.

Kołaczek, P., Rzodkiewicz, M., Karpińska-Kołaczek, M., Hildebrandt-Radke, I., Gałka, M., Jaeger, M., Kneisel, J., Niebieszczański, J., 2025. The impact of Lusatian Urnfield and subsequent prehistoric cultures on lake and woodland ecosystems: insights from multi-proxy palaeoecological investigations at Bruszczewo, western Poland. Veg. Hist. Archaeobotany 0. https://doi.org/10.1007/s00334-024-01022-7.

Kolka, R., Pierce, C., Garrioch, I., Behrens, K., Toner, B.M., 2024. Review of the Influence of Climate Change on the Hydrologic Cycling and Gaseous Fluxes of Mercury in Boreal Peatlands: Implications for Restoration. Water 16, 1154. https://doi.org/10.3390/w16081154.

Kong, S.-R., Yamamoto, M., Shaari, H., Hayashi, R., Seki, O., Mohd Tahir, N., Fadzil, M. F., Sulaiman, A., 2021. The significance of pyrogenic polycyclic aromatic hydrocarbons in Borneo peat core for the reconstruction of fire history. PLoS One 16, e0256853. https://doi.org/10.1371/journal.pone.0256853.

Kosakyan, A., Gomaa, F., Lara, E., Lahr, D.J., 2016. Current and future perspectives on the systematics, taxonomy and nomenclature of testate amoebae. Eur. J. Protistol. 55, 105–117. https://doi.org/10.1016/j.ejop.2016.02.001.

Kosakyan, A., Meisterfeld, R., Lara, E., Duckert, C., Mitchell, E.A.D., 2025. A taxonomic monograph of hyalospheniid testate amoebae (Amoebozoa: Arcellinida: Hyalospheniformes). Éditions Alphil-Presses universitaires suisses, Éditions Alphil-Presses universitaires suisses Société neuchâteloise des sciences naturelles.

Kuder, T., Kruge, M.A., 1998. Preservation of biomolecules in sub-fossil plants from raised peat bogs — a potential paleoenvironmental proxy. Org. Geochem. 29, 1355–1368. https://doi.org/10.1016/s0146-6380(98)00092-8.

Kuhry, P., Vitt, D.H., 1996. Fossil Carbon/Nitrogen Ratios as a Measure of Peat Decomposition. Ecology 77, 271–275. https://doi.org/10.2307/2265676.

Kulczyński, S., 1949. Peatbogs of Polesie. Mémoires de l 'Académie Polonaise des Sciences et des Lettres. B. Sci. Nat. 15, 1–356.

Kurtz, Z.D., Muller, C.L., Miraldi, E.R., Littman, D.R., Blaser, M.J., Bonneau, R.A., 2015. Sparse and compositionally robust inference of microbial ecological networks. PLoS Comput. Biol. 11, e1004226. https://doi.org/10.1371/journal.pcbi.1004226.

Kylander, M.E., Weiss, D.J., Martínez Cortízas, A., Spiro, B., Garcia-Sanchez, R., Coles, B. J., 2005. Refining the pre-industrial atmospheric Pb isotope evolution curve in Europe using an 8000 year old peat core from NW Spain. Earth Planet. Sci. Lett. 240, 467–485. https://doi.org/10.1016/j.epsl.2005.09.024.

Kylander, M.E., Martínez-Cortizas, A., Bindler, R., Greenwood, S.L., Mörth, C.-M., Rauch, S., 2016. Potentials and problems of building detailed dust records using peat archives: An example from Store Mosse (the "Great Bog"), Sweden. Geochim. Cosmochim. Acta 190, 156–174. https://doi.org/10.1016/j.gca.2016.06.028.

Lamentowicz, M., Obremska, M., 2010. A rapid response of testate amoebae and vegetation to inundation of a kettle hole mire. J. Paleolimnol. 43, 499–511. https://doi.org/10.1007/s10933-009-9347-2.

Lamentowicz, M., Balwierz, Z., Forysiak, J., Płóciennik, M., Kittel, P., Kloss, M., Twardy, J., Żurek, S., Pawlyta, J., 2009. Multi-proxy study of anthropogenic and climatic changes in the last two millennia from a small mire in central Poland. Hydrobiologia 631, 213–230. https://doi.org/10.1007/s10750-009-9812-y.

Lamentowicz, M., Van Der Knaap, W., Lamentowicz, Ł., Van Leeuwen, J.F.N., Mitchell, E.A.D., Goslar, T., Kamenik, C., 2010. A near-annual palaeohydrological study based on testate amoebae from a sub-alpine mire: surface wetness and the role of climate during the instrumental period. J. Quat. Sci. 25, 190–202. https://doi.org/10.1002/jqs.1295.

Lamentowicz, M., Gałka, M., Pawlyta, J., Lamentowicz, Ł., Goslar, T., Miotk-Szpiganowicz, G., 2011. Climate change and human impact in the southern Baltic during the last millennium reconstructed from an ombrotrophic bog archive. Studia Quaternaria 28, 3–16.

Lamentowicz, M., Gałka, M., Milecka, K., Tobolski, K., Lamentowicz, Ł., Fiałkiewicz-Kozieł, B., Blaauw, M., 2013. A 1300-year multi-proxy, high-resolution record from a rich fen in northern Poland: reconstructing hydrology, land use and climate change. J. Quat. Sci. 28, 582–594. https://doi.org/10.1002/jqs.2650.

Lamentowicz, M., Gałka, M., Lamentowicz, Ł., Obremska, M., Kühl, N., Lücke, A., Jassey, V.E.J., 2015. Reconstructing climate change and ombrotrophic bog development during the last 4000years in northern Poland using biotic proxies, stable isotopes and trait-based approach. Palaeogeogr. Palaeoclimatol. Palaeoecol. 418, 261–277. https://doi.org/10.1016/j.palaeo.2014.11.015.

Lamentowicz, M., Słowińska, S., Słowiński, M., Jassey, V.E.J., Chojnicki, B.H., Reczuga, M.K., Zielińska, M., Marcisz, K., Lamentowicz, Ł., Barabach, J., Samson, M., Kołaczek, P., Buttler, A., 2016. Combining short-term manipulative experiments with long-term palaeoecological investigations at high resolution to assess the response of Sphagnum peatlands to drought, fire and warming. Mires Peat 18, 1–17. https://doi.org/10.19189/MaP.2016.OMB.244.

Lamentowicz, M., Gałka, M., Marcisz, K., Słowiński, M., Kajukało-Drygalska, K., Dayras, M.D., Jassey, V.E.J., 2019a. Unveiling tipping points in long-term ecological records from Sphagnum-dominated peatlands. Biol. Lett. 15, 20190043. https://doi.org/10.1098/rsbl.2019.0043.

Lamentowicz, M., Kołaczek, P., Mauquoy, D., Kittel, P., Łokas, E., Słowiński, M., Jassey, V.E.J., Niedziółka, K., Kajukało-Drygalska, K., Marcisz, K., 2019b. Always on the tipping point – A search for signals of past societies and related peatland ecosystem critical transitions during the last 6500 years in N Poland. Quat. Sci. Rev. 225, 105954. https://doi.org/10.1016/j.quascirev.2019.105954.

Lamentowicz, M., Kajukało-Drygalska, K., Kołaczek, P., Jassey, V.E.J., Gąbka, M., Karpińska-Kołaczek, M., 2020a. Testate amoebae taxonomy and trait diversity are coupled along an openness and wetness gradient in pine-dominated Baltic bogs. Eur. J. Protistol. 73, 125674. https://doi.org/10.1016/j.ejop.2020.125674.

Lamentowicz, M., Marcisz, K., Guzowski, P., Gałka, M., Diaconu, A.C., Kołaczek, P., 2020b. How Joannites' economy eradicated primeval forest and created anthroecosystems in medieval Central Europe. Sci. Rep. 10, 18775. https://doi.org/10.1038/s41598-020-75692-4.

Lamentowicz, M., Gałka, M., Draga, M., Jassey, V.E.J., Fritz, C., Glatzel, S., Robroek, B., Meyer, H., Lehmann, J., Juszczak, R., Chojnicki, B.H., Knorr, K.-H., 2025. Investigating ecological baselines and critical thresholds in ombrotrophic nemoral peatlands: implications for ecological restoration 0. https://doi.org/10.5194/egusphere-egu24-3047.

Lara, E., Seppey, C.V.W., Garraza, G.G., Singer, D., Quiroga, M.V., Mataloni, G., 2015. Planktonic eukaryote molecular diversity: discrimination of minerotrophic and ombrotrophic peatland pools in Tierra del Fuego (Argentina). J. Plankton Res. https://doi.org/10.1093/plankt/fbv016.

Larocque-Tobler, I., Grosjean, M., Heiri, O., Trachsel, M., Kamenik, C., 2010. Thousand years of climate change reconstructed from chironomid subfossils preserved in varved lake Silvaplana, Engadine, Switzerland. Quat. Sci. Rev. 29, 1940–1949.

Latałowa, M., Pedziszewska, A., Maciejewska, E., Swieta-Musznicka, J., 2013. Tilia forest dynamics, Kretzschmaria deusta attack, and mire hydrology as palaeoecological proxies for mid-Holocene climate reconstruction in the Kashubian Lake District (N Poland). The Holocene 23, 667–677. https://doi.org/10.1177/0959683612467484.

Latałowa, M., Zimny, M., Jędrzejewska, B., Samojlik, T., 2015. Ecological history of Białowieża Forest - Europe's last primeval woodland, in: K., K., C., W. (Eds.), The Ecological History of European Woodland – an Interaction of Environmental and Cultural Forces,. pp. 243–264.

Latałowa, M., Święta-Musznicka, J., Słowiński, M., Pędziszewska, A., Noryśkiewicz, A.M., Zimny, M., Obremska, M., Ott, F., Stivrins, N., Pasanen, L., Ilvonen, L., Holmström, L., Seppä, H., 2019. Abrupt Alnus population decline at the end of the first millennium CE in Europe – The event ecology, possible causes and implications. The Holocene 095968361984697. https://doi.org/10.1177/0959683619846978.

Le Roux, G., Aubert, D., Stille, P., Krachler, M., Kober, B., Cheburkin, A., Bonani, G., Shotyk, W., 2005. Recent atmospheric Pb deposition at a rural site in southern Germany assessed using a peat core and snowpack, and comparison with other archives. Atmos. Environ. 39, 6790–6801. https://doi.org/10.1016/j.atmosenv.2005.07.026.

