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Human impact as reflected in the pollen record, with a focus on the Middle Ages

Ph.D. Thesis

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▆▆ Annotation

Pollen analysis is an integral part of past vegetation reconstructions based on fossil sedimentary records. This thesis introduces the topics of past vegetation development in the area of Central Europe afftected by a combination of climatic events, natural plant dispersal processes, and human impact. A natural site of the former lake Komořany was investigated to address the early periods covering the Late Glacial and majority of the Holocene (~15.6–3.2 ka BP). Moreover, three distinct medieval village sites covering an altitudinal gradient of the Czech territory served for reconstruction of the increased human impact on landscape and vegetation, especially during the High Medieval Period. A multidisciplinary approach including pollen, plant macrofossil, diatom, and palaeo-zoological record in combination with archaeological finds was employed to track the origins and formation of the cultural landscape, focusing on the medieval transformation.

Declaration

I hereby declare that I am the author of this dissertation and that I have used only those sources and literature detailed in the list of references.

České Budějovice, April 4, 2022 Petra Marešová

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signature

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List of papers and author’s contribution

The thesis is based on the following papers:

I. Tichá A., Bešta T., Vondrák D., **Houfková P.**, Jankovská V. (2019) Nutrient availability affected shallow-lake ecosystem response along the Late-Glacial/Holocene transition. *Hydrobiologia* 846: 87-108. (IF = 2.694).

PM performed the pollen analysis, participated in sediment processing and the manuscript preparation. Her contribution was 12 %.

II. **Houfková P.,** Bešta T., Bernardová A., Vondrák D., Pokorný P., Novák J. (2017) Holocene climatic events linked to environmental changes at Lake Komořany Basin, Czech Republic, *Holocene* 27: 1132-1145. (IF = 2.769).

PM performed the pollen analysis, climate reconstruction modelling, and prepared majority of the manuscript. Her contribution was 60 %.

III. Pokorná A., **Houfková P.**, Novák J., Bešta T., Kovačiková L., Nováková K., Zavřel J., Starec P. (2014) The oldest Czech fishpond discovered? An interdisciplinary approach to reconstruction of local vegetation in mediaeval Prague suburbs. *Hydrobiologia* 730: 191-213. (IF = 2.694).

PM performed the pollen analysis and substantially participated in the manuscript preparation. Her contribution was 40 %.

IV. **Houfková P.**, Bumerl J., Pospíšil L., Karlík P., Beneš J., Bernardová A., Hrabalíková M., Janečková Molnárová K., Hejcman M. (2015) Origin and development of long-strip field patterns: A case study of an abandoned medieval village in the Czech Republic. *Catena* 135: 83-91 (IF = 5.198).

PM designed the study, participated in the field sampling, and prepared the manuscript. Her contribution was 65 %.

V. **Houfková P.,** Horák H., Pokorná A., Bešta T., Pravcová I., Novák J., Klír T. (2019) The dynamics of a non-forested stand in the Krušné Mts.: the effect of a short-lived medieval village on the local environment. *Vegetation History and Archaeobotany* 28: 607-621. (IF = 2.375).

PM conceptualized the study, performed the field sampling, sediment separation, pollen analysis, and wrote the manuscript. Her contribution was 67 %.

Co-author agreements

A. Tichá, the first and corresponding author of **Paper I**, acknowledges the stated contribution of Petra Marešová to this manuscript.

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Doc. PhDr. Tomáš Klír, Ph.D.

Contents

1. Introduction

1.1. Contemporary Central European vegetation as a result of Quaternary development

1.1.1. Alternation of glacial and interglacial periods in the Quaternary

Biome distribution on Earth is shaped by its climate. The global diel and annual distribution of temperature, moisture, the resulting continentality etc. are influenced by solar forces, astronomical and geographical factors that have continuously changed during the planet´s history. The shaping of nature has therefore been significantly affected by the past development of these factors. The most recent changes in the Quaternary period (2.58 Ma, Head et al. 2021) were defined by the alternation of glacial and interglacial periods, driven above all by Milankovitch cycles (Hays et al. 1976, Maslin 2016). Generally, during the glacial periods, the ice sheet on the poles grew and biomes moved closer to the equator. In Europe, the Alps created a barrier against their fluent shift southwards. The migration of some species, especially trees, was thus constrained and a number of them became extinct in the area of Central Europe (CE) (e.g. *Celtis*). A corridor between the European Ice Sheet Complex (EISC) and the Alpine glaciers (Ivy-Ochs et al. 2022) strongly supported the migration of species in the east-west direction, e.g. pushing the evergreen broadleaved temperate forest tree taxa (*Zelkova*, *Pterocarya*) to the southern shore of the Black Sea. On the contrary, the spread of certain species varied between the subsequent interglacials, and not all the species (such as *Fagus sylvatica*) contributed equally to the recolonization of each interglacial landscape. The periodical overturn of species responding to the glacial-interglacial cycle is traditionally known as the

Iversen´s cycle (Iversen 1964). The development of flora and vegetation was further tightly connected to soil formation and sedimentary processes, ranging from the long cryocratic stage of the glacial phase to the protocratic, mesocratic, oligocratic and telocratic phases of the interglacial periods (Birks et Birks 2004, Birks 2005).

The last Iversen´s cycle corresponds to the Last Glacial Cycle (LGC, 119–11.7 ka BP), (Andersen et al. 2004, Head 2019) and the Holocene (11.7 ka BP until present). Having in mind the diversity of both the current and the past vegetation, affected by additional factors such as the distribution of azonal biomes (Chytrý 2012) and differences between biogeographical regions (Roleček et al. 2021), two most conspicuous development phases can be identified within each repetition of the Iversen´s cycle: In the area of CE, cold, dry climate and steppe-tundra growing on immature base-rich soils might be reconstructed during the cryocratic phase in contrast to warm, moist climate and temperate deciduous forests growing on fertile soils in the mesocratic phase. Application of this general scheme pinpoints some of the crucial questions regarding the dynamics and patterns of vegetation change in the past. Where did certain species survive the generally extreme conditions (for concept of refugia see Stewart et al. 2010)? How, if so, did the particular species subsequently spread (Giesecke et al. 2017)?

Searching for such answers brings our attention to the spatial and temporal heterogeneity. For instance, the 100 thousand years of the cryocratic phase of the LGC was a rather dynamic epoch. Reflecting the Dansgaard-Oeschger events, a harsh climate during the full glacials (stadials) followed the relatively mild conditions in the interstadials (Rasmussen et al. 2014).

1.1.2. The Last Glacial Maximum

The last full glacial is also called the Last Glacial Maximum (LGM), and according to Huges (2022) it covers roughly 29–19 ka BP. For the period of 25–19 ka BP, Tierney et al. (2020) provided a constraint on global mean LGM cooling of −6.1 °C. By that time, the EISC reached its southmost maximum, altering the exchange of water between the ice and the ocean and causing the global sea level to fall to −134 m (29–21 ka BP) (Lambeck et al. 2014). The ice sheet maximum extent reached two marginal positions corresponding to the Brandenburg (Leszno) Phase (25–24 ka BP) and the Frankfurt (Poznań) Phase (21–19 ka BP) in CE (Marks et al. 2022). Thus, even in CE, a glacial landscape along with other local ice sheets (Alpine, Tatran, and Carpathian) existed. However, the rest of the area cannot be imagined as a uniform steppe-tundra with thermophilous species pushed to the warmer margins of Europe (Huntley et Birks 1983). Chytrý et al. (2019) reconstructed a close modern analogue of such ecosystem in the southeastern Russian Altai Mountains, southern Siberia. These include habitats such as the steppe, mesic and wet grasslands, shrubby tundra, riparian scrub, and patches of open woodland at moister sites. Among the so-called northern or cryptic refugia of temperate species during the LGM, mostly those located in the Alps and Carpathians were closest to the modern Czech territory. Western Carpathians have been demonstrated to be the northern glacial refugium of many plant species (Jankovská et Pokorný 2008, Jamrichová et al. 2014). Jamrichová et al. (2017) modelled the refugia of broadleaved trees in the humid northwestern mountain part of the Western Carpathians. The Slovak Eastern Carpathians were defined as a potential glacial refugium by Juřičková et al. (2019). A boreal open parkland type forest-steppe with a mosaic structure and scattered trees was reconstructed in the Carpathian basin by Sümegi et al. (2022). According to Young et al. (2020), the northern cryptic refugia of *Alnus* sp. may have been located even in Great Britain.

1.1.3. The Last Deglaciation

The transition between LGM and the Holocene is often called the last deglaciation (approximately 19–11 ka BP). During this period, the ice sheets retreated, and the sea level rose (Reyes at al. 2022). These processes are generally believed to be driven by an increased summer incoming solar radiation reaching the Northern Hemisphere (boreal summer insolation), and by rising greenhouse gas concentrations (for further details see e.g. Clark et al. 2012, Ullman et al. 2015, Lora et Ibarra 2019). An increasing ratio of trees and shrubs (particularly shrub-tundra, hemiboreal and boreal forests in CE) compared to grasses (particularly steppe-tundra in CE) fitted the general trend in plant cover shift across all the continents (Kuneš et Abraham 2017, Rey et al. 2020, Adam et al. 2021).

A generally mild climate period of ~14.6–12.9 ka BP, known as the BøllingeAllerød chronozone, was originally used as a biostratigraphical period in Scandinavian terrestrial records (Iversen 1954, Mangerud et al. (1974). An analogous epoch was classified as GI-I (with its cold sub-events a-g) in the Greenland ice-core record (Rasmussen et al. 2014). During the Laurentide Ice Sheet melting, changes in the freshwater income affected the salinity and density of surface water in the North Atlantic Ocean, leading to slowing of the thermohaline circulation for some time (Praetorius et al. 2008). This further led to the onset of a cold stadial period classified as GS-1 in the Greenland ice-cores (Rasmussen et al. 2014), traditionally known as the Younger Dryas chronozone (12.9–11.7 ka BP). According to Renssen et al. (2015), this cooling event was not solely caused by the rapid melt-water influx, but it was rather a combination of a weakening Atlantic Meridional Overturning Circulation (AMOC), moderate negative radiative forcing, and an altered atmospheric circulation. Moreover, an interaction between the millennial and the orbital timescale variability affects the shape and rapidity of the glacial termination (Barker et Knorr 2021). Finally, it seems that also the Younger Dryas impact hypothesis (~12.8 ka BP) has recently attracted a renewed attention (Firestone et al. 2007, Sweatman 2021, Powell 2022).

1.1.4. The Holocene

The Late-Glacial/Holocene boundary at 11.7 ka BP corresponds to rapid warming and is marked by a further general increase in the forest cover. The average forest-cover already could have reached ~48 % in CE, possessing the highest ratio along a belt spanning from the circum-alpine area to central-eastern Europe (Zanon et al. 2018). In the Early Holocene (11.7–8.2 ka BP) a general trend of temperature rise was documented. Intermittent cold events lasting for several decades were documented around 11.4, 9.3 and 8.2 ka BP, mainly in the Atlantic-European region, probably resulting from a collapse of the AMOC due to repeated freshwater outbursts from the Laurentide Ice Sheet (Rassmusssen et al. 2014, Wanner et al. 2015). A global 160 years long

8.2 ka BP cooling episode defined the upper boundary of the Early Holocene (Walker et al. 2018). Apart from the outbursts of Lakes Agassiz, other freshwater forcing hypotheses have recently been suggested (Matero et al. 2017, Aguiar et al. 2021).

A warm and stable climate with a mild trend of decreasing temperature averages was documented in the Middle Holocene (8.2–4.2 ka BP). The Late Holocene (4.2 ka BP until present) can in general be defined by its lower climate stability. In contrast to the Early Holocene cold events, the Late Holocene fluctuations have rather been caused by the covarying influence of the major tropical volcanic eruptions and the Grand Solar Minima (Wanner et al. 2015). The Late Holocene boundary may not be related to a single global forcing (Walker et al. 2018). While no significant climate events have been identified in the northern North Atlantic region (Bradley et Bakke 2019), Pleskot et al. (2020) highlighted several possible causes of an increase in aridity, in particular concerning the mid/low-latitude regions: southward migration of the Intertropical Convergence Zone, Asian monsoon weakening, and atmospheric blocking induced by a strenghtened Siberian High.

Apart from the above-mentioned Holocene general climate trends, millennial-scale climate cycles were identified throughout the Holocene (Maslin et al. 2001). Bond at al. (2001) classified a “1500-year” cycle in the North Atlantic’s caused by the solar forcing. This cycle is known as the Bond cycle, including eight separate Bond events. These have been considered as equivalent to Dansgaard-Oeschger events observed during the LGP (Bond et al. 2001, Rousseau et al. 2022). The two most recent of them seem to correspond to historically known periods, the Little Ice Age

(BE0; ~0.4 ka BP) and the Dark Age Cold Period (BO1~1.4 ka BP). The remaining earlier events were reconstructed as follows: BO2~2.8 ka BP, 3~4.4 ka BP, 4~5.5 ka BP, 5a~7.5 ka BP, 5b~8.1 ka BP, 6~9.4 ka BP, 7~10.3 ka BP, and 8~11.1 ka BP. The occurence of tree taxa has been lately connected to the Bond cycle in a pollen-based study by Poska et al. (2022). Nevertheless, the ± 500 years variance in periodicity (Obrochta et al. 2012), the possible quasiperiodicity (Wanner et al. 2011), and simplification of the forcing mechanisms have been repeatedly highlighted. Wanner et al. (2011) proposed that the cooling events were triggered by a combined effect of solar insolation, slowdown of the thermohaline circulation, and series of tropical volcanic eruptions, including their feedback effects. Later, the authors (Wanner et al. 2015) emphasized that these forcing mechanisms markedly differed between the Early and the Late Holocene.

1.1.5. General trends of tree dispersal in the Holocene

In response to the rapid warming during the Holocene, the proportion of trees in the vegetation cover further increased in Europe. However, the rates of spread differed among the individual tree species. *Corylus*, *Ulmus* and *Alnus* reached at least 1000 m year^{-1} migration rate, *Tilia*, *Quercus*, *Fagus*, and *Carpinus* reached around 400 m year^{-1}, while the migration rate of *Abies* was likely the lowest, around 250 m year^{-1} (Giesecke et al. 2017). The sequence of major vegetation changes in the Scandinavian region, corresponding to postglacial climatic changes, was introduced via the Blytt–Sernander scheme (Sernander 1908, for a complete history see Birks et Seppä 2010). These chronoblocks (preboreal, boreal, atlantic, subboreal and subatlantic) were adapted for CE by Firbas (1949).

Nowadays, the changes of past vegetation are denoted with more exactly defined dates and time intervals (Walker et al. 2018). A detailed review of the development of the Czech flora was recently given by Kuneš et Abraham (2017): while the glacial dominants gradually retreated (among the tree species e.g. *Pinus cembra* and *Larix*), the light-demanding tree species expanded (*Betula*, *Pinus*, *Corylus*, *Alnus*), subsequently followed by the shade-tolerant, climax species (*Acer*, *Fraxinus*, *Tilia*). Mixed oak woodlands (rather an assemblage of two spatially diversified vegetation units: oakwoods and noble hardwoods) and spruce forest formed a distinct altitudinal zonation in the Middle Holocene, the former restricted to lowlands and the latter characteristic for the middle and higher altitudes. The expanding area of woodlands created a bottleneck for open land habitats predominated by the late-glacial flora, such as the steppe and the alpine vegetation (Chytrý et al. 2012, Pokorný et al. 2015, Kuneš et al. 2015, Novák et al. 2019). Spanning into the last phase of the interglacial cycle, changing soil properties (the acidification) favoured among others further expansion of spruce. In the lowlands, a spread of hornbeam from the north-east was affected among other factors by human interventions in the oakwood, while in mid-altitudes the conifer-beech forests emerged.

1.2 The role of human impact in past vegetation change

1.2.1. The Anthropocene

The development of the Holocene vegetation was only briefly outlined above, neglecting one of its main forming forces: the strong influence of human. According to the current understanding, these effects have gradually increased and culminated during the Modern history. For the last 300-200 years, a concept of Anthropocene has been established. Lewis et Maslin (2015) postulated that a new geological epoch, called the Anthropocene Epoch, should be likely delimited by the years 1610 or 1964 AD. Soriano (2020) suggested it is likely going to be submitted for formalization by the Anthropocene Working Group (AWG) as a chronostratigraphic unit of the Geologic Time Scale and will be marked by the Great Acceleration beginning around 1950 AD. In contrast, Gibbard et al. (2022) proposed that defining the Anthropocene as an ongoing geological event would more closely reflect both historical and ongoing human–environment interactions. The temporal scale of anthropogenic global changes was summarized in detail by e.g. Ruddiman et al. (2015), Ellis et al. (2016), and Zalasiewicz et al. (2021).

1.2.2. The ancient origins of human impact: the use of fire and stone tools

Human societies began altering Earth already long time ago by using fire and stone tools (Ellis et al. 2016). The era was initiated by the findings of the earliest hominine stone tools (3.3. Ma) and the earliest fossils of the genus *Homo* (2.8 Ma). From the late Middle Pleistocene (~350–130 ka BP), the first anatomically modern *Homo sapiens* fossils were recovered in Africa (Harmand et al. 2015, Cohen et al. 2022, Vidal et al. 2022). Ecological drivers have been linked to the evolution of *Homo sapiens* and the emergence of the Middle Stone Age technology (for review see Faith et al. 2021, Gosling et al. 2022).

1.2.3. Migration of the modern human affected other hominids and the megafauna

The numerous pulses, timing, and routes of sapients expansions into Eurasia have been subject to a lively scientific debate. The dispersal of modern humans within Africa, and subsequently out of Africa were linked to climate changes (Rito et al. 2019, Beyer et al. 2021), and affected other hominids such as the Neanderthals in Europe, the megafauna, and naturally also the past vegetation. The earliest presence of modern humans in Europe was documented from Grotte Mandrin in France 56.8–51.7 ka BP (Slimak et al. 2022). A long-term coexistence of archaic and modern humans has been implied by agent-based models (Vahdati et al. 2022). The hypothesis that modern humans coexisted with Neanderthals in a geographically defined area was supported by archaeological data in case of Grotte Mandrin. Coeval hominids proved technological divergence, but no obvious cultural exchange in terms of technical traditions. In this case, the replacement of indigenous Neanderthal groups was a complex process during which both populations replaced each other rapidly or even abruptly, at least twice. Although Timmerman (2020) concluded that the decline of Neanderthal population was likely caused by a competitive exclusion by the sapients, Vahdati et al. (2022) argued that the Neanderthal extinction was driven by locally diverse causes such as environmental fluctuations, asymmetry in resource exploitation efficiency, and reproductive rates. The megafaunal extinctions (~50–12.5 ka BP) are in literature often linked to an increased human pressure (e.g. Dembitzer et al. 2022). Hunting and burning by the spreading humans was linked to two abrupt megafaunal extinction episodes in Australia and the Americas (Barnosky et al. 2004). On the contrary, a megafaunal decline has lately been linked solely to a climate change in North America (Stewart et al. 2021). Looking away from the causes and extent of their influence, as humans adapted to the use of more than a single hunting mode, human predation has had a significant impact on animal populations (Montgomery et al. 2022).

1.2.4. Effects of foraging on the landscape

According to the current understanding, foragers modulated the landscape composition by means of burning, indirect cascading effects of hunting, and plant manipulation (Nikulina et al. 2022). As an early example, foragers in the region of the Congo basin occupied and altered parts of the tropical rainforest biome by the use of naturally created patches (Boyette et al. 2022). A traditional scenario that humans inhabited rather non-forested biomes, completely avoiding the forests, had influenced many past recostructions. Yet, the role of forest environment in the human history seems to be underestimated (Scerri et al. 2022). Perhaps suprisingly, also in Europe, the more sedentary way of life of the prehistoric Fennoscandinavian foragers was positively correlated with the occurrence of widespread and diversified forests (Sjögren et Damm 2019). Therefore, woodlands have been a generally valuable resource for the forager populations (Wacnik et al. 2020), and burning was used as one of the important resource management modes (e.g. NE Bohemian Mesolithic, Pokorný et al. 2022). Forest burning frequently changed entire areas such as those of the today´s Andean grasslands that were being burnt and modified by human activity as early as by 12 ka BP (Bush et al. 2022).

1.2.5. The origins of agriculture and roots of urbanization

For a very long time, intended plant cultivation preceded the process of plant domestication and the onset of agriculture (Fuller et al. 2011, 2014). The domestication itself occurred across long periods of time, and in parallel cases (Allaby et al. 2022). As reviewed by Beneš (2018), during the Epipalaeolithic in the Near East (24–11 ka BP), still mainly wild forms of lentil, barley and wheat (for a complete list see e.g. Larson et al. 2014) with no domestication syndromes were cultivated. By the end of the Pre-Pottery Neolithic A (PPNA, ~12–10.8 ka BP), the first domestication syndromes emerged, yet their replacement by full domesticants occured no earlier than during the PPNB (~10.8–8.5 ka BP). According to Allaby et al. (2022), there were biogeographical zones in Western Asia under low-level exploitation and management, hosting wild barley and wheat populations bearing alleles with no or low levels of domestication trends during 25–20 ka BP. During the pre-domestication cultivation period in 12.5–9.5 ka BP, the proportion of wild populations with no domestication traits was gradually decreasing. Fully domesticated populations again prevailed at 9.4–8 ka BP. All these phases were connected to the implementation of sophisticated tools for plant processing and the existence of a settlement network. The economy based on the cultivation of wild plants with the absence of pottery and ground stone axes facilitated the progress of urbanization. Jericho (Tell es-Sultan), an ancient city with a circular-based architecture, was already well established during the PPNA. The evidence of domesticated plants and animals corresponded with the transition to a rectangular architecture in the PPNB (Mithen 2020).

Along with the livestock domestication after 9 ka BP (Larson et Fuller 2014), the spread of farming affected the local land use, yet the change has often been connected with human malnutrition, and spread of disease (Wolfe et al.2007). Gradually, it has resulted in increased forest clearence (Marquer et al. 2014; Fyfe et al. 2015), soil erosion affecting alluvial floodplains (Hoevers et al. 2022), and the emmission of carbon dioxide and methane (Ruddiman et al. 2015).

1.2.6. The spread of agriculture

One of the major migrations during the European Holocene is considered as the Neolithic farmer expansion during which, for the first time, the major building blocks of the Neolithic diet became uniform across large regions of Europe (Racimo et al. 2020). Although immigration definitely played a role in the spread of know-how along with cultivated plants and animals, the indigenous populations remained. How exactly the earliest introduction of agriculture to CE took place and how the Mesolithics adapted is a subject of debate (Ptáková et al. 2021, Sikk et al. 2022, Jacomet et Vandorpe 2022, Smyth et Gillis 2022). Already the Mesolithics arguably impacted the forests in Europe (Kuneš et al. 2008, Divišová et Šída 2015), and could have supported the spread of particular tree species such as *Corylus* (Kuneš et Abraham 2017). However, a pre-Neolithic agriculture has not been sufficiently supported by the data (Jacomet et Vandorpe 2022).

1.2.7. Early effects of land-use on vegetation in the Neolithic

The early effects of land-use on vegetation via farming and forest clearance in CE were identified only in the Neolithic (7–6.5 ka BP)

(Marquer et al. 2017). An archaeological culture connected with the spread of agriculture in CE lowlands since ~7.5 ka BP is called the Linnear Pottery culture (Linearbandkeramik, LBK). Open flat settlements with solitary long-houses reflected the distribution of fruitful soils called chernozem below 400 m a.s.l. (Dreslerová 2012, Poschlod 2015, Kreuz et Marinova 2017). This trend resulted in differential progress of vegetation development in lowlands versus highlands, at least within the Czech territory (Chytrý 2012). Although the settlement behaviour varied over time, the landscape occupation has retained similar general characteristics since 6.6 ka BP until now (Demján et al. 2022).

Both the density of settlement and the intra-site spatial pattern of the settlement site affected the species composition of the cultural landscape (Mercuri et al. 2010, Novák et al. 2021). It seems that the Neolithic populations further expanded the patches of non-forested areas (e.g. Kuneš et al. 2015). This mechanism prevented the tree cover from reaching its theoretical maximum. Later, the scattered settlements, based on small housing units with nearby areas for growing crops and grazing, increased the forest fragmentation while the high connectivity of forests was still preserved. The inhabited areas themselves consisted of man-made habitats divided into arable land with weed vegetation, and settlements and their surroundings with ruderal vegetation (Lososová et al. 2006). The seeds of the weeds naturally spread along with the cultivated domesticants. LBK farmers however likely did not grow all the original crops of the Balkan area and southwest Asia. Kreuz et Marinova (2017) identified a lower crop diversity in the earliest phase of LBK (five crop species) on the contrary to the Bulgarian Neolithic (ten crop species), and favouring legumes (mostly pea) in the later phase of LBK. In the Czech territory, the list of cultivated crops (Dreslerová et Kočár 2013) and particularly the list of non-native plant species – archaeophytes (Pokorná et al. 2018) revealed the newly established Neolithic anthropogenic habitats (7.6–6.2 ka BP) containing the weeds of crop fields and of contemporary fallow land, annual species of trampled and dunged bare soils and perennial species of mesic ruderal grasslands. The shift in landscape structure followed the settlement pattern, placing a long house into its centre, which resulted in the zonation of the enclave based on nutrients and light input. Preferred tree species (e.g. oaks) were also selected by the humans in close vicinity (Kuneš et al. 2015). The grazing and other forest management types contributed to the formation of open woodlands in the settlement surroundings (Kreuz 2008, Novák et al. 2018). Furthermore, the spread of *Fagus* and *Carpinus* was affected by humans in general in the Czech lowlands (Novák et al. 2021).

1.2.8. Human impact as a major driver of the prehistoric vegetation change

The palynological reconstruction based on modern analogs and remote sensing demonstrated that the tree ratio was decreasing rather continuously towards the present-day values in CE following its maximum that reached ≥ 80 % at 8.5–6 ka BP (Zanon et al. 2018). The land-use likely became a major driver of the vegetation composition around 4.5–4 ka BP (Marquer et al. 2017). It corresponded to a peak in human density during the Bronze Age. In addition, the westward migration of the Yamnaya culture peoples to Europe since 4.5 ka BP altered the genetic structure of the local population (Haak et al. 2015) and led to significant changes in the composition of pasture/natural grasslands and broadleaved forest cover. The reduction in the range of broadleaved forest and the increase in the amount of pasture and natural grasslands were much more significant when compared to the rather weak changes in the vegetational landscape reconstructed in association with the Neolithic migration (Racimo et al. 2020). By the onset of the Iron Age, humans caused further changes in the plant cover, altering the ratios among native species and supporting the spread of plants of economic interest even outside of their natural habitats (Sadori et al. 2010). Furthermore, rapid shifts in the rates of vegetation compositional change between 4.6 and 2.9 ka BP suggest that the human impact has gradually exceeded the effects of climatic factors connected to the last deglaciation (Mottl et al. 2021a). Yet, the transformation of society in the Middle Ages affected both the natural and the cultural landscape, and represented a distinct ending to the prehistoric landscape patterns in the Czech territory (see Chapter 1.5 for details).

1.3. Resources and techniques used in palaeoecological reconstruction

Past vegetation, climate development and past human activities can be reconstructed based on data sets originating from investigations in the fields of geology, sedimentology, geochronology, geochemistry, soil science, palaeoecology, palaeoethnobotany, and archaeology. Selection of a particular abiotic or biotic fossil record is based on the particular scientific questions (Battarbee 2000; Birks et Birks 2006).

The records of past nature dynamics are preserved in two basic types of terrestrial environments. The first group is characterized as wet, usually acidic sediments with a high content of organic matter. Avoiding the oxidation, plant micro- and macrofossil such as pollen grains and seeds are usually very well preserved. These types of sediments are frequently deposited in peats, lakes and alluvia (Gębica et al. 2020, Svitavská Svobodová et Janský 2021). On the other hand, the environment rich in carbonates preserves the malacofaunal fossils and bones of vertebrates. The selection of the research site influences above all the spatial scale of the past reconstruction. Local species diversity is usually recorded by the spectra of macro fossils (seeds, malacofauna remains), or both by macro and micro fossils in a patchy landscape. Spectra of micro-particles such as pollen, microcharcoals, or spheroidal carbonaceous particles (SCP), deposited in sediments of large and open basins and plateaus, reflect rather regional trends. To cover both regional and local diversity information, a combination of data from a large open basin with a series of small basins has been suggested (e.g. Sugita 2007, Hellman et al. 2009).

The past climate in the region of CE has been reconstructed mainly based on loess-paleosol, cave speleotems and glacial sequences (Boch et al. 2009). Particular fluctuations may be reconstructed using temporal changes in treeline maxima and hydrological dynamics (Haas et al. 1998, Hormes et al. 2001, Magny 2004, Tinner et al. 1996). Further, climate reconstructions can be based on the above-mentioned biotic spectra, comparing modern analogues and fossil spectra of pollen (Houfková et al. 2017, Zanon et al. 2018, Chevalier et al. 2020), chironomids (Heiri et al. 2014, Kubovčík et al. 2021), and plant macrofossils (Väliranta et al. 2015). Such comparison of fossil biotic spectra and their modern analogues may of course serve for reconstruction of almost any past ecological factor. Species composition of diatom and cladoceran remnants reflects e.g. the amount of salt content in freshwaters, the speed of a water flow, or water pollution (e.g. Smol et al. 2001).

In addition to the sedimentary records, analysis of tree rings respresents a useful method for reconstruction of the past precipitation and temperature variability (Büntgen et al. 2011a, b). Moreover, the uniqueness of subsequent tree ring thickness changes allowed the creation of a dendrochronological sequence by comparing tree rings of both living and dead trees of overlapping ages. Such library extends back over the last 14,000 years. The dead wood of each such tree ring has recorded the corresponding atmospheric radiocarbon (^{14}C) concentration of a particular year. By combining the dendrochronological sequence with other sequences of known age from the varved sediments of Suigetsu lake, Japan and speleothems from Hulu Cave, China, the curve of the past 50 ka years atmospheric ^{14}C content was created (Bronk Ramsey et al. 2020). This provided a basis for an objective dating for fossil samples of an unknown age. Knowing that plants fix the atmospheric ^{14}C into their tissues and that this content starts to decline when the plant dies at a rate determined by the law of radioactive decay, the remaining ^{14}C content in a sample can be measured by accelerator mass spectrometry (AMS) and used to calculate its approximate age.

There are other methods available for dating of fossil samples of an unknown age, e.g. luminescence dating (OSL) for mainly geological sediments. Sequences of decreasing concentrations of the fast-decaying ^{210}Pb radioisotope (22.6 yrs) may be used for a dating of ~100 yrs old undisturbed sediments (Swarzenski 2014, Barsanti et al. 2020). Such chronology should be confirmed using at least one independent tracer, e.g. peaks of ^{137}Cs corresponding to atomic bomb testing in AD 1963–1964 and Chernobyl accident in AD 1986 (Schirone et al. 2022). A stratigraphical sequence of increasing levels in SCP concentrations has been deposited in undisturbed sediments as the result of fallout of byproducts of industrial fossil-fuel combustion (Rose 2015). There are other chronomarkers, such as tephra layers (Lowe 2011), summarized in databases as Tephrabase, VOLCORE or RESET (Bronk Ramsey et al. 2015, Newton et al. 2007, Mahony et al. 2020).

The past development of certain lakes or peat bogs was only moderately or indirectly influenced by humans. Sediments in such habitats were formed predominantly by past natural processes. However, there is a rather smooth gradient between such localities and those that were entirely created by past human activities. Artificial water reservoirs and ponds are usually assessed the same way as archaeological features such as middens or cesspits containing palaeofeces. In such archives, dating of archaeological material, or the use of written records may help with interpretation of the revealed taphonomical processes. Moreover, predominantly archaeological contexts provide numerous specific conditions affecting the preservation of fossils. Phytoliths, starch grains and plant charred fossils are usually preserved even under dry heat. Pollen grains are preserved directly on deposited metal surfaces as they are protected by the metal corrosion products.

