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Reflections of Late Neolithic–Early Bronze Age environments, land use and pile dwelling activities in a new palynological record from the varved sediments of Lake Mondsee, Austria

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A R T I C L E I N F O

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A B S T R A C T

Despite fundamental progress in geoarchaeological research in the Austrian Salzkammergut region, there are still many unanswered questions regarding human activity and its relationship to climate change and the diverse environments during prehistoric times. A new palynological record from the varved composite sediment core MO-05 from the south-eastern part of Lake Mondsee (47°49′N, 13°24′E, 481 m above sea level) provides palaeoecological evidence of a long-term, although possibly discontinuous, Late Neolithic/Copper Age habitation around the study site between ca. 6000 and 4000 cal BP. Agricultural activity during this interval focused on animal husbandry, which had only a minor impact on the natural forest vegetation. A particularly low level of local human activity is indicated at the end of the Late Neolithic between 4200 and 4000 cal BP while palynological indicators of deforestation and agriculture show a re-increase in human activity during the Early to early Middle Bronze Age (ca. 3950–3460 cal BP). Without clear evidence of human activity in the vicinity of the coring site, the increasing agricultural activities were most likely restricted to areas more distant from Lake Mondsee. The end of the Late Neolithic/Copper Age habitation phase with evidence of animal husbandry and local fire activity at 4200 cal BP coincides with the Northgrippian–Meghalayan transition, which is marked by a gradual change in vegetation distribution expressed by a shift to lower scores of the dominant cool mixed (COMX) forest biome. This shift to a cooler and wetter climate regime might have caused the decrease in human activity around this time.

1. Introduction

Annually laminated (i.e. varved) lake sediments are particularly valuable terrestrial archives of past climate and environments (e.g. Czymzik et al., 2013; Kossler et al., 2011; Nakagawa et al., 2021; Stebich et al., 2015; Zander et al., 2021) as well as human activities and human-environment interactions (e.g. Boyall et al., 2024; Litt et al., 2009; Poraj-Górska et al., 2021; Rey et al., 2017) as they can provide high-resolution proxy records with a very robust chronology relying on the counting of annual sediment layers (Bronk Ramsey et al., 2012). Although paleoenvironmental records with independent chronologies are very important (e.g. Brauer et al., 2014; Nakagawa et al., 2012), lakes with varved sediments are relatively rare (e.g. Martin-Puertas et al., 2021). This explains the particular scientific interest to a handful of reference lakes (and sediment cores), leading to continuous long-term research.

One of these lakes is Lake Mondsee, located in Upper Austria north of the European Alps (Fig. 1a-c). The lake with its robustly-dated ~15-m-long composite sediment core MO-05 extracted in 2005 (Lauterbach et al., 2011) can be regarded as a reference site/sedimentary sequence for multiproxy studies of Lateglacial and Holocene environmental dynamics and human-environment interactions in Central Europe (e.g.

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Andersen et al., 2017; Namiotko et al., 2015; Swierczynski et al., 2012, 2013a, 2013b). Recently, the MO-05 sediments have been successfully subjected to high-resolution palynological analysis to comprehensively investigate past changes in regional vegetation, climate and human activities during the Late Mesolithic and Early Neolithic (Schubert et al., 2023) and from the Late Bronze Age to the Migration Period (Schubert et al., 2020). These studies build on previous archaeological (e.g. Kunze, 1986; von Schnurbein, 2009) and palynological (e.g. Draxler, 1977; Schmidt, 1981, 1986) research in the area but provide a much higher temporal resolution (20–25 years) and, more importantly, a much better age control.

The present study deals with a part of the MO-05 composite sediment core that has not yet been palynologically investigated, covering the interval from the Late Neolithic/Copper Age to the early Middle Bronze Age between 6010 and 3460 cal BP. This period is of great interest for both archaeological and environmental research in the region (Kern et al., 2009). Archaeologically, it covers the Late Neolithic/Copper Age Mondsee Culture with a relatively narrow regional distribution mainly in Upper Austria (Frank and Pernicka, 2012). Chronologically and geographically the Mondsee Culture is placed at the periphery of the Funnel Beaker Culture (Ruttkay et al., 2004) and is best known for the remains of pile dwellings (i.e. the UNESCO World Heritage sites: https://whc.unesco.org/en/list/1363/) from the 6th and 5th millennia BP (Ruttkay et al., 2004) found around the lakes Mondsee and Attersee (Fig. 1b). The Mondsee Culture is also famous for the production of the characteristic 'Mondsee copper' (arsenical bronze) and painted ceramics (Frank and Pernicka, 2012; Ruttkay et al., 2004). A multidisciplinary study of sediment profiles from the archaeological pile dwelling site See (Fig. 1a) at Lake Mondsee (Schmidt, 1986) revealed weak and discontinuous evidence of human impact on the vegetation since ca. 5800–4700 cal BP, when pile dwellings were constructed around the lake (Swierczynski et al., 2013b). However, the available data leave uncertainties regarding the timing and intensity of past human-environment interactions in the study area, particularly with regard to the impact of sedentary agricultural populations during the Neolithic and Bronze Age (Schubert et al., 2020).

The scientific discussion about human-environment interactions and their traces in the archaeological and sedimentary archives of Lake Mondsee has a long history (Draxler, 1977; Kunze, 1986; Pucher and Engl, 1997; Schmidt, 1986), dating back to the discovery of the lake shore settlement sites See and Scharfling by Matthäus Much in the 1870s (Reiter, 2008). The pollen record from small Lake Egelsee (Schmidt, 1981), next to the archaeological site Scharfling (Fig. 1a), and from the Moosalm peat bog, situated several kilometres southeast of Lake Mondsee, suggest a first weak human impact on the vegetation during the Late Neolithic/Copper Age in connection with the pile dwellings (Schmidt, 1986). While no pollen of *Plantago lanceolata* or Cerealia, nor spores of coprophilous fungi, were found in the MO-05 record between 9000 and 7000 cal BP (Schubert et al., 2023), palynological analysis of the younger sediments from the same core (Schubert et al., 2020) showed several intervals of moderate human impact between ca. 3500 and 1500 cal BP. However, no intensive deforestation was recorded in the Lake Mondsee catchment until about 350 cal BP (Draxler, 1977; Kunze, 1986).

From a palaeoenvironmental perspective, our interest focuses on the transition from the Middle to the Late Holocene and its reflection in the palynological record of MO-05. The international chronostratigraphic chart (https://stratigraphy.org/chart) places the Northgrippian–Meghalayan boundary at ca. 4200 cal BP. This boundary between the Middle and Late Holocene is commonly associated with the so-called '4.2 ka event', a short-term climatic oscillation ca. 4200–4000 cal BP, which serves as a chronostratigraphic marker linked to a Global Stratotype Section and Point (GSSP) in a stalagmite from Mawmluh Cave, India (Walker et al., 2019). The '4.2 ka event' is – together with the '8.2 ka event' – one of the most widely discussed climate oscillations during the Holocene (e.g. Bini et al., 2019). However, it remains highly controversial in terms of its timing, significance and spatial imprint, as it is only clearly recorded in some proxies but not in large, coherent spatial regions (McKay et al., 2024). Using high-resolution isotopic (Andersen et al., 2017) and palynological records (Schubert et al., 2023) from the MO-05 sediments, the '8.2 ka event' could be successfully traced, particularly with respect to the local and regional consequences of this climate oscillation at the Early–Middle Holocene boundary. Hence, palynological analysis on the younger MO-05 sediments could potentially also provide information regarding the sensitivity of the local vegetation to the climatic/environmental changes around 4200 cal BP.

To fill the above-mentioned knowledge gaps and to reconstruct the climatic and anthropogenic impact on the vegetation around Lake Mondsee, we conducted detailed palynological analysis on a section of the composite sediment core MO-05 that spans the interval between 6010 and 3460 cal BP. Palynology is a common and successfully used approach to uncover details of local land use in prehistoric settlements that developed during the Middle and early Late Holocene in the Alpine and Mediterranean regions (e.g. Dwileski et al., 2025; Mercuri et al., 2019; Rey et al., 2020; Rösch and Lechterbeck, 2016). The resulting records of pollen, microcharcoal particles and non-pollen palynomorphs (NPPs) are discussed together with published proxy records from other

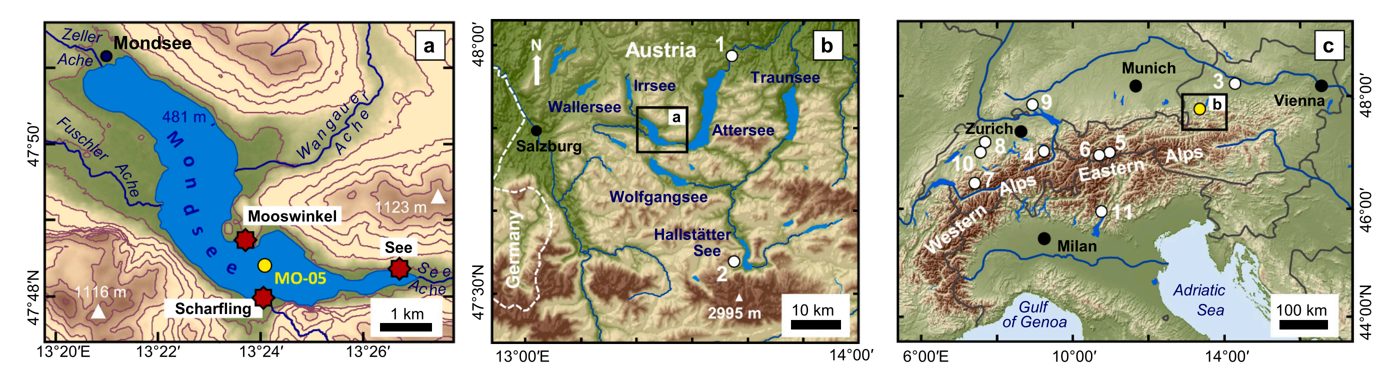

Fig. 1. Topographic maps showing (a) Lake Mondsee with the locations of the three Neolithic pile dwelling sites (red stars) and the composite sediment core MO-05 (yellow dot), (b) the Salzkammergut lake district of Upper Austria, and (c) the location of the study area (black rectangle) in the European Alps. Numbered white dots indicate the locations of other sites with palaeoenvironmental and archaeobotanical records referred to in the text: 1 – Lenzing-Burgstall (Jakobitsch et al., 2022); 2 – Siegmoos (Festi et al., 2021); 3 – Ansfelden-Burgwiese (Jakobitsch et al., 2022); 4 – Lake Grosssee (Dwileski et al., 2025); 5 – Lake Schwarzsee ob Sölden (Ilyashuk et al., 2011); 6 – Kauner Valley (Nicolussi et al. 2005); 7 – Lake Lauenensee (Rey et al., 2013); 8 – Lake Burgäschisee (Rey et al., 2017); 9 – Lake Litzelsee (Rösch and Lechterbeck, 2016); 10 – Lake Moossee (Rey et al., 2020); 11 – Lake Ledro (Magny et al., 2013). The digital elevation models are based on 90-m-resolution Shuttle Radar Topography Mission (SRTM) v4.1 data (Jarvis et al., 2008). Modern state borders and the location of selected modern cities and villages (black dots) are provided for orientation. After Schubert et al. (2023) with modifications.

sites in the Alps and the North Atlantic region and with previously published data on past flood and debris flow occurrence obtained from the MO-05 sediments (see below).

2. Modern environments

The characteristics of Lake Mondsee and its catchment (Fig. 1a) are well-described in previous publications (e.g. Lauterbach et al., 2011; Namiotko et al., 2015; Schubert et al., 2020, 2023; Swierczynski et al., 2013a, 2013b) and can be briefly summarised as follows. The lake is located at 481 m above sea level (a.s.l.) in the Austrian Salzkammergut lake district (Fig. 1b) at the northern margin of the European Alps (Fig. 1c). With a surface area of ~14.2 km^2 and a maximum water depth of ~68 m (Dokulil and Jäger, 1985; Jagsch and Megay, 1982), it is among the largest and deepest lakes of the region. The Fuschler Ache, Wangauer Ache and Zeller Ache are the main tributaries to Lake Mondsee and the outflowing Seeache connects it with adjacent Lake Attersee (Fig. 1a and b).

The study area is characterised by a temperate oceanic climate (Geiger, 1954) with mean annual, July and January air temperatures of +8.5, +18.3 and −1.3 °C, respectively. The average annual precipitation amounts to ~1550 mm, with about one third falling between June and August and the rest being more or less evenly distributed over the rest of the year (all climate data for the period 1981–2010 at the weather station Mondsee (47°50'52" N, 13°22'08" E, 491 m a.s.l.); Central Institute for Meteorology and Geodynamics (ZAMG), Vienna, Austria). Severe floods are associated with heavy rains (often with thunderstorms), which mainly occur during the summer months.

The elevated terrain (481–1700 m a.s.l.) and the complex topography of the Lake Mondsee catchment determine variable climatic conditions and the natural vegetation distribution along the altitudinal gradient. The natural vegetation, fragmentarily preserved near the lake, represents the temperate deciduous forest biome (Prentice et al., 1996) and occupies lowlands and hills below 500 m a.s.l. Characteristic trees are beech (*Fagus*), yew (*Taxus*), linden (*Tilia*), elm (*Ulmus*), willow (*Salix*), maple (*Acer*) and ash (*Fraxinus*) as well as alder (*Alnus*) and birch (*Betula*), which are common along the shoreline and in the floodplain forests. Between 500 and 1000 m a.s.l., species-rich mixed forests (i.e. cool mixed forest biome *sensu* Prentice et al., 1996) dominated by beech and spruce (*Picea*) with an admixture of oak (*Quercus*), fir (*Abies*), Scots pine (*Pinus sylvestris*), maple, ash, linden, alder, hazel (*Corylus*) and hornbeam (*Carpinus*) are common. Coniferous forests of fir and spruce with an admixture of beech and a few other cold-tolerant temperate deciduous trees, representing the cool coniferous forest biome (Prentice et al., 1996), grow between 1000 and 1600/1700 m a.s.l. (Fuchs et al., 2004, 2005). Above this altitude, taiga-like forests dominated by larch (*Larix*) and stone pine (*Pinus cembra*) are described in the Northern Calcareous Alps (Nationalpark, 2016).