Le Roux, G., Fagel, N., De Vleeschouwer, F., Krachler, M., Debaille, V., Stille, P., Mattielli, N., van der Knaap, W.O., van Leeuwen, J.F.N., Shotyk, W., 2012. Volcano- and climate-driven changes in atmospheric dust sources and fluxes since the Late Glacial in Central Europe. Geology 40, 335–338. https://doi.org/10.1130/g32586.1.

Le Roux, G., Fagel, N., Longman, J., Mattielli, N., McCulloch, R.D., De Vleeschouwer, F., 2023. Nd isotopes as a tracer of dust trapped by peat bogs: A reminder of basics. Comment on: « Neodymium isotopes in peat reveal past local environmental disturbances » by.

Lees, K.J., Quaife, T., Artz, R.R.E., Khomik, M., Clark, J.M., 2018. Potential for using remote sensing to estimate carbon fluxes across northern peatlands - A review. Sci. Total Environ. 615, 857–874. https://doi.org/10.1016/j.scitotenv.2017.09.103.

Legendre, P., Legendre, L., 1998. Numerical ecology: Second, English edition. Elsevier, Amsterdam, The Netherlands.

Leifeld, J., Klein, K., Wüst-Galley, C., 2020. Soil organic matter stoichiometry as indicator for peatland degradation. Sci. Rep. 10, 7634. https://doi.org/10.1038/s41598-020-64275-y.

Leppänen, J.J., Piilo, S., Li, Y., Zhang, H., Väliranta, M., 2018. Paleoecological assessment of cladoceran community dynamics in two subarctic peatlands. Wetlands. https://doi.org/10.1007/s13157-018-1118-2.

Lestienne, M., Jamrichová, E., Kuosmanen, N., Diaconu, A.-C., Schafstall, N., Goliáš, V., Kletetschka, G., Šulc, V., Kuneš, P., 2023. Development of high diversity beech forest in the eastern Carpathians. J. Biogeogr. 50, 699–714. https://doi.org/10.1111/jbi.14562.

Lévesque, P.E.M., Dinel, H., Larouche, A., 1988. Guide to the Identification of Plant Macrofossils in Canadian Peatlands. Agriculture Canada.

Li, C., Sonke, J.E., Le Roux, G., Van der Putten, N., Piotrowska, N., Jeandel, C., Mattielli, N., Benoit, M., Wiggs, G.F.S., De Vleeschouwer, F., 2020. Holocene dynamics of the southern westerly winds over the Indian Ocean inferred from a peat dust deposition record. Quat. Sci. Rev. 231, 106169. https://doi.org/10.1016/j.quascirev.2020.106169.

Li, C., Enrico, M., Magand, O., Araujo, B.F., Le Roux, G., Osterwalder, S., Dommergue, A., Bertrand, Y., Brioude, J., De Vleeschouwer, F., Sonke, J.E., 2023a. A peat core Hg stable isotope reconstruction of Holocene atmospheric Hg deposition at Amsterdam Island (37.8oS). Geochim. Cosmochim. Acta 341, 62–74. https://doi.org/10.1016/j.gca.2022.11.024.

Li, C., Jiskra, M., Nilsson, M.B., Osterwalder, S., Zhu, W., Mauquoy, D., Skyllberg, U., Enrico, M., Peng, H., Song, Y., Björn, E., Bishop, K., 2023b. Mercury deposition and redox transformation processes in peatland constrained by mercury stable isotopes. Nat. Commun. 14, 7389. https://doi.org/10.1038/s41467-023-43164-8.

Li, C., Enrico, M., Bishop, K., Roberts, S.J., Hodgson, D.A., Lamentowicz, M., Mauquoy, D., Mestrot, A., Grosjean, M., 2025. Perspectives on using peat records to reconstruct past atmospheric Hg levels. J. Hazard. Mater. 482, 136581. https://doi.org/10.1016/j.jhazmat.2024.136581.

Lisa, D., Rob, S., Keith, E.B., Douglas, D.H., 1995. Problems associated with correlating calibrated radiocarbon-dated pollen diagrams with historical events. The Holocene 5, 118–123.

Loader, N.J., McCarroll, D., Knaap, W.O. van der, Robertson, I., Gagen, M., 2007. Characterizing carbon isotopic variability in *Sphagnum*. The Holocene 17, 403–410. doi: https://doi.org/10.1177/0959683607076474.

Loisel, J., Bunsen, M., 2020. Abrupt Fen-Bog Transition Across Southern Patagonia: Timing, Causes, and Impacts on Carbon Sequestration. Front. Ecol. Evol. 8. https://doi.org/10.3389/fevo.2020.00273.

Loisel, J., Garneau, M., 2010. Late Holocene paleoecohydrology and carbon accumulation estimates from two boreal peat bogs in eastern Canada: Potential and limits of multi-proxy archives. Palaeoclimatology, Palaeoecology in press, Palaeogeography.

Loisel, J., Yu, Z., 2013a. Surface vegetation patterning controls carbon accumulation in peatlands. Geophys. Res. Lett. 40, 5508–5513. https://doi.org/10.1002/grl.50744.

Loisel, J., Yu, Z., 2013b. Holocene peatland carbon dynamics in Patagonia. Quat. Sci. Rev. 69, 125–141. https://doi.org/10.1016/j.quascirev.2013.02.023.

Loisel, J., Yu, Z., Beilman, D.W., Camill, P., Alm, J., Amesbury, M.J., Anderson, D., Andersson, S., Bochicchio, C., Barber, K., 2014. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. The Holocene 24, 1028–1042. https://doi.org/10.1177/0959683614538073.

Loisel, J., Gallego-Sala, A.V., Amesbury, M.J., Magnan, G., Anshari, G., Beilman, D.W., Benavides, J.C., Blewett, J., Camill, P., Charman, D.J., Chawchai, S., Hedgpeth, A., Kleinen, T., Korhola, A., Large, D., Mansilla, C.A., Müller, J., van Bellen, S., West, J. B., Yu, Z., Bubier, J.L., Garneau, M., Moore, T., Sannel, A.B.K., Page, S., Väliranta, M., Bechtold, M., Brovkin, V., Cole, L.E.S., Chanton, J.P., Christensen, T. R., Davies, M.A., De Vleeschouwer, F., Finkelstein, S.A., Frolking, S., Gałka, M., Gandois, L., Girkin, N., Harris, L.I., Heinemeyer, A., Hoyt, A.M., Jones, M.C., Joos, F., Juutinen, S., Kaiser, K., Lacourse, T., Lamentowicz, M., Larmola, T., Leifeld, J., Lohila, A., Milner, A.M., Minkkinen, K., Moss, P., Naafs, B.D.A., Nichols, J., O'Donnell, J., Payne, R., Philben, M., Piilo, S., Quillet, A., Ratnayake, A. S., Roland, T.P., Sjögersten, S., Sonnentag, O., Swindles, G.T., Swinnen, W., Talbot, J., Treat, C., Valach, A.C., Wu, J., 2021. Expert assessment of future vulnerability of the global peatland carbon sink. Nat. Clim. Chang. 11, 70–77. https://doi.org/10.1038/s41558-020-00944-0.

Loisel, J., Sarna, K., Xia, Z., Huang, Y., Yu, Z., 2023. Concordant changes in late Holocene hydroclimate across southern Patagonia modulated by westerly winds and the El Niño–Southern Oscillation. Geology 51, 247–251. https://doi.org/10.1130/g50680.1.

Longman, J., Veres, D., Ersek, V., Haliuc, A., Wennrich, V., 2019. Runoff events and related rainfall variability in the Southern Carpathians during the last 2000 years. Sci. Rep. 9, 5334. https://doi.org/10.1038/s41598-019-41855-1.

Longman, J., Veres, D., Haliuc, A., Finsinger, W., Ersek, V., Pascal, D., Sava, T., Begy, R., 2021. Carbon accumulation rates of Holocene peatlands in central–eastern Europe document the driving role of human impact over the past 4000 years. Clim. Past 17, 2633–2652. https://doi.org/10.5194/cp-17-2633-2021.

Lotter, A., 2003. Multi-proxy climatic reconstructions, in: Mackay, A., Battarbee, R.W., Birks, H.J.B., Oldfield, F. (Eds.), Global Change in the Holocene. pp. 373–383.

Łuców, D., Lamentowicz, M., Kołaczek, P., Łokas, E., Marcisz, K., Obremska, M., Theuerkauf, M., Tyszkowski, S., Słowiński, M., 2021. Pine Forest Management and Disturbance in Northern Poland: Combining High-Resolution 100-Year-Old Paleoecological and Remote Sensing Data. Front. Ecol. Evol. 9. https://doi.org/10.3389/fevo.2021.747976.