1.4. Pollen analysis as a tool for palaeoreconstruction

Pollen analysis provides a powerful tool to address both palaeoecological and archaeological scientific issues. Pollen spectra found in chronologically stratified sediments reflect the past pollen rain corresponding to the particular chronozones. Varved lacustrine sediments provide the best resolution palaeo-archives (Bronk Ramsey et al. 2012). The occurrence of varved sediments is reported worldwide (Ojala et al. 2012, Zolitschka et al. 2015), some of them are located in CE (Tylmann et al. 2013, Ott et al. 2017, Bonk et al. 2021). Each varve corresponds to an annual cycle of deposition in a still deep water body, reflecting a fine seasonal cycle of the lake. Layers summarizing the pollen sedimentation originating from a longer time scale are available in sediments such as those of some shallow lakes exhibiting low sedimentation rates (Willemse 2002, Gąsiorowski 2008). If the differences resulting from the diverse time resolution are accentuated in plotting a well-defined depth-age model, both types of archives may provide the record of past vegetation development, its dynamics, and changes in vegetation cover for a given geographical region (Houfková et al. 2017). Moreover, past human activities and population densities, dynamics of settlement areas, changes in past economies and management types may be reflected in the pollen record. In archaeological research, the results of pollen analysis may specify the history of archaeological features, location of activity areas in a settlement area, composition of the past diet, routes of past trade and import, etc. (Jankovská 1985, Revelles et al. 2017, Šálková et al. 2019, Kozáková et al. 2021).

The outer wall of pollen grains (exine) is composed of the highly resistant biopolymer called sporopollenin. It protects the grain both from physical and chemical deterioration (Armstrong et Brasier 2005). Thanks to this, (1) pollen grains are extremely stable as microfossils in past organic sediments such as peat or gyttja, and (2) pollen can be separated from sediment samples via chemical treatment. Using the acetolysis method and subsequent incubation in hydrofluoric acid, both organic and silicate material in the sediment sample are decomposed (Erdtman 1960, Berglund et Ralska-Jasiewiczova 1986). There are also other methods such as the heavy liquid separation suitable for loess samples with a low pollen content (Munsterman et Kerstholt 1996, Caffrey et Horn 2013). The separated pollen grains and spores may be routinely identified using 200-1000 × magnification of the light microscopy. Particular plant species (e.g. *Centaurea cyanus, Plantago lanceolata*) might be directly identified according to the morphological traits of their pollen grains, while others may exhibit overlapping features, leading to a less precise taxonomic classification into so-called pollen types as summarized by Punt (1976), Punt et Clarke (1980, 1981, 1984), Punt et Blackmore (1991), Punt et al. (1988, 1995, 2003, 2009), Beug (2004), Hesse et al. (2009), and PalDat (2000). Some plant families (e.g. Chenopodiaceae) lack specific traits for species determination, thus their identification is limited solely to the family level. In chemically treated samples, numerous non-pollen particles are preserved. Cell walls of green coccal algae of the genera *Pediastrum*, *Botryococcus*, and *Scenedesmus* are frequently preserved in lentic sediments (Komárek et Jankovská 2001). Conifer stomata may be recovered if a corresponding tree was locally present (Hansen 1995, Sweeney 2004). Concentrations of microcharcoals reflect the regional fire fallout (Tolonen 1986, Umbanhowar et McGrath 1998). Moreover, fungal ascospores, rotifer resting eggs and other plant and animal remains may be determined based on the scientific literature concerning non-pollen palynomorphs (NPPs), (van Geel 2001, Marret et al. 2021).

By counting a minimal pollen sum of at least 500 (without the dominant taxon), the results may be expressed as relative abundances of the individual pollen taxa. Using e.g. Tilia software (Grimm 2011), pollen diagrams usually display relative abundances of selected pollen taxa plotted against a core depth/age based on the depth-age model. Using the pollen relative abundances of the individual plant species brings up the problems connected to different production and dispersal patterns of the pollen among plant species. Numerous pollen grains originating from a few newly grown and mature pines located in a proximity to the future coring site may lead to overestimation of the pine abundance in its vicinity, and on the other hand underestimation of the area covered by low pollen producers. Such issue may be partly overcome by estimating pollen influx. The pollen influx (grains cm^{-2} $year^{-1}$) may be inferred by determining the total pollen count of each pollen taxa using a lycopodium tablet possessing a given count of *Lycopodium* spores, by taking a known volume of a sample (1 cm^3), and by estimating the sedimentation rate (Berglund et Ralska-Jasiewiczova 1986, Hicks et Hyvärinen 1999). Among the numerical methods used in palynology (Birks 2012, Pardoe et al. 2021), multivariate analysis identifies the groups of samples with a similar pollen-assemblage composition. Having a set of chronologically subsequent samples, significant pollen assemblage zones may be clustered using a CONNISS cluster analysis with a fixed position of samples. Moreover, to express the pollen-assemblage diversity some authors use various biodiversity indices such as the Shannon's, Simpson's, and α-index. Changes in the pollen richness across time may be expressed using a rarefaction analysis (Birks et Line 1992). The rate of compositional change may be quantified using R-Ratepol (Mottl et al. 2021b). Yet, whether the pollen-assemblage richness reflects the floristic richness represents a challenging question. The changes in the pollen assemblage richness would reflect the actual species richness assuming the equal and constant pollen production across all plant species. Assuming numerous limitations to the equal representation of plant communities in the pollen spectra as listed below, a problematic relationship between the pollen and floristic richness was reported by Goring et al. (2013): 1) The regional pollen rain is predominantly composed of the pollen that is dispersed by wind. E.g., most of the species of *Acer* are entomophilous and tend to be underestimated in the pollen record. 2) Pollen production and dispersal differs among species. Conifers usually produce many bisaccate pollen grains that easily disperse by wind. 3) However, even the pollen grains of each conifer species differ in size, the smaller pine grains tend to disperse further. 4) Grains of some species such as *Acer* and *Fraxinus* are fragile and do not preserve well. Nevertheless, in their recent review, Birks et al. (2016) still claimed that modern pollen richness reflects both the modern vegetation richness and the landscape structure.

To overcome some of these difficulties, quantitative land-cover reconstruction has been recently introduced, bypassing the issues concerning pollen productivity, taphonomy, pollen dispersal, and atmospheric conditions (Prentice 1985, Sugita 2007, Githumbi et al. 2022). Landscape Reconstruction Algorithm (LRA) combines LOVE estimates and REVEALS models that are based on exact data originating from the modern pollen samples referenced to the surrounding vegetation via pollen productivity estimates (PPEs) or relative pollen productivity estimates (RPPs) (Kuneš et al. 2019, Theuerkauf et Couwenberg 2021). Moreover, REVEALS estimates of vegetation cover were used for evaluation of the past biodiversity, anthropogenic land-cover change, past land cover-climate interactions and for climate modelling (e.g. Trondman et al. 2015).

Grouping the pollen assemblages throughout Europe (Huntley et Birks 1983) created so called “isopollen” maps. These reflected the species migration and allowed biome reconstruction for past spatial intervals. Nowadays, the data on fossil pollen and geochronology are collected in the Czech Quaternary Palynological Database (PALYCZ, Kuneš et al. 2009), and the Eurasian Modern Pollen Database (Davis et al. 2020). Pollen data grouped with complementary data on vertebrates, diatoms, ostracodes, macroinvertebrates, plant macrofossils, insects, and testate amoebae are accessed in the Neotoma database (Goring et al. 2015, Williams et al. 2018). Moreover, the pollen accumulation rates (PARs) have been gathered in the Pollen Monitoring Programme Database (Abraham et al. 2021).

1.5. Reshaping of the cultural landscape in the Middle Ages

1.5.1. Woodland clearance and maintenance

Medieval transformation (Klápště 2012) sets a new frame to the landscape and vegetation that had developed in the prehistoric times. The closest match between the pollen-reconstructed vegetation and the potential natural vegetation in the Czech lands (CL) was recorded for the period AD 500–1000 (Abraham et al. 2016), which immediately predated this change. In this era, different development was recorded in Czech lowlands versus highlands and mountains, still reflecting the status quo set during the Neolithic period.

A significant woodland ratio decline was documented in the lowlands corresponding to the central parts of the CL and their traditional settlement area (Kozáková et al. 2009, Novák et al. 2012, Kozáková et al. 2014, Pokorná et al. 2014, for review see Kuneš et Abraham 2017). This trend was later copied in the highlands and mountains corresponding to marginal parts of the CL (Hrubý et al. 2014, Kozáková et al. 2015, Roleček et al. 2020) that were influenced by large-scale colonization as late as in the High Medieval (mainly in the 13–14th centuries AD; Klápště 2016). The medieval deforestation in the cultural landscape may be indicated by the decrease in the relative abundance of arboreal (AP) and increase in non-arboreal (NAP) pollen. In majority of the above cited studies, this ratio has served as the most straightfoward indicator of the human impact recorded in past pollen spectra. The relationship can be validated only by coupling with independent complementary pieces of evidence such as the archaeological record of settlement areas, and/or written sources (Mercuri et al. 2015, Brázdil et al. 2021). The medieval deforestation significantly affected erosion and alluvial deposition, which resulted in alteration of some alluvial habitats (Chytrý 2017). An increasing frequency of flooding in the CL recorded since the 14th century AD has been linked to both the archaeological and the palaeoecological record in the alluvium of the river Dyje (Petřík et al. 2019). Similarly, half of the sediments in the lower floodplain of Ohře River were identified as younger than 1 ka years, in particular those spanning the last five centuries (Elznicová et al. 2021). A continuous fluvial aggregation corresponding to a long-lasting increase in human impact with delayed response in lower valleys compared to hillslopes was identified in the European loess belt (Verstraeten et al. 2017). On the contrary, analysis of the pollen record in peaty deposits at the edge of the Morava River floodplain excluded similar trends in this region (Matys Grygar et al. 2011).

In addition to simple forest clearance, the trees and forests were subjected to other specific types of management. Whereas selective tree cutting for firewood may be implied from combined results of e.g. charcoal analysis and quantitative pollen reconstruction (Novák et al. 2016), the extent of particular woodland managements such as coppicing, popular in the Late Middle Ages, was evidenced solely by written records (Szabó 2010, Szabó et al. 2015).

Apart from the borderline of CL, forests were not extensive and were economically used by their owners. The forests by Zbečno and Křivoklát (Central Bohemia) possessed the status of a royal hunting ground and were under protection since the 14th centrury AD (Klimek 2014). As another example, the medieval authorities promoted open lowland oakwoods in Hodonínská Dúbrava (South Moravia) by banning their cutting (Jamrichová et al. 2013).

1.5.2. Medieval agriculture

Quantification of human indicators in past pollen spectra using an indicator-species approach (Behre 1981) reflected a remarkable extension of arable land during the Medieval times. The pollen of cultivated plants (crops, *Fagopyrum aesculentum*, *Linum usitatissimum*, *Cannabis sativa*) and their weeds (e.g. *Centaurea cyanus*, *Agrostemma githago*) significantly increased in abundance. The highest increase in abundance was generally recorded in the pollen of *Secale cereale* and *C. cyanus* during the Highly Medieval period (Jankovská 1997). Eventhough *S. cereale* exhibits higher dispersion abilities than other crop species, REVEALS identified a similar trend by reconstructing a significant increase in the proportion of cerealia, particularly in the Elbe River lowland and the NE Bohemia (Abraham et al. 2016). The increasing area of arable fields was naturally followed by the invention and spread of improved agricultural techniques. Most important of them was the three-field rotation system, established already in the early Middle Ages, with the spring cereals (*Triticum*), the winter cereals (*Avena*, *Hordeum*, and *Secale*), and the fallow in three subsequent seasons. This consequently led to a complete differentiation of the fields versus grasslands (Poschlod 2015, Chytrý 2017). Moreover, implementation of the heavy plow further increased the effectiveness of the agricultural production and stimulated economic development. Based on Andersen et al. (2016), it accounted for more than 15 % of the total increase in urbanization (averaged across Europe), leading to colonization of marginal areas by medieval farmers

(Klír 2009, Fanta et al. 2020, Costello 2021). In the CL, High Medieval villages harboured their own long-strip field system called pluzina since the 13th century AD. According to Poschlod (2015), only a relatively few new cultivated species were introduced in CE: *Fagopyrum aesculentum*, *Vigna unguiculata*, *Rumex acetosa*, *Tragopogon porrifolius*, *Pastinaca sativa*, *Brassica oleracea*, *Daucus carota* ssp. *sativus*, *Spinacia oleracea*, and *Cichorium endivia. Vitis vinifera* has been classified as an archeophyte cultivated since the medieval period in CL (Pyšek et al. 2012). The older finds of above-mentioned species from the Iron Age have been rather classified as imports (Šálková et al. 2015, Šálková et al. 2019).

Using the pollen-based indicator species, an array of man-made habitats comprising dry pastures, wet meadows and pastures, grazed forests, and fallow land (for a complete list of pollen types see Behre 1981 and Gaillard 2013) were distinguished throughout the Middle Ages. The records of *Plantago lanceolata* pollen are frequently used as a prominent indicator of animal breeding as a species typical for fallow phases and grazed areas rather than crop cultures (Rösch 2013, Tserendorj et al. 2021). As reconstructed by Pokorná et al. (2018), pastural species avoided by grazing animals, species of wet forests and alluvial meadows were recorded by macro-fossils analysis only as late as in the Early Medieval period (Pokorná et al. 2018). Other habitats under human management were pastures and mown meadows. The area of man-made grasslands and fallows expanded along with the ongoing colonization and forest clearing, including the mid-altitude areas. This process of implementation of the extensive agricultural management has however continued up to the Modern Period (Chytrý 2017). As Hejcman et al. (2013a) reviewed, the occurrence of mown meadows was connected to the medieval spread of the use of a new tool – the long scythe. In the CL, the oldest archaeological finds originated from the turn of the 13th and 14th centuries AD. Moreover, medieval hay meadows were reconstructed based on plant macro fossils analysis originating from medieval towns (e.g. Čulíková 1993). Another example of human management of grasslands is represented by grazing and burning as recorded in the species-rich grasslands in Bílé Karpaty Mts. during the Late Middle Ages (Hájková et al. 2018). Moreover, a generally high diversity of semi-natural grassland types in the cultural landscape in the Middle Ages was reported (Hejcman et al. 2013a). A rather fine structure of non-forested areas composed of natural xerophilous grasslands has been reconstructed in the lowland areas of the CL by means of both pollen and macro remnant analysis during the Early Medieval period (Opravil 1969; Kozáková et Pokorný 2007; Pokorná et al. 2014).

1.5.3. Urban areas

Plant assemblages composed of nitrophilous ruderal species growing on human-made substrata were reconstructed based on the first occurrences of plant macro fossils of the the alien/native species in the Early Middle Ages (AD 580–1200), (Pokorná et al. 2018). The Early Medival Prague incorporated a mosaic of habitats composed of sunlit disturbed patches, revealing young nutrient-rich substrates such as landfills, hosting a vegetation composed mainly of annual plants. On the less disturbed substrates as walls, ruins, or moist and fertile substrates, the ruderal vegetation became denser, and biennial and perennial plants frequently prevailed (Jankovská 2005, Kozáková et al. 2009, Chytrý 2017). During the Higly Medieval urbanization, the number of man-made habitats increased, comprising rural urban synanthropic species on footpaths, ruderal communities on vegetable garden beds, and ornamental species (Święta-Musznicka et al. 2013, Święta-Musznicka et al. 2021). Yet, it seems that the habitats of the High Medieval Prague became more uniform (Kozáková a kol. 2009), and villages often served as local eutrophication centres in the High Middle Ages (Pokorná et al 2014). The elevated nutrient availability has remained the characteristic trait of intravilan plant communities until today as reflected by their species composition (Hejcman et al. 2013b). In addition, the archaeobotanical analyses of urban waste deposits revealed imported plant species (e.g. *Myrtus communis*; *Pimpinella anisum*, *Helleborus viridis*), documenting the long-distance trade (Jankovská 2005, Beneš et al. 2002).

1.6. Aims of the thesis

A general aim of the thesis was to obtain pollen data sets from fossil records to access the continuous memory of the Czech landscape since the pre-historic times, as it was gradually transformed by the combination of climate events and human impact. The fine-scaled and in-detail studies of past vegetation change at selected natural and man-made sites in Czech Republic should provide more precise insights into particular processes forming the Central European vegetation. A rather long time-span of the studies, ranging from the Late Glacial to Late Medieval periods, was selected to track the origins of the human endeavour in this area. Finally, the focus of the thesis lies in obtaining a better picture of the cultural landscape formation during the High Medieval colonization, comparing three village sites across an altitudinal gradient, including the central and the marginal parts of the colonized areas of the Czech Lands.

2. Results

2.1. The most importatnt outcomes of the thesis

The thesis comprises five studies on various aspects of reconstruction of the past human impact recorded in fossil pollen spectra. The first study was dealing with the period of the Late-glacial/Holocene transition in the Central European shallow lake Komořany, demonstrating the dominance of natural processess both in the surrounding vegetation and in the aquatic ecosystem response (Paper I). This topic was further elaborated in the study originating from the same locality, dealing with a sedimentary record of the Holocene dated to interval 11.2–3.2 ka BP. This period was already influenced by human activity, and a pollen-based climate reconstruction together with changes in hydrology revealed both the natural and combined (natural and human) forces affecting the lake development and the surrounding vegetation (Paper II).

In the following studies, major human impact on the landscape development and vegetation cover were identified in the fossil and archaeological record of three medieval villages:

(i) Rybník, originating from the traditional lowland residential area of the CL, i.e. the suburbs of the early medieval Prague, revealing the early history of fishpond farming in the CL (Paper III).

(ii) Landscape transformation of an entire medieval agrarian system of the village Malonín in a highland area of the CL, resulting from the High Medieval colonization (Paper IV).

(iii) Reconstruction of the High Medieval colonization in the mountain area of the Krušné Mts., exploring the concept of short-lived medieval villages, along with the rapid succession of vegetation after the village abandonment (Paper V).

2.2. Paper I. Nutrient availability affected shallow-lake ecosystem response along the Late-glacial/Holocene transition

The Last Deglaciation was partially recorded in the sedimentary record of a former Central European shallow lake Komořany. The selected depth interval covered the period ~15.6–10.8 ka BP to reflect the Late-glacial/Holocene transition. The aquatic conditions were rather uniform, with high nutrient availibility since the lake origin. The shift in aquatic environment was inferred from the decrease in relative abundance of nutrient-demanding species in diatom and chironomid assemblages, dated close to the end of the Late Glacial. It was followed by an increase in concentration of all recorded micro-fossils and by changes in sedimentation processes. In our interpretation, the main driver of the observed shift was the onset of more favourable climate in the Holocene, which supported the increased primary productivity in the lake. Biomass of the primary producers subsequently served as a sink for nutrients, causing the trophic status of the lake to drop.

Results of pollen analysis reflected rather gradual processes in the past plant species composition without any significant events recorded in pollen ratios until ~11 ka BP. A relatively stable ecosystem with gradual changes in aquatic and terrestrial communities was reconstructed. A pollen ratio ~70 % of trees and shrubs (*Pinus sylvestris* type and *Betula*), scattered presence of the *Pinus cembra* pollen type, and relatively high amount of Poaceae, *Artemisia*, *Helianthemum*, *Potentilla*, *Juniperus*, *Salix*, *Betula nana*, and *Alnus viridis*-type may point to a relatively stable occurrence of patchy vegetation in NW Bohemia, with elements of steppe-tundra, shrub-tundra, and hemiboreal forests during the major part of the Last Deglaciation (untill ~11 ka BP). The glacial elements slowly retreated during this period. In pollen spectra, the significant change is reflected by a rapid onset of *Corylus* slightly before 11 ka BP. This is in agreement with the exponential spread of *Corylus* across Europe, which peaked just at around 11.2/11.1 ka BP (Giesecke et al. 2017). The spread of thermophilous tree taxa (*Quercus*, *Tilia* and *Fraxinus*) at the site might be facilitated by a warmer but also more humid phase after the 11.2 ka BP event as previously reconstructed over northern Central Europe (Theuerkauf et al. 2014). Migration of tree species in the Early Holocene was most likely controlled by rather natural causes (Paper I, II) driven by the ongoing climate and soil change and manifesting through other natural prosesses such as the tree species migration lags, the long-distance dispersal probabilities of their seeds, and population growth rates (Clark et al. 1998, Powell et Zimmermann 2004, Giesecke et al. 2017).

2.3. Paper II. Holocene climatic events linked to environmental changes at Lake Komořany Basin, Czech Republic

The study originated from the same locality as in Paper I, the former Central European shallow lake Komořany. It was concerned with a sedimentary record mapping the Early to Late Holocene, corresponding to the time period of 11.2–3.2 ka BP. The onset of sedimentation at the site location of the profile under study started at around 11.2 ka BP. The fluctuation in water depth significantly affected the surface area of the shallow lake, reflecting the short-term climatic events in the Early

Holocene. Palaeopalynological analysis of the profile allowed us to reconstruct the past pollen assemblages and infer a pollen-based climate model according to Nakagawa et al. (2002). A biomization approach employed in the study, grouping the pollen types into general plant functional types (pft), was based on the assumption that the biomes represented climate-induced physiognomic vegetation classes. Relatively dry conditions and stable mean annual temperatures were reconstructed between 9.1 and 6.5 ka BP. Thereafter, warm and wet climate corresponding to the largest lake area was reconstructed in the interval 6.3–4.8 ka BP. This period was followed by a decrease in the mean annual temperature around 4.8/4.7 ka BP, and a corresponding reduction in the lake surface area. Eventhough Paper II focused primarily on the climate forcing, particular changes in hydrology and pollen spectra were, in contrast to the results of Paper I, likely driven both by the climate changes and the human impact. Expansion of grasslands in the area since 5.5 ka BP occurred despite the ongoing humid and warm climate, thus being probably linked to human activity. On the other hand, the increasing trophic status of the lake since 3.5 ka BP was more likely a result of the reduction of the lake area rather than human-caused eutrophication. Generally, we have assumed a complex combined effect of the climate changes and human activities on the past vegetation development as recorded elswhere (Dearing 2006, Dearing et al. 2006, Gaillard et al. 2010). The connection with archaeological investigation and evidence of past human activity (as recorded e.g. by charcoal and microcharcoal analysis) in the region of NW Bohemia has been part of the research in progress and is planned to be published separately.

Demographic estimates (Kozáková et al. 2014), human activity models (Kuneš et al. 2015), and spatio-temporal modelling (Kolář et al. 2016) have been frequently linked to climate reconstructions in other Czech regions. The biomization approach utilized in our study reflects rather the climate-induced changes, however pollen types may be also grouped based on the anthropogenic land cover classes (Fyfe et al. 2015). This approach may be useful for the following research focused on tracking the human impact in the region. Knowing that biomization and pseudobiomization provide only rough estimates of the anthropogenic impact on European biomes (Trondman et al. 2015), a more precise quantification of the past landscape changes using REVEALS reconstructions should be included in the future study.

2.4. Paper III. The oldest Czech fishpond discovered? An interdisciplinary approach to reconstruction of local vegetation in mediaeval Prague suburbs

Major human impact on the landscape and vegetation cover was identified based on archaeobotanical analyses performed along with the archaeological excavation of the Medieval village Rybník. Rybník was firstly recorded in AD 993 in a written record and was located in the traditional lowland residential area of the CL, in the suburbs of the Early Medieval Prague. The area of the village was later transformed as a part of the newly established New Town of Prague after AD 1348. Although performed in a cellar of the house V Tůních no. 1625/II, the rescue archaeological excavation included nowadays recommended field techniques such as profiling and trenching (Rick et al. 2022). Wet sediments of a former water reservoir dated from the 10th to the middle of the 14th century AD were discovered, possessing fossil remains of several species of freshwater fishes. A change from oligotrophic to hypertrophic aquatic conditions corresponded to the change of plant communities in the surrounding area. An original mosaic of habitats exhibiting semi-natural character later became more uniform following the intensification of human pressure, supporting the extension of tramped and ruderal areas. The ratio of arboreal pollen remained rather high (~25 %) in comparison to the record from village Spindelbach located in the marginal areas of the CL, where it dropped to ~11% under the human exploatation (Paper V). However, *Pinus* as a massive pollen producer was likely more abundant in the centre of the CL, and its contribution to the past pollen assemblage in this area could be positively biased although the tree cover distribution might have been rather scattered. This said, the clearance pressure to forests, eventhough recorded also in the case of the upper colline belt in South Bohemia (Paper IV), still seemed to be the most severe in case of the industrial exploatation by mining and glassworking in the marginal areas of the Krušné Mts. (Paper V).

2.5. Paper IV. Origin and development of long-strip field patterns: A case study of an abandoned medieval village in the Czech Republic

Landscape transformation of an entire medieval agrarian system of the former village Malonín in a mid-altitudinal area of the CL was dated to the period between the second half of the 12th century and the first half of the 13th century AD. Our results predated the first written records of the village existence (AD 1349) and the interval of the Highly Medieval colonization (13–14th centuries AD). Conifer-beech forests of the upper colline belt were transformed via the slash-and-burn management into an agrarian system called pluzina. The findings of plant macrofossils of charred fir needles pointed to mixed forest stands with fir, or even forests where fir dominated, prior to the deforestation. This is consistant with the general trend of fir decline recorded in pollen spectra during the High Medieval times in the CL (Kozáková et al. 2011). Fir belonged to one of the four tree species most intensively utilized for historical constructions based on their availability in the CL until 18th century AD (Kolář et al. 2021). The deforestation resulted in subsequent alluvial transformation below the village´s hillslope, reflecting an increased soil errosion. A charred fragment of a *Hordeum* caryopsis suggested that part of the area of this pluzina served for crop cultivation. These results were based on undisturbed soil profiles and were properly dated. The existence of fields was further supported by the soil samples taken in the area of the former field, where the pollen of *Secale cereale* was the most abundant one. This would be consistent with the archaeobotanical reconstruction by Rösch (2013) identifying *S. cereale* and *Avena sativa* as the main crops cultivated on the poorest and most acidic soils in the High Medieval period. *Linum* was another species processed in the village, *Secale* and *Linum* were probably locally cultivated and utilized, but these finds lacked proper age determination as the revealed stratigraphy of soil profiles underwent numerous taphonomical processes. To specify the list of cultivated crops and past patterns of the open land (fields, pastures, meadows, field boundaries), further research should be focused on chronologically stratified alluvial deposits, where the preserved pollen was recorded (Šitnerová et al., in prep.). The studied pluzina in Malonín was chosen as a typical medieval village system and an ongoing research has depicted similar landscape patterns that have developed across the whole area of modern Czech Rebublic (e.g. Šitnerová et al. 2020, Fanta et al. 2020).

2.6. Paper V. The dynamics of a non-forested stand in the Krušné Mts.: the effect of a short-lived medieval village on the local environment

The spread of the High Medieval colonization as recorded in the previous contribution (Paper IV) further affected the marginal mountain area of the Krušné Mts. above 800 m a.s.l. One of the established settlements in studied area, a village Spindelbach, was founded in the second half of the 13th century AD based on archaeological data (Klír 2016). The existence of Spindelbach was reported in written records in AD 1356–1481. Its establishment was in correspondence with the enhanced industrial exploatation of Krušné Mts. (glassworking and mining) which reflected the medieval socio-demographic and economic boom, and might have been as well linked to the favourable climate/weather conditions recorded by written sources in the AD 1260s–1380s in the CL (Brázdil et Kotyza 1995). On the other hand, its desertion corresponded to opposite trends: an era of economic stagnation, and a series of severe winters in the AD 1430s–1450s and 1480s (Brázdil et Kotyza 1995). Such situation in general illustrates the phenomenon of short-lived and abandoned villages/areas (e.g. Dreslerová et al. 2013, Klír et al. 2018, Petr and Vařeka 2019). These areas have preserved some medieval landscape patterns, e.g. the patterns of the long-strip field system (Paper IV) and provided also suitable palaeo-records (Petr and Vařeka 2019, Šitnerová et al. 2020). Following the current trends of the highest taxonomic pollen resolution (Deza-Araujo et al. 2022), a detailed pollen analysis provided data sufficient to demonstrate a rapid vegetation succession after the village abandonment (Paper V), comparable to their modern analogues described in Jehlík (1971) and Balátová-Tuláčková (1981).

3. Conclusions

Sediments of the Central European shallow lake Komořany provided a unique geo-bioarchive reflecting the history of a major part of the Last Deglaciation, the period of the Late-glacial/Holocene transition, and the Holocene until 3.2 ka BP (Papers I and II). The dominance of natural processess both in the surrounding vegetation and in the aquatic ecosystem response was demonstrated at least until the Early Holocene (Paper I). Both the natural and combined (natural and human) forces affecting the lake development and the surrounding vegetation in 11.2–3.2 ka BP period were inferred based on the pollen-based climate reconstruction, reconstruction of changes in the hydrological regime and the aquatic environment, and changes in the past plant assemblages (Paper II). Although the sediment accumulation in the shallow lake was certainly to some extent affected by sediment focusing and other processes (Hilton et al. 1986), it retained a fine palaeoecological record sensitive to climate fluctuations in terms of hydrological changes (water level and surface area). High resolution sampling (~2 mm) proved to be a powerful tool to at least partly overcome the issue connected to low resolution of the historical data (Paper I). Moreover, a relatively detailed sampling of sediment cores throughout the former lake area (Jankovská et Pokorný 2013, Bešta et al. 2015) facilitated the reconstruction of changes in the lake surface area extent in the past (Paper I and II).

Major human impact on the landscape development and vegetation cover was identified in the fossil and archaeological record of three Medieval villages located at distinct elevations, covering the Czech altitudinal gradient (lowland, mid-elevation, and mountains). The village Rybník, located in the suburbs of the Early Medieval Prague, revealed the early history of fishpond farming in the CL, and demonstrated the effects of forthcoming urbanization on the development of plant species composition in a traditional lowland residential area of the CL (216 m a.s.l.), (Paper III). By the time when the village Rybník prosperred and was surrounded by a mosaic of semi-natural habitats, cereal fields, and scattered trees, a slash-and-burn management was underway in the middle-elevation area of South Bohemia (660–735 m a.s.l.), leading to establishment of a complete medieval agrarian system of the village Malonín (Paper IV). Almost in parallel (few years, maximally several decades after the village of Malonín was established), an increased industrial activity in the montane area of the Krušné Mts. stimulated a wave of colonization, including the newly founded village of Spindelbach (800–880 m a.s.l.) (Paper V). The existence of each of these two villages resulted in massive reduction of the conifer-beech forests in their vicinity, likely being more severe in case of the industrial exploatation of the Krušné Mts. (Paper IV, V). In the middle of the 14th century AD (Late Middle Ages), an increased human pressure led to homogenization of urban habitats in the lowlands (Paper III), increased soil errosion down the hillslopes in the mid-elevations (Paper IV), and extreme deforestation of mountain areas in the vicinity of mines (Paper V). These trends have not been reverted (e.g. Izdebski et al. 2022), as the Black Death in AD 1347 avoided the CL. Yet, an era of economic stagnation since AD 1430 resulted in desertion of many villages or entire areas. The abandonement of Spindelbach was followed by rapid vegetation succession and the recovery of a secondary forest favouring *Picea* stands as recorded by the archaeobotanical analyses.

In summary, the studies included in this thesis attempted to deepen our understanding of the vegetation change connected to climatic events and human activity in the Central European context, focusing on the medieval landscape transformation. Our study approach exemplifies the advantages of up-to-date sampling techniques, objective dating, fine-resolution sediment sampling, and elaborate pollen analysis (both quantitatively and in terms of taxonomic resolution). An integrative multidisciplinary approach based on the synthesis of the pollen record with other palaeo- and archaeological data can still provide valuable new insights and help to achieve a better picture of the past human-environment interactions.

4. References

Abraham, V., Hicks, S., Svobodová-Svitavská, H., Bozilova, E., Panajiotidis, S., Filipova-Marinova, M., et al. (2021) Patterns in recent and Holocene pollen accumulation rates across Europe – the Pollen Monitoring Programme Database as a tool for vegetation reconstruction, *Biogeosciences,* 18: 4511-4534.