3. Material and methods

3.1. MO-05 sediment and chronology

For the present study we analysed a 233-cm-long section of the continuous, ~15-m-long composite sediment core MO-05 (47°48'41" N, 13°24'09" E; Fig. 1a). The core was compiled from a series of overlapping ~2-m-long segments recovered in June 2005 using a 90-mm-diameter UWITEC piston corer (Lauterbach et al., 2011). The coring was performed at ~62 m water depth in the southern part of Lake Mondsee near the prehistoric pile dwelling sites Mooswinkel and Scharfling, which lie a few hundred metres to the north and south of the coring site, respectively (Fig. 1a).

The chronology of the Holocene part of MO-05 (Fig. 2) is based on microscopic varve counting and a varve-based sedimentation rate chronology (for more details see the electronic supplement to Lauterbach et al., 2011). The uncertainty of the varve chronology is ±1.25 % as deduced from independent varve counting of two different examiners (Swierczynski et al., 2012, 2013b). According to the published data, the investigated core section (526–759 cm composite depth) consists of varved lake marl with a few detrital layers and covers the interval between 6010 and 3460 cal BP (i.e. calendar years before present, where present is 1950 CE) with an absolute dating uncertainty of ±43 and ±75 years at the top and bottom of the section, respectively (Fig. 2). The varve chronology in this section is supported by nine accelerator mass spectrometry (AMS) radiocarbon (^{14}C) dates of short-lived terrestrial plant macrofossils (Table 1). All ages in the text and figures of this study are given in calendar years BP and the BCE/CE scale is added to the summary figures for better comparability with archaeological records and chronologies.

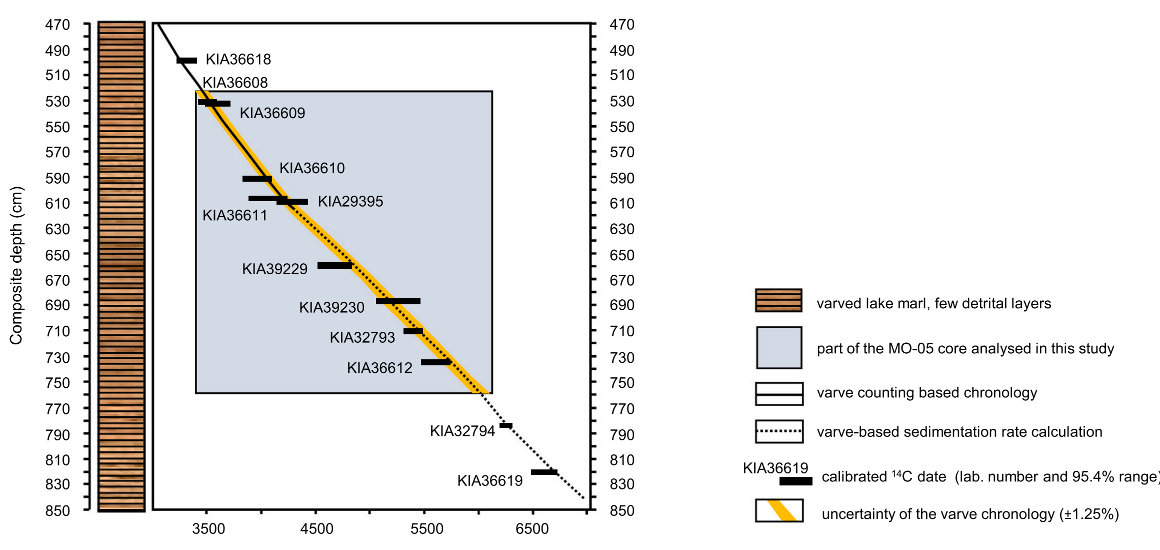

Fig. 2. Schematic lithology and varve counting-based age model for the part of the MO-05 composite sediment core investigated in this study (modified from the electronic supplement to Lauterbach et al., 2011). The orange shading indicates the uncertainty (±1.25 %) of the varve chronology (for details see Swierczynski et al., 2012, 2013b). Black horizontal bars indicate calibrated AMS ^{14}C dates (displayed as 95.4 % probability ranges) of terrestrial plant macrofossil samples (see Table 1 for further details).

Table 1
AMS ^{14}C dates obtained from terrestrial plant macrofossils from the Holocene part of the Lake Mondsee record (after Lauterbach et al., 2011) for the interval ca. 7000–3000 cal BP discussed in this study. All conventional ^{14}C ages (^{14}C BP) were calibrated using the OxCal v.4.4 software (Bronk Ramsey, 1995) and the IntCal20 calibration curve (Reimer et al., 2020). [a] indicates undetermined terrestrial leaf fragments and [b] indicates various undetermined terrestrial plant remains (leaves, wood, seeds).

Laboratory code	Composite depth (cm)	Dated material	Carbon content (mg) / $\delta^{13}C \pm \sigma$ (‰)	AMS ^{14}C age (^{14}C BP ± σ)	Calibrated age (cal BP, 95.4 % probability)	Modelled calendar age (cal BP), counting uncertainty ±1.25 %
KIA36618	496.75	leaves[a]	3.10 / −29.36 ± 0.16	3110 ± 30	3391–3235	3222 ± 40
KIA36608	529.50	plant remains[b]	1.65 / −25.09 ± 0.20	3276 ± 26	3565–3415	3495 ± 44
KIA36609	530.50	stem	0.65 / −27.02 ± 0.39	3369 ± 40	3699–3481	3505 ± 44
KIA36610	589.00	plant remains[b]	2.22 / −27.03 ± 0.25	3618 ± 33	4076–3837	4027 ± 50
KIA36611	604.50	plant remains[b]	0.41 / −29.03 ± 0.36	3697 ± 56	4231–3880	4172 ± 52
KIA29395	607.50	plant remains[b]	4.06 / −29.21 ± 0.04	3848 ± 26	4404–4153	4202 ± 52
KIA39229	657.00	leaves[a]	1.61 / −28.99 ± 0.09	4142 ± 31	4825–4534	4814 ± 60
KIA39230	685.00	leaves[a] & needle	2.28 / −28.77 ± 0.12	4581 ± 34	5447–5054	5144 ± 64
KIA32793	708.75	twig & bark	4.89 / −28.60 ± 0.05	4668 ± 28	5466–5320	5423 ± 68
KIA36612	732.25	wood & leaves	0.97 / −27.69 ± 0.13	4883 ± 41	5724–5483	5700 ± 71
KIA32794	782.25	leaves[a]	1.04 / −30.09 ± 0.15	5462 ± 36	6310–6195	6288 ± 79
KIA36619	818.75	plant remains[b]	1.65 / −26.55 ± 0.13	5809 ± 36	6729–6496	6724 ± 84

3.2. Palynological analysis and visualisation of results

Pollen analysis was performed on 117 sediment samples (1-cm-thick sediment slices, each incorporating 7–12 years) that were taken from MO-05 at a sampling interval of 2 cm, yielding an average temporal resolution of approximately 22 years for the entire record. In accordance with the sustainability mission statement of Freie Universität Berlin in research and teaching as well as the requirements of the European Union and the German Research Foundation (DFG), which stipulate the avoidance of hazardous chemicals (e.g. HF and the acetolysis mixture), we used the environmentally friendly and resource-saving extraction protocol described in Leipe et al. (2019). Chemical preparation of the samples included treatment of a known weight and volume of sediment with cold 10 % HCl to remove carbonates, hot 10 % KOH to remove humic acids and dense media separation using sodium polytungstate (SPT) at a density of 2.1 g cm^{-3} to remove siliceous matter. After SPT treatment, the sample residues were washed twice with distilled water and mounted in glycerol.

In order to estimate pollen, NPP and microcharcoal concentrations (counts cm^{-3}) and annual accumulation rates (counts cm^{-2} a^{-1}), one tablet of exotic *Lycopodium* marker spores (~14,285 spores per tablet) was added to each sample prior to chemical treatment following Stockmarr (1971). Palynomorphs were counted using an Olympus CX31 light microscope at 400 × and 600 × magnification and taxonomically identified with the help of published atlases (Beug, 2004; Demske et al., 2013; Moore and Webb, 1978; Reille, 1992, 1995, 1998; van Geel, 1978, 2001; van Geel et al., 2013) and the institute's reference collection. Microcharcoal particles (10–50, 50–100 and 100–200 μm in size) were counted as a fire proxy (Clark, 1988; Clark et al., 1989; Whitlock and Larsen, 2001). Counted sums vary from 602 to 872 terrestrial pollen grains (698 on average) per sample. Larger totals (>500 terrestrial pollen grains) have been recommended as better suited to reconstruct past vegetation composition without missing rare (<1 %) but informative taxa (Bennett and Willis, 2001; Weng et al., 2006), e.g. indicators of human activities (Litt et al., 2009).

To visualise and discuss the palynological results, the relative abundances of all terrestrial pollen taxa were calculated based on the sum of arboreal pollen (AP) and non-arboreal pollen (NAP) counts taken as 100 %. The percentages for aquatic and spore-producing plant taxa were calculated based on the sum of terrestrial pollen plus the sum of the corresponding group. Other NPP taxa (e.g. algae and fungi) and charcoal particles are presented as concentration values. The resulting diagrams (Fig. 3a-c) were drawn using Tilia software (Grimm, 1993, 2004) and checked for zonation using the CONISS square root transformation of the pollen percentage data and a stratigraphically constrained cluster analysis using the incremental sum of squares approach (Grimm, 1987).

The pollen record generated in this study is discussed in relation to the published data of the recent pollen spectrum, representing the surface sediments of Lake Mondsee accumulated between ca. 1990 and 2005, and the fossil spectra from MO-05, representing the Early–Middle Holocene transition (Schubert et al., 2023). The idea behind this comparison is to illustrate the characteristic features of the analysed interval.

The application of pollen as land use indicators has a long and successful tradition in Europe (see, for example, Mercuri et al., 2019 for a detailed review and references). The indicative anthropogenic pollen indicator (API) taxa can be used individually (Conedera et al., 2004) or/and grouped into sums useful for land cover and land use reconstructions (Mercuri et al., 2019). To discuss the human impact on local vegetation around Lake Mondsee ca. 3500–1500 cal BP, Schubert et al. (2020) used pollen of *Juglans* (as an introduced crop tree), the total percentage of NAP (as an indicator of landscape openness) and the percentage sum of *Artemisia*, Cannabaceae, Chenopodiaceae, *Plantago*, Cerealia type, *Rumex* and *Urtica*, which are commonly considered herbaceous API taxa in Holocene pollen diagrams from Central Europe (e.g. Behre, 1981, 2007; Litt et al., 2009; Rey et al., 2017) and the Mediterranean region (e.g. Mercuri et al., 2019). We follow this approach in the

Fig. 3. Summary diagrams showing the results of the palynological analysis of the interval 6010–3460 cal BP, including (a) tree and shrub taxa (arboreal pollen, %); (b) herbaceous taxa (non-arboreal pollen, %); (c) pollen of aquatic plants (%), fern and moss spores (%), algae and fungi spores and microcharcoal particles (concentrations).

current study.

When inferring human impact from palynological records in Europe, pollen-based evidences are often considered in combination with charcoal concentrations and accumulation rates as indicators of fire activity (e.g. Dwileski et al., 2025; Lestienne et al., 2020; Tinner et al., 1998; Whitlock and Larsen, 2001) and coprophilous fungal spores (e.g. Gill, 2014; van Geel, 2001) as an indicator of grazing animals (e.g. Dwileski et al., 2025; Gauthier and Jouffroy-Bapicot, 2021; Rey et al., 2017; Rösch and Lechterbeck, 2016).

Following van Geel (2001), we interpreted endomycorrhizal *Glomus* chlamydospores associated with roots of various terrestrial plants as an indicator of soil erosion, which may result from enhanced surface runoff and human activities. *Kretzschmaria deusta*, another fungus and plant pathogen, has been suggested as a good indicator for mixed beech and/or mixed oak forests as well as for flood events/soil erosion (van Geel et al., 2013). Schubert et al. (2023) reported a sensitive reaction of *K. deusta* in the Lake Mondsee sediments to the cooling event around 8200 cal BP, suggesting it as a potential proxy for reconstructing Holocene environmental variability.

3.3. Biomisation approach

To interpret the results of the pollen analysis and discuss the effects of natural factors on changes in composition and contents of representative taxa in the Early Holocene record from the MO-05 composite sediment core, Schubert et al. (2023) applied the bioclimatic limits of plant functional types (PFTs) and the assignment of plant/pollen taxa to PFTs to biomes (Table 2) as used in the global vegetation model based on plant physiology and dominance, soil properties and climate (Prentice et al., 1992) and in the reconstructions of vegetation in Europe from modern and Holocene pollen data (e.g. Krikunova et al., 2024; Prentice et al., 1996; Tarasov et al., 1998). For reasons of compatibility, we have chosen the same approach in this study. The calculation of PFT and biome scores for all analysed pollen samples was based on an equation and principle first published by Prentice et al. (1996). Although the dominant biome reconstruction approach does not allow the reconstruction of transitional vegetation types (Prentice et al., 1996), this important information can be obtained by analysing the affinity scores of the representative PFTs/biomes in the study region (Schubert et al., 2023; Tarasov et al., 2022).

4. Results

4.1. Palynological analysis

Microscopic analysis of the 117 sediment samples (see Supplementary Table 1 for original data set) revealed 96 identified palynomorphs, including 32 AP taxa (i.e. trees, shrubs and vines), 47 terrestrial NAP taxa, 5 aquatic plant taxa, 6 terrestrial cryptogam taxa (i.e. ferns and mosses) and 6 taxa representing green algae, fungi and other NPPs (Fig. 3a-c). For terrestrial pollen, only 17 taxa, of which 13 represent trees and tall shrubs, are above 1 %, while the others are below this value. The CONISS analysis applied to the pollen record (Fig. 3a) identifies two main clusters (i.e. MO-05-Ng-a and MO-05-Mg-b), below and above 607 cm depth. This level is dated to ca. 4200 cal BP and separates the Middle (Northgrippian stage) and Late Holocene (Meghalayan stage) in the MO-05 composite sediment core. These two zones show similarities in pollen composition, but some well-defined differences in the percentages of pollen taxa, which can be summarised as follows (Fig. 4a).