Łuców, D., Küttim, M., Słowiński, M., Kołaczek, P., Karpińska-Kołaczek, M., Küttim, L., Salme, M., Lamentowicz, M., 2022. Searching for an ecological baseline: Long-term

ecology of a post-extraction restored bog in Northern Estonia. Quat. Int. 607, 65–78. https://doi.org/10.1016/j.quaint.2021.08.017.
Malmer, N., Holm, E., 1984. Variation in the C/N-Quotient of Peat in Relation to Decomposition Rate and Age Determination with 210 Pb. Oikos 43, 171–182. https://doi.org/10.2307/3544766.
Mann, M.E., 2002. The value of multiple proxies. Science 297, 1481–1482. https://doi.org/10.1126/science.1074318?casa_token=q74OmT3USTQAAAAA:mEsj4kFmy-OyNcPvncnk0GLT40MTlrDfK20EEbXoIanwEotezrfxynG5sh8IoqrH2-Ebr6BRT_OKR688.
Marcisz, K., Tinner, W., Colombaroli, D., Kołaczek, P., Słowiński, M., Fiałkiewicz-Kozieł, B., Łokas, E., Lamentowicz, M., 2015. Long-term hydrological dynamics and fire history over the last 2000 years in CE Europe reconstructed from a high-resolution peat archive. Quat. Sci. Rev. 112, 138–152. https://doi.org/10.1016/j.quascirev.2015.01.019.
Marcisz, K., Colombaroli, D., Jassey, V.E., Tinner, W., Kołaczek, P., Gałka, M., Karpińska-Kołaczek, M., Słowiński, M., Lamentowicz, M., 2016. A novel testate amoebae trait-based approach to infer environmental disturbance in Sphagnum peatlands. Sci. Rep. 6, 33907. https://doi.org/10.1038/srep33907.
Marcisz, K., Lamentowicz, M., Gałka, M., Colombaroli, D., Adolf, C., Tinner, W., 2019. Responses of vegetation and testate amoeba trait composition to fire disturbances in and around a bog in central European lowlands (northern Poland). Quat. Sci. Rev. 208, 129–139. https://doi.org/10.1016/j.quascirev.2019.02.003.
Marcisz, K., Jassey, V.E.J., Kosakyan, A., Krashevska, V., Lahr, D.J.G., Lara, E., Lamentowicz, Ł., Lamentowicz, M., Macumber, A., Mazei, Y., Mitchell, E.A.D., Nasser, N.A., Patterson, R.T., Roe, H.M., Singer, D., Tsyganov, A.N., Fournier, B., 2020a. Testate Amoeba Functional Traits and Their Use in Paleoecology. Front. Ecol. Evol. 8. https://doi.org/10.3389/fevo.2020.575966.
Marcisz, K., Kołaczek, P., Gałka, M., Diaconu, A.-C., Lamentowicz, M., 2020b. Exceptional hydrological stability of a Sphagnum-dominated peatland over the late Holocene. Quat. Sci. Rev. 231, 106180. https://doi.org/10.1016/j.quascirev.2020.106180.
Marcisz, K., Buczek, K., Gałka, M., Margielewski, W., Mulot, M., Kołaczek, P., 2021. Past testate amoeba communities in landslide mountain fens (Polish Carpathians): The relationship between shell types and sediment. The Holocene 0959683621994647. https://doi.org/10.1177/0959683621994647.
Marcisz, K., Czerwiński, S., Lamentowicz, M., Łuców, D., Słowiński, M., 2022. How paleoecology can support peatland restoration. Past Global Changes Magazine 30, 12–13. https://doi.org/10.22498/pages.30.1.12.
Marcisz, K., Belka, Z., Dopieralska, J., Jakubowicz, M., Karpińska-Kołaczek, M., Kołaczek, P., Mauquoy, D., Słowiński, M., Zieliński, M., Lamentowicz, M., 2023a. Neodymium isotopes in peat reveal past local environmental disturbances. Sci. Total Environ. 871, 161859. https://doi.org/10.1016/j.scitotenv.2023.161859.
Marcisz, K., Belka, Z., Dopieralska, J., Jakubowicz, M., Karpińska-Kołaczek, M., Kołaczek, P., Mauquoy, D., Słowiński, M., Zieliński, M., Lamentowicz, M., 2023b. Navigating the limitations, assumptions and conceptual pitfalls of Nd isotope research on peatlands: Reply to the comments of Le Roux et al. (2023) on "Neodymium isotopes in peat reveal past local environmental disturbances" by Marcisz et al. (2023).
Marcisz, K., Bąk, M., Lamentowicz, M., Kołaczek, P., Theurer, T., Matulewski, P., Mauquoy, D., 2025. Substantial changes in land and forest management led to critical transitions in peatland functioning over the last 700 years. Sci. Rep. 15, 18211. https://doi.org/10.1038/s41598-025-02580-0.
Marret, F., O'Keefe, J., Osterloff, P., Pound, M., 2021. Applications of Non-Pollen Palynomorphs: from Palaeoenvironmental Reconstructions to Biostratigraphy. Geological Society of London.
Mauquoy, D., Hughes, P.D.M., Geel, B. van, 2010. A protocol for plant macrofossil analysis of peat deposits. Mires Peat 7, 1–5.
Mauquoy, D., van Geel, B., 2007. Mire and peat macros. In: Encyclopedia of Quaternary Science. Elsevier.
Mauquoy, D., Engelkes, T., Groot, M.H.M., Markesteijn, F., Oudejans, M.G., van der Plicht, J., Van Geel, B., 2002. High-resolution records of late-Holocene climate change and carbon accumulation in north-west European ombrotrophic peat bogs. Palaeogeogr. Palaeoclimatol. Palaeoecol. 186, 275–310. https://doi.org/10.1016/S0031-0182(02)00513-8.
Mauquoy, D., Payne, R.J., Babeshko, K.V., Bartlett, R., Boomer, I., Bowey, H., Evans, C. D., Ring-Hrubesh, F., Muirhead, D., O'Callaghan, M., Piotrowska, N., Rush, G., Sloan, T., Smeaton, C., Tsyganov, A.N., Mazei, Y.A., 2020. Falkland Island peatland development processes and the pervasive presence of fire. Quat. Sci. Rev. 240, 106391. https://doi.org/10.1016/j.quascirev.2020.106391.
Mazurek, M., Dobrowolski, R., Osadowski, Z., 2014. Geochemistry of deposits from spring-fed fens in West Pomerania (Poland) and its significance for palaeoenvironmental reconstruction. Géomorphologie 2014, 323–342.
McCarroll, Julia, Chambers, F.M., Webb, J.C., Thom, T., 2016a. Informing innovative peatland conservation in light of palaeoecological evidence for the demise of Sphagnum imbricatum: the case of Oxenhope Moor, Yorkshire, UK. Mires Peat 18. https://doi.org/10.19189/MaP.2015.OMB.206.
McCarroll, J., Chambers, F.M., Webb, J.C., Thom, T., 2016b. Using palaeoecology to advise peatland conservation: An example from West Arkengarthdale, Yorkshire, UK. J. Nat. Conserv. 30, 90–102. https://doi.org/10.1016/j.jnc.2016.02.002.
McGlone, M., Wilmshurst, J.M., 1999. A Holocene record of climate, vegetation change and peat bog development, east Otago, South Island, New Zealand. J. Q. Sci. 14, 239–254.
McParland, L.C., Collinson, M.E., Scott, A.C., Campbell, G., 2009. The use of reflectance values for the interpretation of natural and anthropogenic charcoal assemblages. Archaeol. Anthropol. Sci. 1, 61. https://doi.org/10.1007/s12520-009-0018-z.
Meisterfeld, R., 2001a. Testate amoebae with filopoda. In: Lee, J.J., Leedale, G.F., Bradbury, P. (Eds.), The Illustrated Guide to the Protozoa. Allen Press, Lawrence, pp. 1054–1084.
Meisterfeld, R., 2001b. Order Arcellinida, Kent 1880. In: Lee, J.J., Leedale, G.F., Bradbury, P. (Eds.), The Illustrated Guide to the Protozoa, Eds. Allen Press, Lawrence, pp. 827–860.
Menberu, M.W., Marttila, H., Ronkanen, A., Haghighi, A.T., Kløve, B., 2021. Hydraulic and Physical Properties of Managed and Intact Peatlands: Application of the Van Genuchten-Mualem Models to Peat Soils. Water Resour. Res. 57, 13. https://doi.org/10.1029/2020wr028624.
Menges, J., Sebag, D., Lebamba, J., Kiahtipes, C., Wotzka, H.-P., Preuß, J., Bwamangele, F.B., Lutonadio, R.K., Guardiola, M., Adatte, T., Stroobandt, Y., Bouillon, S., Garcin, Y., Schefuß, E., 2025. Environmental and climatic evolution of a river-proximal peatland in the Cuvette Centrale, Congo Basin. Q. Sci. Rev. 363, 109445. https://doi.org/10.1016/j.quascirev.2025.109445.
Mieczan, T., Tarkowska-Kukuryk, M., 2017. Microbial Communities as Environmental Indicators of Ecological Disturbance in Restored Carbonate Fen-Results of 10 Years of Studies. Microb. Ecol. https://doi.org/10.1007/s00248-017-0957-3.
Mighall, T., Timberlake, S., Martínez-Cortizas, A., Silva-Sánchez, N., Foster, I.D.L., 2017. Did prehistoric and Roman mining and metallurgy have a significant impact on vegetation? J. Archaeol. Sci. Rep. 11, 613–625. https://doi.org/10.1016/j.jasrep.2016.12.021.
Migliavacca, M., Musavi, T., Mahecha, M.D., Nelson, J.A., Knauer, J., Baldocchi, D.D., Perez-Priego, O., Christiansen, R., Peters, J., Anderson, K., Bahn, M., Black, T.A., Blanken, P.D., Bonal, D., Buchmann, N., Caldararu, S., Carrara, A., Carvalhais, N., Cescatti, A., Chen, J., Cleverly, J., Cremonese, E., Desai, A.R., El-Madany, T.S., Farella, M.M., Fernández-Martínez, M., Filippa, G., Forkel, M., Galvagno, M., Gomarasca, U., Gough, C.M., Göckede, M., Ibrom, A., Ikawa, H., Janssens, I.A., Jung, M., Kattge, J., Keenan, T.F., Knohl, A., Kobayashi, H., Kraemer, G., Law, B.E., Liddell, M.J., Ma, X., Mammarella, I., Martini, D., Macfarlane, C., Matteucci, G., Montagnani, L., Pabon-Moreno, D.E., Panigada, C., Papale, D., Pendall, E., Penuelas, J., Phillips, R.P., Reich, P.B., Rossini, M., Rotenberg, E., Scott, R.L., Stahl, C., Weber, U., Wohlfahrt, G., Wolf, S., Wright, I.J., Yakir, D., Zaehle, S., Reichstein, M., 2021. The three major axes of terrestrial ecosystem function. Nature. https://doi.org/10.1038/s41586-021-03939-9.
Miller, C., Finch, J., Hill, T., Peterse, F., Humphries, M., Zabel, M., Schefuß, E., 2019. Late Quaternary climate variability at Mfabeni peatland, eastern South Africa. Clim. Past 15, 1153–1170. https://doi.org/10.5194/cp-15-1153-2019.
Miola, A., 2012. Tools for Non-Pollen Palynomorphs (NPPs) analysis: A list of Quaternary NPP types and reference literature in English language (1972–2011). Rev. Palaeobot. Palynol. 186, 142–161. https://doi.org/10.1016/j.revpalbo.2012.06.010.
Mitchell, E.A.D., Charman, D.J., Warner, B.G., 2007. Testate amoebae analysis in ecological and paleoecological studies of wetlands: past, present and future. Biodivers. Conserv. 17, 2115–2137. https://doi.org/10.1007/s10531-007-9221-3.
Mulot, M., Villard, A., Varidel, D., Mitchell, E.A.D., 2015. A mesocosm approach to study the response of Sphagnum peatlands to hydrological changes: setup, optimisation and performance. Mires Peat 16, 1–12.
Muscente, A.D., Prabhu, A., Zhong, H., Eleish, A., Meyer, M.B., Fox, P., Hazen, R.M., Knoll, A.H., 2018. Quantifying ecological impacts of mass extinctions with network analysis of fossil communities. Proc. Natl. Acad. Sci. USA 115, 5217–5222. https://doi.org/10.1073/pnas.1719976115.
Naafs, B.D.A., Inglis, G.N., Blewett, J., McClymont, E.L., Lauretano, V., Xie, S., Evershed, R.P., Pancost, R.D., 2019. The potential of biomarker proxies to trace climate, vegetation, and biogeochemical processes in peat: A review. Glob. Planet. Chang. 179, 57–79. https://doi.org/10.1016/j.gloplacha.2019.05.006.
Nichols, J.E., Booth, R.K., Jackson, S.T., Pendall, E.G., Huang, Y.S., 2006. Paleohydrologic reconstruction based on n-alkane distributions in ombrotrophic peat. Org. Geochem. 37, 1505–1513.
Niebieszczański, J., Gałka, M., Hildebrandt-Radke, I., Karpińska-Kołaczek, M., Kołaczek, P., Lamentowicz, M., Rzodkiewicz, M., 2021. When archaeology meets environmental sciences: the Bruszczewo site revisited. In: Treasures of Time: Research of the Faculty of Archaeology of Adam Mickiewicz University in Poznań. Adam Mickiewicz University Poznan, pp. 218–235. https://doi.org/10.14746/wa.2021.11.978-83-946591-9-6.
Nogue, S., de Nascimento, L., Froyd, C.A., Wilmshurst, J.M., de Boer, E.J., Coffey, E.E.D., Whittaker, R.J., Fernandez-Palacios, J.M., Willis, K.J., 2017. Island biodiversity conservation needs palaeoecology. Nat. Ecol. Evol. 1, 181. https://doi.org/10.1038/s41559-017-0181.
Nott, C.J., Xie, S., Avsejs, L.A., Maddy, D., Chambers, F.M., Evershed, R.P., 2000. n-Alkane distributions in ombrotrophic mires as indicators of vegetation change related to climatic variation. Org. Geochem. 31, 231–235. https://doi.org/10.1016/s0146-6380(99)00153-9.
Oliver, T.H., Heard, M.S., Isaac, N.J., Roy, D.B., Procter, D., Eigenbrod, F., Freckleton, R., Hector, A., Orme, C.D., Petchey, O.L., Proenca, V., Raffaelli, D., Suttle, K.B., Mace, G. M., Martin-Lopez, B., Woodcock, B.A., Bullock, J.M., 2015. Biodiversity and Resilience of Ecosystem Functions. Trends Ecol. Evol. 30, 673–684. https://doi.org/10.1016/j.tree.2015.08.009.
Overbeck, F., 1947. Studien zur Hochmoorentwicklung in Niedersachsen und die Bestimmung der Humifizierung bei stratigraphisch-pollenanalytischen Mooruntersuchungen. Planta 35, 1–56. https://doi.org/10.1007/BF01989168.
Özdoğan, K.T., Gelabert, P., Hammers, N., Altınışık, N.E., de Groot, A., Plets, G., 2024. Archaeology meets environmental genomics: implementing sedaDNA in the study of the human past. Archaeol. Anthropol. Sci. 16, 108. https://doi.org/10.1007/s12520-024-01999-2.