Abraham, V., Kuneš, P., Petr, L., Svobodová-Svitavská, H., Kozáková, R., Jamrichová, E., Švarcová, M. G. and Pokorný, P. (2016) A pollen-based quantitative reconstruction of the Holocene vegetation updates a perspective on the natural vegetation in the Czech Republic and Slovakia, *Preslia,* 88: 409-434.

Adam, M., Weitzel, N. and Rehfeld, K. (2021) Identifying Global-Scale Patterns of Vegetation Change During the Last Deglaciation From Paleoclimate Networks, *Paleoceanography and Paleoclimatology,* 36: e2021PA004265.

Aguiar, W., Meissner, K. J., Montenegro, A., Prado, L., Wainer, I., Carlson, A. E. and Mata, M. M. (2021) Magnitude of the 8.2 ka event freshwater forcing based on stable isotope modelling and comparison to future Greenland melting, *Scientific Reports,* 11: 5473.

Allaby, R. G., Stevens, C. J., Kistler, L. and Fuller, D. Q. (2022) Emerging evidence of plant domestication as a landscape-level process, *Trends in Ecology & Evolution,* 37: 268-279.

Andersen, T. B., Jensen, P. S. and Skovsgaard, C. V. (2016) The heavy plow and the agricultural revolution in Medieval Europe, *Journal of Development Economics,* 118: 133-149.

Andersen, K. K., Azuma, N., Barnola, J. M., Bigler, M., Biscaye, P., Caillon, N., et al. (2004) 'High-resolution record of Northern Hemisphere climate extending into the last interglacial period', *Nature,* 431: 147-151.

Armstrong, H. and Brasier, M. (2005) *Microfossils.* Malden, Oxford, Carlton: Blackwell publishing, VII+296 pp.

Balátová-Tuláčková, E. (1981) Phytozönologishce und synökologische Charakteristik der Feuchtwiesen NW-Böhmens. *Rozpravy Československé akademie věd.* Praha: Academia, 90 pp.

Barker, S. and Knorr, G. (2021) Millennial scale feedbacks determine the shape and rapidity of glacial termination, *Nature Communications,* 12: 2273.

Barnosky, A. D., Koch, P. L., Feranec, R. S., Wing, S. L. and Shabel, A. B. (2004) Assessing the causes of late Pleistocene extinctions on the continents, *Science,* 306: 70-5.

Barsanti, M., Garcia-Tenorio, R., Schirone, A., Rozmaric, M., Ruiz-Fernández, A. C., Sanchez-Cabeza, J. A., et al. (2020) Challenges and limitations of the ^{210}Pb sediment dating method: Results from an IAEA modelling interlaboratory comparison exercise, *Quaternary Geochronology,* 59: 101093.

Battarbee, R. W. (2000) Palaeolimnological approaches to climate change, with special regard to the biological record, *Quaternary Science Reviews,* 19: 107-124.

Behre, K.-E. (1981) The intrerpretation of anthropogenic indicators in pollen diagram, *Pollen et Spores,* 23: 225-245.

Beneš, J. (2018) *Počátky zemědělství ve Starém světě: pohled paleoekologie a environmentální archeologie.* České Budějovice: Jihočeská univerzita v Českých Budějovicích, 351 pp.

Beneš, J., Kaštovský, J., Kočárová, R., Kočár, P., Kubečková, K., Pokorný, P. and Starec, P. (2002) Archaeobotany of the Old Prague Town defence system, Czech Republic: Archaeology, macro-remains, pollen, and diatoms, *Vegetation History and Archaeobotany,* 11: 107-120.

Berglund, B. and Ralska-Jasiewiczowa, M. (1986) Pollen analysis and pollen diagrams, in Berglund, B. (ed.) *Handbook of Holocene Palaeoecology and Palaeohydrology*. Chichester: Wiley: 455-484.

Bešta, T., Novák, J., Dreslerová, D., Jankovská, V., Bernardová, A., Lisá, L. and Valentová, D. (2015) Mid-Holocene history of a central European lake: Lake Komořany, Czech Republic, *Boreas,* 44: 563-574.

Beug, H.-J. (2004) *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete.* München: Pfeil, 542 pp.

Beyer, R. M., Krapp, M., Eriksson, A. and Manica, A. (2021) Climatic windows for human migration out of Africa in the past 300,000 years, *Nature Communications,* 12: 4889.

Birks, H. H. and Birks, H. J. B. (2004) The rise and fall of forests, *Science,* 305: 484-5.

Birks, H. H. and Birks, H. J. B. (2006) Multi-proxy studies in palaeolimnology, *Vegetation History and Archaeobotany,* 15: 235-251.

Birks, H. J. B. (2005) Fifty years of Quaternary pollen analysis in Fennoscandia 1954–2004, *Grana,* 44: 1-22.

Birks, H. J. B. (2012) Overview of numerical methods in palaeolimnology, in Birks, H.J.B., Lotter, A.F., Juggins, S. and Smol, J.P. (eds.) *Tracking Environmental Change Using Lake Sediments. Volume 5: Data Handling and Numerical Techniques*. Dordrecht: Kluwer Academic Publishers: 19-92.

Birks, H. J. B. and Line, J. M. (1992) The use of Rarefaction Analysis for Estimating Palynological Richness from Quaternary Pollen-Analytical Data, *The Holocene,* 2: 1-10.

Birks, H. J. B. and Seppä, H. (2010) Late-Quaternary palaeoclimatic research in Fennoscandia – A historical review, *Boreas,* 39: 655-673.

Birks, H. J. B., Felde, V. A., Bjune, A. E., Grytnes, J. A., Seppä, H. and Giesecke, T. (2016) Does pollen-assemblage richness reflect floristic richness? A review of recent developments and future challenges, *Review of Palaeobotany and Palynology,* 228: 1-25.

Boch, R., Spötl, C. and Kramers, J. (2009) High-resolution isotope records of early

Holocene rapid climate change from two coeval stalagmites of Katerloch Cave, Austria, *Quaternary Science Reviews,* 28: 2527-2538.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans Michael, N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I. and Bonani, G. (2001) Persistent Solar Influence on North Atlantic Climate During the Holocene, *Science,* 294: 2130-2136.

Bonk, A., Müller, D., Ramisch, A., Kramkowski, M. A., Noryśkiewicz, A. M., Sekudewicz, I., Gąsiorowski, M., Luberda-Durnaś, K., Słowiński, M., Schwab, M., Tjallingii, R., Brauer, A. and Błaszkiewicz, M. (2021) Varve microfacies and chronology from a new sediment record of Lake Gościąż (Poland), *Quaternary Science Reviews,* 251: 106715.

Boyette, A. H., Lew-Levy, S., Jang, H. and Kandza, V. (2022) Social ties in the Congo Basin: insights into tropical forest adaptation from BaYaka and their neighbours, *Philosophical Transactions of the Royal Society B: Biological Sciences,* 377: 20200490.

Bradley, R. S. and Bakke, J. (2019) Is there evidence for a 4.2 ka BP event in the northern North Atlantic region?, *Climate of the Past,* 15: 1665-1676.

Brázdil, R. and Kotyza, O. (1995) *History of weather and climate in the Czech lands I, Period 1000-1500. Zucher Geographische Schriften* Zurich: Geographisches Institut ETH, 260pp.

Brázdil, R., Dobrovolný, P., Mikšovský, J., Pišoft, P., Trnka, M., Možný, M. and Balek, J. (2021) Documentary-based climate reconstructions in the Czech Lands 1501–2020 CE and their European context, *Climate of the Past Discussion,* 2021: 1-36.

Bronk Ramsey, C., Heaton, T. J., Schlolaut, G., Staff, R. A., Bryant, C. L., Brauer, A., Lamb, H. F., Marshall, M. H. and Nakagawa, T. (2020) Reanalysis of the Atmospheric Radiocarbon Calibration Record from Lake Suigetsu, Japan, *Radiocarbon,* 62: 989-999.

Bronk Ramsey, C., Housley, R. A., Lane, C. S., Smith, V. C. and Pollard, A. M. (2015) The RESET tephra database and associated analytical tools, *Quaternary Science Reviews,* 118: 33-47.

Bronk Ramsey, C., Staff, R. A., Bryant, C. L., Brock, F., Kitagawa, H., van der Plicht, J., et al. (2012) A Complete Terrestrial Radiocarbon Record for 11.2 to 52.8 kyr B.P, *Science,* 338: 370-374.

Büntgen, U., Brázdil, R., Heussner, K. U., Hofmann, J., Kontic, R., Kyncl, T., Pfister, C., Chroma, K. and Tegel, W. (2011a) Combined dendro-documentary evidence of Central European hydroclimatic springtime extremes over the last millennium, *Quaternary Science Reviews,* 30: 3947-3959.

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J. O., Herzig, F., Heussner, K. U., Wanner, H., Luterbacher, J. and Esper, J. (2011b) 2500 Years of European Climate Variability and Human Susceptibility, *Science,* 331: 578-582.

Bush, M. B., Rozas-Davila, A., Raczka, M., Nascimento, M., Valencia, B., Sales, R. K., McMichael, C. N. H. and Gosling, W. D. (2022) A palaeoecological perspective on the transformation of the tropical Andes by early human activity, *Philosophical Transactions of the Royal Society B: Biological Sciences,* 377: 20200497.

Caffrey, M. A. and Horn, S. P. (2013) The use of lithium heteropolytungstate in the heavy liquid separation of samples which are sparse in pollen, *Palynology,* 37: 143-150.

Chevalier, M., Davis, B. A. S., Heiri, O., Seppä, H., Chase, B. M., Gajewski, K., et al. (2020) Pollen-based climate reconstruction techniques for late Quaternary studies, *Earth-Science Reviews,* 210: 103384.

Chytrý, M. (2012) Vegetation of the Czech Republic: diversity, ecology, history and dynamics, *Preslia,* 84: 427-504.

Chytrý, M. (2017) Current Vegetation of the Czech Republic, in Chytrý, M., Danihelka, J., Kaplan, Z. and Pyšek, P. (eds.) *Flora and Vegetation of the Czech Republic*. Cham: Springer International Publishing: 229-337.

Chytrý, M., Horsák, M., Danihelka, J., Ermakov, N., German, D. A., Hájek, M., Hájková, P., Kočí, M., Kubešová, S., Lustyk, P., Nekola, J. C., Pavelková Řičánková, V., Preislerová, Z., Resl, P. and Valachovič, M. (2019) A modern analogue of the Pleistocene steppe-tundra ecosystem in southern Siberia, *Boreas,* 48: 36-56.

Clark, P. U., Shakun, J. D., Baker, P. A., Bartlein, P. J., Brewer, S., Brook, E., et al. (2012) Global climate evolution during the last deglaciation, *Proceedings of the National Academy of Sciences,* 109: E1134-E1142.

Clark, J., Fastie, C., Hurtt, G., Jackson, S., Johnson, C., King, G., Lewis, M., Lynch, J., Pacala, S., Prentice, I., Schupp, E. and Iii, T. (1998) Reids paradox of rapid plant migration - Dispersal theory and interpretation of paleoecological records, *Bioscience,* 48: 13-24.

Cohen, A. S., Campisano, C. J., Arrowsmith, J. R., Asrat, A., Beck, C. C., Behrensmeyer, A. K., et al. (2022) Reconstructing the Environmental Context of Human Origins in Eastern Africa Through Scientific Drilling, *Annual Review of Earth and Planetary Sciences*, 50: online early DOI: 10.1146/annurev-earth-031920-081947

Costello, E. (2021) The Colonisation of Uplands in Medieval Britain and Ireland: Climate, Agriculture and Environmental Adaptation, *Medieval Archaeology,* 65: 151-179.

Čulíková, V. (1993) Rekonstrukce synantropní vegatace středověkého města Mostu (Reconstruction of synanthropic vegetation in the medieval town of Most), Medievalia Archaeologica Bohemica. *Památky archeologické,* Supplementum 2: 181-204.

Davis, B. A. S., Chevalier, M., Sommer, P., Carter, V. A., Finsinger, W., Mauri, A. et al. (2020) The Eurasian Modern Pollen Database (EMPD), version 2, *Earth System Science Data,* 12: 2423-2445.

Dearing, J. A. (2006) Climate-human-environment interactions: resolving our past, *Climate of the Past,* 2: 187-203.

Dearing, J., Battarbee, R., Dikau, R., Larocque, I. and Oldfield, F. (2006) Human-environment interactions: Towards synthesis and simulation, *Regional Environmental Change,* 6: 115-123.

Dembitzer, J., Barkai, R., Ben-Dor, M. and Meiri, S. (2022) Levantine overkill: 1.5 million years of hunting down the body size distribution, *Quaternary Science Reviews,* 276: 107316.

Demján, P., Dreslerová, D., Kolář, J., Chuman, T., Romportl, D., Trnka, M. and Lieskovský, T. (2022) Long time-series ecological niche modelling using archaeological settlement data: Tracing the origins of present-day landscape, *Applied Geography,* 141: 102669.

Deza-Araujo, M., Morales-Molino, C., Conedera, M., Pezzatti, G., Salvatore, P. and Tinner, W. (2022) Influence of taxonomic resolution on the value of anthropogenic pollen indicators, *Vegetation History and Archaeobotany,* 31: 61-84.

Divišová, M. and Šída, P. (2015) Plant Use in the Mesolithic Period. Archaeobotanical Data from the Czech Republic in a European Context – a Review, *Interdisciplinaria Archaeologica - Natural Scieces In Archaeology,* VI: 95-106.

Dreslerová, D. (2012) Human Response to Potential Robust Climate Change around 5500 cal BP in the Territory of Bohemia (the Czech Republic), *Interdisciplinaria Archaeologica - Natural Sciences in Archaeology,* III: 43-55.

Dreslerová, D. and Kočár, P. (2013) Trends in cereal cultivation in the Czech Republic from the Neolithic to the Migration period (5500 B.C.–A.D. 580), *Vegetation History and Archaeobotany,* 22: 257-268.

Dreslerová, D., Waldhauser, J., Abraham, V., Kočár, P., Křivánek, R., Meduna, P. and Sádlo, J. (2013) The Bezděz – Doksy region (Northern Bohemia) in prehistory and the La Tѐne settlement at Okna, *Archeologické rozhledy,* LXV: 535-573.

Ellis, E., Maslin, M., Boivin, N. and Bauer, A. (2016) Involve social scientists in defining the Anthropocene, *Nature,* 540: 192-193.

Elznicová, J., Kiss, T., Sipos, G., Faměra, M., Štojdl, J., Váchová, V. and Matys Grygar, T. (2021) A central European alluvial river under anthropogenic pressure: The Ohře River, Czechia, *Catena,* 201: 105218.

Erdtman, G. (1960) The acetolysis method: a revised description., *Svensk Botanisk Tidskrift,* 54: 561-564.

Faith, J. T., Du, A., Behrensmeyer, A. K., Davies, B., Patterson, D. B., Rowan, J. and Wood, B. (2021) Rethinking the ecological drivers of hominin evolution, *Trends in Ecology & Evolution,* 36: 797-807.

Fanta, V., Zouhar, J., Beneš, J., Bumerl, J. and Sklenicka, P. (2020) How old are the towns and villages in Central Europe? Archaeological data reveal the size of bias in dating obtained from traditional historical sources, *Journal of Archaeological Science,* 113: 105044.

Firbas, F. (1949) *Spät- und nacheiszeitliche Waldgeschichte Mitteleuropas nördlich der Alpen. Band 1.* Jena: Allgemeine Waldgeschichte, 480 pp.

Firestone, R. B., West, A., Kennett, J. P., Becker, L., Bunch, T. E., Revay, Z. S., et al. (2007) Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling, *Proceedings of the National Academy of Sciences,* 104: 16016-16021.

Fuller, D. Q., Denham, T., Arroyo-Kalin, M., Lucas, L., Stevens Ch. J., Qin, L., Allaby R. G. and Purugganan M. D. (2014) Convergent evolution and parallelism in plant domestication revealed by an expanding archaeological record, *Proceedings of the National Academy of Sciences,* 111: 6147-6152.

Fuller, D. Q., Willcox, G. and Allaby, R. G. (2011) Cultivation and domestication had multiple origins: arguments against the core area hypothesis for the origins of agriculture in the Near East, *World Archaeology,* 43: 628-652.

Fyfe, R. M., Woodbridge, J. and Roberts, N. (2015) From forest to farmland: pollen-inferred land cover change across Europe using the pseudobiomization approach, *Global Change Biology,* 21: 1197-1212.

Gaillard, M. J., Sugita, S., Mazier, F., Trondman, A. K., Broström, A., Hickler, T., et. al. (2010) Holocene land-cover reconstructions for studies on land cover-climate feedbacks, *Climate of the Past,* 6: 483-499.

Gaillard, M. J. (2013) Pollen methods and studies/archaeological applications, in Elias, S. and Mock, C.J. (eds.) *Encyclopedia of Quaternary Science*: Waltham: Focal Press (Elsevier): 880-904.

Gąsiorowski, M. 2008. Deposition Rate of Lake Sediments Under Different Alternative Stable States. *Geochronometria,* 32: 29-35.

Gębica, P., Michno, A., Sobucki, M., Czopek, S., Trybała-Zawiślak, K. and Wacnik, A. (2020) Temporal variation of prehistoric human settlement recorded in the oxbow lake deposits of San river (Sandomierz Basin, SE Poland), *Geochronometria,* 46: 148-160.

Gibbard, P., Walker, M., Bauer, A., Edgeworth, M., Edwards, L., Ellis, E., Finney, S., Gill, J. L., Maslin, M., Merritts, D. and Ruddiman, W. (2022) The Anthropocene as an Event, not an Epoch, *Journal of Quaternary Science,* online early DOI: 10.1002/jqs.3416

Giesecke, T., Brewer, S., Finsinger, W., Leydet, M. and Bradshaw, R. H. W. (2017a) Patterns and dynamics of European vegetation change over the last 15,000 years, *Journal of Biogeography,* 44: 1441-1456.

Githumbi, E., Pirzamanbein, B., Lindström, J., Poska, A., Fyfe, R., Mazier, F., Nielsen, A. B., Sugita, S., Trondman, A.-K., Woodbridge, J. and Gaillard, M.-J. (2022) Pollen-Based Maps of Past Regional Vegetation Cover in Europe Over 12 Millennia—Evaluation and Potential, *Frontiers in Ecology and Evolution,* 10: 795794.

Goring, S., Dawson, A., Simpson, G. L., Ram, K., Graham, R. W., Grimm, E. C. and Williams, J. W. (2015) neotoma: A Programmatic Interface to the Neotoma Paleoecological Database, *Open Quaternary,* 1: 1-17.

Goring, S., Lacourse, T., Pellatt, M. G. and Mathewes, R. W. (2013) Pollen assemblage richness does not reflect regional plant species richness: a cautionary tale, *Journal of Ecology,* 101: 1137-1145.

Gosling, W. D., Scerri, E. M. L. and Kaboth-Bahr, S. (2022) The climate and vegetation backdrop to hominin evolution in Africa, *Philosophical Transactions of the Royal Society B: Biological Sciences,* 377: 20200483.

Grimm, E. C. (2011) *Tilia. Version 1.7.16.*

Haak, W., Lazaridis, I., Patterson, N., Rohland, N., Mallick, S., Llamas, B., et al. (2015) Massive migration from the steppe was a source for Indo-European languages in Europe, *Nature,* 522: 207-211.

Haas, J. N., Richoz, I., Tinner, W. and Wick, L. (1998) Synchronous Holocene climatic oscillations recorded on the Swiss Plateau and at timberline in the Alps, *Holocene,* 8: 301-309.

Hájková, P., Jamrichová, E., Petr, L., Dudová, L., Roleček, J., Gálová, A., Dresler, P., Novák, J. and Hájek, M. (2018) Persistence of a vegetation mosaic in a peripheral region: could turbulent medieval history disrupt Holocene continuity of extremely species-rich grasslands?, *Vegetation History and Archaeobotany,* 27: 591-610.

Hansen, B. C. S. (1995) Conifer stomate analysis as a paleoecological tool: an example from the Hudson Bay Lowlands, *Canadian Journal of Botany,* 73(2): 244-252.

Harmand, S., Lewis, J., Feibel, C., Lepre, C., Prat, S., Arnaud, L., et al. (2015) 3.3-million-year-old stone tools from Lomekwi 3, West Turkana, Kenya, *Nature,* 521: 310–315.

Hays, J. D., Imbrie, J. and Shackleton, N. J. (1976) Variations in the Earths Orbit: Pacemaker of the Ice Ages, *Science,* 194: 1121-32.

Head, M. J. (2019) Formal subdivision of the Quaternary System/Period: Present status and future directions, *Quaternary International,* 500: 32-51.

Head, M. J., Pillans, B., Zalasiewicz, J. A. et al. (2021) Formal ratification of subseries for the Pleistocene Series of the Quaternary System, *Episodes,* 44: 241-247.

Iversen, J. (1954) The Late Glacial flora of Denmark and its relation to climate and soil, *Danmarks Geologiske Undersøgelse, 2 Række,* 80: 87-119.

Iversen, J. (1964) Retrogressive Vegetational Succession in the Post-Glacial, *Journal of Animal Ecology,* 33: 59-70.

Izdebski, A., Guzowski, P., Poniat, R., Masci, L., Palli, J., Vignola, C., et al. (2022) Palaeoecological data indicates land-use changes across Europe linked to spatial heterogeneity in mortality during the Black Death pandemic, *Nature Ecology & Evolution,* 6: 297-306.

Heiri, O., Brooks, S. J., Renssen, H., Bedford, A., Hazekamp, M., Ilyashuk, B., et al. (2014) Validation of climate model-inferred regional temperature change for late-glacial Europe, *Nature Communications,* 5: 4914.

Hejcman, M., Hejcmanová, P., Pavlů, V. and Beneš, J. (2013a) Origin and history of grasslands in Central Europe – a review, *Grass and Forage Science,* 68: 345-363.

Hejcman, M., Karlík, P., Ondráček, J. and Klír, T. (2013b) Short-Term Medieval Settlement Activities Irreversibly Changed Forest Soils and Vegetation in Central Europe, *Ecosystems,* 16: 652-663.

Hellman, S., Bunting, M. J. and Gaillard, M. J. (2009) Relevant Source Area of Pollen in patchy cultural landscapes and signals of anthropogenic landscape disturbance in the pollen record: A simulation approach, *Review of Palaeobotany and Palynology,* 153: 245-258.

Hesse, M., Halbritter, H., Zetter, R., Weber, M., Buchner, R., Frosch-Radivo, A. and Ulrich, S. (2009) *Pollen terminology. An illustrated handbook.* Vienna, New York: Springer-Verlag, 264 pp.

Hicks, S. and Hyvärinen, H. (1999) Pollen influx values measured in different sedimentary environments and their palaeoecological implications, *Grana,* 38: 228-242.

Hilton, J., Lishman, J. P. and Allen, P. V. (1986) The dominant processes of sediment distribution and focusing in a small, eutrophic, monomictic lake, *Limnology and Oceanography,* 31: 125-133.

Hoevers, R., Broothaerts, N. and Verstraeten, G. (2022) The potential of REVEALS-based vegetation reconstructions using pollen records from alluvial floodplains, *Vegetation History and Archaeobotany,* online early DOI: 10.1007/s00334-022-00866-1

Hormes, A., Muller, B. U. and Schluchter, C. (2001) The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps, *Holocene,* 11: 255-265.

Houfková, P., Bešta, T., Bernardová, A., Vondrák, D., Pokorný, P. and Novák, J. (2017) Holocene climatic events linked to environmental changes at Lake Komořany Basin, Czech Republic, *The Holocene,* 27: 1132-1145.

Hrubý, P., Hejhal, P., Malý, K., Kočár, P. and Petr, L. (2014) *Centrální Českomoravská vrchovina na prahu vrcholného středověku: archeologie, geochemie a rozbory sedimentárních výplní niv.* Brno: Masarykova univerzita Brno, 264 pp.

Hughes, P. D. (2022) Chapter 27 - Concept and global context of the glacial landforms prior to the Last Glacial Maximum, in Palacios, D., Hughes, P.D., García-Ruiz, J.M. and Andrés, N. (eds.) *European Glacial Landscapes*: Elsevier: 197-199.

Huntley, B. and Birks, H. J. B. (1983) *An atlas of past and present pollen maps for Europe: 0-13000 years ago*. Cambridge: Cambridge University Press, 667 pp.

Ivy-Ochs, S., Monegato, G. and Reitner, J. M. (2022) Chapter 39 - The Alps: glacial landforms prior to the Last Glacial Maximum, in Palacios, D., Hughes, P.D., García-Ruiz, J.M. and Andrés, N. (eds.) *European Glacial Landscapes*: Elsevier: 283-294.

Jacomet, S. and Vandorpe, P. (2022) The search for a needle in a haystack – New studies on plant use during the Mesolithic in southwest Central Europe, *Journal of Archaeological Science: Reports,* 41: 103308.

Jamrichová, E., Petr, L., Borja, J. A., Jankovská, V., Dudová, L., Pokorný, P., Kołaczek, P., Zernitskaya, V., Čierniková, M., Břízová, E., Syrovátka, V., Hájková, P. and Hájek, M. (2017) Pollen-inferred millennial changes in landscape patterns at a major biogeographical interface within Europe, *Journal of Biogeography,* 10: 2386-2397.

Jamrichová, E., Potůčková, A., Horsák, M., Hajnalová, M., Barta, P., Tóth, P. and Kuneš, P. (2014) Early occurrence of temperate oak-dominated forest in the northern part of the Little Hungarian Plain, SW Slovakia, *The Holocene,* 24: 1810-1824.

Jamrichová, E., Szabó, P., Hédl, R., Kuneš, P., Bobek, P. and Pelánková, B. (2013) Continuity and change in the vegetation of a Central European oakwood, *The Holocene,* 23: 44-54.

Jankovská, V. (1985) Pylová analýza vzorků z odpadních jímek středověkého Mostu, *Archeologické rozhledy,* 37: 644-652.

Jankovská, V. (1997) Archeologie a pylová analýza - metodické poznámky (Archaeology and pollen analysis - notes to the method), *Archeologické rozhledy,* 49: 146-147.

Jankovská, V. (2005) Zajímavosti z pyloanalytických výzkumů archeologických objektů, in Hašek, V., Nekuda, R. and Ruttkay, M. (eds.) *Ve službách archeologie VI.* Brno: MVS v Brně, Geodrill Brno a Archeologický ústav SAV Nitra: 235-238.

Jankovská, V. and Pokorný, P. (2008) Forest vegetation of the last full-glacial period in the Western Carpathians (Slovakia and Czech Republic), *Preslia* 80: 307-324.

Jankovská, V. and Pokorný, P. (2013) Reevaluation of the palaeoenvironmental record of the former Komoranske jezero lake: late-glacial and Holocene palaeolimnology and vegetation development in north-western Bohemia, Czech Republic, *Preslia,* 85: 265-287.

Jehlík, V. (1971) Die vegetationsbesiedlung der Dorftrümmer in Nordböhmen. Eine studie über synanthrope vegetation und Flora, *Rozpravy Československé akademie věd: řada matematických a přírodních věd* 81:1-91.

Juřičková, L., Horáčková, J., Jansová, A., Kovanda, J., Harčár, J. and Ložek, V. (2019) A glacial refugium and zoogeographic boundary in the Slovak eastern Carpathians, *Quaternary Research,* 91: 383-398.

Klápště, J. (2012) *The Czech lands in Medieval transformation. East Central and Eastern Europe in the Middle Ages,* Leiden: BRILL, 524 pp.

Klápště, J. (2016) *The archaeology of Prague and the medieval Czech lands, 1100-1600. Studies in the archaeology of medieval Europe,* Shefield: Equinox Publishing, 274 pp.

Klimek, T. (2014) *Krajiny českého středověku.* Praha: Dokořán, 206 pp.

Klír, T. (2009) *The Settlements and Agriculture of the Margins in the Later Middle Age and Early New Age.* Dissertationes Archaeologicae Brunenses/Pragensesque 5, Praha.

Klír, T. (2016) Research of deserted Medieval villages conducted by the Institute of Archaeology at Charles University in Prague, in Nocuń, P., Fokt, K. and Przybyła-Dumin, A. (eds.) *Wieś zaginiona. Stan i perspektywy badań: Vol. 5 Monografie i materiały MGPE.* Chorzów: Muzeum "Górnośląski Park Etnograficzny w Chorzowie": 17-59.

Klír, T., Janovský, M., Malina, O. and Horák, J. (2018) Deserted mediaeval village of Hol and its field system, *Natura Pragensis*, 24: 19-30.

Kolář, J., Macek, M., Tkáč, P. and Szabó, P. (2016) Spatio-temporal modelling as a way to reconstruct patterns of past human activities, *Archaeometry,* 58: 513-528.

Kolář, T., Dobrovolný, P., Szabó, P., Mikita, T., Kyncl, T., Kyncl, J., Sochová, I. and Rybníček, M. (2021) Wood species utilization for timber constructions in the Czech lands over the period 1400–1900, *Dendrochronologia,* 70: 125900.

Komárek, J. and Jankovská, V. (2001) *Review of the green algal genus Pediastrum; implication for pollen-analytical research.* Berlin: J. Cramer., 127 pp.

Kozáková, R. and Pokorný, P. (2007) Dynamics of the biotopes at the edge of a medieval town: pollen analysis of Vltava river sediments in Prague, Czech Republic, *Preslia,* 79: 259-281.

Kozáková, R., Bobek, P., Dreslerová, D., Abraham, V. and Svobodová-Svitavská, H. (2021) The prehistory and early history of the Šumava Mountains (Czech Republic) as seen through anthropogenic pollen indicators and charcoal data, *The Holocene,* 31: 145-159.

Kozáková, R., Pokorný, P., Havrda, J. and Jankovská, V. (2009) The potential of pollen analyses from urban deposits: multivariate statistical analysis of a data set from the medieval city of Prague, Czech Republic, *Vegetation History and Archaeobotany,* 18: 477-488.

Kozáková, R., Pokorný, P., Mařík, J., Čulíková, V., Boháčová, I. and Pokorná, A. (2014) Early to high medieval colonization and alluvial landscape transformation of the Labe valley (Czech Republic): evaluation of archaeological, pollen and macrofossil evidence, *Vegetation History and Archaeobotany,* 23: 701-718.

Kozáková, R., Pokorný, P., Peša, V., Danielisová, A., Čuláková, K. and Svobodová Svitavská, H. (2015) Prehistoric human impact in the mountains of Bohemia. Do pollen and archaeological data support the traditional scenario of a prehistoric "wilderness"?, *Review of Palaeobotany and Palynology,* 220: 29-43.

Kozáková, R., Samonil, P., Kuneš, P., Novák, J., Kočár, P. and Kočárová, R. (2011) Contrasting local and regional Holocene histories of Abies alba in the Czech Republic in relation to human impact: Evidence from forestry, pollen and anthracological data, *The Holocene,* 21: 431-444.

Kreuz, A. (2008) Closed forest or open woodland as natural vegetation in the surroundings of Linearbandkeramik settlements?, *Vegetation History and Archaeobotany,* 17: 51-64.

Kreuz, A. and Marinova, E. (2017) Archaeobotanical evidence of crop growing and diet within the areas of the Karanovo and the Linear Pottery Cultures: a quantitative and qualitative approach, *Vegetation History and Archaeobotany,* 26: 639-657.

Kubovčík, V., Hošek, J., Heiri, O., Rojik, F., Vaterková, S., Trubač, J. and Pokorný, P. (2021) Chironomid-based temperature and environmental reconstructions of the Last Glacial Termination in southern Bohemia, Czech Republic, *Palaeogeography, Palaeoclimatology, Palaeoecology,* 567: 110239.

Kuneš, P. and Abraham, V. (2017) History of Czech Vegetation Since the Late Pleistocene, in Chytrý, M., Danihelka, J., Kaplan, Z. and Pyšek, P. (eds.) *Flora and Vegetation of the Czech Republic*. Cham: Springer International Publishing: 193-227.