In the MO-05-Ng-a zone (759–607 cm; ca. 6010–4200 cal BP), the most abundant taxa (maximum and average values) are *Fagus* (41.5 and 22.1 %), *Alnus* (30.9 and 17.9 %), *Corylus* (21.9 and 13.3 %), *Betula* (11.9 and 2.5 %), *Abies* (21.7 and 10.0 %) and *Picea* (19.5 and 8.5 %). Subdominant taxa are *P. sylvestris* (7.4 and 3.9 %), *Quercus* (7.3 and 4.0 %), *Ulmus* (6.5 and 1.5 %), *Tilia* (3.7 and 1.4 %) and *Salix* (2.6 and 0.5 %). The NAP values do not exceed 6.5 % (average 3.3 %).

The MO-05-Mg-b zone (607–526 cm; ca. 4200–3460 cal BP) shows a marked increase in the pollen contribution of *Fagus* (44.7 and 32.1 %) and *Alnus* (38.2 and 20.4 %), accompanied by a decrease in *Corylus* (14.8 and 9.8 %), *Abies* (15.4 and 9.4 %), *Picea* (8.7 and 5.6 %), *P. sylvestris* (7.0 and 3.3 %), *Quercus* (6.5 and 3.0 %), *Ulmus* (2.2 and 1.0 %), *Tilia* (1.8 and 0.5 %) and *Salix* (1.5 and 0.3 %). The pollen contribution of *Betula* reaches a maximum (19.0 %) in this zone, although the average value is slightly lower (5.0 %). *Juglans* pollen appears for the first time in this zone (543–540 cm; ca. 3610–3585 cal BP). The NAP values are distinctly higher (12.4 and 4.5 %). The first appearance of *Centaurea* (597–596 cm; ca. 4100–4090 cal BP), *Urtica* (569–568 cm; ca. 3850–3840 cal BP) and *Triticum* type pollen (555–554 cm; ca. 3720–3710 cal BP) and more frequent occurrences of the other API taxa, including *Plantago*, *Rumex* and Cerealia type, characterise this zone.

In the analysed section of MO-05, trees and shrubs make up about 88–99 % of the total pollen (Fig. 3a). *Fagus* and *Alnus* are the most abundant taxa, followed by *Corylus*, *Betula*, *Abies* and *Picea*. The terrestrial pollen concentration varies considerably (i.e. ~33,100–195,850 grains cm^{-3}) throughout the record and shows two minima at 756.5 and 630.5 cm, i.e. around 5985 and 4490 cal BP, respectively (Fig. 3a).

Poaceae is by far the largest contributor to the NAP, with maximum values (up to 9.5 %) in the upper part of the record, above 575 cm or younger than 3900 cal BP (Fig. 3b). Other herbaceous taxa do not exceed 1 %, with the exception of Cyperaceae, *Artemisia* and *Rumex*. The NAP concentration curve shows a notable increase from < 5000 grains to 5000–13,200 grains cm^{-3} above 575 cm depth.

The pollen assemblage of the analysed interval (6010–3460 cal BP) compared to the modern pollen assemblage from the lake sediment surface (Fig. 4b), formed under strong human influence, and to the earlier interval (9000–7000 cal BP), with no evidence of human activity at Lake Mondsee (Fig. 4c), shows substantial differences in the abundance and composition of the most common taxa, reflecting a different forest composition during the transition from the Middle to Late Holocene.

The pollen of aquatic plants is poorly represented. Worth mentioning

Table 2
Central European arboreal plant functional types (PFTs) with their characteristic taxa identified in the MO-05 pollen record (this study) assigned to the regional biomes (after Prentice et al., 1996; Schubert et al., 2023). Biome and PFT abbreviations are given in brackets.

Plant functional type (trees and shrubs)	Taxa from the MO-5 record (this study) included	Regional biome
Boreal evergreen conifer (bec)	*Abies*, *Picea*, *Pinus cembra* (i.e. *Haploxylon* type)	Taiga (TAIG), Cool conifer forest (COCO), Cool mixed forest (COMX)
Boreal summer green (bs)	*Alnus*, *Betula*, *Populus*, *Salix*	TAIG, COCO, COMX, Temperate deciduous forest (TEDE)
Eurythermic conifer (ec)	*Juniperus*, *Pinus sylvestris* (i.e. *Diploxylon* type)	TAIG, COCO, COMX, TEDE
Temperate summer green (ts)	*Acer*, *Fraxinus* (*excelsior* type), *Quercus* (deciduous)	COMX, TEDE
Cool-temperate summer green (ts_1)	*Carpinus*, *Corylus*, *Fagus*, *Frangula*, *Tilia*, *Ulmus*	COCO, COMX, TEDE
Warm-temperate summer green (ts_2)	*Fraxinus* (*ornus* type), *Rhamnus*, *Vitis*	TEDE
Cool-temperate broad-leaved evergreen (wte_1)	*Hedera*	TEDE
Heath (h)	Ericales	TAIG, COCO, COMX, TEDE

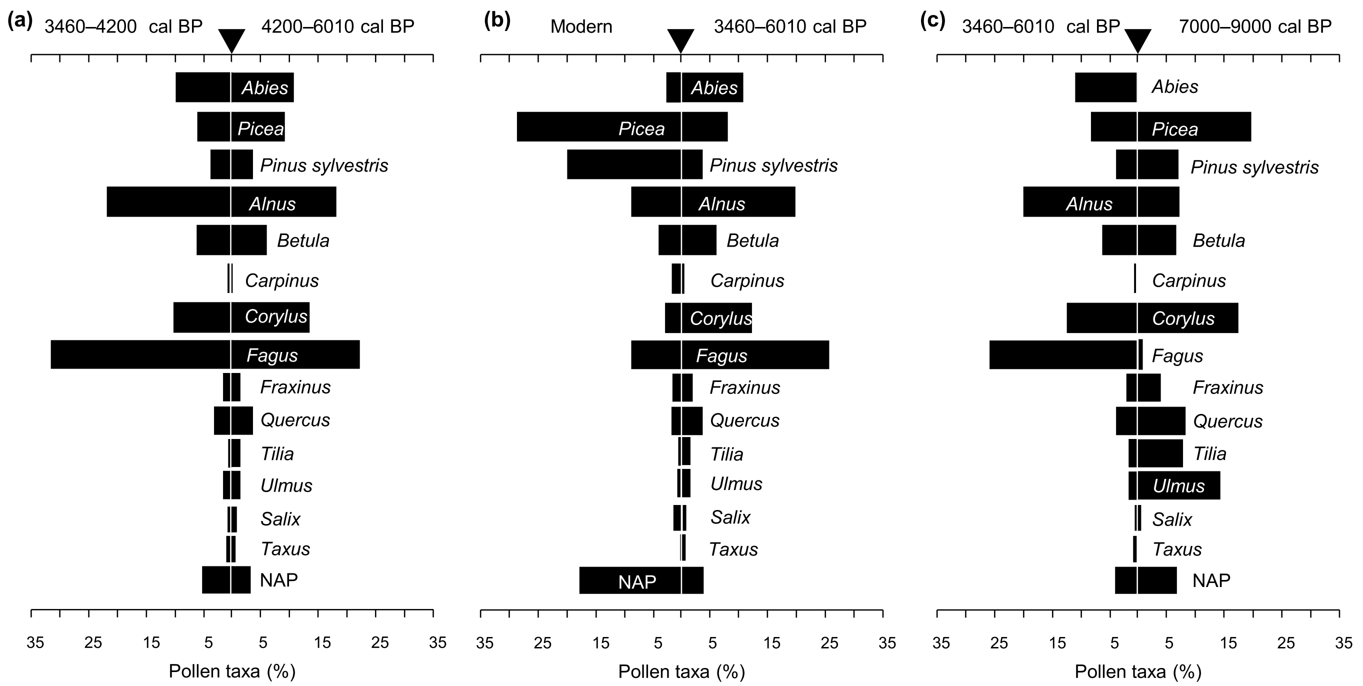

Fig. 4. Mean percentage values and composition of (a) the pollen assemblage from the 6010–3460 cal BP interval (this study) compared to the pollen data representing (b) the surface sediment sample from Lake Mondsee (Schubert et al., 2023) and (c) the ca. 9000–7000 cal BP interval (Schubert et al., 2023) from the MO-05 composite sediment core.

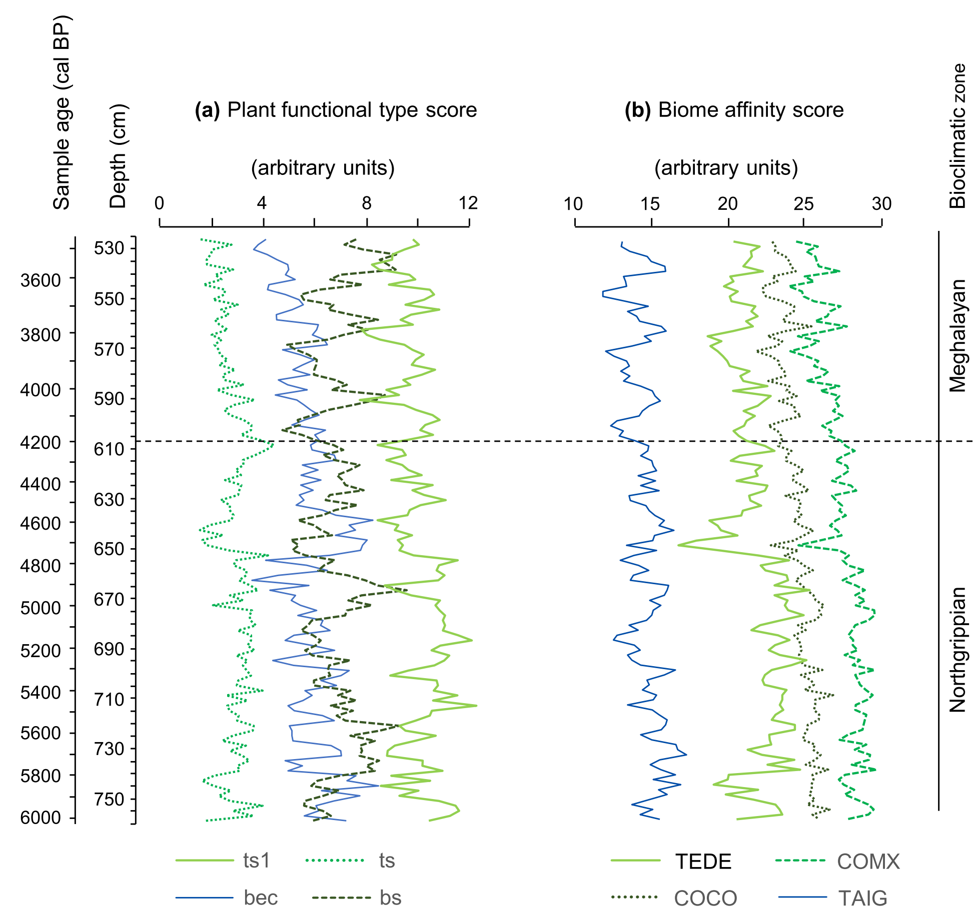

Fig. 5. Graphs summarising the results of the (a) plant functional types (PFTs) and (b) major vegetation types (biomes) score calculation (see Prentice et al., 1996 for details of the method and Table 2 for the taxa assigned to each PFT/biome) for the interval 6010–3460 cal BP.

is the more frequent occurrence of *Myriophyllum* and *Typha* and the disappearance of *Nuphar* and *Nymphaea* in the upper part of the record above 609 cm, ca. 4220 cal BP (Fig. 3c). Spores of *Sphagnum*, *Equisetum* and Polypodiales represent terrestrial cryptogams. Some of the NPPs (Fig. 3c), such as *Glomus* and *K. deusta* fungi, reveal frequent short-term fluctuations, but no clear trends. In contrast, the green algae *Botryococcus* shows high concentrations in the lower and upper intervals and the lowest concentration values between 660 and 560 cm (ca. 4850–3770 cal BP). Ascospores of coprophilous fungi (i.e. *Cercophora*, *Sordaria* and *Sporormiella*) show the highest concentrations in the middle