Page, S.E., 2024. Lowland Tropical Peatlands – A Brief Review of Their Important Role in the Global Carbon Cycle and Biodiversity Support. Media Konservasi 29, 165. https://doi.org/10.29244/medkon.29.2.165.
PAGES, 2k Consortium, 2019. Consistent multidecadal variability in global temperature reconstructions and simulations over the Common Era. Nat. Geosci. https://doi.org/10.1038/s41561-019-0400-0.
Pancost, R.D., Baas, M., van Geel, B., Sinninghe Damsté, J.S., 2002. Biomarkers as proxies for plant inputs to peats: an example from a sub-boreal ombrotrophic bog. Org. Geochem. 33, 675–690. https://doi.org/10.1016/s0146-6380(02)00048-7.
Pancost, R.D., Baas, M., van Geel, B., Sinninghe Damsté, J.S., 2003. Response of an ombrotrophic bog to a regional climate event revealed by macrofossil, molecular and carbon isotopic data. The Holocene 13, 921–932. https://doi.org/10.1191/0959683603hl674rp.
Parducci, L., Väliranta, M., Salonen, J.S., Ronkainen, T., Matetovici, I., Fontana, S.L., Eskola, T., Sarala, P., Suyama, Y., 2015. Proxy comparison in ancient peat sediments: pollen, macrofossil and plant DNA. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 370, 20130382. https://doi.org/10.1098/rstb.2013.0382.
Parry, L.E., Charman, D.J., Blake, W.H., 2013. Comparative dating of recent peat deposits using natural and anthropogenic fallout radionuclides and Spheroidal Carbonaceous Particles (SCPs) at a local and landscape scale. Quat. Geochronol. 15, 11–19. https://doi.org/10.1016/j.quageo.2013.01.002.
Payne, R.J., 2010. Testate amoeba response to acid deposition in a Scottish peatland. Aquat. Ecol. 44, 373–385. https://doi.org/10.1007/s10452-009-9297-9.
Payne, R.J., 2011. Volcanic impacts on peatland microbial communities: A tephropalaeoecological hypothesis-test. Quat. Int. https://doi.org/10.1016/j.quaint.2011.06.019.
Payne, R., Blackford, J., 2005. Simulating the impacts of distal volcanic products upon peatlands in northern Britain: an experimental study on the Moss of Achnacree, Scotland. J. Archaeol. Sci. 32, 989–1001.
Payne, R.J., Blackford, J.J., 2009. Extending the Late Holocene Tephrochronology of the Central Kenai Peninsula, Alaska. ARCTIC 61, 3. https://doi.org/10.14430/arctic22.
Payne, R.J., Ratcliffe, J., Andersen, R., Flitcroft, C.E., 2016. A meta-database of peatland palaeoecology in Great Britain. Palaeogeogr. Palaeoclimatol. Palaeoecol. 457, 389–395. https://doi.org/10.1016/j.palaeo.2016.05.025.
Payne, R.J., Ring-Hrubesh, F., Rush, G., Sloan, T.J., Evans, C.D., Mauquoy, D., 2019. Peatland initiation and carbon accumulation in the Falkland Islands. Quat. Sci. Rev. https://doi.org/10.1016/j.quascirev.2019.03.022.
Pendall, E., Markgraf, V., White, J.W.C., Dreier, M., Kenny, R., 2001. Multi-proxy Record of Late Pleistocene–Holocene Climate and Vegetation Changes from a Peat Bog in Patagonia. Quat. Res. 55, 168–178. https://doi.org/10.1006/qres.2000.2206.
Pleskot, K., Apolinarska, K., Kołaczek, P., Suchora, M., Fojutowski, M., Joniak, T., Kotrys, B., Kramkowski, M., Słowiński, M., Woźniak, M., Lamentowicz, M., 2020. Searching for the 4.2 ka climate event at Lake Spore, Poland. CATENA 191, 104565. https://doi.org/10.1016/j.catena.2020.104565.
Płóciennik, M., Self, A., Birks, H.J.B., Brooks, S.J., 2011. Chironomidae (Insecta: Diptera) succession in Żabieniec bog and its palaeo-lake (central Poland) through the Late Weichselian and Holocene. Palaeogeogr. Palaeoclimatol. Palaeoecol. 307, 150–167. https://doi.org/10.1016/j.palaeo.2011.05.010.
Płóciennik, M., Pawłowski, D., Vilizzi, L., Antczak-Orlewska, O., 2020. From oxbow to mire: Chironomidae and Cladocera as habitat palaeoindicators. Hydrobiologia 847, 3257–3275. https://doi.org/10.1007/s10750-020-04327-6.
Pratte, S., Garneau, M., De Vleeschouwer, F., 2017. Increased atmospheric dust deposition during the Neoglacial in a boreal peat bog from north-eastern Canada. Palaeogeogr. Palaeoclimatol. Palaeoecol. 469, 34–46. https://doi.org/10.1016/j.palaeo.2016.12.036.
Qin, Y.M., Mitchell, E.A.D., Lamentowicz, M., Payne, R.J., Lara, E., Gu, Y.S., Huang, X.Y., Wang, H.M., 2013. Ecology of testate amoebae in peatlands of central China and development of a transfer function for paleohydrological reconstruction. J. Paleolimnol. 50, 319–330. https://doi.org/10.1007/s10933-013-9726-6.
Qin, Y., Li, H., Mazei, Y., Kurina, I., Swindles, G.T., Bobrov, A., Tsyganov, A.N., Gu, Y., Huang, X., Xue, J., Lamentowicz, M., Marcisz, K., Roland, T., Payne, R.J., Mitchell, E.A.D., Xie, S., 2021. Developing a continental-scale testate amoeba hydrological transfer function for Asian peatlands. Quat. Sci. Rev. 258, 106868. https://doi.org/10.1016/j.quascirev.2021.106868.
Ramdzan, K.N.M., Moss, P.T., Heijnis, H., Harrison, M.E., Yulianti, N., 2022. Application of Palaeoecological and Geochemical Proxies in the Context of Tropical Peatland Degradation and Restoration: A Review for Southeast Asia. Wetlands 42, 10. https://doi.org/10.1007/s13157-022-01618-7.
Ramdzan, K.N.M., Moss, P.T., Jacobsen, G., Gallego-Sala, A., Charman, D., Harrison, M.E., Page, S., Mishra, S., Wardle, D.A., Jaya, A., Aswandi Nasir, D., Yulianti, N., 2023. Insights for restoration: Reconstructing the drivers of long-term local fire events and vegetation turnover of a tropical peatland in Central Kalimantan. Palaeogeogr. Palaeoclimatol. Palaeoecol. 628, 111772. https://doi.org/10.1016/j.palaeo.2023.111772.
Rawlins, A., Morris, J., 2010. Social and economic aspects of peatland management in Northern Europe, with particular reference to the English case. Geoderma 154, 242–251. https://doi.org/10.1016/j.geoderma.2009.02.022.
Reczuga, M.K., Swindles, G.T., Grewling, Ł., Lamentowicz, M., 2015. Arcella peruviana sp. nov. (Amoebozoa: Arcellinida, Arcellidae), a new species from a tropical peatland in Amazonia. Eur. J. Protistol. 51, 437–449. https://doi.org/10.1016/j.ejop.2015.01.002.
Richard, D.P., Erin, L.M., Elizabeth, M.B., Zoë, R., Dan, J.C., Edward, R.C.H., Anthony, B., Frank, M.C., Katie, L.H.L., Richard, P.E., 2011. Archaeol as a methanogen biomarker in ombrotrophic bogs. Org. Geochem. 42, 1279–1287. https://doi.org/10.1016/j.orggeochem.2011.07.003.
Roland, T.P., Daley, T.J., Caseldine, C.J., Charman, D.J., Turney, C.S.M., Amesbury, M.J., Thompson, G.J., Woodley, E.J., 2015. The 5.2 ka climate event: Evidence from stable isotope and multi-proxy palaeoecological peatland records in Ireland. Quat. Sci. Rev. 124, 209–223. https://doi.org/10.1016/j.quascirev.2015.07.026.
Ronkainen, T., McClymont, E.L., Tuittila, E.S., Valiranta, M., 2014. Plant macrofossil and biomarker evidence of fen-bog transition and associated changes in vegetation in two Finnish peatlands. The Holocene. https://doi.org/10.1177/0959683614530442.
Rull, V., 2010. Ecology and palaeoecology: two approaches, one objective. Open Ecol. J. 3, 1–5.
Rull, V., 2014. Time continuum and true long-term ecology: from theory to practice. Front. Ecol. Evol. 2. https://doi.org/10.3389/fevo.2014.00075.
Rydin, H., Jeglum, J.K., 2013. The biology of peatlands. Oxford University Press.
Schafstall, N., Svitavská-Svobodová, H., Kadlec, M., Gałka, M., Kuneš, P., Bobek, P., Goliáš, V., Pech, P., Nývlt, D., Hubený, P., Kuosmanen, N., Carter, V.A., Florescu, G., 2024. The absence of disturbances promoted Late Holocene expansion of silver fir (Abies alba) in the Bohemian Forest. Palaeogeogr. Palaeoclimatol. Palaeoecol. 635, 111950. https://doi.org/10.1016/j.palaeo.2023.111950.
Schellekens, J., Horák-Terra, I., Buurman, P., Silva, A.C., Vidal-Torrado, P., 2014. Holocene vegetation and fire dynamics in central-eastern Brazil: Molecular records from the Pau de Fruta peatland. Org. Geochem. 77, 32–42. https://doi.org/10.1016/j.orggeochem.2014.08.011.
Schroeter, N., Toney, J.L., Lauterbach, S., Kalanke, J., Schwarz, A., Schouten, S., Gleixner, G., 2020. How to Deal With Multi-Proxy Data for Paleoenvironmental Reconstructions: Applications to a Holocene Lake Sediment Record From the Tian Shan, Central Asia. Front. Earth Sci. 8, 11. https://doi.org/10.3389/feart.2020.00353.
Schwörer, C., Leunda, M., Alvarez, N., Gugerli, F., Sperisen, C., 2022. The untapped potential of macrofossils in ancient plant DNA research. New Phytol. 235, 391–401. https://doi.org/10.1111/nph.18108.
Seddon, A.W.R., Mackay, A.W., Baker, A.G., Birks, H.J.B., Breman, E., Buck, C.E., Ellis, E.C., Froyd, C.A., Gill, J.L., Gillson, L., Johnson, E.A., Jones, V.J., Juggins, S., Macias-Fauria, M., Mills, K., Morris, J.L., Nogues-Bravo, D., Punyasena, S.W., Roland, T.P., Tanentzap, A.J., Willis, K.J., Aberhan, M., van Asperen, E.N., Austin, W.E.N., Battarbee, R.W., Bhagwat, S., Belanger, C.L., Bennett, K.D., Birks, H.H., Ramsey, C.B., Brooks, S.J., de Bruyn, M., Butler, P.G., Chambers, F.M., Clarke, S.J., Davies, A.L., Dearing, J.A., Ezard, T.H.G., Feurdean, A., Flower, R.J., Gell, P., Hausmann, S., Hogan, E.J., Hopkins, M.J., Jeffers, E.S., Korhola, A.A., Marchant, R., Kiefer, T., Lamentowicz, M., Larocque-Tobler, I., Lopez-Merino, L., Liow, L.H., McGowan, S., Miller, J.H., Montoya, E., Morton, O., Nogue, S., Onoufriou, C., Boush, L.P., Rodriguez-Sanchez, F., Rose, N.L., Sayer, C.D., Shaw, H.E., Payne, R., Simpson, G., Sohar, K., Whitehouse, N.J., Williams, J.W., Witkowski, A., 2014. Looking forward through the past: identification of 50 priority research questions in palaeoecology. J. Ecol. 102, 256–267. https://doi.org/10.1111/1365-2745.12195.
Seppä, H., 2013. Pollen analysis, principles. In: Encyclopedia of Quaternary Science. Elsevier, pp. 794–804. https://doi.org/10.1016/b978-0-444-53643-3.00171-0.
Shotyk, W., Noernberg, T., 2020. Sampling, handling, and preparation of peat cores from bogs: review of recent progress and perspectives for trace element research. Can. J. Soil Sci. 100, 363–380. https://doi.org/10.1139/cjss-2019-0160.
Shotyk, W., Cheburkin, A.K., Appleby, P.G., Fankhauser, A., Kramers, J.D., 1996. Two thousand years of atmospheric arsenic, antimony, and lead deposition recorded in an ombrotrophic peat bog profile, Jura Mountains, Switzerland. Earth Planet. Sci. Lett. 145, E1–E7.
Shotyk, Weiss, Appleby, Cheburkin, Gloor, Kramers, Der Reese, Van, Knaap, W.O., 1998. History of atmospheric lead deposition since 12,370 (14)C yr BP from a peat bog, jura mountains, switzerland. Science 281, 1635–1640. https://doi.org/10.1126/science.281.5383.1635.
Shumilovskikh, L.S., Shumilovskikh, E.S., Schlütz, F., van Geel, B., 2021. NPP-ID: Non-Pollen Palynomorph Image Database as a research and educational platform. Veg. Hist. Archaeobotany. https://doi.org/10.1007/s00334-021-00849-8.
Sillasoo, U., Väliranta, M., Tuittila, E.S., 2011. Fire history and vegetation recovery in two raised bogs at the Baltic Sea. J. Veg. Sci. 22, 1084–1093.
Sim, T.G., Swindles, G.T., Morris, P.J., Baird, A.J., Cooper, C.L., Gallego-Sala, A.V., Charman, D.J., Roland, T.P., Borken, W., Mullan, D.J., Aquino-López, M.A., Gałka, M., 2021. Divergent responses of permafrost peatlands to recent climate change. Environ. Res. Lett. 16, 034001. https://doi.org/10.1088/1748-9326/abe00b.
Šímová, A., Hájková, P., Petr, L., Divíšek, J., Kintrová, K., Hájek, M., 2025. Testate amoebae in an ombrotrophic bog reconcile equivocal palaeoclimate reconstructions for the Western Carpathians. Quat. Sci. Rev. 349, 109062. https://doi.org/10.1016/j.quascirev.2024.109062.
Singer, D., Kosakyan, A., Pillonel, A., Mitchell, E.A.D., Lara, E., 2015. Eight species in the Nebela collaris complex: Nebela gimlii (Arcellinida, Hyalospheniidae), a new species described from a Swiss raised bog. Eur. J. Protistol. 51, 79–85. https://doi.org/10.1016/j.ejop.2014.11.004.
Sjögren, P., Lamentowicz, M., 2008. Human and climatic impact on mires: a case study of Les Amburnex mire, Swiss Jura Mountains. Veg. Hist. Archaeobotany 17, 185–197. https://doi.org/10.1007/s00334-007-0095-9.
Sjörs, H., 1948. Myrvegetation i bergslagen. Sv. växtgeografiska sällsk.
Słowiński, M., Marcisz, K., Płóciennik, M., Obremska, M., Pawłowski, D., Okupny, D., Słowińska, S., Borówka, R., Kittel, P., Forysiak, J., Michczyńska, D.J., Lamentowicz, M., 2016. Drought as a stress driver of ecological changes in peatland - A palaeoecological study of peatland development between 3500 BCE and 200 BCE in central Poland. Palaeogeogr. Palaeoclimatol. Palaeoecol. 461, 272–291. https://doi.org/10.1016/j.palaeo.2016.08.038.