Kuneš, P., Abraham, V., Kovářík, O., Kopecký, M., Břízová, E., Dudová, L., Jankovská, V., Knipping, M., Kozáková, R., Nováková, K., Petr, L., Pokorný, P., Roszková, A., Rybníčková, E., Svitavská-Svobodová, H. and Wacnik, A. (2009) Czech quaternary palynological Database - Palycz: review and basic statistics of the data, *Preslia,* 81: 209-238.

Kuneš, P., Abraham, V., Werchan, B., Plesková, Z., Fajmon, K., Jamrichová, E. and Roleček, J. (2019) Relative pollen productivity estimates for vegetation reconstruction in central-eastern Europe inferred at local and regional scales, *The Holocene,* 29: 1708-1719.

Kuneš, P., Pokorný, P. and Šída, P. (2008) Detection of the impact of early Holocene hunter-gatherers on vegetation in the Czech Republic, using multivariate analysis of pollen data, *Vegetation History and Archaeobotany,* 17: 269-287.

Kuneš, P., Svobodová-Svitavská, H., Kolář, J., Hajnalová, M., Abraham, V., Macek, M., Tkáč, P. and Szabó, P. (2015) The origin of grasslands in the temperate forest zone of east-central Europe: long-term legacy of climate and human impact, *Quaternary Science Reviews,* 116: 15-27.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y. and Sambridge, M. (2014) Sea level and global ice volumes from the Last Glacial Maximum to the Holocene, *Proceedings of the National Academy of Sciences,* 111: 15296-15303.

Larson, G. and Fuller, D. Q. (2014) The Evolution of Animal Domestication, *Annual Review of Ecology, Evolution, and Systematics,* 45: 115-136.

Larson, G., Piperno D. R., Allaby R. G., Purugganan M. D., Andersson, L., Arroyo-Kalin, M., et al. (2014) Current perspectives and the future of domestication studies, *Proceedings of the National Academy of Sciences,* 111: 6139-6146.

Lewis, S. L. and Maslin, M. A. (2015) Defining the Anthropocene, *Nature,* 519: 171-180.

Lora, J. M. and Ibarra, D. E. (2019) The North American hydrologic cycle through the last deglaciation, *Quaternary Science Reviews,* 226: 105991.

Lososová, Z., Chytrý, M., Kühn, I., Hájek, O., Horáková, V., Pyšek, P. and Tichý, L. (2006) Patterns of plant traits in annual vegetation of man-made habitats in central Europe, *Perspectives in Plant Ecology, Evolution and Systematics,* 8: 69-81.

Lowe, D. J. (2011) Tephrochronology and its application: A review, *Quaternary Geochronology,* 6: 107-153.

Magny, M. (2004) Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements, *Quaternary International,* 113: 65-79.

Mahony, S. H., Barnard, N. H., Sparks, R. S. J. and Rougier, J. C. (2020) VOLCORE, a global database of visible tephra layers sampled by ocean drilling, *Scientific Data,* 7: 330.

Mangerud, J., Andersen, S., Berglund, B. and Donner, J. (1974) Quaternary stratigraphy of Norden, a proposal for terminology and classification, *Boreas,* 3: 109-126.

Marks, L., Bitinas, A., Błaszkiewicz, M., Börner, A., Guobyte, R., Rinterknecht, V. and Tylmann, K. (2022) Chapter 49 - Northern Central Europe: glacial landforms from the Last Glacial Maximum, in Palacios, D., Hughes, P.D., García-Ruiz, J.M. and Andrés, N. (eds.) *European Glacial Landscapes*: Elsevier: 381-388.

Marquer, L., Gaillard, M.-J., Sugita, S., Poska, A., Trondman, A.-K., Mazier, F., et al. (2017) Quantifying the effects of land use and climate on Holocene vegetation in Europe, *Quaternary Science Reviews,* 171: 20-37.

Marquer, L., Gaillard, M.-J., Sugita, S., Trondman, A.-K., Mazier, F., Nielsen, A., et al. (2014) Holocene changes in vegetation composition in northern Europe: Why quantitative pollen-based vegetation reconstructions matter, *Quaternary Science Reviews,* 90: 199-216.

Marret, F., O´Keefe, J., Osterloff, P., Pound, M. and Shumilovskikh, L. (2021) *Applications of Non-Pollen Palynomorphs: from Palaeoenvironmental Reconstructions to Biostratigraphy,* London: Geological Society of London, 354 pp.

Maslin, M. (2016) In retrospect: Forty years of linking orbits to ice ages, *Nature,* 540: 208-210.

Maslin, M., Stickley, C. and Ettwein, V. (2001) Holocene Climate Variability, *Encyclopedia of Ocean Sciences,* 2: 1210-1217.

Matero, I. S. O., Gregoire, L. J., Ivanovic, R. F., Tindall, J. C. and Haywood, A. M. (2017) The 8.2 ka cooling event caused by Laurentide ice saddle collapse, *Earth and Planetary Science Letters,* 473: 205-214.

Matys Grygar, T., Nováková, T., Mihaljevič, M., Strnad, L., Světlík, I., Koptíková, L., Lisá, L., Brázdil, R., Máčka, Z., Stachoň, Z., Svitavská-Svobodová, H. and Wray, D. S. (2011) Surprisingly small increase of the sedimentation rate in the floodplain of Morava River in the Strážnice area, Czech Republic, in the last 1300 years, *Catena,* 86: 192-207.

Mercuri, A. M., Allevato, E., Arobba, D., Bandini Mazzanti, M., Bosi, G., Caramiello, R., et al. (2015) Pollen and macroremains from Holocene archaeological sites: A dataset for the understanding of the bio-cultural diversity of the Italian landscape, *Review of Palaeobotany and Palynology,* 218: 250-266.

Mercuri, A. M., Sadori, L. and Blasi, C. (2010) Editorial: Archaeobotany for cultural landscape and human impact reconstructions, *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology,* 144: 860-864.

Mithen, S. (2020) Lost for words: an extraordinary structure at the early Neolithic settlement of WF16, *Humanities and Social Sciences Communications,* 7: 125.

Montgomery, R. A., Raupp, J., Miller, S. A., Wijers, M., Lisowsky, R., Comar, A., Bugir, C. K. and Hayward, M. W. (2022) The hunting modes of human predation and potential nonconsumptive effects on animal populations, *Biological Conservation,* 265: 109398.

Mottl, O., Flantua Suzette, G. A., Bhatta Kuber, P., Felde Vivian, A., Giesecke, T., Goring, S., Grimm Eric, C., Haberle, S., Hooghiemstra, H., Ivory, S., Kuneš, P., Wolters, S., Seddon Alistair, W. R. and Williams John, W. (2021a) Global acceleration in rates of vegetation change over the past 18,000 years, *Science,* 372: 860-864.

Mottl, O., Grytnes, J.-A., Seddon, A. W. R., Steinbauer, M. J., Bhatta, K. P., Felde, V. A., Flantua, S. G. A. and Birks, H. J. B. (2021b) Rate-of-change analysis in paleoecology revisited: A new approach, *Review of Palaeobotany and Palynology,* 293: 104483.

Munsterman, D. and Kerstholt, S. (1996) Sodium polytungstate, a new non-toxic alternative to bromoform in heavy liquid separation, *Review of Palaeobotany and Palynology,* 91: 417-422.

Nakagawa, T., Tarasov, P. E., Nishida, K., Gotanda, K. and Yasuda, Y. (2002) Quantitative pollen-based climate reconstruction in central Japan: application to surface and Late Quaternary spectra, *Quaternary Science Reviews,* 21: 2099-2113.

Newton, A., Dugmore, A. and Gittings, B. (2007) Tephrabase: Tephrochronology and the development of a centralised European database, *Journal of Quaternary Science,* 22: 737-743.

Nikulina, A., MacDonald, K., Scherjon, F., A. Pearce, E., Davoli, M., Svenning, J.-C., et al. (2022) Tracking Hunter-Gatherer Impact on Vegetation in Last Interglacial and Holocene Europe: Proxies and Challenges, *Journal of Archaeological Method and Theory*, online early 10.1007/s10816-021-09546-2

Novák, J., Abraham, V., Houfková, P., Kočár, P., Vaněček, Z. and Peška, J. (2018) History of the Litovelské Pomoraví woodland (NE Czech Republic): A comparison of archaeo-anthracological, pedoanthracological, and pollen data, *Quaternary International,* 463: 352-362.

Novák, J., Abraham, V., Kočár, P., Petr, L., Kočárová, R., Nováková, K., Houfková, P., Jankovská, V. and Vaněček, Z. (2016) Middle- and upper-Holocene woodland history in central Moravia (Czech Republic) reveals biases of pollen and anthracological analysis, *The Holocene,* 27: 349-360.

Novák, J., Kočárová, R., Kočár, P. and Abraham, V. (2021) Long–term history of woodland under human impact, archaeoanthracological synthesis for lowlands in Czech Republic, *Quaternary International,* 593-594: 195-203.

Novák, J., Lisá, L., Pokorný, P. and Kuna, M. (2012) Charcoal analyses as an environmental tool for the study of Early Medieval sunken houses infills in Roztoky near Prague, Czech Republic, *Journal of Archaeological Science,* 39: 808-817.

Novák, J., Roleček, J., Dresler, P. and Hájek, M. (2019) Soil charcoal elucidates the role of humans in the development of landscape of extreme biodiversity, *Land Degradation & Development,* 30: 1607-1619.

Obrochta, S. P., Miyahara, H., Yokoyama, Y. and Crowley, T. J. (2012) A re-examination of evidence for the North Atlantic "1500-year cycle" at Site 609, *Quaternary Science Reviews,* 55: 23-33.

Ojala, A. E. K., Francus, P., Zolitschka, B., Besonen, M. and Lamoureux, S. F. (2012) Characteristics of sedimentary varve chronologies – A review, *Quaternary Science Reviews,* 43: 45-60.

Opravil, E. (1969) Synantropní rostliny dvou středověkých objektů ze SZ Čech, *Preslia,* 41: 248-257.

Ott, F., Kramkowski, M., Wulf, S., Plessen, B., Serb, J., Tjallingii, R., Schwab, M., Słowiński, M., Brykała, D., Tyszkowski, S., Putyrskaya, V., Appelt, O., Błaszkiewicz, M. and Brauer, A. (2017) Site-specific sediment responses to climate change during the last 140 years in three varved lakes in Northern Poland, *The Holocene,* 28: 464-477.

PalDat – a palynological database (2000 onwards, available at www.paldat.org)

Pardoe, H. S., Cleal, C. J., Berry, C. M., Cascales-Miñana, B., Davis, B. A. S., et al. (2021) Palaeobotanical experiences of plant diversity in deep time. 2: How to measure and analyse past plant biodiversity, *Palaeogeography, Palaeoclimatology, Palaeoecology,* 580: 110618.

Petr, L. and Vařeka, P. (2019) Palynology research of water reservoirs of later mediaeval and post-mediaeval deserted villages in West Bohemia, Czech Republic, *Archaeological and Anthropological Sciences,* 11: 4059-4073.

Petřík, J., Petr, L., Adameková, K., Prišťáková, M., Potůčková, A., Lenďáková, Z., Frączek, M., Dresler, P., Macháček, J., Kalicki, T. and Lisá, L. (2019) Disruption in an alluvial landscape: Settlement and environment dynamics on the alluvium of the river Dyje at the Pohansko archaeological site (Czech Republic), *Quaternary International,* 511: 124-139.

Pleskot, K., Apolinarska, K., Kołaczek, P., Suchora, M., Fojutowski, M., Joniak, T., Kotrys, B., Kramkowski, M., Słowiński, M., Woźniak, M. and Lamentowicz, M. (2020) Searching for the 4.2 ka climate event at Lake Spore, Poland, *Catena,* 191: 104565.

Pokorná, A., Houfková, P., Novák, J., Bešta, T., Kovačiková, L., Nováková, K., Zavřel, J. and Starec, P. (2014) The oldest Czech fishpond discovered? An interdisciplinary approach to reconstruction of local vegetation in mediaeval Prague suburbs, *Hydrobiologia,* 730: 191-213.

Pokorná, A., Kočár, P., Novák, J., Šálková, T., Žáčková, P., Komárková, V., Vaněček, Z. and Sádlo, J. (2018) Ancient and Early Medieval man-made habitats in the Czech Republic: conization history and vegetation changes, *Preslia,* 90: 171-193.

Pokorný, P., Bobek, P., Šída, P., Novák, J., Ptáková, M. and Walls, M. (2022) Managing wilderness? Holocene-scale, human-related disturbance dynamics as revealed in a remote, forested area in the Czech Republic, *The Holocene*, online early DOI: 10.1177/09596836221080762

Pokorný, P., Chytrý, M., Juřičková, L., Sádlo, J., Novák, J. and Ložek, V. (2015) Mid-Holocene bottleneck for central European dry grasslands: Did steppe survive the forest optimum in northern Bohemia, Czech Republic?, *The Holocene,* 25: 716-726.

Poschlod, P. (2015) The origin and development of the Central European man-made landscape, habitat and species diversity as affected by climate and its changes – a review, *Interdisciplinaria Archaeologica - Natural Sciences in Archaeology,* VI: 197–221.

Poska, A., Väli, V., Vassiljev, J., Alliksaar, T. and Saarse, L. (2022) Timing and drivers of local to regional scale land-cover changes in the hemiboreal forest zone during the Holocene: A pollen-based study from South Estonia, *Quaternary Science Reviews,* 277: 107351.

Powell, J. and Zimmermann, N. (2004) Multi-Scale analysis of seed dispersal contributes to the resolution of Reids paradox, *Ecology,* 85: 490-506.

Powell, J. L. (2022) Premature rejection in science: The case of the Younger Dryas Impact Hypothesis, *Science Progress,* 105: 00368504211064272.

Praetorius, S. K., McManus, J. F., Oppo, D. W. and Curry, W. B. (2008) Episodic reductions in bottom-water currents since the last ice age, *Nature Geoscience,* 1: 449-452.

Prentice, I. C. (1985) Pollen representation, source area, and basin size: Toward a unified theory of pollen analysis, *Quaternary Research,* 23: 76-86.

Ptáková, M., Šída, P., Vondrovský, V. and Pokorný, P. (2021) Islands of difference: an ecologically explicit model of Central European neolithisation, *Environmental Archaeology,* online early DOI: 10.1080/14614103.2021.1985918.

Punt, W. 1976. *The Northwest European pollen flora, parts 1-7.* Amsterdam: Elsevier.

Punt, W. and Blackmore, S. (1991) *The Northwest European pollen flora, parts 44-51.* Amsterdam: Elsevier, 275 pp.

Punt, W. and Clarke, G. (1980) *The Northwest European pollen flora, parts 8-20.* Amsterdam: Elsevier, 265 pp.

Punt, W. and Clarke, G. (1981) *The Northwest European pollen flora, parts 21-28.* Amsterdam: Elsevier, 138 pp.

Punt, W. and Clarke, G. (1984) *The Northwest European pollen flora, parts 29-37.*

Amsterdam: Elsevier, 369 pp.

Punt, W., Blackmore, S. and Clarke, G. (1988) *The Northwest European pollen flora, parts 38-43.* Amsterdam: Elsevier, 154 pp.

Punt, W., Blackmore, S. and Hoen, P. (1995) *The Northwest European pollen flora, parts 52-56.* Amsterdam: Elsevier, 275 pp.

Punt, W., Blackmore, S., Hoen, P. and Stafford, P. (2003) *The Northwest European pollen flora, parts 57-68.* Amsterdam; London: Elsevier, 183 pp.

Punt, W., Blackmore, S., Hoen, P. and Stafford, P. (2009) *The Northwest European Pollen Flora, part 70.* Amsterdam: Elsevier, 187 pp.

Pyšek, P., Danihelka, J., Sádlo, J., Chrtek, J., Chytrý, M., Jarošík, V., Kaplan, Z., Krahulec, F., Moravcová, L., Pergl, J., Štajerová, K. and Tichý, L. (2012) Catalogue of alien plants of the Czech Republic (2nd edition): checklist update, taxonomic diversity and invasion patterns, *Preslia,* 84: 155-255.

Racimo, F., Woodbridge, J., Fyfe R. M., Sikora, M., Sjögren, K.-G., Kristiansen, K. and Vander Linden, M. (2020) The spatiotemporal spread of human migrations during the European Holocene, *Proceedings of the National Academy of Sciences,* 117: 8989-9000.

Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B., et al. (2014) A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy, *Quaternary Science Reviews,* 106: 14-28.

Renssen, H., Mairesse, A., Goosse, H., Mathiot, P., Heiri, O., Roche, D. M., Nisancioglu, K. H. and Valdes, P. J. (2015) Multiple causes of the Younger Dryas cold period, *Nature Geoscience,* 8: 946-949.

Revelles, J., Casas, F., Morera, N., Barcelo, J., Berrocal Barberà, A., López-Bultó, O., Maicher, C., Le Bailly, M., Piqué, R., Palomo, A. and Terradas, X. (2017) Use of space and site formation processes in a Neolithic lakeside settlement. Pollen and non-pollen palynomorphs spatial analysis in La Draga (Banyoles, NE Iberia), *Journal of Archaeological Science,* 81: 101-115.

Rey, F., Gobet, E., Schwörer, C., Hafner, A., Szidat, S. and Tinner, W. (2020) Climate impacts on vegetation and fire dynamics since the last deglaciation at Moossee (Switzerland), *Climate of the Past,* 16: 1347-1367.

Reyes, A. V., Carlson, A. E., Milne, G. A., Tarasov, L., Reimink, J. R. and Caffee, M. W. (2022) Revised chronology of northwest Laurentide ice-sheet deglaciation from ^{10}Be exposure ages on boulder erratics, *Quaternary Science Reviews,* 277: 107369-107369.

Rick, T. C., Alsharekh, A. M., Braje, T. J., Crowther, A., Erlandson, J. M., Fuller, D. Q., et al. (2022) Coring, profiling, and trenching: Archaeological field strategies for investigating the Pleistocene-Holocene-Anthropocene continuum, *Quaternary International*, online early DOI: 10.1016/j.quaint.2022.02.011

Rito, T., Vieira, D., Silva, M., Conde-Sousa, E., Pereira, L., Mellars, P., Richards, M. B. and Soares, P. (2019) A dispersal of Homo sapiens from southern to eastern Africa immediately preceded the out-of-Africa migration, *Scientific Reports,* 9: 4728.

Roleček, J., Abraham, V., Vild, O., Svitavská-Svobodová, H., Jamrichová, E., Plesková, Z., Pokorný, P. and Kuneš, P. (2021) Holocene plant diversity dynamics shows a distinct biogeographical pattern in temperate Europe*, Journal of Biogeography,* 48: 1366-1376.

Roleček, J., Svitavská-Svobodová, H., Jamrichová, E., Dudová, L., Hájková, P., Kletetschka, G., Kuneš, P. and Abraham, V. (2020) Conservation targets from the perspective of a palaeoecological reconstruction: the case study of Dářko peat bog in the Czech Republic, *Preslia,* 92: 87-114.

Rösch, M. (2013) Land use and food production in central Europe from the Neolithic to the Medieval period: change of landscape, soils and agricultural systems according to archaeobotanical data, in Kerig, T. and Zimmermann, A. (eds.) *Economic archaeology: from structure to performance in European archaeology*. Bonn: Habelt. 109-127.

Rose, N. L. (2015) Spheroidal carbonaceous fly ash particles provide a globally synchronous stratigraphic marker for the Anthropocene, *Environmental Science & Technology,* 49: 4155-4162.

Rousseau, D. D., Bagniewski, W. and Ghil, M. (2022) Abrupt climate changes and the astronomical theory: are they related?, *Climate of the Past,* 18: 249-271.

Ruddiman, W. F., Ellis, E. C., Kaplan, J. O. and Fuller, D. Q. (2015) Defining the epoch we live in, *Science,* 348: 38-39.

Sadori, L., Mercuri, A. M. and Mariotti Lippi, M. (2010) Reconstructing past cultural landscape and human impact using pollen and plant macroremains, *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology,* 144: 940-951.

Šálková, T., Bezděk, A., Březinová, H., Farkašová, K., Houfková, P., Chvojka, O., et al. (2015) Bioarchaeological reconstruction of the funeral rite – case study based on organic material from the Hallstatt Period tumulus at the site Zahrádka (South Bohemia, Czech Republic), *Památky archeologické,* 106: 95-135.

Šálková, T., Chvojka, O., Hlásek, D., Jiřik, J., John, J., Novák, J., Kovačiková, L. and Beneš, J. (2019) Crops along the trade routes? Archaeobotany of the Bronze Age in the region of South Bohemia (Czech Republic) in context with longer distance trade and exchange networks, *Archaeological and Anthropological Sciences,* 11: 5569–5590.

Scerri, E. M. L., Roberts, P., Yoshi Maezumi, S. and Malhi, Y. (2022) Tropical forests in the deep human past, *Philosophical Transactions of the Royal Society B: Biological Sciences,* 377: 20200500.

Schirone, A., Rožmarić, M., Barsanti, M., Raiteri, G., Sanchez-Cabeza, J. A., García-Tenorio, R. and Osvath, I. (2022) Assessment of measurement accuracy in ^{210}Pb dating sediment methods, *Quaternary Geochronology,* 69: 101255.

Sernander, R. (1908) On the evidences of Postglacial changes of climate furnished by the peat-mosses of Northern Europe, *Geologiska Föreningen i Stockholm Förhandlingar,* 30: 465-473.

Sikk, K., Caruso, G., Rosentau, A. and Kriiska, A. (2022) Comparing contemporaneous hunter-gatherer and early agrarian settlement systems with spatial point process models: Case study of the Estonian Stone Age, *Journal of Archaeological Science: Reports,* 41: 103330.

Šitnerová, I., Beneš, J., Trpáková, I., Bumerl, J., Komárková, V., Majerovičová, T., Hrabáková, L. and Molnarová, K. (2020) Landscape Transformed: Archaeological, Historical and Environmental Dating of the Early Modern Field System in Valštejn, Czech Republic, *Interdisciplinaria Archaeologica, Natural Sciences in Archaeology,* XI: 89-101.

Sjögren, P. and Damm, C. (2019) Holocene vegetation change in northernmost Fennoscandia and the impact on prehistoric foragers 12 000-2000 cal. a BP – A review, *Boreas,* 48: 20-35.

Slimak, L., Zanolli, C., Higham, T., Frouin, M., Schwenninger, J.-L., Arnold Lee, J., et al. (2022) Modern human incursion into Neanderthal territories 54,000 years ago at Mandrin, France, *Science Advances,* 8: eabj9496.

Smol, J. P. (2001) *Terrestrial, algal, and siliceous indicators. Tracking environmental change using lake sediments,* Dordrecht: Springer, 371 pp.

Smyth, J. and Gillis, R. (2022) Food and Farming Systems in the Neolithic – an Impossible Vista?, *Environmental Archaeology,* 27: 1-7.

Soriano, C. (2020) On the Anthropocene formalization and the proposal by the Anthropocene Working Group, *Geologica Acta,* 18: 1-10.

Stewart, J. R., Lister, A. M., Barnes, I. and Dalén, L. (2010) Refugia revisited: individualistic responses of species in space and time, *Proceedings of the Royal Society B: Biological Sciences,* 277: 661-671.

Stewart, M., Carleton, W. C. and Groucutt, H. S. (2021) Climate change, not human population growth, correlates with Late Quaternary megafauna declines in North America, *Nature Communications,* 12: 965.

Sugita, S. (2007) Theory of quantitative reconstruction of vegetation II: all you need is LOVE, *The Holocene,* 17: 243-257.

Sümegi, P., Molnár, D., Náfrádi, K., Makó, L., Cseh, P., Törőcsik, T., Molnár, M. and Zhou, L. (2022) Vegetation and land snail-based reconstruction of the palaeocological changes in the forest steppe eco-region of the Carpathian Basin during last glacial warming, *Global Ecology and Conservation,* 33: e01976.

Svitavská-Svobodová, H. and Janský, B. (2021) Contribution to the European Pollen Database in Neotoma: a pollen diagram of Rokytecká slať mire, Bohemian Forest/Šumava (Czech Republic), *Vegetation History and Archaeobotany,* 30: 831-834.

Swarzenski, P. W. (2014) ^{210}Pb Dating, in Rink, W.J. and Thompson, J. (eds.)

Encyclopedia of Scientific Dating Methods. Dordrecht: Springer Netherlands: 1-11.

Sweatman, M. B. (2021) Earth-Science Reviews The Younger Dryas impact hypothesis: Review of the impact evidence, *Earth-Science Reviews,* 218: 103677-103677.

Sweeney, C. A. (2004) A key for the identification of stomata of the native conifers of Scandinavia, *Review of Palaeobotany and Palynology,* 128: 281-290.

Święta-Musznicka, J., Badura, M., Pędziszewska, A. and Latałowa, M. (2021) Environmental changes and plant use during the 5th-14th centuries in medieval Gdańsk, northern Poland, *Vegetation History and Archaeobotany,* 30: 363-381.

Święta-Musznicka, J., Latałowa, M., Badura, M. and Gołembnik, A. (2013) Combined pollen and macrofossil data as a source for reconstructing mosaic patterns of the early medieval urban habitats – a case study from Gdańsk, N. Poland, *Journal of Archaeological Science,* 40: 637-648.

Szabó, P. (2010) Ancient woodland boundaries in Europe, *Journal of Historical Geography,* 36: 205-214.

Szabó, P., Müllerová, J., Suchánková, S. and Kotačka, M. (2015) Intensive woodland management in the Middle Ages: spatial modelling based on archival data, *Journal of Historical Geography,* 48: 1-10.

Theuerkauf, M. and Couwenberg, J. (2021) Pollen productivity estimates strongly depend on assumed pollen dispersal II: Extending the ERV model, *The Holocene*, online early DOI: 10.1177/09596836211041729.

Theuerkauf, M., Bos, J. A. A., Jahns, S., Janke, W., Kuparinen, A., Stebich, M. and Joosten, H. (2014) *Corylus* expansion and persistent openness in the early Holocene vegetation of northern central Europe, *Quaternary Science Reviews,* 90: 183-198.

Tierney, J. E., Zhu, J., King, J., Malevich, S. B., Hakim, G. J. and Poulsen, C. J. (2020) Glacial cooling and climate sensitivity revisited, *Nature,* 584: 569-573.

Timmermann, A. (2020) Quantifying the potential causes of Neanderthal extinction: Abrupt climate change versus competition and interbreeding, *Quaternary Science Reviews,* 238: 106331.

Tinner, W., Ammann, B. and Germann, P. (1996) Treeline fluctuations recorded for 12,500 years by soil profiles, pollen, and plant macrofossils in the Central Swiss Alps, *Arctic and Alpine Research,* 28: 131-147.

Tolonen, K. (1986) Charred particle analysis, in BE, B. (ed.) *Handbook of Holocene Palaeoecology and Palaeohydrology*. Chichester: John Wiley and Sons: 485-496.

Trondman, A. K., Gaillard, M. J., Mazier, F., Sugita, S., Fyfe, R., Nielsen, A. B., et al. (2015) Pollen-based quantitative reconstructions of Holocene regional vegetation cover (plant-functional types and land-cover types) in Europe suitable for climate modelling, *Global Change Biology,* 21: 676-697.

Tserendorj, G., Marinova, E., Lechterbeck, J., Behling, H., Wick, L., Fischer, E., Sillmann, M., Märkle, T. and Rösch, M. (2021) Intensification of agriculture in southwestern Germany between the Bronze Age and Medieval period, based on archaeobotanical data from Baden-Württemberg, *Vegetation History and Archaeobotany,* 30: 1-12.

Tylmann, W., Zolitschka, B., Enters, D. and Ohlendorf, C. (2013) Laminated lake sediments in northeast Poland: distribution, preconditions for formation and potential for paleoenvironmental investigation, *Journal of Paleolimnology,* 50: 487-503.

Ullman, D. J., Carlson, A. E., Anslow, F. S., LeGrande, A. N. and Licciardi, J. M. (2015) Laurentide ice-sheet instability during the last deglaciation, *Nature Geoscience,* 8: 534-537.

Umbanhowar, C. E. and McGrath, M. J. (1998) Experimental production and analysis of microscopic charcoal from wood, leaves and grasses, *Holocene,* 8: 341-346.

Vahdati, A. R., Weissmann, J. D., Timmermann, A., Ponce de León, M. and Zollikofer, C. P. E. (2022) Exploring Late Pleistocene hominin dispersals, coexistence and extinction with agent-based multi-factor models, *Quaternary Science Reviews,* 279: 107391.

Väliranta, M., Salonen, J. S., Heikkilä, M., Amon, L., Helmens, K., Klimaschewski, A., Kuhry, P., Kultti, S., Poska, A., Shala, S., Veski, S. and Birks, H. H. (2015) Plant macrofossil evidence for an early onset of the Holocene summer thermal maximum in northernmost Europe, *Nature Communications,* 6: 6809.

Van Geel, B. (2001) Non-Pollen Palynomorphs, in Smol, J.P., Birks, H.J.B., Last, W.M., Bradley, R.S. and Alverson, K. (eds.) *Tracking Environmental Change Using Lake Sediments: Terrestrial, Algal, and Siliceous Indicators*. Dordrecht: Springer Netherlands: 99-119.

Verstraeten, G., Broothaerts, N., Van Loo, M., Notebaert, B., DHaen, K., Dusar, B. and De Brue, H. (2017) Variability in fluvial geomorphic response to anthropogenic disturbance, *Geomorphology,* 294: 20-39.

Vidal, C. M., Lane, C. S., Asrat, A., Barfod, D. N., Mark, D. F., Tomlinson, E. L., Tadesse, A. Z., Yirgu, G., Deino, A., Hutchison, W., Mounier, A. and Oppenheimer, C. (2022) Age of the oldest known *Homo sapiens* from eastern Africa, *Nature,* 601: 579-583.

Walker, M., Head, M., Berkelhammer, M., Björck, S., Cheng, H., Cwyna, L., Fisher, D., Gkinis, V., Long, A., Lowe, J., Newnham, R. and Weiss, H. (2018) Formal ratification of the subdivision of the Holocene Series/ Epoch (Quaternary System/Period): Two new Global Boundary Stratotype Sections and Points (GSSPs) and three new stages/ subseries, *Episodes,* 41: 213-223.

Wanner, H., Mercolli, L., Grosjean, M. and Ritz, S. P. (2015) Holocene climate variability and change; a data-based review, *Journal of the Geological Society,* 172: 254-263.

Wanner, H., Solomina, O., Grosjean, M., Ritz, S. P. and Jetel, M. (2011) Structure and origin of Holocene cold events, *Quaternary Science Reviews,* 30: 3109-3123.

Willemse, N. W. (2002) *Holocene sedimentation history of the shallow Kangerlussuaq lakes, West Greenland. Monographs on Greenland, Geoscience* Copenhagen:

Museum Tusculanum Press, 48 pp.

Williams, J. W., Grimm, E. C., Blois, J. L., Charles, D. F., Davis, E. B., Goring, S. J., et al. (2018) The Neotoma Paleoecology Database, a multiproxy, international, community-curated data resource, *Quaternary Research,* 89: 156-177.

Wolfe, N., Dunavan, C. and Diamond, J. (2007) Origins of Major Human Infectious Diseases, *Nature,* 447: 279-83.

Young, D., Green, C., Batchelor, C., Austin, P., Elias, S., Athersuch, J. and Lincoln, P. (2020) Macrofossil evidence of alder (*Alnus* sp.) in Britain early in the Late Glacial Interstadial: implications for the northern cryptic refugia debate, *Journal of Quaternary Science,* 36: 40-55.

Zalasiewicz, J., Waters, C. N., Ellis, E. C., Head, M. J., Vidas, D., Steffen, W., et al. (2021) The Anthropocene: comparing its meaning in geology (chronostratigraphy) with conceptual approaches arising in other disciplines, *Earths Future,* 9: e2020EF001896.

Zanon, M., Davis, B. A. S., Marquer, L., Brewer, S. and Kaplan, J. O. (2018) European Forest Cover During the Past 12,000 Years: A Palynological Reconstruction Based on Modern Analogs and Remote Sensing, *Frontiers in Plant Science,* 9: 253.