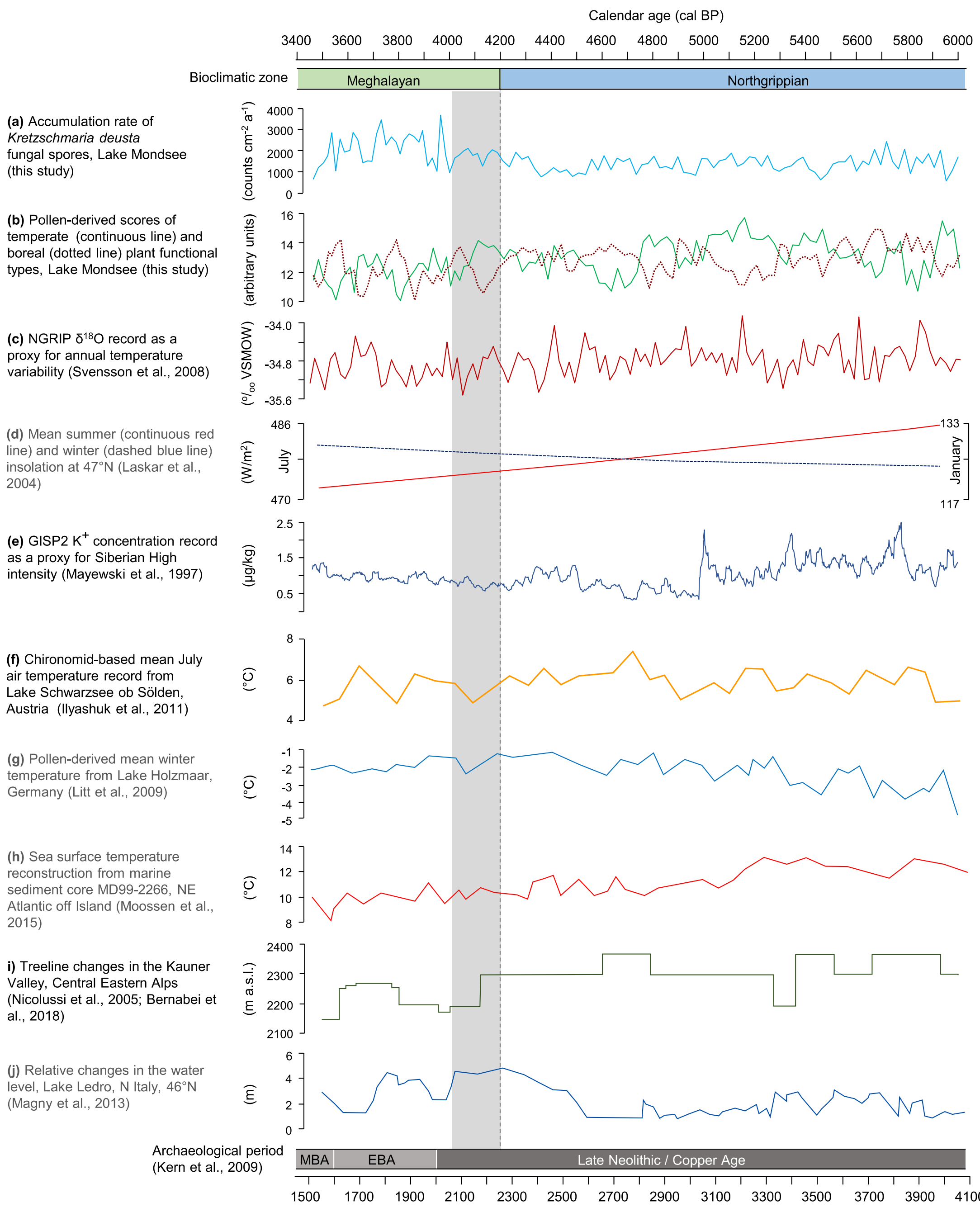

Fig. 6. Summary chart showing selected results of this study along with published climate proxy records discussed in the text. (a) Changes in the accumulation rate (influx) of *Kretzschmaria deusta* ascospores in the MO-05 record (this study); (b) affinity score sums of warm-loving temperate deciduous (ts_1 + ts) and cold-tolerant boreal (bs + bec) tree/shrub plant functional types (PFTs) in the MO-05 record (this study; the taxa assigned to each PFT are listed in Table 2); (c) NGRIP $\delta^{18}O$ record as a proxy for annual temperature variability (Svensson et al., 2008); (d) mean summer and winter insolation at 47° N (Laskar et al., 2004); (e) GISP2 K^+ concentration record as a proxy for Siberian High intensity (Mayewski et al., 1997); (f) chironomid-based mean July air temperature record from Lake Schwarzsee ob Sölden, Austria (Ilyashuk et al., 2011); (g) pollen-derived mean winter temperature from Lake Holzmaar, Germany (Litt et al., 2009); (h) sea surface temperature reconstruction from marine sediment core MD99–2266, NE Atlantic off Island (Moossen et al., 2015); (i) treeline changes in the Kauner Valley, central eastern Alps (Nicolussi et al., 2005; Bernabei et al., 2018); (j) relative changes in the water level of Lake Ledro, northern Italy (Magny et al., 2013). The vertical dashed line indicates the Northgrippian–Meghalayan boundary at 4200 cal BP (Walker et al., 2019) and the vertical grey band indicates the statistically defined 200-year interval associated with the '4.2 ka event' (McKay et al., 2024). Regional archaeological chronology after Kern et al. (2009). Abbreviations are given for Middle Bronze Age (MBA) and Early Bronze Age (EBA).

part of the record (Fig. 3c). Microcharcoal particles occur throughout the record, but the larger fractions are more abundant and show higher concentration values below 607 cm depth, particularly between ca. 4750 and 4200 cal BP (Fig. 3c).

4.2. Biome reconstruction

The application of the biome reconstruction method to the MO-05 pollen record shows the highest score for the cool mixed forest (COMX) biome during the analysed interval, followed by the cool conifer (COCO) and temperate deciduous forest (TEDE) biomes (Fig. 5b). Among the PFTs, the cool-temperate summer green (ts_1) has the highest score, followed by the boreal summer green (bs), boreal evergreen conifer (bec) and temperate summer green (ts) PFTs (Fig. 5a).

5. Discussion

5.1. Middle to Late Holocene vegetation and climate dynamics at Lake Mondsee

The new MO-05 pollen record provides detailed insights into the vegetation history of the Lake Mondsee catchment between 6010 and 3460 cal BP, covering the transition from the Middle to the Late Holocene. The quantitative biome reconstruction (Fig. 5b) shows the dominance of the COMX biome in the catchment throughout the study interval, with the COCO and TEDE biomes being co-dominant. The general decrease in affinity scores of the dominant COMX biome ca. 4200–3460 cal BP (Fig. 5b) is consistent with the decreasing AP values in the MO-05-Mg-b pollen zone (Fig. 3a), which likely reflects an overall trend towards a more open landscape. The AP diagram (Fig. 3a) demonstrates the regular occurrence of indicators of the TEDE biome (e.g. *Acer*, *Fraxinus*, *Quercus*, *Fraxinus*, *Hedera*, etc.), suggesting that the forest composition of the narrow low-altitude zone around the lake was already similar to the natural forest patches growing there today. The relatively narrow space occupied by the TEDE biome compared to the COMX biome (Fuchs et al., 2004, 2005), which also contains more taxa and is a larger pollen producer (Prentice et al., 1996), explains the lower scores of the former in the pollen spectra from Lake Mondsee (Schubert et al., 2023).

The pollen composition and mean percentages in the surface sediments of Lake Mondsee (Schubert et al., 2023) compared to the fossil pollen assemblage of MO-05 between 6010 and 3460 cal BP (Fig. 5b) reveal some differences in the proportions (average values) of the contributing taxa. For example, higher proportions of *Picea* (28.7 vs 8.0 %), *P. sylvestris* (19.9 vs 3.8 %) and NAP (17.8 vs 3.9 %) and lower proportions of *Abies* (2.1 vs 10.5 %), *Alnus* (8.7 vs 19.5 %), *Betula* (3.7 vs 6.2 %), *Fagus* (8.4 vs 25.5 %) and *Corylus* (2.8 vs 12.3 %) are observed in the surface sediments. These differences may reflect natural changes in the vegetation cover during the Late Holocene, as well as the impact of human activities in the lake catchment (Beiwl and Mühlemann, 2008), including landscape opening (and retreat of natural forest vegetation), construction activities and planting for economic (e.g. *Picea*, *Pinus*) and recreational/gardening purposes (e.g. *Carpinus*, *Castanea*, *Juglans*, *Betula*, various herbaceous taxa). However, natural factors such as climate, soil development and competition between tree species must be considered when discussing changes in vegetation (Litt et al., 2009).

The sensitive response of European pollen records to decadal/centennial-scale temperature and moisture variability in the North Atlantic region (Svensson et al., 2008; Fig. 6c), primarily controlled by solar insolation forcing (Laskar et al., 2004; Fig. 6d), the intensity of the Siberian High (Mayewski et al., 1997, 2004; Fig. 6e) and North Atlantic sea surface temperature (Demény et al., 2021; Moossen et al., 2015) and circulation (Ayache et al., 2018; Olsen et al., 2012) has been discussed in a large number of previous studies focusing on Holocene vegetation dynamics and their control mechanisms (e.g. Davis et al., 2003; Dwileski et al., 2025; Feurdean et al., 2008; Herzschuh et al., 2023; Krikunova et al., 2024; Litt et al., 2009; Rey et al., 2020). Gradual changes in summer and winter insolation are considered the primary driver of Holocene hydroclimate changes in Europe (Demény et al., 2021). During the study period, insolation at the latitude of Lake Mondsee shows a decrease in summer and an increase in winter (Fig. 6d), resulting in milder winters and cooler summers. Milder winter conditions are also indicated by a notable decrease in the intensity of the Siberian High after ca. 5000 cal BP (Fig. 6e). The MO-05 pollen record obtained in this study (e.g. Figs. 3–5) and published proxy-based temperature reconstructions (e.g. Litt et al., 2009; Fig. 6g; Moossen et al., 2015; Fig. 6h) support this scenario, but the century-scale climate variability is superimposed and may partially obscure general trends, as in the chironomid-based reconstruction of mean July air temperatures from the high mountain Lake Schwarzsee ob Sölden (Fig. 1c) in the Austrian Alps (e.g. Ilyashuk et al., 2011; Fig. 6f). However, mean July temperatures estimated at 1000 m a.s.l. using six chironomid records from the Swiss Alps and eastern France (Heiri et al., 2015) and treeline changes in the Kauner Valley (Fig. 1c) in the central Eastern Alps (Bernabei et al., 2018; Nicolussi et al., 2005; Fig. 6i) clearly show a decrease in summer temperatures and a lowering of the treeline, respectively.

The changes in the MO-05 pollen record suggest that both winter and summer temperatures and changes in atmospheric precipitation should be involved to explain long- and short-term changes in taxa composition and relative abundance. We are not aware of any quantitative rainfall reconstruction from the study area. However, indirect evidence such as a notable increase in the water level of Lake Ledro in northern Italy (Fig. 1c) and several other lakes north of 40° N (Magny et al., 2013; Fig. 6j) suggests a more humid environment after ca. 4400 cal BP, possibly as a result of reduced summer evaporation and an increased contribution of winter precipitation to the regional hydrological budget (Perşoiu, et al., 2017). The increase in the influx of the parasitic fungus *K. deusta* (Fig. 6a) in MO-05 also indicates increased soil erosion (van Geel et al., 2013), likely related to increased surface runoff during the Late Holocene.

The CONISS analysis places the boundary between the Middle and Late Holocene clusters in the MO-05 pollen record at ca. 4200 cal BP, which is consistent with the chronological position of the Northgrippian–Meghalayan boundary (Walker et al., 2019). In the pollen-based biome reconstruction (Fig. 5b), this boundary separates the Middle Holocene zone with generally higher scores of the dominant COMX biome (~28 on average) from the Late Holocene zone with lower COMX scores (~26 on average). This change is parallel to the decreasing trend observed in the ts PFT scores (Fig. 5a). The difference between the Middle and Late Holocene pollen assemblages is well illustrated by comparing the mean percentage values of the major pollen taxa (Fig. 4a). Among the other proxies from MO-05, the change in the influx of *K. deusta* (Fig. 6a, van Geel et al., 2013) reflects the Middle–Late Holocene transition rather well. The biomisation results (Fig. 5) show two oscillations in the dominant PFT and biome scores, including two (i.e. positive and negative) oscillations in the sum of boreal (bs+bec) and temperate deciduous (ts_1+ts) PFT scores between 4200 and 4000 cal BP (Fig. 6b). These oscillations, centred at ca. 4150 and 4050 cal BP, are indicative of warmer/drier and cooler/wetter climate oscillations, respectively, and coincide with higher and lower $\delta^{18}O$ values (i.e. warmer and colder conditions) in the NGRIP ice core record from Greenland (Svensson et al., 2008; Fig. 6c). However, none of the two oscillations is particularly prominent in terms of amplitude and duration compared to other century-scale oscillations observed in the Lake Mondsee biome and PFT scores (Fig. 6b) and the NGRIP $\delta^{18}O$ record (Fig. 6c). Although our record does not show a striking event (i.e. a pronounced century-scale increase/decrease in values) between 4200 and 4000 cal BP, it does show a transition centred on 4200 cal BP, which can still be considered a robust chronostratigraphic marker for the Middle–Late Holocene boundary in the study region. This picture is consistent with a complex pattern of climate variability reported by Bini et al. (2019) and McKay et al. (2024), who also found numerous climate oscillations between 4500 and 3500 cal BP and highlighted the spatial heterogeneity (i.e. regionally/altitudinally weaker, stronger or no response) of different proxies.

Similar to the Lake Mondsee pollen record, other records from the northwestern Alps show notable changes in pollen assemblage composition at the Northgrippian–Meghalayan boundary/transition. In the pollen diagram from Lake Grosssee (Fig. 1c) in the eastern Swiss Alps (Dwileski et al., 2025), a decrease in the pollen percentages of lowland trees begins around 4200 cal BP. Another record of mountain vegetation from Lake Lauenensee in the Bernese Alps (Rey et al., 2013; Fig. 1c) supports the time around 4200 cal BP as a representative boundary, marking the onset of the Late Holocene landscape opening and a distinct change in the AP composition (i.e. a decrease in *Quercus* and an increase in *Alnus viridis* proportions). In the record from Lake Moossee (Fig. 1c) in