Słowiński, M., Brauer, A., Guzowski, P., Związek, T., Obremska, M., Theuerkauf, M., Dietze, E., Schwab, M., Tjallingii, R., Czaja, R., Ott, F., Błaszkiewicz, M., 2021. The role of Medieval road operation on cultural landscape transformation. Sci. Rep. 11. https://doi.org/10.1038/s41598-021-00090-3.

Słowiński, M., Obremska, M., Avirmed, D., Woszczyk, M., Adiya, S., Łuców, D., Mroczkowska, A., Halaś, A., Szczuciński, W., Kruk, A., Lamentowicz, M., Stańczak, J., Rudaya, N., 2022. Fires, vegetation, and human-The history of critical transitions during the last 1000 years in Northeastern Mongolia. Sci. Total Environ. 838, 155660. https://doi.org/10.1016/j.scitotenv.2022.155660.

Sole, R.V., Montoya, J.M., 2001. Complexity and fragility in ecological networks. Proc. R. Soc. Biol. Sci. (Series B) 268, 2039–2045.

Stiftung, Michael Succow, 2023. PEATLAND ATLAS. Facts and figures about wet climate guardians.

Strobel, P., Henning, T., Bliedtner, M., Mosher, S.G., Rahimova, H., Haberzettl, T., Kirsten, K.L., Lehndorff, E., Power, M.J., Zech, M., Zech, R., 2024. Holocene fire dynamics and their climatic controls on the southern Cape coast of South Africa - A 7.2 ka multi-proxy record from the peatland Vankervelsvlei. Quat. Sci. Rev. 325, 108464. https://doi.org/10.1016/j.quascirev.2023.108464.

Succow, M., Jeschke, L., 1990. Moore in der Landschaft : Entstehung, Haushalt, Lebewelt, Verbreitung, Nutzung und Erhaltung der Moore, 2, Aufl. ed. Urania-Vlg, Leipzig.

Succow, M., Joosten, H., 2001. Landschaftsökologische Moorkunde. Sweizerbart, Stüttgart.

Summerhayes, C.P., Zalasiewicz, J., Head, M., Syvitski, J., Barnosky, A., Cearreta, A., Fiałkiewicz-Koziel, B., Grinevald, J., Leinfelder, R., McCarthy, F., McNeill, J.R., Saito, Y., Wagreich, M., Waters, C., Williams, M., Zinke, J., 2024. The Duration of the Anthropocene Epoch: A Synthesis 0. https://doi.org/10.2139/ssrn.4788354.

Sutherland, W.J., Freckleton, R.P., Godfray, H.C.J., Beissinger, S.R., Benton, T., Cameron, D.D., Carmel, Y., Coomes, D.A., Coulson, T., Emmerson, M.C., Hails, R.S., Hays, G.C., Hodgson, D.J., Hutchings, M.J., Johnson, D., Jones, J.P.G., Keeling, M.J., Kokko, H., Kunin, W.E., Lambin, X., Lewis, O.T., Malhi, Y., Mieszkowska, N., Milner-Gulland, E.J., Norris, K., Phillimore, A.B., Purves, D.W., Reid, J.M., Reuman, D.C., Thompson, K., Travis, J.M.J., Turnbull, L.A., Wardle, D.A., Wiegand, T., 2013. Identification of 100 fundamental ecological questions. J. Ecol. 101, 58–67. https://doi.org/10.1111/1365-2745.12025.

Swindles, G.T., Plunkett, G., Roe, H.M., 2007. A multi-proxy climate record from a raised bog in County Fermanagh, Northern Ireland: a critical examination of the link between bog surface wetness and solar variability. J. Quat. Sci. 22, 667–679.

Swindles, G.T., Lawson, I.T., Savov, I.P., Connor, C.B., Plunkett, G., 2011. A 7000 yr perspective on volcanic ash clouds affecting northern Europe. Geology 39, 887–890. https://doi.org/10.1130/g32146.1.

Swindles, G.T., Patterson, R.T., Roe, H.M., Galloway, J.M., 2012. Evaluating periodicities in peat-based climate proxy records. Quat. Sci. Rev. 41, 94–103. https://doi.org/10.1016/j.quascirev.2012.03.003.

Swindles, G.T., Reczuga, M., Lamentowicz, M., Raby, C.L., Turner, T.E., Charman, D.J., Gallego-Sala, A., Valderrama, E., Williams, C., Draper, F., Honorio Coronado, E.N., Roucoux, K.H., Baker, T., Mullan, D.J., 2014. Ecology of testate amoebae in an Amazonian peatland and development of a transfer function for palaeohydrological reconstruction. Microb. Ecol. 68, 284–298. https://doi.org/10.1007/s00248-014-0378-5.

Swindles, G.T., Morris, P.J., Mullan, D., Watson, E.J., Turner, T.E., Roland, T.P., Amesbury, M.J., Kokfelt, U., Schoning, K., Pratte, S., Gallego-Sala, A., Charman, D.J., Sanderson, N., Garneau, M., Carrivick, J.L., Woulds, C., Holden, J., Parry, L., Galloway, J.M., 2015a. The long-term fate of permafrost peatlands under rapid climate warming. Sci. Rep. 5, 17951. https://doi.org/10.1038/srep17951.

Swindles, G.T., Watson, E., Turner, T.E., Galloway, J.M., Hadlari, T., Wheeler, J., Bacon, K.L., 2015b. Spheroidal carbonaceous particles are a defining stratigraphic marker for the Anthropocene. Sci. Rep. 5, 10264. https://doi.org/10.1038/srep10264.

Swindles, G.T., Green, S.M., Brown, L., Holden, J., Raby, C.L., Turner, T.E., Smart, R., Peacock, M., Baird, A.J., 2016a. Evaluating the use of dominant microbial consumers (testate amoebae) as indicators of blanket peatland restoration. Ecol. Indic. 69, 318–330. https://doi.org/10.1016/j.ecolind.2016.04.038.

Swindles, G.T., Lamentowicz, M., Reczuga, M., Galloway, J.M., 2016b. Palaeoecology of testate amoebae in a tropical peatland. Eur. J. Protistol. 55, 181–189. https://doi.org/10.1016/j.ejop.2015.10.002.

Swindles, G.T., Morris, P.J., Whitney, B., Galloway, J.M., Gałka, M., Gallego-Sala, A., Macumber, A.L., Mullan, D., Smith, M.W., Amesbury, M.J., Roland, T.P., Sanei, H., Patterson, R.T., Sanderson, N., Parry, L., Charman, D.J., Lopez, O., Valderamma, E., Watson, E.J., Ivanovic, R.F., Valdes, P.J., Turner, T.E., Lähteenoja, O., 2018. Ecosystem state shifts during long-term development of an Amazonian peatland. Glob. Chang. Biol. 24, 738–757. https://doi.org/10.1111/gcb.13950.

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., Warner, B., 2025. Climate and water-table levels regulate peat accumulation rates across Europe. PLoS One 20, e0327422. https://doi.org/10.1371/journal.pone.0327422.

Sytiuk, A., Céréghino, R., Hamard, S., Delarue, F., Guittet, A., Barel, J.M., Dorrepaal, E., Küttim, M., Lamentowicz, M., Pourrut, B., Robroek, B.J.M., Tuittila, E., Jassey, V.E. J., 2022. Predicting the structure and functions of peatland microbial communities from Sphagnum phylogeny, anatomical and morphological traits and metabolites. J. Ecol. 110, 80–96. https://doi.org/10.1111/1365-2745.13728.

Tanneberger, F., Moen, A., Barthelmes, A., Lewis, E., Miles, L., Sirin, A., Tegetmeyer, C., Joosten, H., 2021. Mires in Europe—Regional Diversity. Cond. Protect. Div. 13, 381. https://doi.org/10.3390/d13080381.

Taylor, B., Strüder-Kypke, M., Siemensma, F., 2025. A new species of testate amoeba, *Arcella prismatica* sp. nov. (Amoebozoa: Arcellinida), from peatlands in Ontario and Quebec, Canada. Can. Field Naturalist 138, 1–15. https://doi.org/10.22621/cfn.v138i1.3195.

Team R Core, 2024. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Tfaily, M.M., Cooper, W.T., Kostka, J.E., Chanton, P.R., Schadt, C.W., Hanson, P.J., Iversen, C.M., Chanton, J.P., 2014. Organic matter transformation in the peat column at Marcell Experimental Forest: Humification and vertical stratification. Organic matter dynamics. J. Geophys. Res. Biogeosci. 119, 661–675. https://doi.org/10.1002/2013jg002492.

Theurer, T., Muirhead, D., Jolley, D., Mauquoy, D., 2021. The applicability of Raman spectroscopy in the assessment of palaeowildfire intensity. Palaeogeogr. Palaeoclimatol. Palaeoecol. 570, 110363. https://doi.org/10.1016/j.palaeo.2021.110363.

Theurer, T., Naszarkowski, N., Muirhead, D.K., Jolley, D., Mauquoy, D., 2022. Assessing Modern Calluna Heathland Fire Temperatures Using Raman Spectroscopy: Implications for Past Regimes and Geothermometry. Front. Earth Sci. 10. https://doi.org/10.3389/feart.2022.827933.

Theurer, T., Mauquoy, D., Hadden, R., Muirhead, D., Campbell-Lochrie, Z., Córdoba, S. V., von Scheffer, C., Coathup, D.T., 2024. A novel proxy for energy flux in multi-era wildfire reconstruction. Sci. Rep. 14, 26409. https://doi.org/10.1038/s41598-024-78219-3.

Thomas, C.L., Jansen, B., Czerwiński, S., Gałka, M., Knorr, K.-H., van Loon, E.E., Egli, M., Wiesenberg, G.L.B., 2023. Comparison of paleobotanical and biomarker records of mountain peatland and forest ecosystem dynamics over the last 2600 years in central Germany. Biogeosciences 20, 4893–4914. https://doi.org/10.5194/bg-20-4893-2023.

Tinner, W., Hu, F.S., 2003. Size parameters, size-class distribution and area-number relationship of microscopic charcoal: relevance for fire reconstruction. The Holocene 13, 499–505.

Tobolski, K., 2000. Przewodnik do oznaczania torfów i osadów jeziornych. Vademecum Geobotanicum, PWN, Warszawa.

Tolonen, K., 1986. Rhizopod analysis. In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons, pp. 645–666.

Tolonen, K., Warner, B.G., Vasander, H., 1992. Ecology of Testaceans (Protozoa: Rhizopoda) in mires in southern Finland: I. Autecology. Arch. Protistenkd. 142, 119–138.

Turetsky, M.R., Manning, S.W., Wieder, R.K., 2004. Dating recent peat deposits. Wetlands 24, 324–356.

Turetsky, M.R., Benscoter, B., Page, S., Rein, G., van der Werf, G.R., Watts, A., 2015. Global vulnerability of peatlands to fire and carbon loss. Nat. Geosci. 8, 11–14. https://doi.org/10.1038/ngeo2325.

Twiddle, C.L., Bunting, M.J., 2010. Experimental investigations into the preservation of pollen grains: A pilot study of four pollen types. Rev. Palaeobot. Palynol. 162, 621–630. https://doi.org/10.1016/j.revpalbo.2010.08.003.

Umbanhowar, C.E., Mcgrath, M.J., 1998. Experimental production and analysis of microscopic charcoal from wood, leaves and grasses. The Holocene 8, 341–346. https://doi.org/10.1191/095968398666496051.

Vachula, R.S., 2018. A usage-based size classification scheme for sedimentary charcoal. The Holocene 29, 523–527. https://doi.org/10.1177/0959683618816520.