Zolitschka, B., Francus, P., Ojala, A. E. K. and Schimmelmann, A. (2015) Varves in lake sediments – a review, *Quaternary Science Reviews,* 117: 1-41.

5. Publications

5.1. Paper I.

Hydrobiologia
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PRIMARY RESEARCH PAPER

Nutrient availability affected shallow-lake ecosystem response along the Late-Glacial/Holocene transition

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Abstract Shallow lowland lakes undergo long-lasting natural eutrophication processes, which can be studied through the development of communities of aquatic organisms. However, records showing millennial-scale trophic status variability in these water bodies are rare. Two radiocarbon-dated sedimentary profiles from former (now destroyed by brown coal mining) Lake Komořany (Central Europe, Czech Republic) served for a multi-proxy study of biological remains (diatoms, chironomids, pollen) supplemented by X-ray fluorescence (XRF) and loss-on-ignition (LOI). The age–depth model and palynostratigraphy confirm a continuous Late-Glacial to Early-Holocene record. The results suggest consistent in-lake conditions with high nutrient availability since the lake origin in the Late-Glacial period. A distinct shift at the Late-Glacial/Holocene boundary evidenced by an enhancement in diatom valve concentration and a lithological interface was foregone by a qualitative change in diatom and chironomid assemblages along with rise in LOI. It suggests that a major transformation occurred before the onset of the Holocene. As this qualitative change was characterized by a decrease in relative abundance of nutrient-demanding species, we propose an indirect climatic control by means of nutrient availability as the main driver of the aquatic species composition.

Keywords Central Europe · Diatoms · Chironomids · Pollen · Lake ontogeny · Climate change

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Introduction

Abrupt climatic changes connected with the Late-Glacial/Holocene (LG/H) transition distinctly altered the species composition of terrestrial (e.g. Lotter, 1999; Hošek et al., 2014; Orbán et al., 2018) and freshwater communities (e.g. Goslar et al., 1993; Birks & Ammann, 2000; Heiri et al., 2014) in Europe. Lacustrine sediments serve as sensitive natural archives of these environmental changes (Cohen, 2003). Temperate shallow lakes provide a separate and highly complex category of sedimentary records due to their polymictic regime and distinct influence of macrophyte vegetation to ecosystem dynamics (Scheffer, 2004; Bennion et al., 2010). They can remain in a stable state supported by various mechanisms until crossing the critical nutrient threshold, leading to a change in the lake's trophic state (Scheffer 1990; Jeppesen et al., 1998; Scheffer & Van Nes, 2007).

The trophic state development of shallow lowland lakes is driven by natural and anthropogenic factors (Cohen, 2003; Nõges et al., 2003). Although great attention is paid to human-induced eutrophication, shallow lowland lakes naturally tend towards a higher trophic state. Limited stratification in shallow basins prevents phosphorus losses to the hypolimnion and furthermore sustains phosphorus recycling at the water–sediment interface (Scheffer, 2004), which is favoured by a large bottom surface-to-water volume area ratio (Wetzel, 2001). Higher mean temperatures in low altitudes may further naturally enhance the input of nutrients due to faster weathering (Cardoso et al., 2007) but simply the large ratio between the catchment and lacustrine area and the terminal position in the hydrological cycle cause natural eutrophy (Cremer et al., 2004). Fortunately, the past trophic state can be estimated from the sedimentary record without directly measuring it. Such reconstructed past environmental conditions are based on multi-proxy studies combining sedimentary characteristics and biotic variables (Birks & Birks, 2006). For trophic state reconstruction, diatom and chironomid indicators are often used for their sensitivity to diverse aspects of trophic conditions (Brodersen & Lindegaard, 1999; Hall & Smol, 2010). Diatom and chironomid species composition is also affected by other factors including the abundance and diversity of macrophytes (Sayer et al., 1999; Brodersen et al., 2001; Sayer et al., 2010; Vermaire et al., 2013; Tarrats et al., 2018), water depth (Bennion, 1995; Barley et al., 2006) and chironomids additionally to the oxygen level (Brodersen & Quinlan, 2006). Despite this, and because of that their paleorecords represent an imprint of various environmental driving factors, diatoms and chironomids have a great potential to elucidate complex shallow-water ecosystem changes.

Although shallow lakes frequently occur in Central Europe, few studies have investigated the response of the lacustrine ecosystem to the LG/H transition in lowland shallow lake basins in this region. Shallow thermokarstic lakes in Poland (Apolinarska et al., 2012; Drzymulska et al., 2015; Gałka et al., 2015; Kołaczek et al., 2015; Pedziszewska et al., 2015; Mendyk et al., 2016; Zawiska et al., 2019) demonstrate lacustrine development along the gradient of glacier influence depending on the position towards the line of glaciation (Mirosław-Grabowska & Zawisza, 2018). German lowlands provide records of Holocene onset from the deeper Sacrower See (Kirilova et al., 2009; Enters et al., 2010) and shallow floodplain lakes of the Jeetzel Valley (Turner et al., 2013, 2014). Late-Glacial sediments were studied in the Pannonian Basin in paleolake Šúr (Petr et al., 2013) and in the largest lake of Central Europe—Balaton (Sümegi et al., 2008). In the Czech Republic, paleolimnological studies of the LG/H transition in shallow lowland lakes are lacking. From Czech non-montane localities at middle altitudes, a detailed record of the LG was found in the former Lake Švarcenberk (Pokorný & Jankovská, 2000; Hošek et al., 2014) and the LG/H transition was documented in the shallow lake Velanská Cesta (Bešta et al., 2009). Our target locality, Lake Komořany, reached the largest surface area (max ~ 25 km^2) compared to other shallow lakes in the region of the Czech Republic.

A relatively high trophic state and ingrowth by aquatic plants were recorded in the Early Preboreal in Lake Komořany (Jankovská, 1983; Řeháková, 1983, 1986; Jankovská & Pokorný, 2013) but the initial trophic state of this lake before the climate change at the LG/H transition remains unexplored. As European shallow lowland lakes have undergone long-lasting cultural eutrophication (Anderson, 1995) since the Neolithic Age (Dreßler et al., 2011), scarce opportunities exist to study their dynamics and climatic relations without anthropogenic impact. Therefore, the reconstruction of past climatically induced trophic state changes at the LG/H transition may reveal important mechanisms hardly accessible by the research of more recent records.

The aim of this study is to investigate the response of a very shallow large lowland lake ecosystem to climatic changes at the LG/H transition. By analysing sedimentary diatoms, chironomids, pollen and geochemistry, we specifically aim to (i) detect effects of the climate on the lacustrine biota and (ii) reconstruct possible trophic state changes during the investigated period.

Study site

The former Lake Komořany was situated in northwestern Bohemia, the Czech Republic, at the foothills of the Krušné Mountains at 230 m a. s. l. (50°32′N, 13°32′E) (Fig. 1). Its origin is likely linked to a Late-Glacial landslide event and the subsequent damming of the Bílina River (Hurník, 1969). This lowland, large (max. surface area ~ 25 km^2) and very shallow lake (max. depth ~ 10 m) represented a unique water body type among other localities available in the region (Vondrák et al., 2015). The lake was gradually filled in with sediment until the artificial draining of its last remains (~ 2 km^3) and surrounding mires in 1834 (Pokorný, 1963). Unfortunately, the last remnants of the unique lake sediment archive were destroyed in the 1980s by surface coal mining, because of an overlying Tertiary coalfield located in the Most Basin. However, several profiles were taken just before the complete removal of sediments and have been stored for further research (Jankovská, 1983, 1984, 1988; Jankovská & Pokorný, 2013).

Although its sediments have been investigated since the 19th century (Wettstein, 1896; Lühne, 1897), most studies have dealt with vegetation succession during the Holocene while the Late-Glacial (LG) record was only considered marginally (Rudolph, 1926; Losert, 1940; Neustupný, 1985). Similarly, the research of diatom succession was systematically conducted only in the Holocene sedimentary sequence (Řeháková, 1983, 1986; Bešta et al., 2015; Houfková et al., 2017). Our study presents the first multi-proxy research of the Lake Komořany record representing the LG/H transition based on the basal part of the profiles PK-1-L and PK-1-M.

Materials and methods

Sampling and lithology

Studied profiles PK-1-L and PK-1-M were sampled from the bottom of the former Dřínov reservoir by V. Jankovská, J. Kyncl, J. Klápště and J. Beneš in 1987 using Kubiena tins (50 × 10 × 8 cm metal boxes with one 50 × 10 cm side open). The profiles were stored at 4°C until 2008 when they were lithologically described and subsampled.

The basal parts of the profiles PK-1-L (128–143.6 cm) and PK-1-M (134–148 cm) were chosen for further analyses due to their supposed LG age. PK-1-L was subsampled at regular intervals of 2 mm (in two sections in depth of 139.4–140 cm and 142–143.6 cm at intervals of 4 mm) and processed for diatom, pollen and X-ray fluorescence (XRF) analyses. PK-1-M was subsampled at regular intervals of 1 cm and provided sufficient material for chironomid analysis. This was done due to low chironomid head capsule concentration in the sediment (see also Houfková et al., 2017) and the resulting need for relatively large samples (> 8 g of dry sediment). Additionally, XRF analysis was also processed on samples from PK-1-M.

The frequency and size of silica grains were subjectively monitored using a light microscope in parallel to diatom analysis in the profile PK-1-L. Four categories of clastic silica quantity were determined using a nominal scale: 0—grains absent or negligible, 1—grains rare, 2—grains common, 3—grains abundant and larger pieces (> 100 µm) present.

Chronology

Five bulk samples from the PK-1-L profile were dated by ^{14}C AMS at the Center for Applied Isotope Studies (CAIS), University of Georgia, USA (Table 1). A Poisson-process deposition model (Bronk Ramsey, 2008) with k = 2.5 (Bronk Ramsey & Lee, 2013) based on the IntCal 13 calibration curve (Reimer et al., 2013) was constructed using the OxCal 4.2.4 application (Bronk Ramsey, 2013) with a boundary at the depth of 134 cm where sedimentation rate changed considerably. The basal bulk sample of the PK-1-M profile was dated using the same methods to date the start of sedimentation. The profiles were correlated by

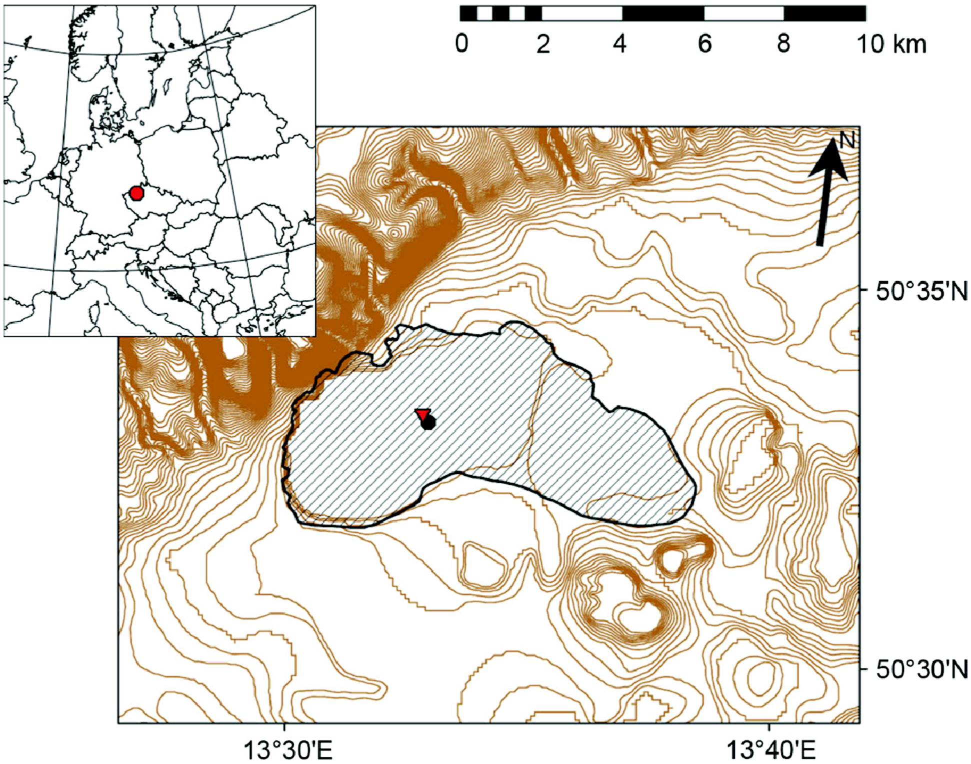


Fig. 1 Map of the study site with locations of the cores. The location of the former Lake Komořany (Czech Republic, Central Europe) indicated by a red dot. The location of the profiles PK-1-L (black dot) and PK-1-M (red triangle) indicated inside the estimated maximal area of the lake (hatched area) using a 230 m a. s. l. threshold, taken after Bešta et al. (2015)

the fitting of Rb/Sr ratio curves acquired using XRF (Fig. 2).

Diatom analysis

The diatom record was analysed from 2-mm-thick layers in 0.4–0.6-mm intervals from the core PK-1-L. In total, 32 samples were processed from the depth interval of 128–143.6 cm. Laboratory processing and the subsequent quantitative analysis of diatom content followed standard procedures (Battarbee et al., 2001). After boiling in 30% hydrogen peroxide, the subsamples were carefully rinsed with distilled water. Purified solutions were thinned and an accurate volume gauged onto cover slides. Permanent mounts were created using Naphrax® mounting resin. The concentration of valves per dry weight (DW) of sediment was estimated using divinylbenzene microspheres as an internal standard.

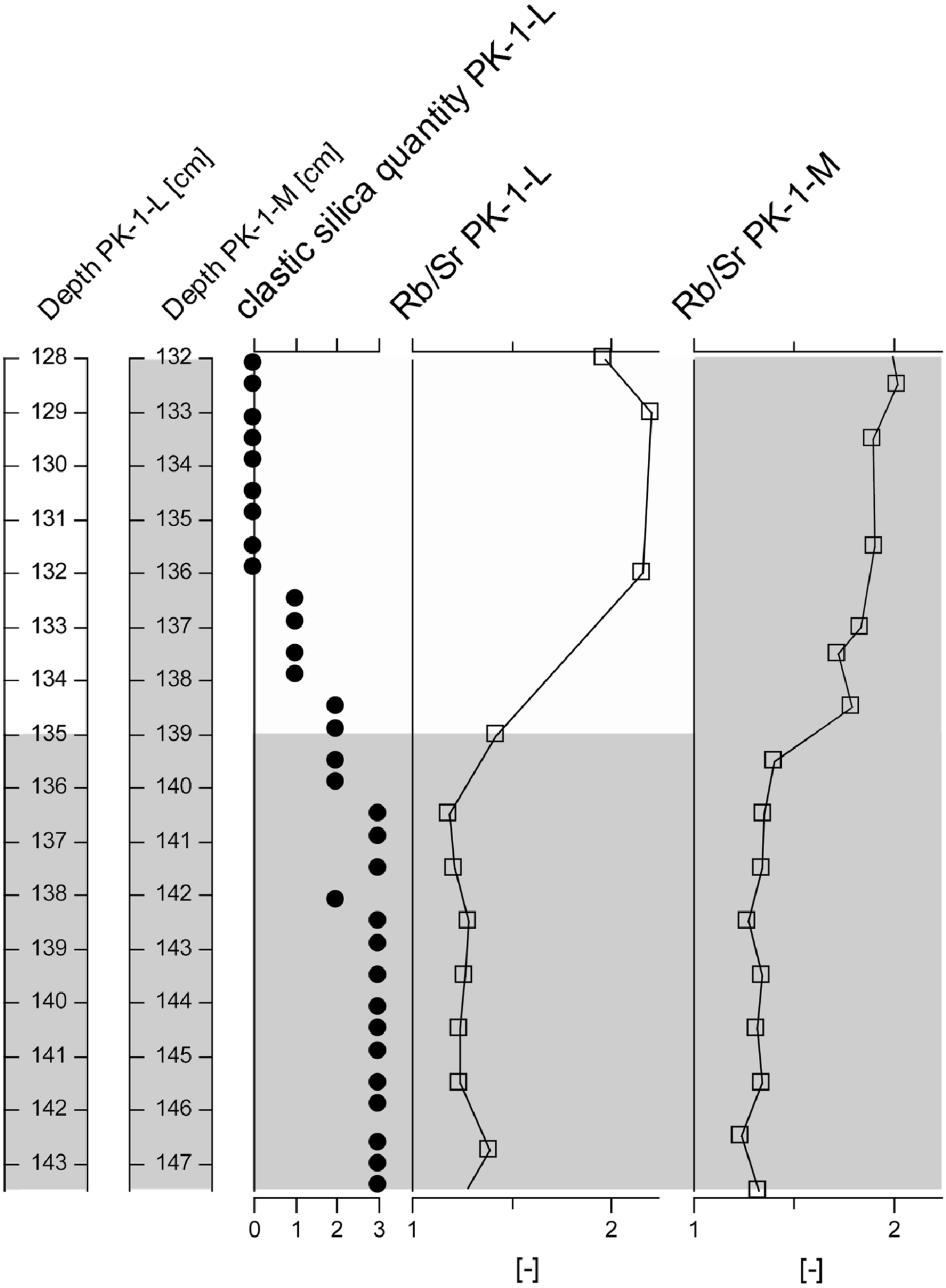
At least 500 diatom valves were counted in each sample excluding dominant fragilarioid taxa (i.e. $> 30\%$: *Staurosira construens* f. *construens* Ehrenberg, *Staurosira construens* f. *venter* (Ehrenberg) Bukhtiyarova). The dominants were enumerated

Table 1 List of radiocarbon dates from the PK-1-L and PK-1-M profiles, Lake Komořany

Sample ID (UGAMS#)	Profile	Depth (cm)	^{14}C age (year BP)	±	^{14}C age (cal year BP; interval of 95.4 probability)
10,365	PK-1-L	114.2	8,420	30	9,555–9,140
9,461	PK-1-L	134	9,960	30	12,020–11,195
10,366	PK-1-L	136.5	10,940	30	13,100–12,670
10,367	PK-1-L	139.5	12,640	35	15,465–14,230
9,462	PK-1-L	144.5	13,130	40	16,265–15,230
9,463	PK-1-M	147	13,810	40	15,449–15,109

The uncalibrated dates (^{14}C age) and their intervals (±) are quoted in radiocarbon years before 1950 AD (year BP). Intervals of calibrated dates (cal year BP) are counted using Poisson-process deposition model in OxCal 4.2.4 (Bronk Ramsey, 2013) using IntCal13 calibration curve (Reimer et al., 2013)

Fig. 2 Lithology and correlation of the profiles PK-1-L and PK-1-M. Clastic silica quantity from profile PK-1-L quoted in four categories: 0—grains absent or negligible, 1—grains rare, 2—grains common, 3—grains abundant and larger pieces (> 100 µm) present. Rb/Sr ratios plotted for both profiles. Clayey gyttja represented by a grey background, layered gyttja represented by a white background



separately in the resolution of 100 valves per sample. A similar approach has been already adopted in several studies (e.g. Battarbee, 1986; Heinsalu et al., 2008; Demiddele et al., 2016) in the case of a high abundance of fragilarioid taxa. Diatom slides were observed under × 1,000 magnification using the light microscope Nikon Eclipse E400 with a Canon EOS650D camera. Determination followed Krammer & Lange-Bertalot (1986, 1988, 1991a, b), Krammer (2000, 2002, 2003) and Lange-Bertalot (2001). Nomenclature was updated according to AlgaeBase (Guiry & Guiry, 2019) and unified with the approach of last diatom analyses from Lake Komořany (Bešta et al., 2015; Houfková et al., 2017). Autecology of constituent taxa was specified using mainly Denys (1991) and Van Dam et al. (1994) and complemented with information from determination literature where necessary.

Chironomid and other Diptera analyses

For chironomid analysis, 14 1-cm-thick layers from the core PK-1-M were used (depth interval of 130–144 cm according to PK-1-L profile's scale). A known weight of dry sediment (8.6–22.3 g) was deflocculated in 1% potassium hydroxide at 70°C for 20 min and washed with distilled water onto a sieve with 100-µm mesh size. The remaining material was transferred from the sieve into a modified Sedgewick-Rafter counting chamber and all head capsules were picked with a needle using a stereomicroscope (×40 to ×50 magnification). After dehydration in 80% ethyl alcohol, head capsules were mounted on slides in Euparal® mounting medium and identified using a light microscope (125 to ×250 magnification). Taxonomical and autecological determination mainly follows Wiederholm (1983) and Brooks et al. (2007). When mentum was damaged or worn and mandibles or premandibles were not available, a higher taxonomic group was identified. Chironomid head capsule concentration was estimated by counting all head capsules in the samples.

Pollen analysis

Pollen analysis was conducted on the same samples as diatom analysis, i.e. from 2 mm-thick layers in 0.4–0.6-mm intervals from the core PK-1-L (128–143.6 cm depth). Sediment samples were boiled in potassium hydroxide, sieved, acetolysed and incubated in fluoric acid according to Faegri & Iversen (1989). A known quantity of *Lycopodium* spores (three tablets) was added to each sample prior to the treatment to determine the absolute pollen concentration (Stockmarr, 1971). Pollen was counted under a Nikon Eclipse 80i optical microscope at magnifications of × 400 to × 1000. At least 500 pollen determinations were conducted per sample. Taxonomic identifications followed Punt (1976), Eide (1981), Punt & Clarke (1980, 1981, 1984), Punt et al. (1988, 1995, 2003), Punt & Blackmore (1991), Beug (2004) and Punt & Hoen (2009). Reworked pollen grains of presumably the Tertiary period were identified according to Stuchlík (2001).

Numerical analysis

Significant diatom (DAZ), pollen (PAZ) and chironomid (CAZ) assemblage zones were based on CONISS (Constrained Incremental Sums of Squares) (Grimm, 1987). From chironomid and diatom dataset, uncertain gathering categories were excluded for further clustering using R 3.2.4 (R Core Team, 2016). From the pollen dataset, unidentified objects and Tertiary and aquatic plants' pollen were removed. Relative species abundances were processed by Hellinger transformation prior to clustering by CONISS and testing by the Broken-Stick model (MacArthur, 1957; Legendre & Legendre, 1998). Diatom assemblage zones (DAZ) were calculated both from the entire assemblage and from dominant-free species data (without taxa > 30%: *Staurosira construens* f. *construens*, *Staurosira construens* f. *venter*).

Geochemistry

Dry weights of sediment samples were determined by drying them at 105°C for six hours during diatom analysis and at 50°C for 24 h during chironomid analysis (Boyle, 2001) in order to obtain standardized sediment weights for quantitative analysis of the biological proxies.

Loss-on-ignition (LOI) analysis was conducted at 550°C for 4 h according to Heiri et al. (2001) to quantify the relative proportion of organic matter in the sediment.

For the X-ray fluorescence measurements (XRF), a Delta Professional Handheld XRF analyser with 9-mm (uncollimated) spot size was used. Every 1-cm-thick layer was exposed three times for 3 min with two beams in "Geochem mode"—the first beam of up to 11 keV for lighter elements for 90 s and a second beam of up to 50 keV for heavier elements for 90 s. Presented data (%) are arithmetic averages from the three measurements.

Results

Lithology

A sharp lithological interface between clayey and layered gyttja was observed at the depth of 135 cm in the PK-1-L profile (Fig. 2). The PK-1-M profile was created by clayey gyttja without remarkable lithological change. The concentration of clastic silica decreased around the lithological boundary towards the Holocene and larger grains disappeared (Fig. 2). The Rb/Sr ratio increased 1.5 times at the lithological boundary in the PK-1-L profile (Fig. 2).

Chronology

A Poisson-process deposition model (Fig. 3) based on five radiocarbon data (Tab. 1) demonstrated a change of sedimentation rate at the lithological interface in the profile PK-1-L. The studied depth interval covered period ~ 15,600–10,800 cal year BP. The sedimentation rate of the clayey gyttja (depth 143.6–135 cm) was 430 year/cm on average, while the average sedimentation rate of layered gyttja (depth 135–128 cm) was 160 year/cm.

Diatom record

Altogether, 105 diatom taxa were observed in the 32 studied samples. The diatom valve concentration allowed to achieve the intended total counts in all samples with the exception of the most basal one (143.2–143.6 cm). The layered gyttja provided generally higher concentrations of diatom valves than the clayey gyttja from the basal part of the profile (Fig. 4).

Tiny fragilarioid taxa (*Staurosira* Ehrenberg, *Staurosirella* Williams & Round, *Pseudostaurosira* Williams & Round) predominated along the whole studied interval. The diatom relative abundance record was divided into two significant diatom assemblage zones, (DAZ 1, DAZ 2) and the second zone was divided into two non-significant subzones (Fig. 4).

DAZ 1 (143.6–136.2 cm, 15,600–12,600 cal year BP) was characterized by the dominance of *Staurosira construens* f. *venter*, accompanied by subdominant *Staurosira construens* var. *binodis* (Ehrenberg) Hamilton and *Fragilaria heidenii* Østrup. *Pseudostaurosira polonica* (Witak & Lange-Bertalot) Morales & Edlund, *Gyrosigma acuminatum* (Kützing) Rabenhorst and *Planothidium joursacense* (Héribaud-Joseph) Lange-Bertalot reached a considerable abundance (> 0.5%) within this zone only. *Aulacoseira ambigua* (Grunow) Simonsen was the only noticeable representative of euplanktonic taxa in DAZ 1.

DAZ 2a (136.2–131.2 cm, 12,600–11,100 cal year BP) started with a gradual increase in the total concentration of diatom valves. *S. construens* f. *venter* declined, and consequently *Staurosira construens* f. *construens* became dominant after the distinct increase in its relative abundance. *Staurosirella pinnata* (Ehrenberg) Williams & Round rose slightly at the beginning of the zone, whereas *S. construens* var. *binodis* decreased in abundance at the end of the zone. Two other euplanktonic taxa *Lindavia* cf. *balatonis* (Pantocsek) Nakov et al. and *Staurosirella berolinensis* (Lemmermann) Bukhtiyarova reached noticeable relative abundance beside *A. ambigua* being continuously present. The upper subzone boundary was defined using CONISS with excluded dominant taxa only.

DAZ 2b (131.2–128 cm, 11,100–10,800 cal year BP) reflected growth of less abundant motile benthic taxa *Geissleria schoenfeldii* (Hustedt) Lange-Bertalot & Metzeltin, *Navicula laterostrata* Hustedt, *Navicula radiosa* Kützing and *Sellaphora vitabunda* (Hustedt) Mann, accompanied by *Fragilaria capucina* s. l. Desmazières. Prevailing *S. construens* f. *construens* remained without any significant change. *S. construens* f. *venter* rose slightly, whereas relative abundance of *S. construens* var. *binodis* and all euplanktonic species decreased.

Chironomid and other Diptera records

A total number of 35 chironomid and two other dipteran morphotaxa were identified at the studied depth interval separated into 14 1-cm-thick layers (Fig. 5, Table 2). The concentration of head capsules was extremely low and oscillated between two and six individuals per gram of dry sediment. To produce statistically robust reconstructions and associated interpretations, large samples of dry weight from 9 to 23 g were analysed. The subsequent picking of head capsules yielded 29–110 individuals per sample. Chironomid abundance decreased temporarily at the depth of 140.5 cm and from 135.5 cm started to decrease continually towards the onset of the Holocene. Due to poor preservation, some of the findings were identified only to genus or subfamily level. *Chironomus plumosus*-type, *C. anthracinus*-type, and *Procladius* were the most abundant taxa along the studied profile. Two significant chironomid assemblage zones were defined (CAZ 1 and 2).