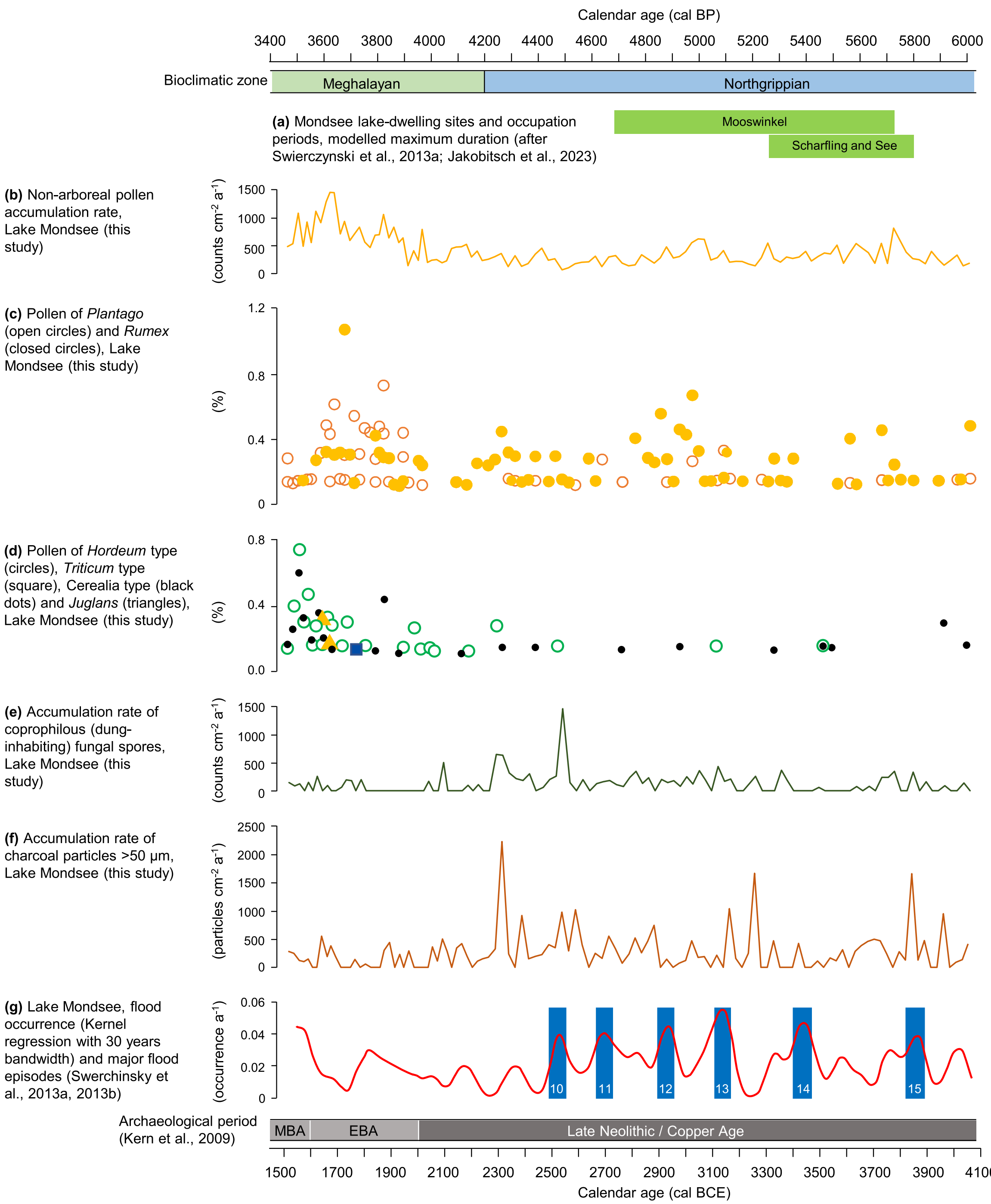

Fig. 7. Summary chart showing selected records used to discuss human activities and human-environment interactions at Lake Mondsee during the 6010–3460 cal BP interval. (a) Mondsee Lake dwelling sites and occupation periods, modelled maximum duration (after Swierczynski et al., 2013a; Jakobitsch et al., 2023); (b) changes in the non-arboreal pollen (NAP) accumulation rate in the MO-05 record (this study); (c) pollen percentages of the selected anthropogenic pollen indicator (API) taxa *Plantago* and *Rumex* in the MO-05 record (this study); (d) pollen percentages of the selected API taxa *Hordeum* type, *Triticum* type, Cerealia type and *Juglans* in the MO-05 record (this study); (e) changes in the accumulation rate of coprophilous fungal spores in the MO-05 record (this study); (f) changes in the accumulation rate of charcoal particles representing 50–100 and 100–200 µm fractions in the MO-05 record (this study); (g) flood occurrence (red line: Kernel regression with 30 years bandwidth) and numbered major flood episodes at Lake Mondsee (after Swierczynski et al., 2013a, 2013b). Bioclimatic zones after Walker et al. (2019). Regional archaeological chronology after Kern et al. (2009). Abbreviations are given for Middle Bronze Age (MBA) and Early Bronze Age (EBA).

western Switzerland (Rey et al., 2020), a marked decline in the proportion of *Fagus* occurred after 4000 cal BP. Further north, high-resolution pollen records from the lakes Holzmaar and Meerfelder Maar in western Germany (Litt et al., 2009) show a marked change in the composition of the temperate deciduous forest, indicated by a shift from *Corylus* to *Fagus* dominance in the pollen assemblage at ca. 4200 cal BP. However, all these changes in vegetation likely reflect a gradual insolation-driven climate change superimposed by low-amplitude climate fluctuations. Although there is obvious site-to-site variability in forest composition, reflecting the effects of local climate, elevation and soil properties, all records show an increasing contribution of herbaceous pollen (including an increasing number of API taxa) after 4000 cal BP, indicating increased human impact in different parts of the Alps (e.g. Andrič et al., 2020; Dwileski et al., 2025; Perego et al., 2025; Rey et al., 2020).

5.2. Traces of human activities in the MO-05 sediments and the surrounding area

In the MO-05 sediments, the total NAP percentages (Fig. 3b) and accumulation rates (Fig. 7b) are relatively low (i.e. 1.2–6.5 % and <500 grains cm^{-2} a^{-1}) before 3900 cal BP, indicating a well-forested landscape around the lake. Between 6000 and 3500 cal BP, the contribution of herbaceous pollen to the terrestrial pollen sum was even lower (i.e. 4.9 vs 6.6 %) than between 9000 and 7000 a BP, an interval with a warmer and drier regional climate (Schubert et al., 2023). Several minor peaks in the NAP percentage curve are recorded between 5900 and 5500 cal BP as well as at about 4970 and 4130 cal BP, but a notable increase occurs only after 3900 cal BP.

Using ^{14}C dates of wooden remains from the three pile dwelling sites at Lake Mondsee (Fig. 1a) in a Bayesian modelling approach, Swierczynski et al. (2013a) suggested that the occupation period was divided into two phases: the first (ca. 5800–5250 cal BP) at the sites Scharfling and See and the second (ca. 5400–4700 cal BP) at the site Mooswinkel (Swierczynski et al., 2013a; Fig. 7a). However, results of recent archaeological excavations at Mooswinkel (a 70 × 40 m settlement nowadays submerged under water) together with twelve new AMS ^{14}C dates on terrestrial plant material, provide evidence that the site was already occupied between ca. 5720 and 5320 cal BP (Jakobitsch et al., 2023 and references therein). Taken together, the previous and new results suggest that all three pile dwelling sites were active during the first occupation phase, while the occupation of Mooswinkel may have lasted until ca. 4700 cal BP. Although there is so far no information on later occupational phases at Lake Mondsee, pile dwellings still existed during the Early and Middle Bronze Age at neighbouring Lake Attersee and at some other lakes in the European Alps (Ruttkay et al., 2004).

The palynological data from MO-05 suggest that human impact on the forests around the lake was rather weak during the entire pile dwelling period between ca. 5800 and 4700 cal BP, remained weak until the end of the Late Neolithic/Copper Age, and only increased after ca. 4000 cal BP with the onset of the Early Bronze Age (EBA) in the region (Kern et al., 2009). This is broadly in agreement with other well-dated pollen records from the Alps (Fig. 1c), showing comparable trends with some spatio-temporal differences. For example, NAP percentages in the Lake Grosssee record (1619 m a.s.l.) from the lower subalpine belt of the Glarus Alps in Switzerland (Dwileski et al., 2025) remain low (about 5–7 %) before 5000 cal BP and show a very weak increase thereafter, with the first small peak (17 %) around 3500 cal BP, followed by a decline to < 10 %. The nearby record from Lake Moossee (Rey et al., 2020; Fig. 1c) located at 512 m a.s.l. also demonstrates very low NAP percentages (<10 %) prior to ca. 4000 cal BP, with three minor peaks at ca. 5700, 5400 and 4950 cal BP, and more notable peaks at ca. 3950 and 3500 cal BP. During this interval, ca. 3610–3585 cal BP, *Juglans* pollen appears for the first time in the MO-05 record. To our knowledge, this is the earliest securely dated find of walnut pollen in the records from the Swiss and Austrian Alps. Studies in the European Alps (e.g. Andrič et al., 2020; Conedera et al., 2004; Schubert et al., 2023) have shown that *Juglans* started to appear regularly in pollen records since ca. 2100 cal BP, reflecting the spread of Roman settlements. However, the first walnut trees may have been introduced into the study area much earlier.

The appearance of *Plantago*, *Rumex* (Fig. 7c) and Cerealia type pollen (Fig. 7d) in the MO-05 sediments at ca. 6000–5900 cal BP predates the construction phase of the pile dwellings and suggests a possible human presence/appearance at Lake Mondsee already at that time. However, pollen transport from more distant areas and the spread of 'synanthropic plants' resulting from the trampling and browsing of wild animals cannot be ruled out entirely. Pollen indicators of agricultural activity (i.e. *Hordeum* and Cerealia types) are rare and discontinuous throughout the entire pile dwelling interval (Fig. 7d), disappearing from the record between 4700 and 4500 cal BP. Although both pollen taxa reappear in small quantities after this time, a notable (though still moderate) increase is only recorded after ca. 3850 cal BP, together with the increase in other NAP taxa and the first appearance of *Urtica*. Nettles are strongly associated with human activities and typically indicate elevated levels of phosphate and nitrogen in the soil (e.g. Behre, 1981). The appearance of a single *Triticum* type pollen (Fig. 3b) is dated to ca. 3700 cal BP. Although this evidence points to the presence of plant cultivation in the study area, it suggests that agriculture was not an important activity at Lake Mondsee during the Late Neolithic/Copper Age.

The pollen record from Litzelsee (Fig. 1c), a small lake at 413 m a.s.l. in the Lake Constance region, provides very detailed information (i.e. temporal resolution ~15 years and ~1000 counted grains per sample) on the prehistoric land use at the northern margin of the western Alps (Rösch and Lechterbeck, 2016). This record shows that although individual Cerealia type pollen grains have been present since ca. 7000 cal BP, indicating the beginning of Neolithic agriculture, a permanent opening of the forest caused by extensive ploughing and animal browsing did not begin until the Bronze Age. In contrast, land use during the Neolithic was significantly different, i.e. no permanent open land was created, but shifting slash-and-burn agriculture was used, as indicated by the numerous finds of microcharcoal in the Neolithic-dated palynological samples and the expansion of secondary forest taxa such as *Corylus* (Rösch and Lechterbeck, 2016). The MO-05 record also shows higher accumulation rates for the larger charcoal fraction before 4200 cal BP (Fig. 7f), with several peaks corresponding to peaks in the *Corylus* percentage curve (Fig. 3), indicating more frequent use of fire during the Late Neolithic/Copper Age at Lake Mondsee. However, the generally low absolute values and rare occurrence of Cerealia type pollen indicate a rather low level of human activity, including slash-and-burn agriculture, compared to the Lake Constance region.

Another high-resolution pollen record from Lake Burgäschisee (Fig. 1c), a lowland lake located southwest of Lake Constance at 465 m a.s.l. in a landscape characterised by intensive agriculture, indicates the onset of agricultural activities ca. 6500 cal BP, while single archaeological finds and local pile dwellings are dated to the period after 6250 cal BP and ca. 5950 cal BP, respectively (Rey et al., 2017), i.e. earlier than at Lake Mondsee.

To date, the most detailed records of agricultural activity in the region come from the Late Neolithic/Copper Age settlements of Lenzing-Burgstall and Ansfelden-Burgwiese (Jakobitsch et al., 2022). The excavations at Lenzing-Burgstall (Fig. 1b), situated on a small plateau above the River Ager, 25 km northeast of the MO-05 coring site, revealed settlement activities at ca. 5550 cal BP (Mondsee Group) and ca. 4850 cal BP (possibly Cham Group). Ansfelden-Burgwiese (Fig. 1c) is situated on a small cape above the confluence of the rivers Traun and Krems, about 80 km northeast of the MO-05 coring site. Although situated closer to the Donau River valley, the site has direct connection to the Attersee-Mondsee lake system via the rivers Ager and Traun. Settlement activities at Ansfelden-Burgwiese are documented from ca. 6500 cal BP until the Middle Ages (Jakobitsch et al., 2022). Abundant charred plant remains (i.e. >25,000 in total) revealed well-developed agricultural practices and a rich spectrum of cultivated crops north of the Salzkammergut lake district, including barley, einkorn and emmer wheat, lentils and large quantities of hazelnuts at Lenzing-Burgstall, complemented by free-threshing wheat, *Triticum* cf. *timopheevii* and *Triticum spelta* at Ansfelden-Burgwiese. This rich assemblage of cultivated and wild plant remains has been dated to the first half of the 6th millennium BP (Jakobitsch et al., 2022), i.e. to the time of the pile dwellings at Lake Mondsee, where the pollen indicators from the MO-05 record suggest much weaker and possibly discontinuous agricultural activities near the coring site.

Based on the macrofossil assemblage (i.e. presence of *Plantago*, *Rumex*, *Juniperus* and other plants resistant to trampling and promoted by grazing), Jakobitsch et al. (2022) suggested that cereal fields were used for grazing by cattle and sheep/goats after harvest. A similar interpretation was proposed for the Late Neolithic/Copper Age pile dwelling sites in Switzerland and southwestern Germany (Jacomet et al., 2004, 2016). In the MO-05 record (Fig. 3), *Plantago* and *Rumex* pollen appear discontinuously and in very small amounts (Fig. 7c). A slight increase to > 0.6 % is recorded ca. 4970 cal BP (i.e. during the later occupational phase at Mooswinkel) and during the EBA ca. 3850–3650 cal BP. Together with coprophilous fungal spores (Fig. 7e), this may indicate the presence of grazing animals. However, the absence of dung inhabiting fungi at ca. 5570–5370 and 3970–3770 cal BP raises questions about the continuity and extent of pastoral activity. A cumulative single influx peak (1450 spores cm^{-2} a^{-1}) of *Cercophora*, *Sordaria* and *Sporomiella* (Fig. 3c), commonly used as dung indicators, is detected at 4490 cal BP. It is, however, worth mentioning that much lower influx values recorded in the sediment of Lake Bastani in the Corsican mountains have been used to discuss Late Neolithic pastoralism (Lestienne et al., 2020). Moreover, a palynological study from Lake Grosssee in the eastern Swiss Alps also interpreted a rather low influx of 100–345 coprophilous fungal spores cm^{-2} a^{-1} as indicative for pastural activity around the lake (Dwileski et al., 2025).

The pollen record from the Siegmoos peat bog (1100 m a.s.l.) near Lake Hallstätter See in the Austrian Alps (Fig. 1b) provides insight into the impact of prehistoric salt exploitation on the local vegetation and environment over the last 5700 years (Festi et al., 2021). Their study shows that salt extraction began in the 6th millennium BP, with phases of maximum impact on vegetation documented around 3300 cal BP and after ca. 500 cal BP. Similar to the MO-05 record (Fig. 3b), the NAP taxa in the Siegmoos record show generally low values before 3500 cal BP. A slight increase is observed ca. 5050–4550 cal BP, when pasture indicator pollen taxa and coprophilous fungal spores were sporadically recorded, and ca. 3850–3550 cal BP, when a greater diversity of human impact indicators (e.g. *Plantago*, *Rumex*, *Urtica* and Apiaceae) and the first cereal pollen appeared (Festi et al., 2021). Both intervals correspond well with the intervals of increased human impact in the MO-05 record (e.g. Fig. 7c). This may indicate a regional trend and/or a direct connection between the communities around Mondsee-Attersee and Hallstätter See, which are only a day's walk apart. For the Bronze Age at least, the economic contacts between the agricultural communities living by the large pre-alpine lakes and the salt miners of Hallstatt are very likely as indicated by the archaeological and archaeobotanical evidence (Barth and Grabner, 2003; Kowarik et al., 2015).