Vachula, R., Rehn, E., 2022. Modeled dispersal patterns for wood and grass charcoal are different: Implications for paleofire reconstruction. The Holocene 33. https://doi.org/10.1177/09596836221131708.

Vachula, R., Sheppard, R., Cheung, A., 2022. Preservation biases are pervasive in Holocene paleofire records. Palaeogeogr. Palaeoclimatol. Palaeoecol. 602, 111165. https://doi.org/10.1016/j.palaeo.2022.111165.

Väliranta, M., Korhola, A., Seppä, H., Tuittila, E.-S., Sarmaja-Korjonen, K., Laine, J., Alm, J., 2007. High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: a quantitative approach. The Holocene 17, 1093–1107.

Väliranta, M., Blundell, A., Charman, D.J., Karofeld, E., Korhola, A., Sillasoo, U., Tuittila, E.S., 2012. Reconstructing peatland water tables using transfer functions for plant macrofossils and testate amoebae: A methodological comparison. Quat. Int. 268, 34–43. https://doi.org/10.1016/j.quaint.2011.05.024.

Väliranta, M., Salonen, J.S., Heikkila, M., Amon, L., Helmens, K., Klimaschewski, A., Kuhry, P., Kultti, S., Poska, A., Shala, S., Veski, S., Birks, H.H., 2015. Plant macrofossil evidence for an early onset of the Holocene summer thermal maximum in northernmost Europe. Nat. Commun. 6, 6809. https://doi.org/10.1038/ncomms7809.

van Bellen, S., Larivière, V., 2020. The ecosystem of peatland research: a bibliometric analysis. Mires Peat 26, 1–30. https://doi.org/10.19189/MaP.2020.RSC.StA.1977.

van Bellen, S., Mauquoy, D., Payne, R.J., Roland, T.P., Hughes, P.D.M., Daley, T.J., Loader, N.J., Street-Perrott, F.A., Rice, E.M., Pancotto, V.A., 2017. An alternative approach to transfer functions? Testing the performance of a functional trait-based model for testate amoebae. Palaeogeogr. Palaeoclimatol. Palaeoecol. 468, 173–183. https://doi.org/10.1016/j.palaeo.2016.12.005.

van Bellen, S., Shotyk, W., Magnan, G., Davies, L., Nason, T., Mullan-Boudreau, G., Garneau, M., Noernberg, T., Bragazza, L., Zaccone, C., 2020. Carbon and nitrogen accumulation rates in ombrotrophic peatlands of central and northern Alberta, Canada, during the last millennium. Biogeochemistry 151, 251–272.

van der Knaap, W.O., Lamentowicz, M., van Leeuwen, J.F.N., Hangartner, S., Leuenberger, M., Mauquoy, D., Goslar, T., Mitchell, E.A.D., Lamentowicz, Ł.,

Kamenik, C., 2011. A multi-proxy, high-resolution record of peatland development and its drivers during the last millennium from the subalpine Swiss Alps. Quat. Sci. Rev. 30, 3467–3480. https://doi.org/10.1016/j.quascirev.2011.06.017.
Van der Putten, N., Stieperaere, H., Verbruggen, C., Ochyra, R., 2004. Holocene palaeoecology and climate history of South Georgia (sub-Antarctica) based on a macrofossil record of bryophytes and seeds. The Holocene 14, 382–392. https://doi.org/10.1191/0959683604hl714rp.
Van der Putten, N., Hébrard, J.-P., Verbruggen, C., Van de Vijver, B., Disnar, J.-R., Spassov, S., de Beaulieu, J.-L., De Dapper, M., Keravis, D., Hus, J., Thouveny, N., Frenot, Y., 2008. An integrated palaeoenvironmental investigation of a 6200 year old peat sequence from Ile de la Possession, Iles Crozet, sub-Antarctica. Palaeogeogr. Palaeoclimatol. Palaeoecol. 270, 179–195. https://doi.org/10.1016/j.palaeo.2008.09.014.
Van der Putten, N., Verbruggen, C., Björck, S., Michel, E., Disnar, J.-R., Chapron, E., Moine, B.N., de Beaulieu, J.-L., 2015. The Last Termination in the South Indian Ocean: A unique terrestrial record from Kerguelen Islands (49°S) situated within the Southern Hemisphere westerly belt. Quat. Sci. Rev. 122, 142–157. https://doi.org/10.1016/j.quascirev.2015.05.010.
van Geel, B., 1978. A palaeoecological study of Holocene peat bog sections in Germany and the Netherlands. Rev. Palaeobot. Palynol. 25, 1–120. https://doi.org/10.1016/0034-6667(78)90040-4.
van Geel, B., Aptroot, A., 2006. Fossil ascomycetes in Quaternary deposits. Nova Hedwigia 82, 313–329. https://doi.org/10.1127/0029-5035/2006/0082-0313.
van Geel, B., Hallewas, D.P., Pals, J.P., 1983. A late holocene deposit under the Westfriese Zeedijk near Enkhuizen (Prov. of Noord-Holland, The Netherlands): Palaeoecological and archaeological aspects. Rev. Palaeobot. Palynol. 38, 269–335. https://doi.org/10.1016/0034-6667(83)90026-x.
van Geel, B., Mur, L.R., Ralska-Jasiewiczowa, M., Goslar, T., 1994. Fossil akinetes of Aphanizomenon and Anabaena as indicators for medieval phosphate-eutrophication of Lake Gosciaz (Central Poland). Rev. Palaeobot. Palynol. 83, 97–105. https://doi.org/10.1016/0034-6667(94)90061-2.
van Geel, B., Guthrie, R.D., Altmann, J.G., Broekens, P., Bull, I.D., Gill, F.L., Jansen, B., Nieman, A.M., Gravendeel, B., 2011. Mycological evidence of coprophagy from the feces of an Alaskan Late Glacial mammoth. In: Quaternary Science ReviewsBeringia and Beyond: Papers Celebrating the Scientific Career of Andrei Vladimirovich Sher, 1939–2008 30, pp. 2289–2303. https://doi.org/10.1016/j.quascirev.2010.03.008.
van Geel, B., Heijnis, H., Charman, D.J., Thompson, G., Engels, S., 2014. Bog burst in the eastern Netherlands triggered by the 2.8 kyr BP climate event. The Holocene. https://doi.org/10.1177/0959683614544066.
van Leeuwen, J.F.N., Froyd, C.A., Van Der Knaap, W.O., Coffey, E.E., Tye, A., Willis, K.J., 2008. Fossil pollen as a guide to conservation in the Galapagos. Science 322, 1206.
Vanneste, H., De Vleeschouwer, F., Martinez-Cortizas, A., von Scheffer, C., Piotrowska, N., Coronato, A., Le Roux, G., 2015. Late-glacial elevated dust deposition linked to westerly wind shifts in southern South America. Sci. Rep. 5, 11670. https://doi.org/10.1038/srep11670.
De Vleeschouwer, Francois Fagel, N., Cheburkin, A., Pazdur, A., Sikorski, J., Mattielli, N., Renson, V., Fialkiewicz, B., Piotrowska, N., Le Roux, G., 2009a. Anthropogenic impacts in North Poland over the last 1300 years - A record of Pb, Zn, Cu, Ni and S in an ombrotrophic peat bog. Sci. Total Environ. 407, 5674–5684.
De Vleeschouwer, François Piotrowska, N., Sikorski, J., Pawlyta, J., Cheburkin, A., Le Roux, G., Lamentowicz, M., Fagel, N., Mauquoy, D., 2009b. Multi-proxy evidence of `Little Ice Age' palaeoenvironmental changes in a peat bog from northern Poland. The Holocene 19, 625–637. https://doi.org/10.1177/0959683609104027.
von Scheffer, C., De Vleeschouwer, F., Le Roux, G., Unkel, I., 2023. Mineral dust and lead deposition from land use and metallurgy in a 4800-year-old peat record from the Central Alps (Tyrol, Austria). Q. Int. https://doi.org/10.1016/j.quaint.2023.03.018.
Wacnik, A., Tylmann, W., Bonk, A., Goslar, Tomasz, Enters, D., Meyer-Jacob, C., Grosjean, M., 2016. Determining the responses of vegetation to natural processes and human impacts in north-eastern Poland during the last millennium: combined pollen, geochemical and historical data. Veg. Hist. Archaeobotany 25, 479–498. https://doi.org/10.1007/s00334-016-0565-z.
Wang, B., Behling, H., 2025. Holocene vegetation and environmental changes of peat ecosystems in southwestern and northeastern Amazonia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 673, 113010. https://doi.org/10.1016/j.palaeo.2025.113010.
Wardle, D.A., 2002. Communities and ecosystems: linking the aboveground and belowground components, Monographs in population biology; 34. Princeton University Press, Princeton.