CAZ 1 (143.5–136 cm, 15,600–12,500 cal year BP) was characterized by the dominance of *C.*

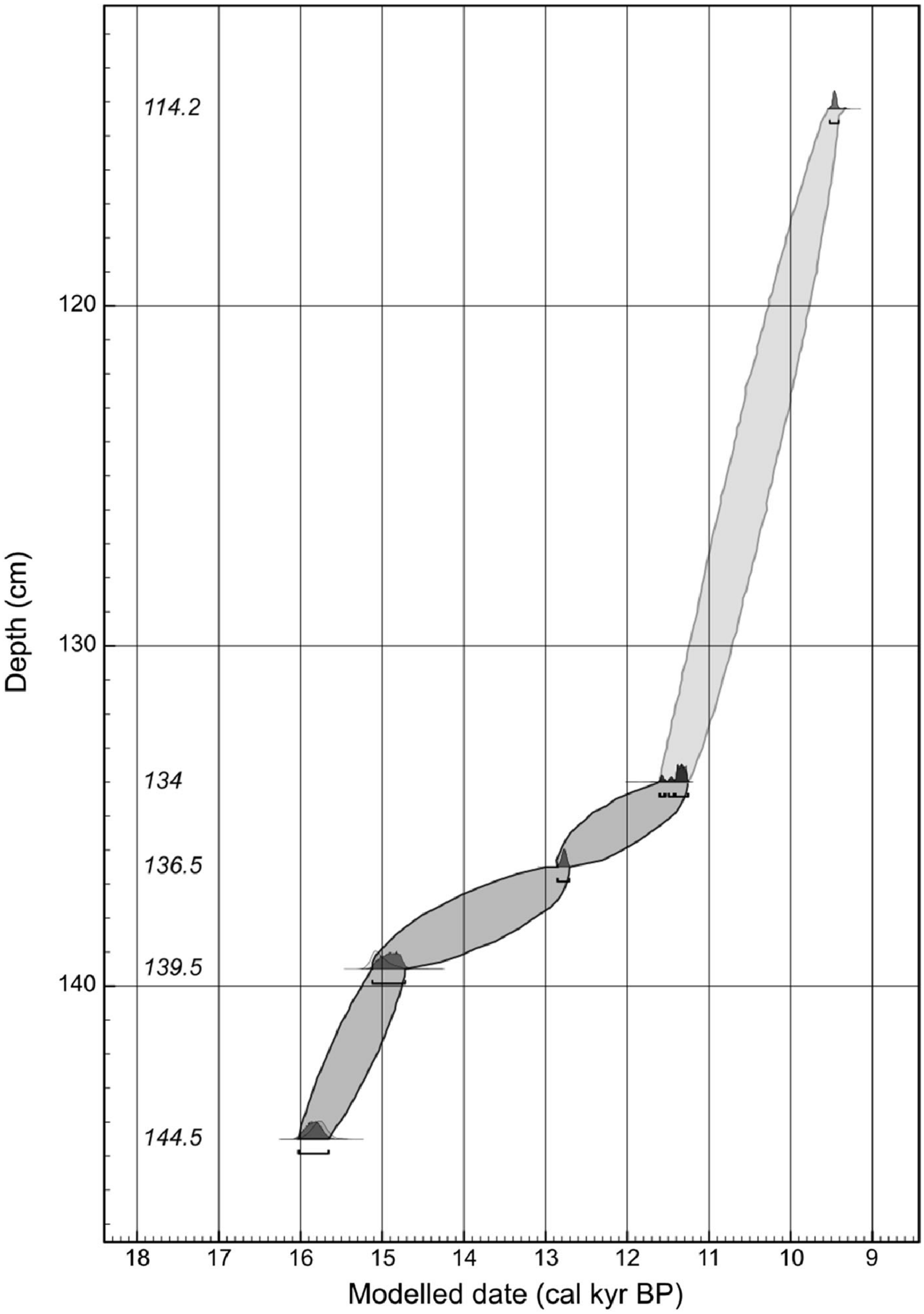


Fig. 3 Age–depth model for the profile PK-1-L. Poisson-process deposition model (Bronk Ramsey, 2008) with $k = 2.5$ (Bronk Ramsey & Lee, 2013) based on the IntCal 13 calibration curve (Reimer et al., 2013) constructed using the OxCal 4.2.4 application (Bronk Ramsey, 2013)

plumosus-type, particularly in the basal part (> 80%) and decreasing towards 24% at the depth of 140.5 cm. This temporary drop in *C. plumosus*-type relative abundance coincided with the decrease in total abundance of chironomid head capsules (number of individuals/head capsules per 1 g of dry sediment), *C. anthracinus*-type establishment and an increase in *Procladius*. Then the relative abundance of dominant *C. plumosus*-type recovered to ∼ 30–40% and the total chironomid abundance also increased. The dominant taxa (> 15% at least in one layer) were accompanied by several subdominant taxa (4–15% at least in one layer)—the *Cladotanytarsus mancus*-type, *Einfeldia dissidens/natchitocheae*-type, *Microchironomus*, *Stictochironomus rosenschoeldi*-type and *Tanytarsus lugens*-type. Several head capsules of the *T. lugens*-type had typical mandibles with three inner and two dorsal teeth but their surficial tooth was

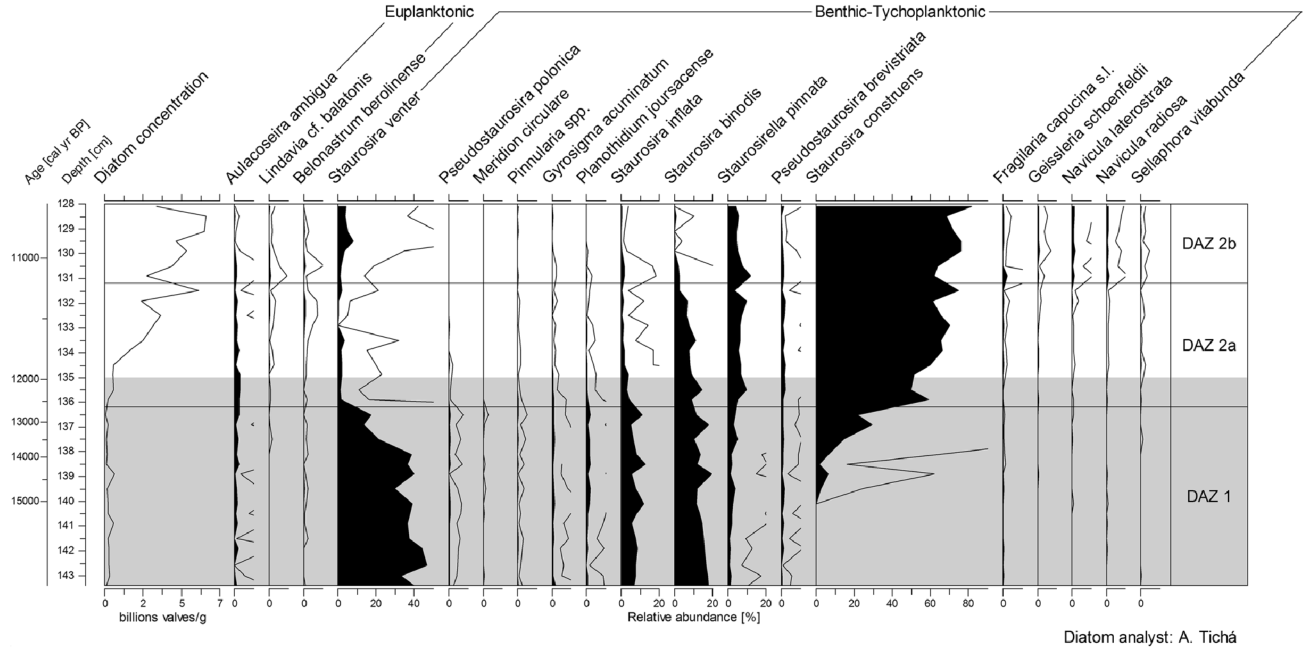


Fig. 4 Stratigraphical diagram of diatom relative abundances from the profile PK-1-L. Diatom concentration curve expressed as number of valves per 1 g of dry sediment. Relative abundances represented by a black silhouette, lines corresponding to 10 times of exaggeration. Significant diatom assemblage zones (DAZ 1, DAZ 2) and non-significant subzones (DAZ 2a, DAZ 2b) defined by CONISS (stratigraphically constrained cluster analysis) and Broken-Stick model. Clayey gyttja indicated by a grey background, layered gyttja indicated by a white background

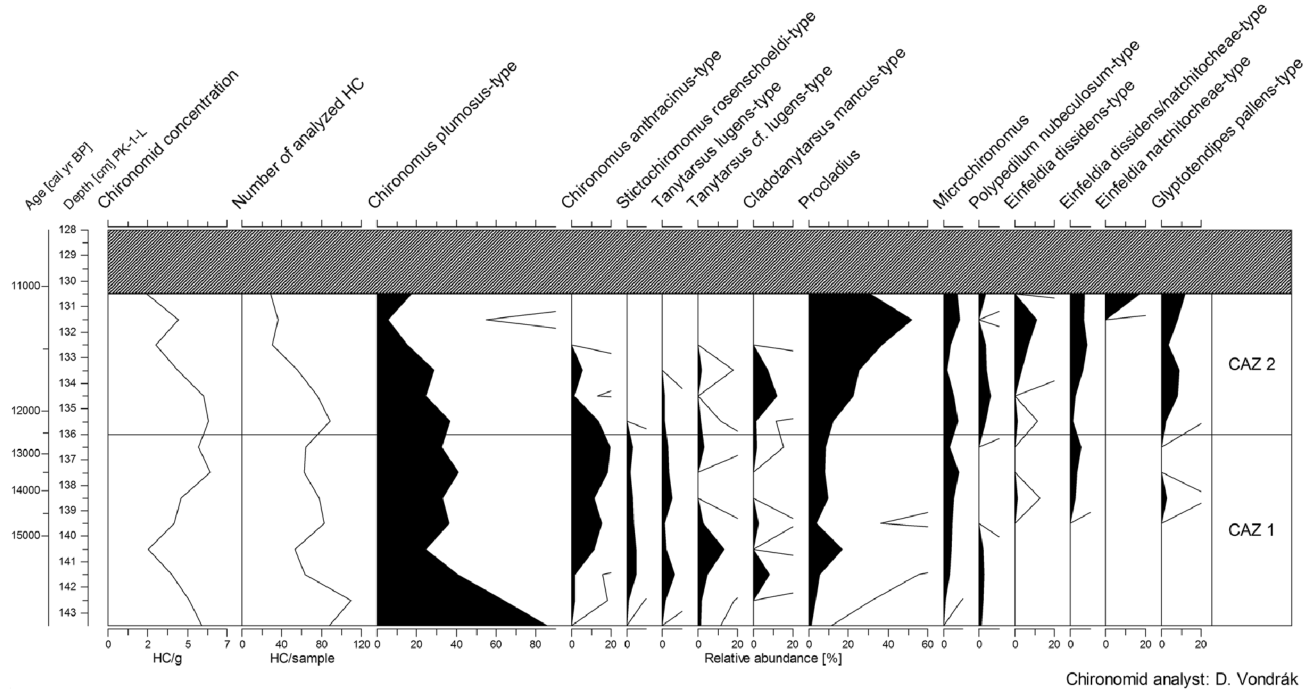


Fig. 5 Stratigraphical diagram of chironomid relative abundances from the profile PK-1-M. Depth expressed in PK-1-L depth scale. Chironomid concentration curve expressed as number of HC (head capsules) per 1 g of dry sediment. Relative abundances represented by a black silhouette, lines corresponding to 10 times of exaggeration. Significant chironomid assemblage zones (CAZ 1, CAZ 2) defined by CONISS (stratigraphically constrained cluster analysis) and Broken-Stick model. Not-studied depth interval indicated by hatched area

Table 2 List of common diatom (> 0.5%) and chironomid (> 4%) taxa found in the studied record with affiliation according to lake trophic state preferences

Trophic state preference	Diatom taxa	Chironomid taxa
Eutraphentic	*Aulacoseira ambigua*	*Chironomus anthracinus*-type
	Fragilaria heidenii	*Chironomus plumosus*-type
	Gyrosigma acuminatum	*Einfeldia dissidens*-type
	Lindavia cf. *balatonis*	*Einfeldia dissidens/natchitocheae*-type
	Staurosirella berolinensis	*Einfeldia natchitocheae*-type
		Polypedilum nubeculosum-type
Meso-eutraphentic	*Navicula radiosa*	*Cladotanytarsus mancus*-type
	Planothidium joursacense	*Glyptotendipes pallens*-type
	Staurosira construens f. *construens*	*Microchironomus*
	Staurosira construens f. *venter*	*Procladius*
	Staurosira construens var. *binodis*	*Stictochironomus rosenschoeldi*-type
Mesotraphentic	*Fragilaria capucina* s. l.	
	Geissleria schoenfeldii	
Oligo-mesotraphentic	*Pseudostaurosira polonica*	
	Sellaphora vitabunda	
Oligotraphentic		*Tanytarsus lugens*-type*? Tanytarsus* cf. *lugens*-type
Indifferent	*Pseudostaurosira brevistriata*	
	Staurosirella pinnata	

Species ecology is based on observations summarized by Wiederholm (1983), Van Dam et al. (1994) and Brooks et al. (2007). *S. construens* f. *construens* and *S. construens* f. *venter* not included in the Fig. 7

strongly reduced. These findings are presented as the *T.* cf. *lugens*-type.

CAZ 2 (136–130.5 cm, 12,500–11,000 cal year BP) showed a gradual decline of *C. plumosus*-type as well as a decline in the total abundance of head capsules in the sediment. *Procladius* increased distinctly in reverse and became the most abundant taxon. Besides these two taxa, only *Einfeldia natchitocheae*-type exceeded the relative abundance of 15% in the uppermost layer. *C. anthracinus*-type and *T.* (cf.) *lugens*-type progressively disappeared from the record. *Stictochironomus rosenschoeldi*-type was completely missing, *Microchironomus* remained present, *Cladotanytarsus mancus*-type reappeared in the lower half of the CAZ 2 and disappeared again at 133 cm and the *Einfeldia dissidens/natchitocheae*-type increased. In addition, several new subdominants (relative abundance of 4–15%) appeared—the *Einfeldia dissidens*-type, *Polypedilum nubeculosum*-type and *Glyptotendipes pallens*-type.

Besides the chironomid remains, the presence of *Chaoborus flavicans* (Meigen, 1830) mandibles in both CAZ 1 and CAZ 2, and one head capsule of family Simuliidae in CAZ 2 was documented.

Pollen record

Three significant pollen assemblage zones (PAZ) were determined (Fig. 6) with a total of 107 pollen and spore types recorded. Pollen types of Tertiary origin numbering 15 were recorded mainly in PAZ 1. The recovered pollen grains were well preserved. Total pollen concentration reached ca 1.7–5 × 10^5 grains g^{-1} in PAZ 1 and amplified to ca 1–2.5 × 10^6 grains g^{-1} in PAZ 2 and 3. *Pinus sylvestris*-type and *Betula pubescens*-type pollen were the most abundant (~ 70–80%) in PAZ 1 (143.3–135.7 cm, 15,600–12,300 cal year BP). Pollen of shrubs (*Juniperus*, *Salix* and *Alnus alnobetula*) reached ~ 5% abundance and non-arboreal pollen (NAP) ~ 20–30%. Aquatic species were above all represented by pollen of the *Myriophyllum spicatum*-type, *Alisma plantago-aquatica*-type and *Oenanthe fistulosa*-type. Some rare and rather thermophilous species such as

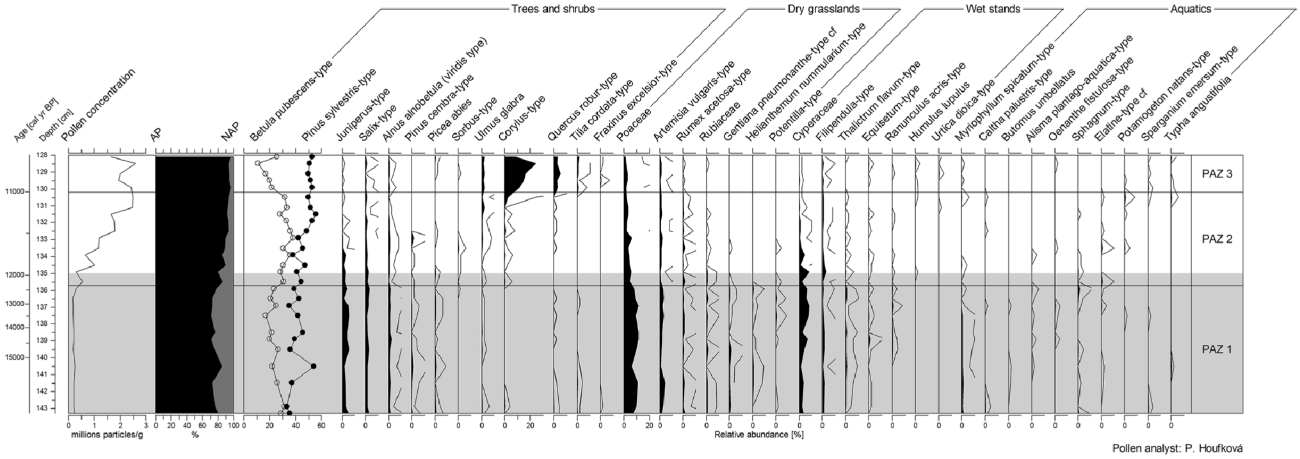


Fig. 6 Stratigraphical diagram of pollen relative abundances from the profile PK-1-L. Pollen concentration curve expressed as number of particles per 1 g of dry sediment. Relative abundances of AP (arboreal pollen) represented by a black silhouette, relative abundances of NAP (non-arboreal pollen) represented by a dark grey silhouette. Relative species abundances represented by black silhouettes, lines corresponding to 10 times of exaggeration. Significant pollen assemblage zones (PAZ 1, PAZ 2, PAZ 3) defined by CONISS (stratigraphically constrained cluster analysis) and Broken-Stick model. Clayey gyttja indicated by a grey background, layered gyttja indicated by a white background

Butomus umbellatus were recorded. The pollen of light demanding species (the *Corylus avellana*-type), the deciduous species of the Quercetum mixtum (the *Quercus robur*-group, *Tilia cordata*-type, *Ulmus*-type and *Fraxinus excelsior*-type) and *Picea*-type were of extremely low abundance. By the end of the zone, spores of *Sphagnum* and pollen of the *Elatine*-type were recorded. An increase in the abundance of the pollen of trees and shrubs of up to 90% proceeded in PAZ 2 (135.7–130.2 cm, 12,300–11,000 cal year BP). In PAZ 3 (130.2–128 cm, 11,000–10,800 cal - year BP), pollen of the *Corylus avellana* increased in abundance above 20% and was succeeded by pollen of deciduous species of the Quercetum mixtum. Hygrophilous and water species were above all represented by pollen of the *Typha angustifolia* and the *Sparganium emersum*-type.

Trophic state indication

The succession of diatom and chironomid ecological groups suggested a decreasing trend of nutrient availability during the LG/H transition (Fig. 7). The most abundant taxa of each ecological group are listed in Table 2. Diatom ecological groups are presented without dominant fragilarioid taxa; however, they remained significant owing to the exclusion of dominants since the phase of diatom valves' counting. Eutraphentic diatom species abundance decreased at the DAZ 1/DAZ 2 boundary. Similarly, eutraphentic chironomids became less abundant after the CAZ 1/CAZ 2 boundary. While meso-eutraphentic diatoms decreased later at the DAZ 2a/DAZ 2b boundary inversely to the increase of mesotraphentic and oligotraphentic diatom species, meso-eutraphentic chironomids increased at the CAZ 1/CAZ 2 boundary. Higher relative abundances of oligotraphentic chironomids in CAZ 1 were driven by *Tanytarsus lugens*-type presence (Table 2).

Diatom valve concentration increased at the LG/H boundary. Similarly, the pollen concentration of aquatic macrophytes increased slightly with the onset of the Holocene during PAZ 2 and later distinctly at PAZ 3 (Fig. 8). Both variables are in more or less direct proportion to the primary productivity of diatoms and aquatic macrophytes respectively.

Loss-on-ignition (LOI) had a distinct rising trend ranging between 1.5 and 10.4% in the LG and between 13 and 16.5% in the Holocene but it remained at a relatively low level along the whole studied interval of the PK-1-L profile (max. 16.5% at 129–129.8 cm) (Fig. 8). Fe/Mn ratio decreased twice at the lithological boundary, when average values for the LG (91.1) and for the Holocene were compared (41.2) (Fig. 8).

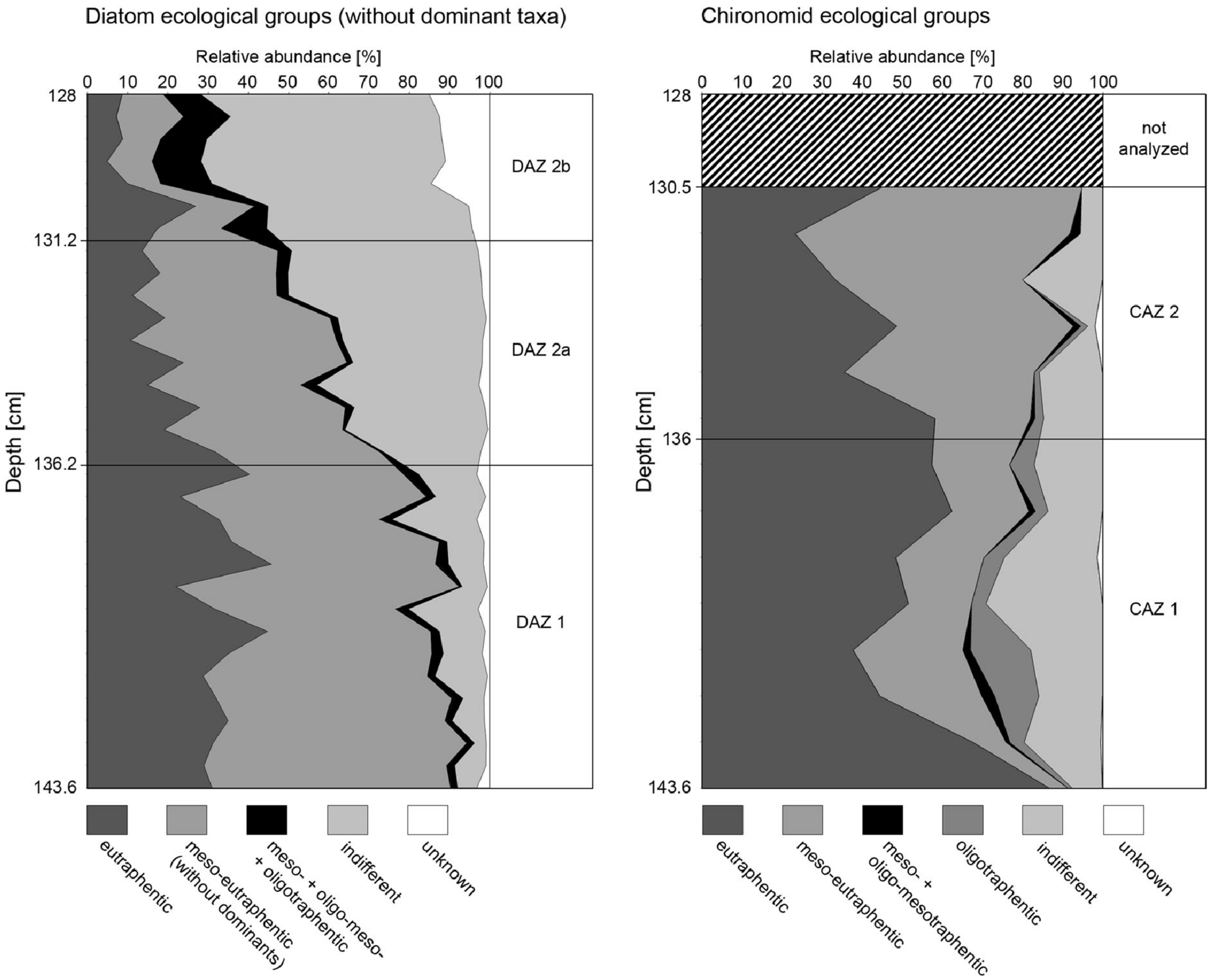


Fig. 7 Stratigraphical diagram of diatom and chironomid ecological groups. Chironomid relative abundances shown for whole assemblage, diatom relative abundances shown for assemblage counted without two dominant fragilarioid taxa. Significant diatom assemblage zones (DAZ) and chironomid assemblage zones (CAZ) defined by CONISS (stratigraphically constrained cluster analysis) and Broken-Stick model. Not-studied depth interval indicated by a hatched area

Discussion

The effect of climate on lacustrine biota

At the Late-Glacial/Holocene transition (LG/H), a gradual succession of aquatic and terrestrial biota without any sharp interface was recorded in Lake Komořany. The remarkable feature of this transition is the asynchronous change in diatom species composition and their productivity indicated by diatom valve concentration (Fig. 4). While diatom productivity abruptly increased and changed the character of sediment at the supposed LG/H boundary (135–134.5 cm, 12,000–11,700 cal year BP) (Figs. 2, 4), the main shift in both dominant and rarer diatom taxa along with change in chironomid assemblage and rise in LOI had taken place slightly before (136.5–136 cm, 12,800–12,500 cal year BP) this lithological interface (Fig. 4). Therefore, there must have been two, qualitatively different, breakthroughs in ecosystem response. The chronologically first change could have resulted from ecosystem response to the warmer second half of the Younger Dryas period (Stuiver et al., 1995) which is of considerable influence on the lowland lakes (Goslar et al., 1993; Zawiska et al., 2015) and was detected also in a diatom record from a shallow lake situated in the southern part of the Czech Republic (Bešta et al.,

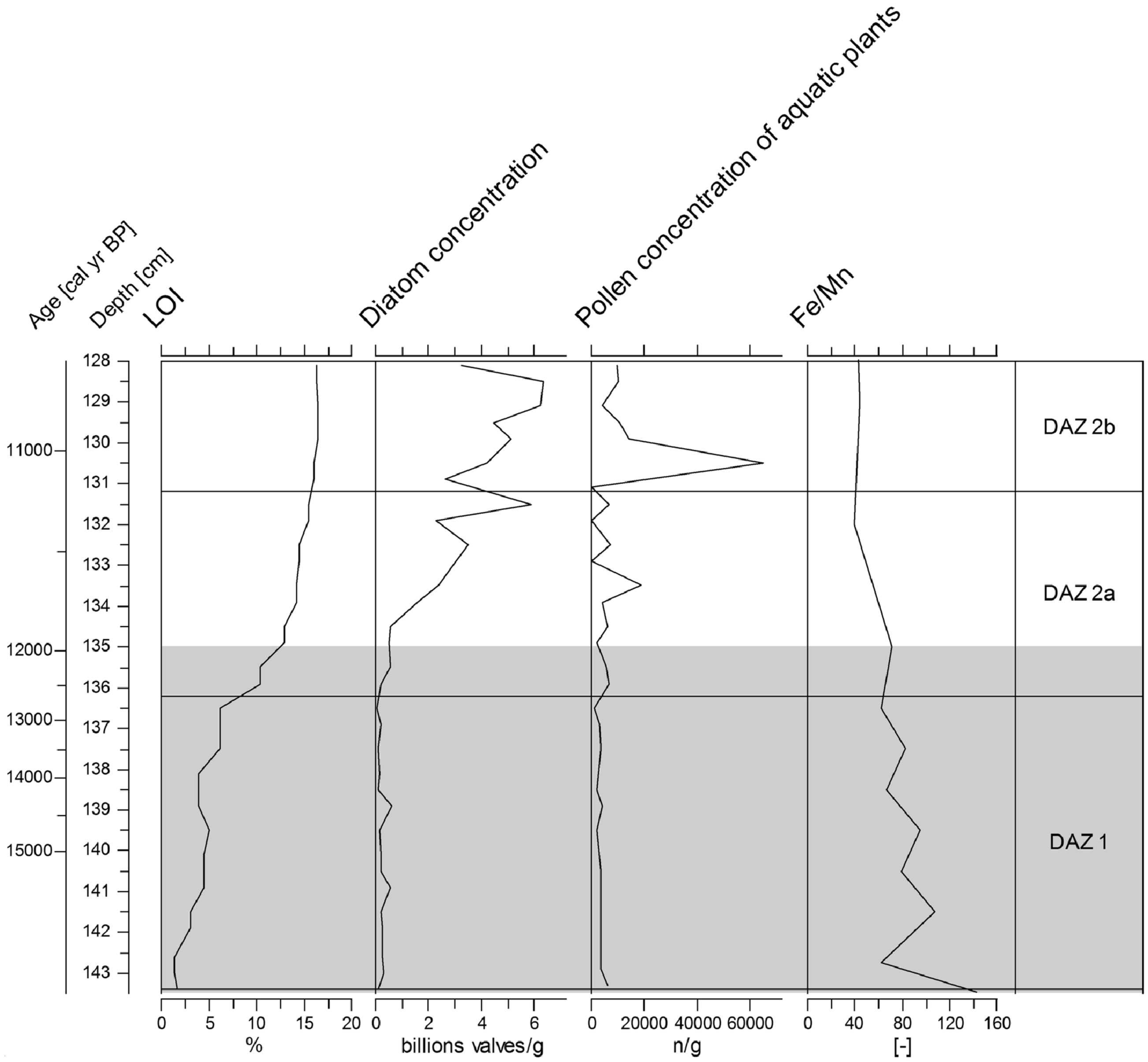


Fig. 8 Stratigraphical diagram of variables representing lacustrine trophic state from the profile PK-1-L. LOI (loss-on-ignition) represents percentages of organic matter. Diatom and pollen concentration curves expressed as number of particles per 1 g of dry sediment. Fe/Mn ratio based on XRF analysis. Significant diatom assemblage zones (DAZ 1, DAZ 2) and non-significant subzones (DAZ 2a, DAZ 2b) defined by CONISS (stratigraphically constrained cluster analysis) and Broken-Stick model. Clayey gyttja indicated by a grey background, layered gyttja indicated by a white background

2009). Although the climatic forcing of the first discussed event is far behind the resolution of our sedimentary record, we did not find another possible trigger of such changes. Therefore, we put it here as a provisional explanation, since a rather gradual process without the detection of generally accepted LG periods (e.g. Allerød) was observed in the profile. This is consonant with the view that neither a particular event nor even a biostratigraphic episode (cf. Rasmussen et al., 2014) can be distinguished for the LG terrestrial record from Lake Komořany. The second event, characterized by the abrupt rise in diatom productivity, is synchronous with the LG/H boundary (Fig. 2). It offers a bold conclusion that the first recorded change preceding the LG/H boundary was more prominent, since there was a shift in both chironomid and diatom species composition (quality), whereas only diatom valve concentration (quantity) changed during the second shift. The second quantitative shift in diatom assemblage, i.e. the increase in productivity of dominant fragilarioids, could be connected with spread of suitable littoral habitats with emergent aquatic macrophytes as the fragilarioids possibly prefer emergent substrates to colonize (Sayer et al., 1999). Whatever the case, the shift in productivity could not be biassed by enhanced sedimentation rate (allochthonous material input), since than the valve concentration had to drop.

Terrestrial vegetation showed gradual change with the continual disappearance of steppe and tundra indicators (e.g. *Artemisia*, *Helianthemum*, *Potentilla*, *Juniperus*, *Salix*, *Betula nana*, *Alnus viridis*-type) and a successive increase in wood's proportion. *Pinus* and *Betula* trees were present in the region perhaps in the form of a patchy woodland during the LG (16,300/15,200–11,700 cal year BP). Such scattered patches of hemiboreal forest, further indicated by the presence (< 1.5%) of *Pinus cembra*-type pollen (Fig. 6), were reconstructed at low altitudes in the Bohemian Massif (Kuneš et al., 2008). The spread of mixed deciduous forest starts very early with the scattered occurrence of pollen of some thermophilous trees (*Quercus robur*-type, *Tilia cordata*-type) (Fig. 6). Such early findings of these taxa are also usually thought to originate in a long-distance transport or reworked material (Pokorný, 2002; Ralska-Jasiewiczowa et al., 2004). Even though the steppe vegetation probably persisted during the Holocene in the adjacent thermophilous hilly region of České Středohoří (Pokorný et al., 2015), the pollen of the steppe elements almost disappeared from the Lake Komořany record until 5,500 cal year BP (Houfková et al., 2017).

The recorded gradual development of terrestrial vegetation documents a very limited climatic forcing of the studied lowland environment at the LG/H transition transferring to a less pronounced response of the lacustrine ecosystem. We found a distinct shift in the relative abundances of diatoms and chironomids but only minor changes in species compositions (Figs. 4, 5). An addition of several new diatom and chironomid taxa to the persisting Late-Glacial species composition rather than their complete substitution generally characterizes the changes in Lake Komořany aquatic assemblages. A similar pattern was also recorded in other lowland eutrophic lakes in central Europe at the Holocene onset (Kirilova et al., 2009; Turner et al., 2014).

Low water depth is considered as one of the driving factors causing relatively stable aquatic assemblage composition in Lake Komořany because it determines the frequency of mixing in the whole water column (Scheffer, 2004). The long-lasting shallow character of Lake Komořany could explain the predominance of diatom fragilarioid taxa known to thrive in polymictic shallow waters (Bennion, 1995). Observed diatom assemblages represent a typical pioneer species composition well known from other Late-Glacial lakes (Haworth 1976; Denys et al. 1990) and large shallow lakes in general (Heinsalu et al., 2008; Buczkó et al., 2019). This is consistent with the dominance of fragilarioid tychoplanktonic taxa throughout the existence of Lake Komořany (Bešta et al., 2015; Houfková et al., 2017). Observed invariable diatom composition indicates a shallow lacustrine character without extensive phases of deep water during the LG and weak climate forcing of the lake ecosystem. Nevertheless, subtle water-level fluctuations can be inferred from the pollen of macrophytes typical of disturbed wet stands (among others *Sphagnum* or *Elatine,* Fig. 6). The water-level rise caused by humification at the onset of the Holocene was proven by the start of sedimentation in the more elevated parts of the basin (Houfková et al., 2017). This is further supported by the outset of diatom euplanktonics *Staurosirella berolinensis* and *Lindavia* cf. *balatonis* (Fig. 4). An analogous water-level rise was also described in other European records (Magny, 2004; Bos et al., 2007). The shift to the lake with more stable littoral parts is further indicated by a presence of pollen of *Typha angustifolia* or *Humulus lupulus* ~ 11,200 cal year BP (PAZ 3) (Fig. 6).

Although the water level strongly influenced the general character of observed aquatic assemblages, it fails to explain species composition changes during the LG in Lake Komořany. Therefore, the change in trophic state was tracked as a potential prominent device in how climate indirectly influenced the lacustrine ecosystem.

Trophic state reconstruction

Our results document mesotrophic to eutrophic conditions already since the lake formation in the LG (Figs. 7, 8). Various aspects of the lacustrine trophic state were reconstructed, through aquatic macrophytes, primary productivity and nutrient availability.

Aquatic macrophytes shape the regime of shallow lakes (Jeppesen et al., 1998) and affect species composition of chironomid and diatom assemblages (Sayer et al., 1999; Brodersen et al., 2001; Vermaire et al., 2013; Tarrats et al., 2018). Even in the LG, *Myriophyllum spicatum* was a dominant component of aquatic macrophyte assemblage (Fig. 6) but absolute concentrations of aquatic macrophytes' pollen were distinctly lower than later on in the Early Holocene (Fig. 8). Nevertheless, the lower volume of water in the LG and submergent character of *M. spicatum* could have made its vegetation an important habitat for small fragilarioids and *Gyrosigma acuminatum* (Fig. 4), a diatom frequently observed on aquatic macrophytes (Dong et al., 2008). The first evidence of heightened macrophyte growth at the onset of the Holocene is documented by an increase in *Einfeldia dissidens*-type and *Glyptotendipes pallens*-type (Fig. 5), two chironomid taxa associated with aquatic macrophytes (Brodersen et al., 2001). The subsequent increase in the pollen concentration of aquatic macrophytes and the spread of broad-leaved species (*Potamogeton natans*-type, *Sparganium emersum*-type, *Typha angustifolia*) are linked with the onset of the Holocene (Fig. 6). This littoral vegetation provided more stable bottom habitats enabling the establishment of an epipelic diatom community including *Navicula radiosa* and other motile benthic diatoms (*Geissleria schoenfeldii*, *Navicula laterostrata*, *Sellaphora vitabunda*) (Fig. 4). Moreover, we must consider not only the substantial influence of aquatic macrophytes on nutrient availability by bottom stabilization but also the direct consumption of phosphorus during enhanced growth under the Holocene favourable climate. Aquatic macrophytes can affect the lacustrine trophic state as they serve as effective phosphorus sink and mitigate sediment resuspension (Canfield & Jones, 1984; Jeppesen et al., 1998). Furthermore, the lower abundance of macrophytes during the LG could strengthen the sensitivity of benthic diatoms including small fragilarioid taxa to the concentration of epilimnetic phosphorus (Werner & Smol, 2005).