Reviewing the history of husbandry in Austria from the Neolithic to the Roman Period, Schmölcke et al. (2018) concluded that cattle and sheep (both known in the region before ca. 6000 cal BP) were the most important domesticated animals, but also noted that the role of sheep in human subsistence shifted between periods of greater and lesser importance, strongly determined by environmental factors (e.g. humid and cold climate and densely forested landscape). Zooarchaeological research at Lake Mondsee (Pucher and Engl, 1997) confirmed sheep bones in the cultural layers assigned to the interval ca. 5750–5150 cal BP (Schmölcke et al., 2018), although more precise dating and the size of the herd at any given time remain unclear. Jakobitsch et al. (2023) investigated the livestock keeping at the Mooswinkel pile dwellings through the analysis of botanical remains in animal dung and concluded that cattle, goats and/or sheep were evidently kept inside the settlement during the study interval ca. 5720–5320 cal BP. In the same cultural layers, cultivated plants are represented by threshing remains of *Hordeum vulgare* and three species of *Triticum*, as well as seeds of *Linum usitatissimum* and *Papaver somniferum*. The botanical assemblage also consists of a long list of wild ruderal and forest taxa.

Accumulation rates of coprophilous fungal spores in the MO-05 record decrease again during the EBA (Fig. 7e) in contrast to the highest values of NAP (Fig. 7b) and other pollen indicators of human activity (Fig. 7c, d). This can be interpreted as a simultaneous decline in grazing near the MO-05 coring site (i.e. at the local scale) and increasing human impact more distant in the lake catchment and at a larger regional scale (e.g. Dwileski et al., 2025; Kothieringer et al., 2015; Rey et al., 2013). Some support for such interpretation provides the charcoal record from MO-05, which shows an increase in the small (i.e. regional), but a decrease in the larger (i.e. local) fraction concentrations (Fig. 3c) and influx (Fig. 7f) during the EBA. There is a good hope that forthcoming results of archaeological excavations and archaeobotanical analysis of material from the pile dwelling sites at the lakes Mondsee and Attersee will provide more directly dated information for checking different hypotheses about the subsistence strategies of prehistoric populations in the Salzkammergut region.

In summary, the results from the MO-05 sediments indicate a rather weak and possibly discontinuous human impact on the environment during the analysed interval. Palynological indicators show a weak increase in deforestation and agricultural activities in the wider area during the EBA, while a decrease in the influx of coprophilous fungal spores and the larger charcoal fraction probably indicates a weaker human impact in the vicinity of the coring site. Our results further support Swierczynski et al. (2013a, 2013b), who examined the MO-05 sediments for possible human impacts on detrital matter flux, but didn't find a clear increase during the time interval in focus, suggesting an insignificant impact of human land use activity on the mobilization of detrital catchment material (Fig. 7g). Consequently, the flood record derived from the MO-05 sediments represents the local and regional-scale hydrological situation, weather and climatic variability and is not anthropogenically biased (Swierczynski et al., 2013a, 2013b). An attempt to correlate the sediment-based flood record with the observed change in the construction technique of the pile dwellings suggested that the construction of the possibly younger Mooswinkel site on piles above the water might indicate an adaptation to increased flood risk and/or a general rise in lake level, which contrasts the earlier dwellings at Scharfling and See sites that were built directly on the wetlands (Swierczynski et al., 2013a). The piles at Mooswinkel, found at a depth of two to three metres, reaching down to about seven metres (Jakobitsch et al., 2023), support the notable rise of the lake level, which could have caused the abandonment of the dwelling sites at Scharfling and See. The modelled beginnings of the occupation period at Scharfling and See (ca. 5800 cal BP) coincides with flood episode 15 (Swierczynski et al., 2013a, 2013b), while the end of the occupation at all three sites is not associated with any of the major flood episodes (Fig. 7g). This could suggest that socio-economic factors, together with climate and hydrology, probably influenced the life and activities of the relatively small local population. The abandonment of the pile dwellings at Lake Mondsee could also be linked to the movement of the people to neighbouring Lake Attersee, which has a notably higher number of pile dwelling sites (Jakobitsch et al., 2023) or to the lowlands further north, which are more suitable for agriculture (Jakobitsch et al., 2022). It is important to note the uncertainties in the modelled settlement periods, which in reality could be shorter than suggested by the OxCal-based (Bronk Ramsey, 2009) *Phase* model introduced by Swierczynski et al. (2013a). Some support for shorter occupation periods of the Lake Mondsee pile dwellings is provided by the charcoal and pollen data (Fig. 7) obtained in our study. However, this hypothesis cannot be tested without thorough archaeological work, supported by a rigorous ^{14}C dating programme.

6. Conclusions

The combination of the robust varve counting-based chronology of the MO-05 composite sediment core and the high-resolution pollen record allowed us to investigate the impact of the '4.2 ka event' on the natural vegetation around Lake Mondsee. Our record shows no evidence of climate cooling or any other notable event-like changes at 4200 cal BP and therefore does not support a global significance of the '4.2 ka event'. On the other hand, the pollen record and the CONISS analysis pinpoint more gradual regional vegetation changes that occurred at the Northgrippian–Meghalayan boundary around 4200 cal BP, marking the beginning of a new climatic regime in the study region in the Late Holocene. This shift was a response to hydroclimatic changes driven by insolation-induced long-term summer cooling and winter warming. We suggest that the regional climate became more humid at this time, mainly controlled by higher winter (rain and snow) precipitation and reduced evaporation during summer. The MO-05 palynological and sediment records indicate that the climate/vegetation transition, which began at 4200 cal BP, lasted for about two centuries. This is consistent with published pollen records from Central Europe, which show a major change in vegetation and forest composition around this time.

The current MO-05 palynological record also contributes to the better understanding of human activities and their relationships with climate and the environment. Disturbance on the natural forests around the lake was weak throughout the Late Neolithic/Copper Age. Agricultural activities of early farmers settling at the archaeological sites of Mooswinkel, Scharfling and See were probably mainly based on small-scale animal husbandry and less on crop cultivation. The animal husbandry and local fire proxy records, supported by the robust chronology, corroborate the beginning of human settlement activity at the lake around 5800 cal BP, as suggested by ^{14}C data from cultural layers. While it remains unclear from the archaeological records whether small-size pile dwelling occupation in the south-eastern part of the lake was continuous between 5800 and 4700 cal BP, the new MO-05 records show evidence for absence or only very weak human activities between 5500 and 5400 cal BP. Although the archaeological records do not provide evidence of pile dwelling sites after 4700 cal BP, our data suggest that animal husbandry was continued by local farmers settling around Lake Mondsee until 4200 cal BP. The related settlements, which were perhaps located at higher elevations than the known, waterlogged sites, were possibly destroyed by erosional processes. The palynological records from the period 4200–4000 cal BP (i.e. the end of the Late Neolithic/Copper Age) indicate a phase of weak human influence/low populations in the study region by low levels of deforestation, animal husbandry and fire activity, which may have been a response to the climatic changes around the Middle–Late Holocene transition. The subsequent increase in deforestation and agricultural activities during the EBA did not affect the south-eastern shores of Lake Mondsee, but took place mainly in more distant areas, perhaps around Lake Attersee or in the lowlands to the north.

CRediT authorship contribution statement

Anna Schubert: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tarasov Pavel:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Achim Brauer:** Writing – review & editing, Validation, Resources, Investigation, Funding acquisition. **Franziska Kobe:** Writing – review & editing, Validation, Software, Methodology. **Christian Leipe:** Writing – review & editing, Visualization. **Stefan Lauterbach:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.qeh.2025.100076.

References

Andersen, N., Lauterbach, S., Erlenkeuser, H., Danielopol, D.L., Namiotko, T., Hüls, M., Belmecheri, S., Dulski, P., Nantke, C., Meyer, H., Chapligin, B., von Grafenstein, U., Brauer, A., 2017. Evidence for higher-than-average air temperatures after the 8.2 ka event provided by a Central European δ^{18}O record. Quat. Sci. Rev. 172, 96–108. https://doi.org/10.1016/j.quascirev.2017.08.001.

Andrič, M., Sabatier, P., Rapuc, W., Ogrinc, N., Dolenec, M., Arnaud, F., von Grafenstein, U., Šmuc, A., 2020. 6600 years of human and climate impacts on lake-catchment and vegetation in the Julian Alps (Lake Bohinj, Slovenia). Quat. Sci. Rev. 227, 106043. https://doi.org/10.1016/j.quascirev.2019.106043.

Ayache, M., Swingedouw, D., Mary, Y., Eynaud, F., Colin, C., 2018. Multi-centennial variability of the AMOC over the Holocene: a new reconstruction based on multiple proxy-derived SST records. Glob. Planet. Change 170, 172–189. https://doi.org/10.1016/j.gloplacha.2018.08.016.

Barth, F.E., Grabner, M., 2003. Wirtschaftliche Aussenbeziehungen des spätbronzezeitlichen Hallstatt. Mitt. der Anthropol. Ges. Wien. 133, 85–89.

Behre, K.-E., 1981. The interpretation of anthropogenic indicators in pollen diagrams. Pollen et Spores 23, 225–245.

Behre, K.-E., 2007. Evidence for Mesolithic agriculture in and around central Europe? Veg. Hist. Archaeobotany 16, 203–219.

Beiwl, C., Mühlemann, H., 2008. Atlas der natürlichen Seen Österreichs mit einer Fläche ≥50 ha. Morphometrie–Typisierung–Trophie. Bundesamt für Wasserwirtschaft. Vienna.

Bennett, K.D., Willis, K.J., 2001. Pollen. In: Smol, J.P., Birks, J.H.B., Last, W.M., Bradley, R.S., Alverson, K. (Eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal and Siliceous Indicators. Kluwer, Dordrecht, pp. 5–32.

Bernabei, M., Bontadi, J., Nicolussi, K., 2018. Observations on Holocene subfossil tree remains from high-elevation sites in the Italian Alps. Holocene 28, 2017–2027. https://doi.org/10.1177/0959683618798149.

Beug, H.-J., 2004. Leitfaden der Pollenbestimmung: für Mitteleuropa und angrenzende Gebiete. Pfeil, München. https://doi.org/10.1002/jqs.915.

Bini, M., Zanchetta, G., Perşoiu, A., Cartier, R., Català, A., Cacho, I., Dean, J.R., Di Rita, F., Drysdale, R.N., Finnè, M., Isola, I., Jalali, B., Lirer, F., Magri, D., Masi, A., Marks, L., Mercuri, A.M., Peyron, O., Sadori, L., Sicre, M.-A., Welc, F., Zielhofer, C., Brisset, E., 2019. The 4.2 ka BP event in the Mediterranean region: an overview. Clim. Past 15, 555–577. https://doi.org/10.5194/cp-15-555-2019.

Boyall, L., Martin-Puertas, C., Tjallingii, R., Milner, A.M., Blockley, S.P.E., 2024. Holocene climate evolution and human activity as recorded by the sediment record of lake Diss Mere, England. J. Quat. Sci. 39, 972–986. https://doi.org/10.1002/jqs.3646.

Brauer, A., Hajdas, I., Blockley, S.P.E., Bronk Ramsey, C., Christl, M., Ivy-Ochs, S., Moseley, G.E., Nowaczyk, N.N., Rasmussen, S.O., Roberts, H.M., Spötl, C., Staff, R.

A., Svensson, A., 2014. The importance of independent chronology in integrating records of past climate change for the 60-8 ka INTIMATE time interval. Quat. Sci. Rev. 106, 47–66. https://doi.org/10.1016/j.quascirev.2014.07.006.

Bronk Ramsey, C., 1995. Radiocarbon calibration and analysis of stratigraphy: the OxCal program. Radiocarbon 37, 425–430. https://doi.org/10.1017/S0033822200030903.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360. https://doi.org/10.1017/S0033822200033865.

Bronk Ramsey, C., Staff, R.A., Bryant, C.L., Brock, F., Kitagawa, H., van der Plicht, J., Schlolaut, G., Marshall, M.H., Brauer, A., Lamb, H.F., Payne, R.L., Tarasov, P.E., Haraguchi, T., Gotanda, K., Yonenobu, H., Yokoyama, Y., Tada, R., Nakagawa, T., 2012. A complete terrestrial radiocarbon record for 11.2 to 52.8 kyr B.P. Science 338, 370–374. https://doi.org/10.1126/science.1226660.

Clark, J.S., 1988. Particle motion and theory of charcoal analysis: source area, transport, deposition, and sampling. Quat. Res. 30, 67–80. https://doi.org/10.1016/0033-5894(88)90088-9.

Clark, J.S., Merkt, J., Müller, H., 1989. Post-glacial fire, vegetation, and human history on the northern alpine forelands, south-western Germany. J. Ecol. 77, 897–925. https://doi.org/10.2307/2260813.

Conedera, M., Krebs, P., Tinner, W., Pradella, M., Torriani, D., 2004. The cultivation of *Castanea sativa* (Mill.) in Europe, from its origin to its diffusion on a continental scale. Veg. Hist. Archaeobotany 13, 161–179. https://link.springer.com/article/10.1007/s00334-004-0038-7.

Czymzik, M., Brauer, A., Dulski, P., Plessen, B., Naumann, R., von Grafenstein, U., Scheffler, R., 2013. Orbital and solar forcing of shifts in Mid- to Late Holocene flood intensity from varved sediments of pre-alpine Lake Ammersee (southern Germany). Quat. Sci. Rev. 61, 96–110. https://doi.org/10.1016/j.quascirev.2012.11.010.

Davis, B.A., Brewer, S., Stevenson, A.C., Guiot, J., Data Contributors, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quat. Sci. Rev. 22, 1701–1716. https://doi.org/10.1016/S0277-3791(03)00173-2.

Demény, A., Kern, Z., Hatvani, I.G., Torma, C., Topál, D., Frisia, S., Leél-Őssy, S., Czuppon, G., Surányi, G., 2021. Holocene hydrological changes in Europe and the role of the North Atlantic ocean circulation from a speleothem perspective. Quat. Int. 571, 1–10. https://doi.org/10.1016/j.quaint.2020.10.061.

Demske, D., Tarasov, P.E., Nakagawa, T., Suigetsu Project Members, 2013. Atlas of pollen, spores and further non-pollen palynomorphs recorded in the glacial-interglacial late Quaternary sediments of Lake Suigetsu, central Japan. Quat. Int. 290-291, 164–238. https://doi.org/10.1016/j.quaint.2012.02.002.