Warner, B.G., 1990a. Methods in Quaternary Ecology, Geosciences Canada. Geological Association of Canada.
Warner, B.G., 1990b. Testate Amoebae (Protozoa), in: Methods in Quaternary Ecology. Geosci. Can. 65–74.
Warner, B.G., Charman, D.J., 1994. Holocene Changes on a Peatland in Northwestern Ontario Interpreted from Testate Amebas (Protozoa) Analysis. Boreas 23, 270–279.
Waters, C.N., Head, M.J., Zalasiewicz, J., McCarthy, F.M.G., Wing, S.L., Haff, P.K., Williams, M., Barnosky, A.D., Fiałkiewicz-Kozieł, B., Leinfelder, R., McNeill, J.R., Rose, N.L., Steffen, W., Summerhayes, C.P., Wagreich, M., An, Z., Cearreta, A., Cundy, A.B., Fairchild, I.J., Gałuszka, A., Hajdas, I., Han, Y., Ivar do Sul, J.A., Jeandel, C., Syvitski, J., Turner, S.D., Zinke, J., 2023. Response to Merritts et al. (2023): The Anthropocene is complex. Defining it is not. Earth Sci. Rev. 238, 104335. https://doi.org/10.1016/j.earscirev.2023.104335.
Watson, E.J., Kołaczek, P., Słowiński, M., Swindles, G.T., Marcisz, K., Gałka, M., Lamentowicz, M., 2017. First discovery of Holocene Alaskan and Icelandic tephra in Polish peatlands. J. Quat. Sci. 32, 457–462. https://doi.org/10.1002/jqs.2945.
Weijers, J.W.H., Schouten, S., Spaargaren, O.C., Sinninghe Damsté, J.S., 2006. Occurrence and distribution of tetraether membrane lipids in soils: Implications for the use of the TEX86 proxy and the BIT index. Org. Geochem. 37, 1680–1693. https://doi.org/10.1016/j.orggeochem.2006.07.018.
Weiss, D., Shotyk, W., Kempf, O., 1999. Archives of atmospheric lead pollution. Naturwissenschaften 86, 262–275.
Whitlock, C., Larsen, C., 2001. Charcoal as a fire proxy. In: Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal, and Siliceous Indicators. Springer, pp. 75–97. https://doi.org/10.1007/0-306-47668-1_5.
Whitlock, C., Tinner, W., 2010. Fire in the Earth System, 55e57, p. 18.
William, S., 1988. 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.
Williams, J.W., Blois, J.L., Shuman, B.N., 2011. Extrinsic and intrinsic forcing of abrupt ecological change: case studies from the late Quaternary. J. Ecol. 99, 664–677. https://doi.org/10.1111/j.1365-2745.2011.01810.x.
Williams, J.W., Grimm, E.C., Blois, J.L., Charles, D.F., Davis, E.B., Goring, S.J., Graham, R.W., Smith, A.J., Anderson, M., Arroyo-Cabrales, J., Ashworth, A.C., Betancourt, J.L., Bills, B.W., Booth, R.K., Buckland, P.I., Curry, B.B., Giesecke, T., Jackson, S.T., Latorre, C., Nichols, J., Purdum, T., Roth, R.E., Stryker, M., Takahara, H., 2018. The Neotoma Paleoecology Database, a multi-proxy, international, community-curated data resource. Quat. Res. 89, 156–177. https://doi.org/10.1017/qua.2017.105.
Williams, M., Zalasiewicz, J., Barnosky, A.D., Leinfelder, R., Head, M.J., Waters, C.N., McCarthy, F.M.G., Cearreta, A., Aldridge, D.C., McGann, M., Hamilton, P.B., Summerhayes, C.P., Syvitski, J., Zinke, J., Cundy, A.B., Fiałkiewicz-Kozieł, B., McNeill, J.R., Kuwae, M., Rose, N.L., Turner, S.D., Saito, Y., Wagreich, M., Stegner, M.A., Yasuhara, M., Han, Y., Wrisdale, A., Holmes, R., Berrio, J.C., 2024. Palaeontological signatures of the Anthropocene are distinct from those of previous epochs. Earth Sci. Rev. 104844. https://doi.org/10.1016/j.earscirev.2024.104844.
Willis, K.J., Bailey, R.M., Bhagwat, S.A., Birks, H.J.B., 2010. Biodiversity baselines, thresholds and resilience: Testing predictions and assumptions using palaeoecological data. Trends Ecol. Evol. 25, 583–591.
Wilmshurst, J.M., Wiser, S.K., Charman, D.J., 2003. Reconstructing Holocene water tables in New Zealand using testate amoebae: differential preservation of tests and implications for the use of transfer functions. The Holocene 13, 61–72.
Winton, R.S., Benavides, J.C., Mendoza, E., Uhde, A., Hastie, A., Honorio Coronado, E.N., Hernandez Ortega, A.G., Paukku, S., Mullins, B., del Aguila Pasquel, J., Aymard-Corredor, G.A., Baker, T.R., Draper, F.C., Flores Llampazo, G., Herrera, R., Phillips, O.L., Reyna Huaymacari, J.M., ter Steege, H., Stropp, J., Lawson, I.T., Gallego-Sala, A.V., Boom, A., Wehrli, B., Hoyt, A.M., 2025. Widespread carbon-dense peatlands in the Colombian lowlands. Environ. Res. Lett. 20, 054025. https://doi.org/10.1088/1748-9326/adbc03.
Wochal, D., Marcisz, K., Barabach, J., Bąk, M., Lamentowicz, M., 2025. The Fen that vanished: The untold story of drainage and peat extraction in Bagno Chlebowo peatland with implications for nature conservation. Glob. Ecol. Conserv. 61, e03647. https://doi.org/10.1016/j.gecco.2025.e03647.
Wood, J.R., Perry, G.L.W., Wilmshurst, J.M., 2017. Using palaeoecology to determine baseline ecological requirements and interaction networks for de-extinction candidate species. Funct. Ecol. 31, 1012–1020. https://doi.org/10.1111/1365-2435.12773.
Woodward, C., Shulmeister, J., Larsen, J., Jacobsen, G.E., Zawadzki, A., 2014. Landscape hydrology. The hydrological legacy of deforestation on global wetlands. Science 346, 844–847. https://doi.org/10.1126/science.1260510.
Wyatt, K.H., McCann, K.S., Rober, A.R., Turetsky, M.R., 2021. Trophic interactions regulate peatland carbon cycling. Ecol. Lett. https://doi.org/10.1111/ele.13697.
Xu, J., Morris, P.J., Liu, J., Holden, J., 2018. 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.
Yang, H., Rose, N.L., Battarbee, R.W., 2001. Dating of recent catchment peats using spheroidal carbonaceous particle (SCP) concentration profiles with particular reference to Lochnagar, Scotland. The Holocene 11, 593–597. https://doi.org/10.1191/095968301680223549.
Yeloff, D., Mauquoy, D., 2006. The influence of vegetation composition on peat humification: implications for palaeoclimatic studies. Boreas 35, 662–673. https://doi.org/10.1111/j.1502-3885.2006.tb01172.x.
Yeloff, D., Bennett, K., Blaauw, M., Mauquoy, D., Sillasoo, U., Vanderplicht, J., Van Geel, B., 2006. High precision 14C dating of Holocene peat deposits: A comparison of Bayesian calibration and wiggle-matching approaches. Quat. Geochronol. 1, 222–235. https://doi.org/10.1016/j.quageo.2006.08.003.
Yeloff, D., Broekens, P., Innes, J., van Geel, B., 2007. Late Holocene vegetation and land-use history in Denmark: A multi-decadally resolved record from Lille Vildmose, northeast Jutland. Rev. Palaeobot. Palynol. 146, 182–192. https://doi.org/10.1016/j.revpalbo.2007.04.001.
Young, D.M., Baird, A.J., Charman, D.J., Evans, C.D., Gallego-Sala, A.V., Gill, P.J., Hughes, P.D.M., Morris, P.J., Swindles, G.T., 2019. Misinterpreting carbon accumulation rates in records from near-surface peat. Sci. Rep. 9. https://doi.org/10.1038/s41598-019-53879-8.
Yu, Z., 2006. Holocene carbon accumulation of fen peatlands in boreal western Canada: A complex ecosystem response to climate variation and disturbance. Ecosystems 9, 1278–1288.
Yu, Z.C., 2012. Northern peatland carbon stocks and dynamics: a review. Biogeosciences 9, 4071–4085. https://doi.org/10.5194/bg-9-4071-2012.
Yu, Z.C., Beilman, D.W., Jones, M.C., 2009. Sensitivity of northern peatlands to Holocene climate change. In: Baird, A., Belyea, L., Comas, X., Reeve, A., Slater, L. (Eds.), AGU Geophysical Monograph, Carbon Cycling in Northern Peatlands, pp. 55–69.
Yu, Z.C., Loisel, J., Brosseau, D.P., Beilman, D.W., Hunt, S.J., 2010. Global peatland dynamics since the Last Glacial Maximum. Geophys. Res. Lett. 37. https://doi.org/10.1029/2010gl043584.