Diatom and chironomid ecological groups in our record show a clear trend from more towards less nutrient-demanding taxa (Fig. 7). We attempted to reduce the influence of poor fragilarioid indicators (Bennion, 1995; Sayer, 2001; Bennion et al., 2010) by excluding the dominant *Staurosira* spp. from our assessment. Moreover, the nutrient concentration signal of remaining fragilarioid taxa (*F. heidenii*, *Pseudostaurosira brevistriata* (Grunow) Williams & Round, *P. polonica*, *S. berolinensis*, *S. pinnata*, *S. construens* var. *binodis*) was considered with caution. Such an approach provides a clear signal of decreasing nutrient availability towards the Holocene through decreasing eutraphentic and increasing meso- and oligotraphentic diatom species (Fig. 7). Additionally, the substitution of two diatom dominants, *S. construens* f. *venter* and *S. construens* f. *construens* (Fig. 4), could be explained by nutrient availability since *S. construens* f. *venter* tolerates higher concentrations of organically bound nitrogen compared to *S. construens* f. *construens* (Van Dam et al., 1994). Although the coenococcal algae *Pediastrum kawraiskyi* Schmidle, used typically as an indicator of cold and oligotrophic conditions, was found in Late-Glacial sediments of Lake Komořany (Komárek & Jankovská, 2001; Jankovská & Pokorný, 2013), its presence during cold periods in a naturally eutrophic lake documented by Turner et al. (2014) questioned the indicative value for nutrient levels. A more probable connection of *P. kawraiskyi* to low temperatures rather than low nutrient level supports our interpretation of there being relatively high nutrient levels since the LG.

Chironomid ecological preferences follow a similar trend showing a substitution of eutraphentic dominants for meso-eutraphentic taxa (Fig. 7). The most abundant chironomids of our record, namely *Chironomus anthracinus*-type, *C. plumosus*-type and *Procladius* (Fig. 5, Table 2), often produce very abundant populations in highly productive lakes with low clarity and oxygen depletion or anoxia near the bottom (Nagell & Landahl, 1978; Matěna, 1989; Hamburger et al., 1994). Characteristic cold stenothermic taxa inhabiting oligotrophic and well-oxygenated waters (e.g. the *Heterotrissocladius grimshawi*-type or *Micropsectra* spp.) are missing, although reported in many European records, including LG sediments of lowland shallow lakes (Brooks et al., 1997; Brodersen & Lindegaard, 1999; Płóciennik et al., 2011; Bos et al., 2017) or Czech LG lakes situated in elevations of above 900 m a. s. l. (Kletetschka et al., 2018). Furthermore, mesotraphentic species (e.g. the *Derotanypus* or *Corynocera ambigua*-type) present in regional mid-altitude lakes (400–900 m a. s. l.) (Hošek et al., 2014; Hájková et al., 2016) are also absent from Lake Komořany records. The only exception are rare findings of *Tanytarsus lugens*-type, a morpho-taxon typical of the profundal in oligotrophic lakes (Brooks et al., 2007).

Driving mechanisms of nutrient availability

We make the case that nutrient availability was a probable factor in the Lake Komořany ecosystem change at the LG/H transition. Similar decreases in the nutrient level at the time of the climate amelioration are known from Scandinavian (Björk, 2010), Polish (Apolinarska et al., 2012) and German lowland lakes (Kirilova et al., 2009; Turner et al., 2014). In case of Lake Komořany record, this reduction in nutrient availability was likely accompanied by changes in the catchment erosion intensity, duration of seasonal anoxia and shift in primary productivity.

1. More intensive catchment erosion during the colder and drier period could have enhanced nutrient availability in the LG. A higher input of inorganic material into Lake Komořany is clearly indicated by an increased proportion of clastic particles in the LG parts of the profiles (Fig. 2). Although a decrease of Rb at the LG/H transition corresponds with more intensive erosion from catchment during the LG (cf. Hošek et al., 2014), our lower values of Rb/Sr ratio in LG (Fig. 2) contradict trends usually observed for colder periods (Jin et al., 2006). This is caused by a distinct decrease of Sr at the LG/H transition, most likely linked to the affinity of Sr to Ca (Jin et al., 2006) and a decrease of alkalinity towards the Holocene.
2. Seasonal anoxia under prolonged winter stratification causes an internal recycling of sedimentary phosphorus (Wetzel, 2001). The presence of *Chironomus anthracinus*-type, *C. plumosus*-type and *Stictochironomus rosenschoeldi*-type during the LG (Fig. 5) suggests at least seasonally anoxic conditions near the lake bottom (Nagell & Landahl, 1978; Int Panis et al.,1995), whereas *Tanytarsus lugens*-type presence indicates well-oxygenated conditions (Brooks et al., 2007). This discrepancy could be explained by the presence of a mosaic of different habitats in the lake and a possible restriction of *T. lugens*-type (Fig. 5) to a better oxygenated environment near the inflow of the Bílina River. The above-mentioned taxa are characteristic of our LG record and disappeared or declined with the onset of the Holocene. Higher Fe/Mn ratios (Fig. 8) also suggest at least seasonal anoxic conditions leading to higher nutrient concentrations during the LG. On the other hand, we cannot rule out the possibility that anoxic conditions affected Early Holocene chironomid assemblages as well. Chironomid concentration became very low (Fig. 5) documenting unfavourable conditions. Profundal taxa decreased and were partially replaced by littoral taxa. Therefore, the effect of oxygen depletion caused by the enhanced decomposition of biomass produced after climate amelioration cannot be fully excluded.
3. Higher primary productivity in the Early Holocene was able to enhance competition for available nutrients and made them a limiting factor in contrast to the LG. Both growing terrestrial and aquatic vegetation serve as a phosphorus sink and can make nutrients unavailable for algal primary producers (Canfield & Jones, 1984; Tabacchi et al., 2000). While primary productivity rises, a phosphorus turnover in the lake increases but its instantaneous concentrations often decrease or fluctuate (Wetzel, 2001). In Lake Komořany, a higher biomass production of terrestrial and/or aquatic vegetation was suggested by an increasing proportion of organic matter in sediment (Fig. 8) and higher pollen concentration (Fig. 6). An increase of algal biomass in the Early Holocene is documented by higher diatom valve concentration (Fig. 4). Additionally, the limitation of biomass production by harsh conditions during the LG possibly allowed a higher availability of nutrients for surviving organisms. Light availability and mechanical disturbances are supposed key limiting factors for primary productivity during the LG in Lake Komořany: (a) Severe light attenuation by turbid inorganic particles is expected during the LG as a consequence of the potentially stronger input of minerogenic material by the tributary (the Bílina River). As we found only indications of a slightly higher input of particles in the LG (Fig. 2) and the sedimentation rate remained low (Fig. 3), the turbidity of particles by water column mixing seems to be a more important factor than the absolute amount of washed-in material. The potential input of

particles could also fertilize benthic algae surviving in shallower parts where physical conditions were more stable and light more available (Stevenson et al., 1996). This could thus amplify the discrepancy between the low primary productivity and the presence of the nutrient-demanding taxa. Restricted favourable habitats did not allow heightened biomass production. (b) Mechanical disturbances by turbulent water conditions or prolonged ice-cover could impede the biomass growth of algal mats and aquatic macrophytes as frequent disturbance reduces benthic biomass (Stevenson et al., 1996).

These processes could cause either lower absolute nutrient level towards the Holocene or at least raise relative nutrient availability in the LG. Although absolute nutrient concentration in the lacustrine ecosystem could be higher in the Holocene, the instantaneous nutrient availability was lower due to the fast nutrient turnover. In Lake Komořany, the presence of nutrient-demanding diatoms and chironomids in the Late-Glacial period and their subsequent decrease towards the Holocene agrees with this hypothesis. Furthermore, the same timing of main species compositional change in diatom and chironomid assemblages with the increase in organic matter proportion supports the influence of changes in catchment and/or in-lake primary productivity to ecosystem structuring. Other enriching mechanisms such as erosion from the catchment and anoxia seem to be of less importance. Primary productivity is considered the main driving factor of change in lacustrine nutrient availability in Lake Komořany at the LG/H transition.

Limits of the sedimentary record

Interpretation of the large shallow lowland lakes' records brings various constrictions particularly due to the specific features of in-lake sedimentation such as the low inflow of allochthonous material, the possible resuspension of sediments by waves in polymictic regime or the effective oxidation of deposited organic matter (Blais & Kalff, 1995; Scheffer, 2004). The aforementioned factors result in a low sedimentation rate, which reduces stratigraphic resolution of the natural archive. Our study faced an absence of terrestrial macrofossils for radiocarbon dating and very low time resolution of the record. Bulk sediment was used for AMS ^{14}C dating with reference to previous successful application to Holocene material from Lake Komořany (Bešta et al., 2015; Houfková et al., 2017). Although negligible bias was supposed, possible errors obliged us to take the modelled chronology with reserve.

Our results provided a clear evidence of LG record from both studied profiles. The continuous development of assemblages and geochemical variables suggested undisturbed sedimentation without more extensive reworking. The presence of minor hiatuses cannot be excluded but they do not threaten the aims of this study. The depth–age model was supported by palynostratigraphy. In particular, the observed peak of *Corylus avellana* (24%, ~ 10,800 cal year BP) was seen to be identical to the peak recorded in the PK-1-C profile from Lake Komořany (26%, ~ 11,000 cal year BP) (Houfková et al., 2017), which is in accordance with data from other sites in Central Europe (Theuerkauf et al., 2014).

Conclusion

A relatively stable ecosystem with gradual changes in aquatic and terrestrial communities was recorded in Lake Komořany at the Late-Glacial/Holocene transition. Two major, almost certainly climatically driven, shifts were recorded in the studied profiles: (i) the qualitative one with changes in species composition of the diatom and chironomid communities foregoing the LG/H boundary and (ii) the quantitative one at the LG/H boundary distinguishable by the enhanced diatom valve concentrations and the lithological change. These shifts were linked with two opposite trends: decreasing inferred trophic status and increasing primary productivity towards the Holocene. This discrepancy between nutrient availability and primary productivity can be best explained by a sink of nutrients in biomass produced after the climatic amelioration. In other words, nutrients became a limiting factor only after the onset of Holocene favourable climate. The species composition and primary productivity were therefore shaped by the climate change indirectly by means of nutrient availability.

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References

Anderson, N. J., 1995. Naturally eutrophic lakes: reality, myth or myopia? Trends in Ecology and Evolution 10: 137–138.

Apolinarska, K., M. Woszczyk & M. Obremska, 2012. Late Weichselian and Holocene palaeoenvironmental changes in northern Poland based on the Lake Skrzynka record. Boreas 41: 292–307.

Barley, E. M., I. R. Walker, J. Kurek, L. C. Cwynar, R. W. Mathewes, K. Gajewski & B. P. Finney, 2006. A northwest north American training set: distribution of freshwater midges in relation to air temperature and lake depth. Journal of Paleolimnology 36: 295–314.

Battarbee, R. W., 1986. Diatom Analysis. In Berglund, B. E. (ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. Wiley, Chichester: 527–570.

Battarbee, R. W., V. J. Jones, R. J. Flower, N. G. Cameron, H. Bennion, L. Carvalho & S. Juggins, 2001. Diatoms. In Smol, J. P., H. J. B. Birks & W. M. Last (eds), Tracking Environmental Change Using Lake Sediments, Vol. 3. Terrestrial, Algal and Siliceous Indicators. Kluwer Academic Publishers, Dordrecht: 155–202.

Bennion, H., 1995. Surface-sediment diatom assemblages in shallow, artificial, enriched ponds, and implications for reconstructing trophic status. Diatom Research 10: 1–19.

Bennion, H., C. D. Sayer, J. Tibby & H. J. Carrick, 2010. Diatoms as Indicators of Environmental Change in Shallow Lakes. In Smol, J. P. & E. F. Stoermer (eds), The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge: 152–173.

Bešta, T., J. Šafránková, M. Pouzar, J. Novák & K. Nováková, 2009. Late Pleistocene-Early Holocene transition recorded in the sediments of a former shallow lake in the Czech Republic. Hydrobiologia 631: 107–120.

Bešta, T., J. Novák, D. Dreslerová, V. Jankovská, A. Bernardová, L. Lisá & D. Valentová, 2015. Mid-Holocene history of a central European lake: lake Komořany, Czech Republic. Boreas 44: 563–574.

Beug, H. J., 2004. Leitfaden der Pollenbestimmung fur Mitteleuropa und angrenzende Gebiete. Friedrich Pfeil, München.

Birks, H. H. & B. Ammann, 2000. Two terrestrial records of rapid climatic change during the glacial–Holocene transition (14,000–9,000 calendar years B. P.) from Europe. Proceedings of the National Academy of Sciences of the USA 97: 1390–1394.

Birks, H. H. & H. J. B. Birks, 2006. Multi-proxy studies in palaeolimnology. Vegetation History and Archaeobotany 15: 235–251.

Björk, S., 2010. The Evolution of Lakes and Wetlands. In Eiseltová, M. (ed.), Restoration of Lakes, Streams, Floodplains, and Bogs in Europe Wetlands: Ecology, Conservation and Management, Vol. 3. Springer, Dordrecht: 25–35.

Blais, J. M. & J. Kalff, 1995. The influence of lake morphometry on sediment focusing. Limnology and Oceanography 40: 582–588.

Bos, J. A. A., B. Van Geel, J. Van Der Plicht & S. J. P. Bohncke, 2007. Preboreal climate oscillations in Europe: wiggle-match dating and synthesis of Dutch high-resolution multi-proxy records. Quaternary Science Reviews 26: 1927–1950.

Bos, J. A. A., P. De Smedt, H. Demiddele, W. Z. Hoek, R. Langohr, V. Marcelino, N. Van Asch, D. Van Damme, T. Van der Meeren, J. Verniers, P. Boeckx, M. Boudin, M. Court-Picon, P. Finke, V. Gelorini, S. Gobert, O. Heiri, K. Martens, F. Mostaert, L. Serbruyns, M. Van Strydonck & P. Crombé, 2017. Multiple oscillations during the Lateglacial as recorded in a multi-proxy, high-resolution record of the Moervaart palaeolake (NW Belgium). Quaternary Science Reviews 162: 26–41.

Boyle, J. F., 2001. Inorganic geochemical methods in palaeolimnology. In Last, W. M. & J. P. Smol (eds), Tracking environmental Change Using Lake Sediments. Volume 2: Physical and Geochemical Methods. Kluwer Academic Publishers, Dordrecht: 83–142.

Brodersen, K. P. & C. Lindegaard, 1999. Classification, assessment and trophic reconstruction of Danish lakes using chironomids. Freshwater Biology 42: 143–157.

Brodersen, K. P. & R. Quinlan, 2006. Midges as palaeoindicators of lake productivity, eutrophication and hypolimnetic oxygen. Quaternary Science Reviews 25: 1995–2012.

Brodersen, K. P., B. V. Odgaard, O. Vestergaard & N. John Anderson, 2001. Chironomid stratigraphy in the shallow and eutrophic Lake Søbygaard, Denmark: chironomid-macrophyte co-occurrence. Freshwater Biology 46: 253–267.

Bronk Ramsey, C., 2008. Deposition models for chronological records. Quaternary Science Reviews 27: 42–60.

Bronk Ramsey, C., 2013. OxCal 4.2.4 online program. https://c14.arch.ox.ac.uk/oxcal/OxCal.html. OxCal Project web.

Bronk Ramsey, C. & S. Lee, 2013. Recent and planned developments of the program Oxcal. Radiocarbon 55: 720–730.

Brooks, S. J., J. J. Lowe & F. E. Mayle, 1997. The late devensian lateglacial palaeoenvironmental record from Whitrig Bog, SE Scotland. 2. Chironomidae (Insecta: Diptera). Boreas 26: 297–308.

Brooks, S.J., P.G. Langdon & O. Heiri, 2007. The identification and use of palaearctic chironomidae larvae. Palaeoecology, Technical Guide No. 10. Quaternary Research Association, London.

Buczkó, K., É. Ács, K. Báldi, V. Pozderka, M. Braun, T. Kiss & J. Korponai, 2019. The first high resolution diatom record from Lake Balaton, Hungary in Central Europe. Limnetica 38: 417–430.

Canfield Jr., D. E. & J. R. Jones, 1984. Assessing the trophic status of lakes with aquatic macrophytes. Lake and Reservoir Management 1: 446–451.

Cardoso, A. C., A. Solimini, G. Premazzi, L. Carvalho, A. Lyche & S. Rekolainen, 2007. Phosphorus reference concentrations in European lakes. Hydrobiologia 584: 3–12.

Cohen, A. S., 2003. Paleolimnology: The History and Evolution of Lake Systems. Oxford University Press, New York.

Cremer, H., A. D. Buijse, A. F. Lotter, W. Oosterberg & M. Staras, 2004. The palaeolimnological potential of diatom assemblages in floodplain lakes of the Danube Delta, Romania: a pilot study. Hydrobiologia 513: 7–26.

Demiddele, H., P. Finke & P. Crombé, 2016. Diatom-based palaeoecology of a late-glacial palaeolake in the Moervaart area (northwestern Belgium) in relation to its prehistoric occupation. Notae Praehistoricae 36: 29–46.

Denys, L., 1991. A checklist of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements. I. Introduction, ecological code and complete list. Professional Paper Belgische Geologische Dienst 246.

Denys, L., C. Verbruggen & P. Kiden, 1990. Palaeolimnological aspects of a late-Glacial shallow lake in Sandy Flanders, Belgium. Hydrobiologia 214: 273–278.

Dong, X., H. Bennion, R. Battarbee, X. Yang, H. Yang & E. Liu, 2008. Tracking eutrophication in Taihu lake using the diatom record: potential and problems. Journal of Paleolimnology 40: 413–429.

Dreßler, M., A. Schwarz, T. Hübener, S. Adler & B. W. Scharf, 2011. Use of sedimentary diatoms from multiple lakes to distinguish between past changes in trophic state and climate: evidence for climate change in northern Germany during the past 5,000 years. Journal of Paleolimnology 45: 223–241.

Drzymulska, D., M. Fiłoc, M. Kupryjanowicz, K. Szeroczyńska & P. Zieliński, 2015. Postglacial shifts in lake trophic status based on a multiproxy study of a humic lake. Holocene 25: 495–507.

Eide, F., 1981. Key for northwest european Rosaceae pollen. Grana 20: 101–118.

Enters, D., E. Kirilova, A. F. Lotter, A. Lücke, J. Parplies, S. Jahns, G. Kuhn & B. Zolitschka, 2010. Climate change and human impact at Sacrower See (NE Germany) during the past 13,000 years: a geochemical record. Journal of Paleolimnology 43: 719–737.

Faegri, K. & J. Iversen, 1989. Textbook of Pollen Analysis, 4th ed. Wiley, Chichester.

Gałka, M., K. Tobolski & I. Bubak, 2015. Late Glacial and Early Holocene lake level fluctuations in NE Poland tracked by macro-fossil, pollen and diatom records. Quaternary International 388: 23–38.

Goslar, T., T. Kuc, M. Ralska-Jasiewiczowa, K. Rózánski, M. Arnold, E. Bard, B. Van Geel, M. E. Pazdur, K. Szeroczyńska, B. Wicik, K. Wieckowski & A. Walanus, 1993. High-resolution lacustrine record of the Late Glacial/ Holocene transition in Central Europe. Quaternary Science Reviews 12: 287–294.

Grimm, E. C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers & Geosciences 13: 13–35.

Guiry, M.D. & G.M. Guiry, 2019. AlgaeBase. World-wide electronic publication. National University of Ireland. Galway. http://www.algaebase.org. Accessed 7 July 2019

Hájková, P., P. Pařil, L. Petr, B. Chattová, T. M. Grygar & O. Heiri, 2016. A first chironomid-based summer temperature reconstruction (13–5 ka BP) around 49 N in inland Europe compared with local lake development. Quaternary Science Reviews 141: 94–111.

Hall, R. I. & J. P. Smol, 2010. Diatoms as Indicators of Lake Eutrophication. In Smol, J. P. & E. F. Stoermer (eds), The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge: 122–151.

Hamburger, K., P. C. Dall & C. Lindegaard, 1994. Energy metabolism of *Chironomus anthracinus* (Diptera: Chironomidae) from the profundal zone of Lake Esrom, Denmark, as a function of body size, temperature and oxygen concentration. Hydrobiologia 294: 43–50.

Haworth, E. Y., 1976. Two Late-Glacial (Late Devensian) diatom assemblage profiles from northern Scotland. The New Phytologist 77: 227–256.

Heinsalu, A., H. Luup, T. Alliksaar, P. Nõges & T. Nõges, 2008. Water level changes in a large shallow lake as reflected by the plankton: periphyton-ratio of sedimentary diatoms. Hydrobiologia 599: 23–30.

Heiri, O., A. F. Lotter & G. Lemcke, 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25: 101–110.

Heiri, O., S. J. Brooks, H. Renssen, A. Bedford, M. Hazekamp, B. Ilyashuk, E. S. Jeffers, B. Lang, E. Kirilova, S. Kuiper, L. Millet, S. Samartin, M. Toth, F. Verbruggen, J. E. Watson, N. Van Asch, E. Lammertsma, L. Amon, H. H. Birks, H. J. B. Birks, M. F. Mortensen, W. Z. Hoek, E. Magyari, C. Munõz Sobrino, H. Seppä, W. Tinner, S. Tonkov, S. Veski & A. F. Lotter, 2014. Validation of climate model-inferred regional temperature change for late-glacial Europe. Nature Communications 5: 1–7.

Hošek, J., P. Pokorný, V. Kubovčík, I. Horáček, P. Žáčková, J. Kadlec, F. Rojik, L. Lisá & S. Bučkuliaková, 2014. Late glacial climatic and environmental changes in eastern-central Europe: correlation of multiple biotic and abiotic proxies from the Lake Švarcenberk, Czech Republic. Palaeogeography, Palaeoclimatology, Palaeoecology 396: 155–172.

Houfková, P., T. Bešta, A. Bernardová, D. Vondrák, P. Pokorný & J. Novák, 2017. Holocene climatic events linked to environmental changes at Lake Komořany Basin, Czech Republic. The Holocene 27: 1–14.

Hurník, S., 1969. Příspěvek ke geologické problematice tzv. Komořanského jezera [Contribution to the geology of so-called Lake Komořany]. Mostecko-Litvínovsko, Regionální Studie 6: 5–14.

Int Panis, L., B. Goddeeris & R. F. Verheyen, 1995. On the Relationship Between the Oxygen Microstratification in a Pond and the Spatial Distribution of the Benthic Chironomid Fauna. In Cranston, P. (ed.), From Genes to Ecosystems. Canberra, C.S.I.R.O.: 482.

Jankovská, V., 1983. Palynologische Forschung am ehemaligen Komořany-See (Spätglazial bis Subatlantikum). Věstník Ústředního ústavu geologického 58: 99–107.

Jankovská, V., 1984. Radiokarbondatierung der Sedimente aus dem ehemaligen Komořany-See (NW-Böhmen). Věstník Ústředního ústavu geologického 59: 235–236.

Jankovská, V., 1988. Palynologische Erforschung archäologischer Proben aus dem Komořanské jezero-See bei Most (NW-Böhmen). Folia Geobotanica et Phytotaxonomica 23: 45–77.

Jankovská, V. & P. Pokorný, 2013. Reevaluation of the palaeoenvironmental record of the former Komořanské jezero lake: Late-Glacial and Holocene palaeolimnology and vegetation development in north-western Bohemia, Czech Republic. Preslia 85: 265–287.

Jeppesen, E., M. Sondergaard, M. Sondergaard & K. Christoffersen, 1998. The Structuring Role of Submerged Macrophytes in Lakes. Ecological Studies Vol. 131. Springer, LLC: 1–423.

Jin, Z., J. Cao, J. Wu & S. Wang, 2006. A Rb/Sr record of catchment weathering response to Holocene climate change in inner Mongolia. Earth Surface Processes and Landforms 31: 285–291.

Kirilova, E., O. Heiri, D. Enters, H. Cremer, A. F. Lotter, B. Zolitschka & T. Hübener, 2009. Climate-induced changes in the trophic status of a Central European lake. Journal of Limnology 68: 71–82.

Kletetschka, G., D. Vondrák, J. Hruba, V. Prochazka, L. Nabelek, H. Svitavská-Svobodová, P. Bobek, Z. Horicka, J. Kadlec & M. Takac, 2018. Cosmic-impact event in lake sediments from central Europe postdates the laacher see eruption and marks onset of the younger dryas. Journal of Geology 126: 561–575.

Kołaczek, P., J. Mirosław-Grabowska, M. Karpińska-Kołaczek & R. Stachowicz-Rybka, 2015. Regional and local changes inferred from lacustrine organic matter deposited between the Late Glacial and mid-Holocene in the Skaliska Basin (north-eastern Poland). Quaternary International 388: 51–63.

Komárek, J. & V. Jankovská, 2001. Review of the green algal genus *Pediastrum*; Implication for pollen-analytical research. Bibliotheca Phycologica 108.

Krammer, K., 2000. Diatoms of Europe. Diatoms of the European Inland Waters and Comparable Habitats. The Genus Pinnularia, Vol. 1. A.R.G. Gantner Verlag K.G., Ruggell.

Krammer, K., 2002. Diatoms of Europe. Diatoms of the European Inland Waters and Comparable Habitats. Cymbella, Vol. 3. A.R.G. Gantner Verlag K.G., Ruggell.

Krammer, K., 2003. Diatoms of Europe. Diatoms of the European Inland Waters and Comparable Habitats. Cymbopleura, Delicata, Navicymbula, Gomphocymbellopsis, Afrocymbella, Vol. 4. A.R.G. Gantner Verlag K.G., Ruggell.

Krammer, K. & H. Lange-Bertalot, 1986. Bacillariophyceae, 1. Teil: Naviculaceae. In H. Ettl, J. Gerloff, H. Heynig, D. Mollenhauer (eds), Süßwasserflora von Mitteleuropa (Band 2/1). Gustav Fischer Verlag, Jena.

Krammer, K. & H. Lange-Bertalot, 1988. Bacillariophyceae, 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In H. Ettl, J. Gerloff, H. Heynig, D. Mollenhauer (eds), Süßwasserflora von Mitteleuropa (Band 2/2). Gustav Fischer Verlag, Jena.

Krammer, K. & H. Lange-Bertalot, 1991a. Bacillariophyceae, 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. In Ettl, H., J. Gerloff, H. Heynig & D. Mollenhauer (eds), Süßwasserflora von Mitteleuropa (Band 2/3). Gustav Fischer Verlag, Jena.

Krammer, K. & H. Lange-Bertalot, 1991b. Bacillariophyceae, 4. Teil: Achnanthaceae, Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema. In H. Ettl, J. Gerloff, H. Heynig, D. Mollenhauer (eds), Süßwasserflora von Mitteleuropa (Band 2/4). Gustav Fischer Verlag, Jena.

Kuneš, P., B. Pelánková, M. Chytrý, V. Jankovská, P. Pokorný & L. Petr, 2008. Interpretation of the last-glacial vegetation of eastern-central Europe using modern analogues from southern Siberia. Journal of Biogeography 35: 2223–2236.

Lange-Bertalot, H., 2001. Diatoms of Europe. Diatoms of Europeaen Inland Waters and Comparable Habitats. Navicula sensu stricto, 10 Genera Separated from Navicula sensu lato, Frustulia, Vol. 2. A.R.G. Gantner Verlag K.G., Ruggell.

Legendre, P. & L. Legendre, 1998. Numerical Ecology. Elsevier, Amsterdam.

Losert, H., 1940. Beiträge zur spät- und nacheiszeitlichen Vegetationsgeschichte Innerböhmens, I. Der Kommerner See. Beihefte zum Botanischen Centralblatt 60B: 346–394.

Lotter, A. F., 1999. Late-Glacial and Holocene vegetation history and dynamics as shown by pollen and plant macrofossil analyses in annually laminated sediments from Soppensee, central Switzerland. Vegetation History and Archaeobotany 8: 165–184.

Lühne, V., 1897. Über ein subfossiles Vorkommen von Diatomaceen in Böhmen. Österreichische botanische Zeitschrift 9: 316–319.

MacArthur, R. H., 1957. On the relative abundance of bird species. Proceedings of the National Academy of Sciences 43: 293–295.

Magny, M., 2004. Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. Quaternary International 113: 65–79.

Matěna, J., 1989. Seasonal dynamics of a *Chironomus plumosus* (L.) (Diptera, Chironomidae) population from a fish pond in southern Bohemia. Internationale Revue der gesamten Hydrobiologie und Hydrographie 74: 599–610.

Mendyk, Ł., M. Markiewicz, R. Bednarek, M. Świtoniak, W. W. Gamrat, I. Krześlak, M. Sykuła, L. Gersztyn & A. Kupniewska, 2016. Environmental changes of a shallow kettle lake catchment in a young glacial landscape (Sumowskie Lake catchment), North-Central Poland. Quaternary International 418: 116–131.

Mirosław-Grabowska, J. & E. Zawisza, 2018. Reaction of the lake environment to the Holocene warming depending on the distance to the maximum extent of the Vistulian ice sheet. Catena 171: 494–504.

Nagell, B. & C.-C. Landahl, 1978. Resistance to Anoxia of *Chironomus plumosus* and *Chironomus anthracinus* (Diptera) Larvae. Holarctic Ecology 1: 333–336.

Neustupný, E., 1985. On the Holocene period in the Komořany Lake area. Památky archeologické 76: 9–70.

Nõges, P., T. Nõges, L. Tuvikene, H. Smal, S. Ligeza, R. Kornijów, W. Peczula, E. Bécares, F. Garcia-Criado, C. Alvarez-Carrera, C. Fernandez-Alaez, C. Ferriol, R. M. Miracle, E. Vicente, S. Romo, E. Van Donk, W. Van De Bund, J. P. Jensen, E. M. Gross, L. A. Hansson, M. Gyllström, M. Nykänen, E. De Eyto, K. Irvine, D. Stephen, S. Collings & B. Moss, 2003. Factors controlling hydrochemical and trophic state variables in 86 shallow lakes in Europe. Hydrobiologia 506–509: 51–58.

Orbán, I., H. H. Birks, I. Vincze, W. Finsinger, I. Pál, E. Marinova, G. Jakab, M. Braun, K. Hubay, T. Bíró & E. K. Magyari, 2018. Treeline and timberline dynamics on the northern and southern slopes of the Retezat Mountains (Romania) during the late glacial and the Holocene. Quaternary International 477: 59–78.

Pedziszewska, A., W. Tylmann, M. Witak, N. Piotrowska, E. Maciejewska & M. Latałowa, 2015. Holocene environmental changes reflected by pollen, diatoms, and geochemistry of annually laminated sediments of Lake Suminko in the Kashubian Lake District (N Poland). Review of Palaeobotany and Palynology 216: 55–75.

Petr, L., P. Žácková, T. M. Grygar, A. Píšková, M. Krížek & V. Treml, 2013. Šúr, a former late-glacial and Holocene lake at the westernmost margin of the Carpathians. Preslia 85: 239–263.

Płóciennik, M., A. Self, H. J. B. Birks & S. J. Brooks, 2011. Chironomidae (Insecta: Diptera) succession in Żabieniec bog and its palaeo-lake (central Poland) through the Late Weichselian and Holocene. Palaeogeography, Palaeoclimatology, Palaeoecology 307: 150–167.