Dokulil, M., Jäger, P., 1985. General limnological characterization of the Trumer Lakes, Mondsee, Attersee and Traunsee. In: Danielopol, D.L., Schmidt, R., Schultze, E. (Eds.), Contributions to the paleolimnology of the Trumer Lakes (Salzburg) and the lakes Mondsee, Attersee and Traunsee (Upper Austria). Limnologisches Institut der Österreichischen Akademie der Wissenschaften, Mondsee, pp. 16–24.

Draxler, I., 1977. Pollenanalytische Untersuchungen von Mooren zur spät- und postglazialen Vegetationsgeschichte im Einzugsgebiet der Traun. Jahrb. der Geol. Bundesanst. 120, 131–163. https://hdl.handle.net/10013/epic.35583.d001.

Dwileski, A.R., Rey, F., Morlock, M.A., Glaus, N., Szidat, S., Vogel, H., Anselmetti, F.S., Heiri, O., 2025. Holocene vegetation change at Grosssee, eastern Swiss Alps: effects of climate and human impact. Veg. Hist. Archaeobot. 34, 331–348. https://doi.org/10.1007/s00334-024-01014-7.

Festi, D., Brandner, D., Grabner, M., Knierzinger, W., Reschreiter, H., Kowarik, K., 2021. 3500 years of environmental sustainability in the large-scale alpine mining district of Hallstatt, Austria. J. Archaeol. Sci. Rep. 35, 102670. https://doi.org/10.1016/j.jasrep.2020.102670.

Feurdean, A., Klotz, S., Mosbrugger, V., Wohlfarth, B., 2008. Pollen-based quantitative reconstructions of Holocene climate variability in NW Romania. Palaeogeogr. Palaeoclimatol. Palaeoecol. 260, 494–504. https://doi.org/10.1016/j.palaeo.2007.12.014.

Frank, C., Pernicka, E., 2012. Copper artefacts of the Mondsee Group and their possible sources. In: Midgley, M.S., Sanders, J. (Eds.), Lake Dwellings after Robert Munro. Proceedings from the Munro International Seminar: The Lake Dwellings of Europe 22nd and 23rd October 2010, University of Edinburgh. Sidestone Press, Leiden, pp. 113–138.

Fuchs, K., Hacker, W., Nußbaumer, E., 2005. Naturraumkartierung Oberösterreich. Landschaftserhebung Gemeinde Innerschwand. Endbericht. Gutachten Naturschutzabteilung Oberösterreich 0386, 1–64. https://www.zobodat.at/pdf/GUTNAT_0386_0001-0064.pdf.

Fuchs, K., Hacker, W., Pinterits, S., 2004. Raumeinheit Attersee-Mondsee-Becken. Natur und Landschaft/Leitbilder für Oberösterreich. Band 12, 1–91. https://www.land-oberoesterreich.gv.at/Mediendateien/Formulare/Dokumente%20LWLD%20Abt_N/Attersee-Mondsee-Becken.pdf.

Gauthier, E., Jouffroy-Bapicot, I., 2021. Detecting human impacts: non-pollen palynomorphs as proxies for human impact on the environment. In: Marret, F., O'Keefe, J., Osterloff, P., Pound, M., Shumilovskikh, L. (Eds.), Applications of Non-Pollen Palynomorphs: from Palaeoenvironmental Reconstructions to Biostratigraphy. Geological Society London Special Publications 511, London, pp. 233–244. https://doi.org/10.1144/SP511-2020-54.

Geiger, R., 1954. Klassifikation der Klimate nach W. Köppen. Landolt-Börnstein – Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, alte Serie 3. Springer, Berlin, pp. 603–607. https://koeppen-geiger.vu-wien.ac.at/pdf/Koppen_1918.pdf..

Gill, J.L., 2014. Ecological impacts of the late Quaternary megaherbivore extinctions. New Phytol. 201, 1163–1169. https://doi.org/10.1111/nph.12576.

Grimm, E.C., 1987. CONISS: a Fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Comput. Geosci. 13, 13–35. https://doi.org/10.1016/0098-3004(87)90022-7.

Grimm, E.C., 1993. TILIA 2.0 Version b.4 (Computer Software). Illinois State Museum, Research and Collections Center, Springfield.

Grimm, E.C., 2004. TGView. Illinois State Museum, Research and Collections Center, Springfield.

Heiri, O., Ilyashuk, B., Millet, L., Samartin, S., Lotter, A.F., 2015. Stacking of discontinuous regional palaeoclimate records: Chironomid-based summer temperatures from the Alpine region. Holocene 25, 137–149. https://doi.org/10.1177/0959683614556382.

Herzschuh, U., Böhmer, T., Li, C., Chevalier, M., Dallmeyer, A., Cao, X., Bigelow, N.H., Nazarova, L., Novenko, E.Y., Park, J., Peyron, O., Rudaya, N.A., Schlütz, F., Shumilovskikh, L.S., Tarasov, P.E., Wang, Y., Wen, R., Xu, Q., Zheng, Z., 2023. LegacyClimate 1.0: A dataset of pollen-based climate reconstructions from 2594 Northern Hemisphere sites covering the late Quaternary. Earth Syst. Sci. Data 15, 2235–2258. https://doi.org/10.5194/essd-15-2235-2023.

Ilyashuk, E.A., Koinig, K.A., Heiri, O., Ilyashuk, B.P., Psenner, R., 2011. Holocene temperature variations at a high-altitude site in the Eastern Alps: a chironomid record from Schwarzsee ob Sölden, Austria. Quat. Sci. Rev. 30, 176–191. https://doi.org/10.1016/j.quascirev.2010.10.008.

Jacomet, S., Ebersbach, R., Akeret, Ö., Antolín, F., Baum, T., Bogaard, A., Brombacher, C., Bleicher, N.K., Heitz-Weniger, A., Hüster-Plogmann, H., Gross, E., Kühn, M., Rentzel, P., Steiner, B.L., Wick, L., Schibler, J.M., 2016. On-site data cast doubts on the hypothesis of shifting cultivation in the late Neolithic (c. 4300–2400 cal. BC): landscape management as an alternative paradigm. Holocene 26, 1858–1874. https://doi.org/10.1177/0959683616645941.

Jacomet, S.T., Leuzinger, U., Schibler, J. (Eds.), 2004. Die Jungsteinzeitliche Seeufersiedlung Arbon Bleiche 3: Umwelt und Wirtschaft. Archäologie im Thurgau 12. Amt für Archäeologie, Frauenfeld.

Jagsch, A., Megay, K., 1982. Mondsee. In: Wurzer, E. (Ed.), Seenreinhaltung in Österreich. Bundesministerium für Land- und Forstwirtschaft 6. Wien, Wasserwirtschaft, pp. 155–163.

Jakobitsch, T., Dworsky, C., Heiss, A.G., Kühn, M., Rosner, S., Leskovar, J., 2023. How animal dung can help to reconstruct past forest use: a late Neolithic case study from the Mooswinkel pile dwelling (Austria). Archaeol. Anthropol. Sci. 15, 20. https://doi.org/10.1007/s12520-023-01724-5.

Jakobitsch, T., Heiss, A.G., Kowarik, K., Maurer, J., Trebsche, P., Taylor, T., 2022. Food and farming beyond the Alpine lake zone: the archaeobotany of the Copper Age settlements of Lenzing-Burgstall and Ansfelden-Burgwiese in Upper Austria, and an early occurrence of *Triticum spelta* (spelt). Veg. Hist. Archaeobot. 31, 123–136. https://doi.org/10.1007/s00334-021-00843-0.

Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled Seamless SRTM Data V4. International Centre for Tropical Agriculture (CIAT).

Kern, A., Kowarik, K., Reschreiter, H., Rausch, A.W., Thommes, J., Taylor, T.G., 2009. Kingdom of Salt: 7000 years of Hallstatt. Naturhistorisches Museum Wien, Vienna.

Kossler, A., Tarasov, P., Schlolaut, G., Nakagawa, T., Marshall, M., Brauer, A., Staff, R., Ramsey, C.B., Bryant, C., Lamb, H., Demske, D., Gotanda, K., Haraguchi, T., Yokoyama, Y., Yonenobu, H., Tada, R., 2011. Onset and termination of the late-glacial climate reversal in the high-resolution diatom and sedimentary records from the annually laminated SG06 core from Lake Suigetsu, Japan. Palaeogeogr. Palaeoclimatol. Palaeoecol. 306, 103–115. https://doi.org/10.1016/j.palaeo.2011.04.004.

Kothieringer, K., Walser, C., Dietre, B., Reitmaier, T., Haas, J.N., Lambers, K., 2015. High impact: early pastoralism and environmental change during the Neolithic and Bronze Age in the Silvretta Alps (Switzerland/Austria) as evidenced by archaeological, palaeoecological and pedological proxies. Z. für Geomorphol. 59, Suppl. 2, 177–198. https://doi.org/10.1127/zfg_suppl/2015/S-59210.

Kowarik, K., Reschreiter, H., Klammer, J., Grabner, M., Winner, G., 2015. Umfeld und Versorgung des Hallstätter Salzbergbaus von der Mittelbronzezeit in die Ältere Eisenzeit. Bergauf Bergab 10, 309–318.

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

Kunze, W., 1986. Mondsee – 5000 Jahre Geschichte und Kultur. Selbstverlag der Gemeinde, Mondsee.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-term numerical solution for the insolation quantities of the Earth. Astron. Astrophys. 428, 261–285. https://doi.org/10.1051/0004-6361:20041335.

Lauterbach, S., Brauer, A., Andersen, N., Danielopol, D.L., Dulski, P., Hüls, M., Milecka, K., Namiotko, T., Obremska, M., von Grafenstein, U., 2011. Environmental responses to Lateglacial climatic fluctuations recorded in the sediments of pre-Alpine Lake Mondsee (northeastern Alps) (Declakes Participants). J. Quat. Sci. 26, 253–267. https://doi.org/10.1002/jqs.1448.

Leipe, C., Kobe, F., Müller, S., 2019. Testing the performance of sodium polytungstate and lithium heteropolytungstate as non-toxic dense media for pollen extraction from lake and peat sediment samples. Quat. Int. 516, 207–214. https://doi.org/10.1016/j.quaint.2018.01.029.

Lestienne, M., Jouffroy-Bapicot, I., Leyssenne, D., Sabatier, P., Debret, M., Albertini, P.-J., Colombaroli, D., Didier, J., Hély, C., Vannière, B., 2020. Fires and human activities as key factors in the high diversity of Corsican vegetation. Holocene 30, 244–257. https://doi.org/10.1177/0959683619883025.

Litt, T., Schölzel, C., Kühl, N., Brauer, A., 2009. Vegetation and climate history in the Westeifel Volcanic Field (Germany) during the past 11000 years based on annually laminated lacustrine maar sediments. Boreas 38, 679–690. https://doi.org/10.1111/j.1502-3885.2009.00096.x.

Magny, M., Combourieu-Nebout, N., de Beaulieu, J.L., Bout-Roumazeilles, V., Colombaroli, D., Desprat, S., Francke, A., Joannin, S., Ortu, E., Peyron, O., Revel, M., Sadori, L., Siani, G., Sicre, M.A., Samartin, S., Simonneau, A., Tinner, W., Vannière, B., Wagner, B., Zanchetta, G., Anselmetti, F., Brugiapaglia, E., Chapron, E., Debret, M., Desmet, M., Didier, J., Essallami, L., Galop, D., Gilli, A., Haas, J.N., Kallel, N., Millet, L., Stock, A., Turon, J.L., Wirthet, S., 2013. North-South palaeohydrological contrasts in the central Mediterranean during the Holocene: tentative synthesis and working hypotheses. Clim. Past 9, 2043–2071. https://doi.org/10.5194/cp-9-2043-2013.

Martin-Puertas, C., Walsh, A.A., Blockley, S.P.E., Harding, P., Biddulph, G.E., Palmer, A., Ramisch, A., Brauer, A., 2021. The first Holocene varve chronology for the UK: based on the integration of varve counting, radiocarbon dating and tephrostratigraphy from Diss Mere (UK). Quat. Geochronol. 61, 101134. https://doi.org/10.1016/j.quageo.2020.101134.

Mayewski, P., Meeker, L.D., Twickler, M.S., Whitlow, S., Yang, Q., Prentice, M., 1997. Major features and forcing of high latitude Northern Hemisphere circulation using a 110,000-year-long glaciochemical series. J. Geophys. Res. 102, 26345–26366. https://doi.org/10.1029/96JC03365.

Mayewski, P.A., Rohling, E.E., Stager, J.C., Karlén, W., Maasch, K.A., Meeker, L.D., Meyerson, E.A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R.R., Steig, E.J., 2004. Holocene climate variability. Quat. Res. 62, 243–255. https://doi.org/10.1016/j.yqres.2004.07.001.

McKay, N.P., Kaufman, D.S., Arcusa, S.H., Kolus, H.R., Edge, D.C., Erb, M.P., Hancock, C. L., Routson, C.C., Żarczyński, M., Marshall, L.P., Roberts, G.K., Telles, F., 2024. The 4.2 ka event is not remarkable in the context of Holocene climate variability. Nat. Commun. 15, 6555. https://doi.org/10.1038/s41467-024-50886-w.

Mercuri, A.M., Florenzano, A., Burjachs, F., Giardini, M., Kouli, K., Masi, A., Picornell-Gelabert, L., Revelles, J., Sadori, L., Servera-Vives, G., Torri, P., Fyfe, R., 2019. From influence to impact: the multifunctional land use in Mediterranean prehistory emerging from palynology of archaeological sites (8.0-2.8 ka BP). Holocene 29, 830–846. https://doi.org/10.1177/0959683619826631.

Moore, P.D., Webb, J.A., 1978. An illustrated guide to pollen analysis. Hodder and Stoughton, London-Sydney-Auckland-Toronto.

Moossen, H., Bendle, J., Seki, O., Quillmann, U., Kawamura, K., 2015. North Atlantic Holocene climate evolution recorded by high-resolution terrestrial and marine biomarker records. Quat. Sci. Rev. 129, 111–127. https://doi.org/10.1016/j.quascirev.2015.10.013.

Nakagawa, T., Gotanda, K., Haraguchi, T., Danhara, T., Yonenobu, H., Yokoyama, Y., Brauer, A., Yokoyama, Y., Tada, R., Takemura, K., Staff, R.A., Payne, R., Bronk Ramsey, C., Bryant, C., Brock, F., Schlolaut, G., Marshall, M., Tarasov, P., Lamb, H., Suigetsu 2006 Project Members, 2012. SG06, a perfectly continuous and varved sediment core from Lake Suigetsu, Japan: stratigraphy and potential for improving the radiocarbon calibration model and understanding of late Quaternary climate changes. Quat. Sci. Rev. 36, 164–176. https://doi.org/10.1016/j.quascirev.2010.12.013.