Yu, Z., Beilman, D.W., Frolking, S., MacDonald, G.M., Roulet, N.T., Camill, P., Charman, D.J., 2011. Peatlands and Their Role in the Global Carbon Cycle. EOS Trans. Am. Geophys. Union 92, 97–98. https://doi.org/10.1029/2011EO120001.

Yu, Z.C., Vitt, D.H., Wieder, R.K., 2014. Continental fens in western Canada as effective carbon sinks during the Holocene. The Holocene 24, 1090–1104. https://doi.org/10.1177/0959683614538075.

Zaccone, C., Rein, G., D'Orazio, V., Hadden, R.M., Belcher, C.M., Miano, T.M., 2014. Smouldering fire signatures in peat and their implications for palaeoenvironmental reconstructions. Geochim. Cosmochim. Acta 137, 134–146. https://doi.org/10.1016/j.gca.2014.04.018.

Zaccone, C., Plaza, C., Ciavatta, C., Miano, T.M., Shotyk, W., 2018. Advances in the determination of humification degree in peat since Achard (1786) : Applications in geochemical and paleoenvironmental studies. Earth Sci. Rev. 185, 163–178. https://doi.org/10.1016/j.earscirev.2018.05.017.

Zak, D., McInnes, R.J., 2022. A call for refining the peatland restoration strategy in Europe. J. Appl. Ecol. https://doi.org/10.1111/1365-2664.14261.

Zalasiewicz, J., Head, M.J., Waters, C.N., Turner, S.D., Haff, P.K., Summerhayes, C., Williams, M., Cearreta, A., Wagreich, M., Fairchild, I., Rose, N.L., Saito, Y., Leinfelder, R., Fiałkiewicz-Kozieł, B., An, Z., Syvitski, J., Gałuszka, A., McCarthy, F. M.G., Ivar do Sul, J., Barnosky, A., Cundy, A.B., McNeill, J.R., Zinke, J., 2023. The Anthropocene within the Geological Time Scale: a response to fundamental questions. Episodes. https://doi.org/10.18814/epiiugs/2023/023025.

Zhang, H., Amesbury, M.J., Piilo, S.R., Garneau, M., Gallego-Sala, A., Väliranta, M.M., 2020. Recent Changes in Peatland Testate Amoeba Functional Traits and Hydrology Within a Replicated Site Network in Northwestern Québec, Canada. Front. Ecol. Evol. 8. https://doi.org/10.3389/fevo.2020.00228.

Zhang, H., Väliranta, M., Swindles, G.T., Aquino-López, M.A., Mullan, D., Tan, N., Amesbury, M., Babeshko, K.V., Bao, 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., Zhao, Y., 2022. 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.

Zheng, Y., Zhou, W., Xie, S., Yu, X., 2009. A comparative study of n-alkane biomarker and pollen records: an example from southern China. Sci. Bull. 54, 1065–1072. https://doi.org/10.1007/s11434-008-0563-3.