Nakagawa, T., Tarasov, P., Staff, R., Bronk Ramsey, C., Marshall, M., Schlolaut, G., Bryant, C., Brauer, A., Lamb, H., Haraguchi, T., Gotanda, K., Kitaba, I., Kitagawa, H., van der Plicht, J., Yonenobu, H., Omori, T., Yokoyama, Y., Tada, R., Yasuda, Y., Suigetsu 2006 Project Members, 2021. The spatio-temporal structure of the Lateglacial to early Holocene transition reconstructed from the pollen record of Lake Suigetsu and its precise correlation with other key global archives: implications for palaeoclimatology and archaeology. Glob. Planet. Change 202, 103493. https://doi.org/10.1016/j.gloplacha.2021.103493.

Namiotko, T., Danielopol, D.L., von Grafenstein, U., Lauterbach, S., Brauer, A., Andersen, N., Hüls, M., Milecka, K., Baltanás, A., Geiger, W., DecLakes Participants, 2015. Palaeoecology of Late Glacial and Holocene profundal ostracoda of pre-Alpine lake Mondsee (Austria) - a base for further (palaeo-) biological research. Paleogeog. Paleoclimatol. Paleoecol. 419, 23–36. https://doi.org/10.1016/j.palaeo.2014.09.009.

Nationalpark O.ö. Kalkalpen Ges.m.b.H., 2016. Natürliche Buchenwälder des Nationalpark Kalkalpen, Schutz und Erbe alter Wälder. Schriftenreihe Nationalpark Kalkalpen Band 16. https://www.zobodat.at/pdf/NP-Kalkalpen-Bericht_20_Jahre_0001.pdf.

Nicolussi, K., Kaufmann, M., Patzelt, G., Plicht van der, J., Thurner, A., 2005. Holocene tree-line variability in the Kauner Valley, Central Eastern Alps, indicated by dendrochronological analysis of living trees and subfossil logs. Veg. Hist. Archaeobot. 14, 221–234. https://doi.org/10.1007/s00334-005-0013-y.

Olsen, J., Anderson, N., Knudsen, M., 2012. Variability of the North Atlantic oscillation over the past 5,200 years. Nat. Geosci. 5, 808–812. https://doi.org/10.1038/ngeo1589.

Perego, R., Furlanetto, G., Rapi, M., Ravazzi, C., 2025. Plant-human interactions: from pristine forest to Bronze Age farming–vegetation history and depositional processes off-shore the lake dwelling of Lavagnone, N-Italy. Veg. Hist. Archaeobot. 34, 459–487. https://doi.org/10.1007/s00334-024-01027-2.

Perşoiu, A., Onac, B.P., Wynn, J.G., Blaauw, M., Ionita, M., Hansson, M., 2017. Holocene winter climate variability in Central and Eastern Europe. Sci. Rep. 7, 1196. https://doi.org/10.1038/s41598-017-01397-w.

Poraj-Górska, A.I., Bonk, A., Żarczyński, M., Kinder, M., Tylmann, W., 2021. Varved lake sediments as indicators of recent cultural eutrophication and hypolimnetic hypoxia in lakes. Anthropocene 36, 100311. https://doi.org/10.1016/j.ancene.2021.100311.

Prentice, I.C., Cramer, W., Harrison, S.P., Leemans, R., Monserud, R.A., Solomon, A.M., 1992. A global biome model based on plant physiology and dominance, soil properties and climate. J. Biogeogr. 19, 117–134. https://doi.org/10.2307/2845499.

Prentice, I.C., Guiot, J., Huntley, B., Jolly, D., Cheddadi, R., 1996. Reconstructing biomes from palaeoecological data: a general method and its application to European pollen data at 0 and 6 ka. Clim. Dyn. 12, 185–194. https://doi.org/10.1007/s003820050102.

Pucher, E., Engl, K., 1997. Studien zur Pfahlbauforschung in Österreich, Materialien I, die Pfahlbauten des Mondsees, Tierknochenfunde. Mitteilungen der Prähistorischen Kommission der Österreichischen Akademie der Wissenschaften 33, 1–150.

Reille, M., 1992. Pollen et spores d'Europe et d'Afrique du nord. Laboratoire de botanique historique et palynologie, URA CNRS, Marseille, France.

Reille, M., 1995. Pollen et spores d'Europe et d'Afrique du nord. Supplement I. Laboratoire de botanique hislorique el palynologie, URA CNRS, Marseille, France.

Reille, M., 1998. Pollen et spores d'Europe et d'Afrique du nord. Supplement 2. Laboratoire de botanique historique et palynologie, URA CNRS, Marseille, France.

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

Reiter, V., 2008. Aktueller Forschungsstand der Mondsee-Funde in der Studiensammlung des Institutes für Ur- und Frühgeschichte der Universität Wien. Archäologie Österreichs 19 (1), 38–43.

Rey, F., Gobet, E., Schwörer, C., Hafner, A., Szidat, S., Tinner, W., 2020. Climate impacts on vegetation and fire dynamics since the last deglaciation at Moossee (Switzerland). Clim. Past 16, 1347–1367. https://doi.org/10.5194/cp-16-1347-2020.

Rey, F., Gobet, E., van Leeuwen, J.F.N., Gilli, A., van Raden, U.J., Hafner, A., Wey, O., Rhiner, J., Schmocker, D., Zünd, J., Tinner, W., 2017. Vegetational and agricultural dynamics at Burgäschisee (Swiss Plateau) recorded for 18,700 years by multi-proxy evidence from partly varved sediments. Veg. Hist. Archaeobot. 26, 571–586. https://doi.org/10.5194/cp-2019-121.

Rey, F., Schwörer, C., Gobet, E., Colombaroli, D., van Leeuwen, J.F.N., Schleiss, S., Tinner, W., 2013. Climatic and human impacts on mountain vegetation at Lauenensee (Bernese Alps, Switzerland) during the last 14,000 years. Holocene 23, 1415–1427. https://doi.org/10.1177/0959683613489585.

Rösch, M., Lechterbeck, J., 2016. Seven millennia of human impact as reflected in a high resolution pollen profile from the profundal sediments of Litzelsee, Lake Constance region, Germany. Veg. Hist. Archaeobot. 25, 339–358. https://doi.org/10.1007/s00334-015-0552-9.

Ruttkay, E., Cichocki, O., Pernicka, E., Pucher, E., 2004. Prehistoric lacustrine villages on the Austrian lakes – past and recent research developments. Living on the lake in prehistoric Europe: 150 years of lake-dwelling research. London. Routledge, pp. 50–68.

Schmidt, R., 1981. Grundzüge der spät- und postglazialen Vegetations- und Klimageschichte des Salzkammergutes (Österreich) aufgrund palynologischer Untersuchungen von See- und Moorprofilen. Mitteilungen der Kommission für Quartärforschung der Österreichischen Akademie der Wissenschaften 3, 1–96.

Schmidt, R., 1986. Palynologie, Stratigraphie und Großreste von Profilen der neolithischen Station See am Mondsee, Oberösterreich. Archaeol. Austriaca 70, 227–235.

Schmölcke, U., Gross, D., Nikulina, E.A., 2018. The history of sheep husbandry in Austria from the Neolithic to the Roman Period. Annalen des Naturhistorischen Museums Wien, Serie A 120, 101–126.

Schubert, A., Lauterbach, S., Leipe, C., Scholz, V., Brauer, A., Tarasov, P.E., 2020. Anthropogenic and climate controls on vegetation changes between 1500 BCE and 500 CE reconstructed from a high-resolution pollen record from varved sediments of Lake Mondsee, Austria. Palaeogeogr. Palaeoclimatol. Palaeoecol. 559, 109976. https://doi.org/10.1016/j.palaeo.2020.109976.

Schubert, A., Lauterbach, S., Leipe, C., Brauer, A., Tarasov, P.E., 2023. Visible or not? Reflection of the 8.2 ka BP event and the Greenlandian–Northgrippian boundary in a new high-resolution pollen record from the varved sediments of Lake Mondsee, Austria. Quat. Sci. Rev. 308, 108073. https://doi.org/10.1016/j.quascirev.2023.108073.

Stebich, M., Rehfeld, K., Schlütz, F., Tarasov, P.E., Liu, J., Mingram, J., 2015. Holocene vegetation and climate dynamics of NE China based on the pollen record from Sihailongwan Maar Lake. Quat. Sci. Rev. 124, 275–289. https://doi.org/10.1016/j.quascirev.2015.07.021.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores 13, 614–621.

Svensson, A., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Davies, S.M., Johnsen, S.J., Muscheler, R., Parrenin, F., Rasmussen, S.O., Röthlisberger, R., Seierstad, I., Steffensen, J.P., Vinther, B.M., 2008. A 60000 year Greenland stratigraphic ice core chronology. Clim. Past 4, 47–57. https://doi.org/10.5194/cp-4-47-2008.

Swierczynski, T., Brauer, A., Lauterbach, S., Martín-Puertas, C., Dulski, P., von Grafenstein, U., Rohr, C., 2012. A 1600 yr seasonally resolved record of decadal-scale flood variability from the Austrian Pre-Alps. Geology 40, 1047–1050. https://doi.org/10.1130/G33493.1.

Swierczynski, T., Lauterbach, S., Dulski, P., Brauer, A., 2013a. Late Neolithic Mondsee Culture in Austria: living on lakes and living with flood risk? Clim. Past 9, 1601–1612. https://doi.org/10.5194/cp-9-1601-2013.

Swierczynski, T., Lauterbach, S., Dulski, P., Delgado, J., Merz, B., Brauer, A., 2013b. Mid- to late Holocene flood frequency changes in the northeastern Alps recorded in varved sediments of Lake Mondsee (Upper Austria). Quat. Sci. Rev. 80, 78–90. https://doi.org/10.1016/j.quascirev.2013.08.018.

Tarasov, P.E., Savelieva, L.A., Kobe, F., Korotkevich, B.S., Long, T., Kostromina, N.A., Leipe, C., 2022. Lateglacial and Holocene changes in vegetation and human subsistence around Lake Zhizhitskoye, East European midlatitudes, derived from radiocarbon-dated pollen and archaeological records. Quat. Int. 623, 184–197. https://doi.org/10.1016/j.quaint.2021.06.027.

Tarasov, P.E., Webb III, T., Andreev, A.A., Afanas'eva, N.B., Berezina, N.A., Bezusko, L. G., Blyakharchuk, T.A., Bolikhovskaya, N.S., Cheddadi, R., Chernavskaya, M.M., Chernova, G.M., Dorofeyuk, N.I., Dirksen, V.G., Elina, G.A., Filimonova, L.V., Glebov, F.Z., Guiot, J., Gunova, V.S., Harrison, S.P., Jolly, D., Khomutova, V.I., Kvavadze, E.V., Osipova, I.M., Panova, N.K., Prentice, I.C., Saarse, L., Sevastyanov, D.V., Volkova, V.S., Zernitskaya, V.P., 1998. Present-day and mid-Holocene biomes reconstructed from pollen and plant macrofossil data from the Former Soviet Union and Mongolia. J. Biogeogr. 25, 1029–1053. https://doi.org/10.1046/j.1365-2699.1998.00236.x.

Tinner, W., Conedera, M., Ammann, B., Gäggeler, H.W., Gedye, S., Jones, R., Sägesser, B., 1998. Pollen and charcoal in lake sediments compared with historically documented forest fires in southern Switzerland since AD 1920. Holocene 8, 31–42. https://doi.org/10.1191/095968398667205430.

van Geel, B., 1978. A palaeoecological study of Holocene peat bog sections in Germany and the Netherlands, based on the analysis of pollen, spores and macro and microscopic remains of fungi, algae, cormophytes and animals. Rev. Palaeobot. Palynol. 25, 1–120. https://doi.org/10.1016/0034-6667(78)90040-4.

van Geel, B., 2001. Non-pollen palynomorphs. In: Smol, J.P., Birks, J.H.B., Last, W.M., Bradley, R.S., Alverson, K. (Eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal and Siliceous Indicators. Kluwer, Dordrecht, pp. 99–119. https://doi.org/10.1007/0-306-47668-1_6.

van Geel, B., Engels, S., Martin-Puertas, C., Brauer, A., 2013. Ascospores of the parasitic fungus *Kretzschmaria deusta* as rainstorm indicators during a late Holocene beech-forest phase around lake Meerfelder Maar, Germany. J. Paleolimnol. 50, 33–40. https://doi.org/10.1007/s10933-013-9701-2.

von Schnurbein, S. (Ed.), 2009. Atlas der Vorgeschichte: Europa von den ersten Menschen bis Christi Geburt. Konrad Theiss Verlag, Stuttgart.

Walker, M., Head, M.J., Lowe, J., Berkelhammer, M., Björck, S., Cheng, H., Cwynar, L.C., Fisher, D., Gkinis, V., Long, A., Newnham, R., Rasmussen, S.O., Weiss, H., 2019. Subdividing the Holocene Series/Epoch: formalization of stages/ages and subseries/subepochs, and designation of GSSPs and auxiliary stratotypes. J. Quat. Sci. 34, 173–186. https://doi.org/10.1002/jqs.3097.

Weng, C., Hooghiemstra, H., Duivenvoorden, J.F., 2006. Challenges in estimating past plant diversity from fossil pollen data: statistical assessment, problems, and possible solutions. Divers. Distrib. 12, 310–318. https://doi.org/10.1111/j.1366-9516.2006.00230.x.

Whitlock, C., Larsen, C.P.S., 2001. Charcoal as a fire proxy. In: Smol, J.P., Birks, J.H.B., Last, W.M., Bradley, R.S., Alverson, K. (Eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal and Siliceous Indicators. Kluwer, Dordrecht, pp. 75–97. https://doi.org/10.1007/0-306-47668-1_5.

Zander, P.D., Żarczyński, M., Vogel, H., Tylmann, W., Wacnik, A., Sanchini, A., Grosjean, M., 2021. A high-resolution record of Holocene primary productivity and water-column mixing from the varved sediments of Lake Żabińskie, Poland. Sci. Total Environ. 755, 1–16. https://doi.org/10.1016/j.scitotenv.2020.143713.