Pokorný, O., 1963. Několik poznámek k historickému vývoji Komořanského jezera [Some remarks to the historical development of Lake Komořany]. Sborník Československé společnosti zeměpisné 1: 52–57.

Pokorný, P., 2002. A high-resolution record of Late-Glacial and Early-Holocene climatic and environmental change in the Czech Republic. Quaternary International 91: 101–122.

Pokorný, P. & V. Jankovská, 2000. Long-term vegetation dynamics and the infilling process of a former lake (Švarcenberk, Czech Republic). Folia Geobotanica 35: 433–457.

Pokorný, P., M. Chytrý, L. Juřičková, J. Sádlo, J. Novák & V. Ložek, 2015. Mid-Holocene bottleneck for central European dry grasslands: did steppe survive the forest optimum in northern Bohemia, Czech Republic? The Holocene 25: 716–726.

Punt, W., 1976. The Northwest European Pollen Flora: Parts 1–7. Elsevier, Amsterdam.

Punt, W. & S. Blackmore, 1991. The Northwest European Pollen Flora: Parts 44–51. Elsevier, Amsterdam.

Punt, W. & G. Clarke, 1980. The Northwest European Pollen Flora: Parts 8–20. Elsevier, Amsterdam.

Punt, W. & G. Clarke, 1981. The Northwest European Pollen Flora: Parts 21–28. Elsevier, Amsterdam.

Punt, W. & G. Clarke, 1984. The Northwest European Pollen Flora: Parts 29–37. Elsevier, Amsterdam.

Punt, W. & P. Hoen, 2009. The Northwest European Pollen Flora: Part 70. Elsevier, Amsterdam.

Punt, W., S. Blackmore & G. Clarke, 1988. The Northwest European Pollen Flora: Parts 38–43. Elsevier, Amsterdam.

Punt, W., S. Blackmore & P. Hoen, 1995. The Northwest European Pollen Flora: Parts 52–56. Elsevier, Amsterdam.

Punt, W., S. Blackmore, P. Hoen & P. J. Stafford, 2003. The Northwest European Pollen Flora: Parts 57–68. Elsevier, Amsterdam.

R Core Team, 2016. R: A Language and Environment for Statistical Computing.

Ralska-Jasiewiczowa, M., M. Latalowa, K. Wasylikowa, K. Tobolski, E. Madeyska, H. E. Wright & C. Turner (eds), 2004. Late Glacial and Holocene History of Vegetation in Poland Based on Isopollen Maps. W. Szafer Institute of Botany, Polish Academy of Sciences, Krakow.

Rasmussen, S. O., M. Bigler, S. P. Blockley, T. Blunier, S. L. Buchardt, H. B. Clausen, I. Cvijanovic, D. Dahl-Jensen, S. J. Johnsen, H. Fischer, V. Gkinis, M. Guillevic, W. Z. Hoek, J. J. Lowe, J. B. Pedro, T. Popp, I. K. Seierstad, J. Peder, A. M. Svensson, P. Vallelonga, B. M. Vinther, M. J. C. Walker, J. J. Wheatley & M. Winstrup, 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. Quaternary Science Reviews 106: 14–28.

Řeháková, Z., 1983. Diatom succession in the post-glacial sediments of the Komořany Lake, North-West Bohemia, Czechoslovakia. Hydrobiologia 103: 241–245.

Řeháková, Z., 1986. The Postglacial history of diatom-bearing sediments of the former Lake Komorany (North-West Bohemia). Antropozoikum 17: 87–134.

Reimer, P. J., E. Bard, A. Bayliss, J. W. Beck, P. G. Blackwell, C. Bronk, R. Caitlin, E. B. Hai & R. L. Edwards, 2013. Intcal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55: 1869–1887.

Rudolph, K., 1926. Pollenanalytische Untersuchungen im thermophilen Florengebiet Böhmens: der ‘Kommerner See’ bei Brüx. Berichten der Deutschen Botanischen Gesellschaft 4: 239–248.

Sayer, C. D., 2001. Problems with the application of diatom-total phosphorus transfer functions: examples from a shallow English lake. Freshwater Biology 46: 743–757.

Sayer, C. D., N. Roberts, J. Sadler, C. David & P. M. Wade, 1999. Biodiversity changes in a shallow lake ecosystem: a multi-proxy palaeolimnological analysis. Journal of Biogeography 26: 97–114.

Sayer, C. D., T. A. Davidson, J. I. Jones & P. G. Langdon, 2010. Combining contemporary ecology and palaeolimnology to understand shallow lake ecosystem change. Freshwater Biology 55: 487–499.

Scheffer, M., 1990. Multiplicity of stable staes in freshwater systems. Hydrobiologia 200: 475–486.

Scheffer, M., 2004. The Story of Some Shallow Lakes. In Usher, M. B. (ed.), Ecology of Shallow Lakes. Kluwer Academic Publishers, Dordrecht.

Scheffer, M. & E. H. Van Nes, 2007. Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size. Hydrobiologia 584: 455–466.

Stevenson, R. J., M. L. Bothwell & R. L. Lowe (eds), 1996. Algal Ecology. Freshwater Benthic Ecosystems. Academic Press, San Diego.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores 13: 615–621.

Stuchlík, L., 2001. Atlas of Pollen and Spores of the Polish Neogene. W. Szafer Institute of Botany, Krakow.

Stuiver, M., P. M. Grootes & T. F. Braziunas, 1995. The GISP2 δ18O climate record of the past 16,500 years and the role of the sun, ocean, and volcanoes. Quaternary Research 44: 341–354.

Sümegi, P., S. Gulyás & G. Jakab, 2008. Holocene paleoclimatic and paleohydrological changes in Lake Balaton as inferred from a complex quantitative environmental historical study of a lacustrine sequence of the Szigliget embayment. Documenta Praehistorica 35: 33–44.

Tabacchi, E., L. Lambs, H. Guilloy, A.-M. Planty-Tabacchi, E. Muller & H. Decamps, 2000. Impacts of riparian vegetation on hydrological processes. Hydrological Processes 14: 2959–2976.

Tarrats, P., M. Cañedo-Argüelles, M. Rieradevall & N. Prat, 2018. The influence of depth and macrophyte habitat on paleoecological studies using chironomids: Enol Lake (Spain) as a case study. Journal of Paleolimnology 60: 97–107.

Theuerkauf, M., J. A. A. Bos, S. Jahns, W. Janke, A. Kuparinen, M. Stebich & H. Joosten, 2014. Corylus expansion and persistent openness in the early Holocene vegetation of northern central Europe. Quaternary Science Reviews 90: 183–198.

Turner, F., J. F. Tolksdorf, F. Viehberg, A. Schwalb, K. Kaiser, F. Bittmann, U. von Bramann, R. Pott, U. Staesche, K. Breest & S. Veil, 2013. Lateglacial/Early Holocene fluvial reactions of the Jeetzel river (Elbe valley, northern Germany) to abrupt climatic and environmental changes. Quaternary Science Reviews 60: 91–109.

Turner, F., R. Pott, A. Schwarz & A. Schwalb, 2014. Response of Pediastrum in German floodplain lakes to Late Glacial climate changes. Journal of Paleolimnology 52: 293–310.

Van Dam, H., A. Mertens & J. Sinkeldam, 1994. A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. Netherlands Journal of Aquatic Ecology 28: 117–133.

Vermaire, J. C., M.-H. Greffard, É. Saulnier-Talbot & I. Gregory-Eaves, 2013. Changes in submerged macrophyte abundance altered diatom and chironomid assemblages in a shallow lake. Journal of Paleolimnology 50: 447–456.

Vondrák, D., J. Prach & P. Houfková, 2015. Sediments of postglacial lakes in the Czech Republic-unique natural archives overlooked by (Czech) limnology. In V. Rádková & J. Bojková (eds), XVII. konference České limnologické společnosti a Slovenskej limnologickej spoločnosti 'Voda-věc veřejná' – Sborník příspěvků. Brno: ČLS and Masarykova univerzita v Brně: 162–167.

Werner, P. & J. P. Smol, 2005. Diatom-environmental relationships and nutrient transfer functions from contrasting shallow and deep limestone lakes in Ontario, Canada. Hydrobiologia 533: 145–173.

Wettstein, R., 1896. Über ein subfossiles Vorkommen von Trapa natans in Böhmen. Lotos 44: 252–258.

Wetzel, R. G., 2001. Limnology. Lake and River Ecosystems. Academic Press, San Diego.

Wiederholm, T., 1983. Chironomidae of the Holarctic region. Keys and diagnoses. Part 1. Larvae. Entomologica Scandinavica 19: 1–457.

Zawiska, I., M. Słowiński, A. Correa-Metrio, M. Obremska, T. Luoto, L. Nevalainen, M. Woszczyk & K. Milecka, 2015. The response of a shallow lake and its catchment to Late Glacial climate changes – a case study from eastern Poland. Catena 126: 1–10.

Zawiska, I., K. Apolinarska & M. Woszczyk, 2019. Holocene climate vs. catchment forcing on a shallow, eutrophic lake in eastern Poland. Boreas 48: 166–178.

5.2. Paper II.

Research paper

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Holocene climatic events linked to environmental changes at Lake Komořany Basin, Czech Republic

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Abstract

Former Lake Komořany, located in Northwest Bohemia in Central Europe, provides multiple proxies (pollen, plant macrofossils, diatoms, chironomids and sediment chemistry) that allowed reconstruction of the development of its aquatic environment and catchment, throughout the Holocene. In order to reconstruct the climatic forcing of this development, we performed a pollen-based reconstruction of climate changes using the best modern analogue method. The climate reconstruction was successful for the interval of 10.0–3.2 ka BP. We demonstrate that shifts in climate were coupled with biotic changes within the lacustrine environment. Both processes were interconnected mainly through changes in the water level status of the lake. The most significant climatic and environmental changes were recorded at 9.1, 6.3, 4.8/4.7, 3.8 and 3.5 ka BP.

Keywords

Central Europe, climate reconstruction, Holocene, lacustrine, palaeolimnology, pollen

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Introduction

The Holocene epoch (11.7 ka BP–present) was formally proposed to be subdivided into three sub-series, separated by the early-Holocene–middle-Holocene boundary at 8.2 ka BP and the middle-Holocene–late-Holocene boundary at 4.2 ka BP (Walker et al., 2012). The 8.2-ka BP event is now considered to have been a global short-term cooling episode caused by the massive meltwater release from glacial lakes into the North Atlantic clearly reflected in the isotopic signal in Greenland ice cores (Rasmussen et al., 2014). In Central Europe (CE), it was identified mainly in the record of cave speleothems (Boch et al., 2009; Fohlmeister et al., 2012; Wackerbarth et al., 2012), in limnic sediments (Heiri et al., 2004; Magny, 2004; Magny et al., 2007; Mirosław-Grabowska and Zawisza, 2014; Von Grafenstein et al., 1999) or in tree-ring width records (Spurk et al., 2002). Although there exists evidence of a rapid vegetation change associated with the 8.2-ka event (Tinner and Lotter, 2001), and decreasing summer temperatures occurring even until 7.6 ka BP in the alpine region (Heiri et al., 2004), temperature anomalies based on pollen reconstructions were less distinct across CE than they were in the rest of the continent (Davis et al., 2003).

The 4.2-ka BP event, a mid-/low-altitude aridification that coincided with a weakening of intertropical convergence zone activity and the onset of the modern El Niño Southern Oscillation regime (Walker et al., 2012), was described less often from CE. A pollen-based temperature reconstruction did not separate the middle-Holocene and late-Holocene at all (Davis et al., 2003). Even though complex environmental changes are very well ascribed for the late-Holocene period (e.g. Kuneš et al., 2015), above all the irreversible switch in soil chemistry described from Czech sandstone areas (Ložek, 1998; Pokorný and Kuneš, 2005), no clear link has been shown for the 4.2-ka BP climatic changes. An abrupt shift to a cooler late-Holocene climate was reconstructed in the alpine region later on, around 4.0–3.7 ka BP (Heiri et al., 2003) or at 3.8 ka BP (Haas et al., 1998).

The above-described two climatic changes that established the Holocene boundaries were possibly major and important but not the sole factors (Mayewski et al., 2004; Rasmussen et al., 2014; Wanner, 2011). Temporal changes in treeline maxima, glacial extension, hydrology and fossil chironomid record provided data on further CE Holocene climatic fluctuations (Haas et al., 1998; Heiri et al., 2003; Hormes et al., 2001; Tinner et al., 1996), including an 11.4-ka BP event (Rasmussen et al., 2014), referred to as the Preboreal oscillations (Bešta et al., 2009; Hošek et al., 2014), declining summer temperature at 10.7–10.5 ka BP (Heiri et al., 2004), climate changes initiated at ca. 6.3 ka BP (Arbogast et al., 2006; Kalis et al., 2003), oscillations at 5.6–5.3 ka BP (Magny et al., 2006) and a shift in the alpine region between 5 and 4 ka BP

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from the dominant Atlantic climate influence to the more Mediterranean (Schmidt et al., 2006).

Past vegetation development, climate changes and human activities can be reconstructed from the spectra of biotic and abiotic factors originating from archives (Kaiser et al., 2012) including peatlands (Speranza et al., 2000; Svobodová et al., 2002; Veron et al., 2014) and limnic sediments (Battarbee, 2000; Birks and Birks, 2006). Natural lakes are common in the formerly glaciated regions of CE and exceptionally possess annually laminated sediments (Bonk et al., 2015; Dörfler et al., 2012; Dreibrodt and Wiethold, 2015; Tylmann et al., 2013). On the contrary, natural lakes are rather rare in the former extraglacial areas of CE, represented, for example, by maar lakes (Zolitschka et al., 2000) or by shallow lakes (Löffler, 1979). In the area of the Czech Republic (CR), most of the lakes were gradually infilled during the Holocene (Vondrák et al., 2015).

The large and shallow Lake Komořany was situated in a lowland basin (the Most Basin), and its surroundings were under the long-term influence of human activity (Bešta et al., 2015; Neustupný, 1985). Based on the settings of the lake and the surrounding geomorphology, the lake represents a favourable site reflecting changes shaped by both external and internal forces. Being so unique for the lowlands of the CR, Lake Komořany represents a traditional site for palaeoecological studies based on diatom (Řeháková, 1983, 1986) and pollen analyses (Losert, 1940; Rudolph, 1926). A comprehensive palynological study (Jankovská and Pokorný, 2013) summarized the general development of vegetation in the late Glacial and throughout the entire Holocene; however, this study did not explicitly show the major climatic changes. A long stable period (9.0–4.7 ka BP) in the lacustrine environment was postulated based on multiple evidence inferred from a sediment core located in the lake littoral (Bešta et al., 2015). However, a comprehensive study using multiple available proxies (pollen, diatoms, plant macrofossils, chironomids, charcoal and sediment chemistry) covering most of the Holocene has been lacking.

The objective of this study was to track Holocene climate changes via a pollen-based reconstruction using the best modern analogue method developed by Nakagawa et al. (2002) and to distinguish climate shifts using pollen and climate data sets from CE. As climate reconstructions based on biotic proxies are affected by numerous factors such as human impact (Birks et al., 2010; Gaillard et al., 2010), we attempted to link these shifts to local processes based on the reconstruction of the development of the aquatic environment and lake-level changes (Guiot et al., 1993). Based on the approaches mentioned above, we attempted to answer the following questions:

1. Do the most distinct climate events in a lowland area of semi-continental CE correspond to the inner Holocene boundaries at 8.2 and 4.2 ka BP?
2. Does the pollen-based climate reconstruction correspond to internal lacustrine processes of a shallow and large lake?

Study area

Lake Komořany was located at 230 m a.s.l. in the Most Basin and formed the largest water body in the area of the CR in the Holocene period (Figure 1a and b). The lake basin is superimposed on crystalline and metamorphic rocks of the Krušné Mountains (Ore Mountains) within Miocene sediments of the Northern Bohemian Brown Coal Basin (Řeháková, 1986). The large and shallow Lake Komořany originated at the onset of the late Glacial (Jankovská and Pokorný, 2013). The reconstructions of the lake varied from an overestimated area of 70 km^2 (Zapletal, 1954) to the existence of a vast moorland without any standing water (Pokorný, 1963). The reasonable reconstruction of its maximum extent is 25 km^2 with the depth not exceeding 10 m (Bešta et al., 2015; Hurník, 1969; Rudolph, 1926). Even though the lake was filled for most of its existence, the draining instructions from 1831 referred to a water surface equal to 1.94 km^2 and a floodplain area of 17.4 km^2 (Stanzl, 1832). Beginning about 100 years ago, the area has been completely destroyed due to surface mining of brown coal situated below the limnic sediments.

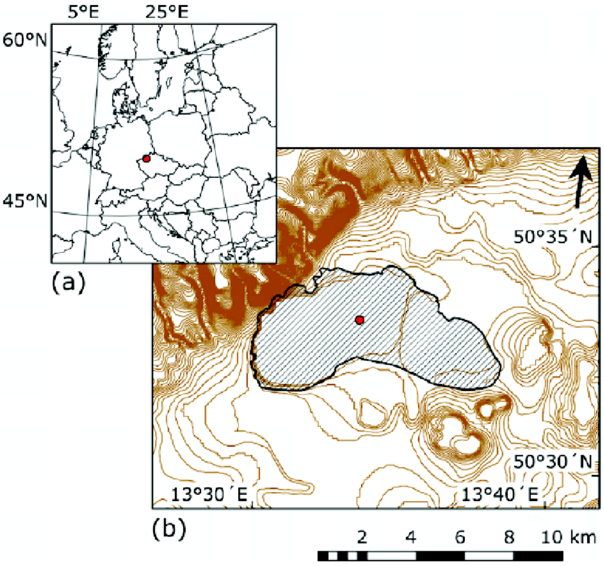


Figure 1. (a) Location of former Lake Komořany, NW Bohemia, Czech Republic, is indicated by a dot. The grid of 45–60°N and 5–25°E corresponds to the area of pollen and climate data training sets. (b) Location of the core PK-1-C is indicated by a dot. The hatched area marks the estimated maximal area of the lake using a 230 m a.s.l. threshold, taken after Bešta et al. (2015).

Lake Komořany was situated in the Bohemian thermophyticum in the lee of the Krušné Mountains (Ore Mountains). The slopes of the Krušné Mountains are at present covered mainly by beech forests. Its supramontane belt is formed mainly by spruce forests, while minerotrophic mires and bogs occur on the plateaus. The thermophilous Lounsko-Labské Středohoří, located to the south-east of the lake, are characterized by the presence of volcanic hills, which are in many cases covered by steppe vegetation on their south-facing slopes (Chytrý, 2012). According to the floristic evidence, fossil snail and pollen records, steppe vegetation has persisted throughout the entire Holocene (Pokorný et al., 2015). The present vegetation of the volcanic hills, which lie to the east and at higher elevations from the lake, is mainly forest vegetation of *Fagion sylvaticae, Carpinion betuli* and *Tilio platyphylli-Acerion*.

The climate is moderately warm and moderately dry with moderate winters. The mean summer temperature ranges from 15°C to 17°C, and the mean annual total precipitation is 400–500 mm based on the 40-year average according to the Czech Hydrometeorological Institute (Tolasz et al., 2007).

Methods

Fieldwork, sampling and lithology

Profile PK-1-C (50.543°N, 13.544°E; Figure 1b) was collected in Kubiena boxes (50 × 10 × 10 cm^3) during the extension of a brown coal mine in the late 1980s. A 78-cm profile was divided into 1 cm layers, where possible. More precise sampling was not reliable due to sediment dehydration making the sections hard to divide. Lithological description was based on Troels-Smith (1955).

Radiocarbon dating

Since seeds of terrestrial plants and charcoals were absent in the majority of samples, accelerator mass spectrometer (AMS) ^{14}C dating was performed on seven *gyttja* samples in the CAIS laboratory (US). A Poisson-process deposition model (Bronk Ramsey, 2008, 2009) with 10 and 40 postulated events per centimetre ($k=10$ in the depth interval of 78–20 cm and $k=40$ in 20–0 cm) was constructed using the OxCal 4.2 online application (Bronk Ramsey, 2014) based on the IntCal 13 (Reimer et al., 2013) calibration curve.

Microfossils analysis

Sediment samples (0.3 g dry weight (DW)) were prepared according to Fægri and Iversen (1989). Three tablets of *Lycopodium* spores were added to each sample to determine the absolute pollen concentration (Stockmarr, 1971) with 500 pollen determinations conducted per sample. The total count was increased up to at least 300 counts excluding dominant pollen types. Taxonomic identifications followed Punt (1976), Punt and Blackmore (1991), Punt et al. (1988, 1995, 2003, 2009), Punt and Clarke (1980, 1981, 1984) and Beug (2004). Reworked pollen grains of Tertiary age were identified according to Stuchlik (2001). The presence of non-pollen palynomorphs (e.g. algal and invertebrate remains) was recorded (Komárek and Jankovská, 2001; Van Geel, 2001).

Diatom analysis

Sediment samples were prepared as described by Bešta et al. (2015). Determination followed CE diatom floras (Krammer and Lange-Bertalot, 1986, 1988, 1991a, 1991b). Species traits were determined according to Van Dam et al. (1994) and Laird et al. (2011). Diatoms were grouped according to Denys (1991).

Geochemistry

Organic matter and carbonate contents were measured by loss on ignition (LOI_{550}, LOI_{950}; Dean, 1974; Heiri et al., 2001). Concentrations of metal elements were determined in the AcmeLabs Laboratory (Canada) as described in Bešta et al. (2015). The method detection limits and relative standard deviations were as follows: Fe (0.01%; 3.11%), Mn (2 ppm, 4.11%) and P (0.001%, 2.06%). Concentration of total phosphorus (TP) was used as an indicator of the trophic status in the lake independently of diatom-inferred total phosphorus (DI-TP). Evidence of anoxic conditions in the lake was based on Fe and Mn concentrations and the Fe/Mn ratio (Boyle, 2001).

Plant macrofossil analysis

Sediment of every second sample was soaked in 5% KOH and washed through sieves down to a diameter of 250 µm (Wasylikowa, 1986). Macrofossils (plant seeds and fragments, charcoal pieces and charophyte oogonia) were recovered and identified according to Anderberg (1994), Berggren (1981), Cappers et al. (2006), Schweingruber et al. (1990) and Krause (1986). The numbers of finds were transformed to a DW of 10 g.

Chironomids, cladocerans and bryozoans

The preparation technique used for cleaning and mounting of chironomid head capsules (HCs) and cladoceran ephippia onto microscope slides of selected samples was described by Brooks et al. (2007). Chironomid taxonomy followed Brooks et al. (2007) and Wiederholm (1983). Bryozoan remains (resting eggs) were recovered along with plant macrofossils and identified according to Francis (2001). Cladoceran remains were identified according to Szeroczyńska and Sarmaja-Korjonen (2007).

Quantitative pollen-based climate and biome reconstruction

A biome reconstruction was based on Prentice et al. (1996). Pollen taxa were assigned to European plant functional types (PFTs); biomes with the highest affinity scores were used for the reconstruction. A quantitative pollen-based climate reconstruction was done using Polygon 2.3.3 (Nakagawa et al., 2002). The pollen record of samples from ca. 1.1 ka BP and originating from 241 cores with robust ^{14}C chronology including 265 dated layers (Supplementary Table S1, available online) were taken from the Czech Pollen Database PALYCZ (Kuneš et al., 2009) and the European Pollen Database (Fyfe et al., 2009) and used as the best modern analogues (Abraham et al., 2016). Both complete pollen spectra, excluding aquatic species and selected pollen types, which according to Prentice et al. (1996) define PFTs, were used as training sets. Cores were located in the spatial window of 45–60°N and 05–25°E, focusing on the area of CE, including alpine regions and adjacent areas of Northern Europe (Figure 1a). The climate data were based on a set of meteorological data from the same spatial window covering the time period from 1961 to 1990. Interpolated data were assigned to coordinates that represented the centre points of $0.5° \times 0.5°$ grid cells (New et al., 2002). The chosen climate variables were mean annual temperature (T_{ann}), annual precipitation (P_{ann}) and mean temperature of the warmest (T_w) and the coolest (T_c) months. The modern climate at the core sites was estimated in a 1° radius by interpolation using Polation 1.1. Use of this radius reduced the number of used sites from 241 to 222. A temperature lapse rate of 0.6°C/100 m (Nakagawa et al., 2002) and a precipitation lapse rate with the highest R1 (10 mm/100 m) were used as the difference in elevation between each pollen site and the nearest meteorological site. To reconstruct the climate variables, the data, including all pollen types, were square root transformed to test the effect of rare species. On the contrary, selected data corresponding to the PFTs were not transformed to test the effect of the dominant taxa. Using PolCalib 3.0, the reconstruction having higher correlation coefficients (accuracy) between the observed and estimated climatic variables (R) was chosen as the most reliable.

Quantitative diatom reconstruction of TP and pH

DI-TP and pH (DI-pH) were calculated using weighted averaging (WA) with inverse (pH) and classical (TP) deshrinking. The computations were based on the combined TP and pH training data sets available on the European Diatom Database (EDDI). The modern analogue technique (MAT) was used as a measure of the similarity of the reconstructed sample with the training set (Birks, 2012).

Cluster analysis and data processing

Stratigraphic diagrams, each with a CONISS cluster dendrogram (Grimm, 1987), were created using Tilia 1.5.12 (Grimm, 2011). To determine the significant accumulation zones (SAZs), a broken stick model (Legendre and Legendre, 1998; MacArthur, 1957) was calculated in R 2.11.0 (R Development Core Team, 2010) and Tinn-R 2.3.5.2 (Faria, 2009). SAZs were based on the results of pollen assemblage zone (PAZ) and diatom assemblage zone (DAZ) analyses. The results of other analyses were considered with respect to DAZ. Linear correlations were performed in R 2.11.0 (R Development Core Team, 2010) in order to test the relationships between DI-TP and TP concentrations. The Holocene boundaries to which the results were compared follow the dating proposal of Walker et al. (2012).

Results

Profile description and lithology

The PK-1-C profile was composed of two lithological units: (1) Lso3, Ld1 in PAZ-1 and PAZ-3-5, and (2) Lso2, Ga2, Ld+ in PAZ-2. The bedrock was composed of gravel and sand (Ag3, Ga1). The top of recovered profile does not reflect the end of sedimentation at the locality since the uppermost layer was already removed with the preceding overburden.

Radiocarbon dating

A Bayesian model (Figure 2) based on six AMS ^{14}C data (Table 1) revealed a sedimentation rate of 130 yr/cm on average in the depth of 78–20 cm, while the layers corresponding to depths of 20–0 cm had an average sedimentation rate of 35 yr/cm. Intrusion of old reworked material caused outlier classification of the ^{14}C date from 76 cm (PAZ-2).

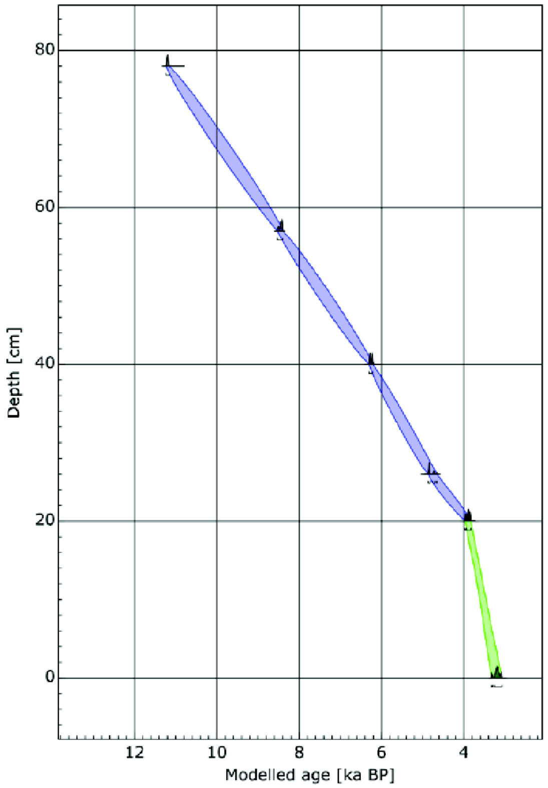


Figure 2. A Poisson-process deposition model (Bronk Ramsey, 2008, 2009) with 10 postulated events per centimetre ($k = 10$) in 78–20 cm and 40 ($k = 40$) in 20–0 cm constructed using the OxCal 4.2 online application (Bronk Ramsey, 2014) based on the IntCal 13 (Reimer et al., 2013) calibration curve.

Microfossils analysis

Five PAZs were determined (Figure 3) with a total of 190 pollen types recorded. The number of pollen types varied between 19 and 53 per one sample. Concentration in PAZ-2 (1–2.10^5 grains/gDW) was one order of magnitude lower than the other PAZs (1–4.10^6 grains/gDW). Green coccal algae were poorly preserved in a majority of samples; therefore, we considered that the reconstructed trends would not be reliable. The pollen record depicted the relatively early occurrence (PAZ-1, 11.2–11.0 ka BP) of light-demanding species (*Corylus avellana*) and deciduous species of the Quercetum mixtum. Pollen spectra from the samples classified to PAZ-2 (11.0–10.0 ka BP) were composed of mixed pollen of different ages and origins, based on the 25–45% of pollen being from herbaceous and grass communities and by the presence of Tertiary pollen grains redeposited from the watershed. PAZ-3 (9.8–6.5 ka BP) was characterized by an increase in the abundance of *Alnus glutinosa*-type, *Picea abies* and *Fraxinus excelsior*; a low ratio (3–7%) of herbaceous and grass communities; and the occurrence of *Hedera helix* and *Viscum* pollen grains. An increase in the abundance of *Fagus* pollen up to 20% characterized PAZ-4 (6.5–3.9 ka BP). *Carpinus* and *Abies* formed a stable proportion in the pollen spectrum in PAZ-5 (3.8–3.2 ka BP), while other arboreal pollen (AP) decreased in abundance. The presence of anthropogenic indicators (AIs) was already characteristic in PAZ-4. Pollen grains of grazing indicators, such as *Plantago lanceolata, Calluna vulgaris, Rumex acetosella* and *Odontites*-type, were detected. Nitrophilous species increased in abundance. In PAZ-5, the pollen curves of cereal species became continuous and significant. The occurrences of rare herbaceous and shrub species were more frequent in PAZ-4 and PAZ-5.

The pollen and spores of aquatic species depicted the vegetation development directly in the lake. Hygrophilous and water species were represented by pollen of the *Typha latifolia*-type and *Sparganium emersum*-type in PAZ-1. Spores of *Sphagnum* and pollen grains of Cyperaceae, *Typha latifolia*-type and *Typha angustifolia* were recorded in PAZ-2. Pollen of *Trapa natans, Nymphaea alba*, and *Myriophyllum spicatum* were recorded in PAZ-3b. These species further increased in abundance along with *Oenanthe aquatica* pollen grains in PAZ-5.

Diatom analysis

Diatom valves were well preserved at high concentrations (10^7–10^{10} valves/gDW). A total of 157 diatom species and varieties were recorded. Three DAZs were distinguished in the studied section (Figure 4). DAZ-1 (11.2–10.0 ka BP) consisted of samples

Table 1. List of radiocarbon dates from the PK-1-C profile, Lake Komořany, Czech Republic (50.543°N, 13.544°E). The quoted uncalibrated dates (^{14}C age) and their intervals (±) were given by CAIS laboratory in radiocarbon years before 1950 (yr BP). Intervals of calibrated dates (cal. yr BP) were based on a Bayesian model in the OxCal 4.2 online application.

Sample ID (UGAMS#)	Depth (cm)	^{14}C age (yr BP)	±	^{14}C age (cal. yr BP; interval of 95.4 probability)
4743	0	3000	30	3075–3326
5464	20	3580	25	3831–3971
16331	26	4280	30	4821–4957
4744	40	5450	30	6204–6300
5465	57	7660	30	8400–8538
12,297	76	12,040	30	13,765–14,013
4748	78	9750	30	11,150–11,235

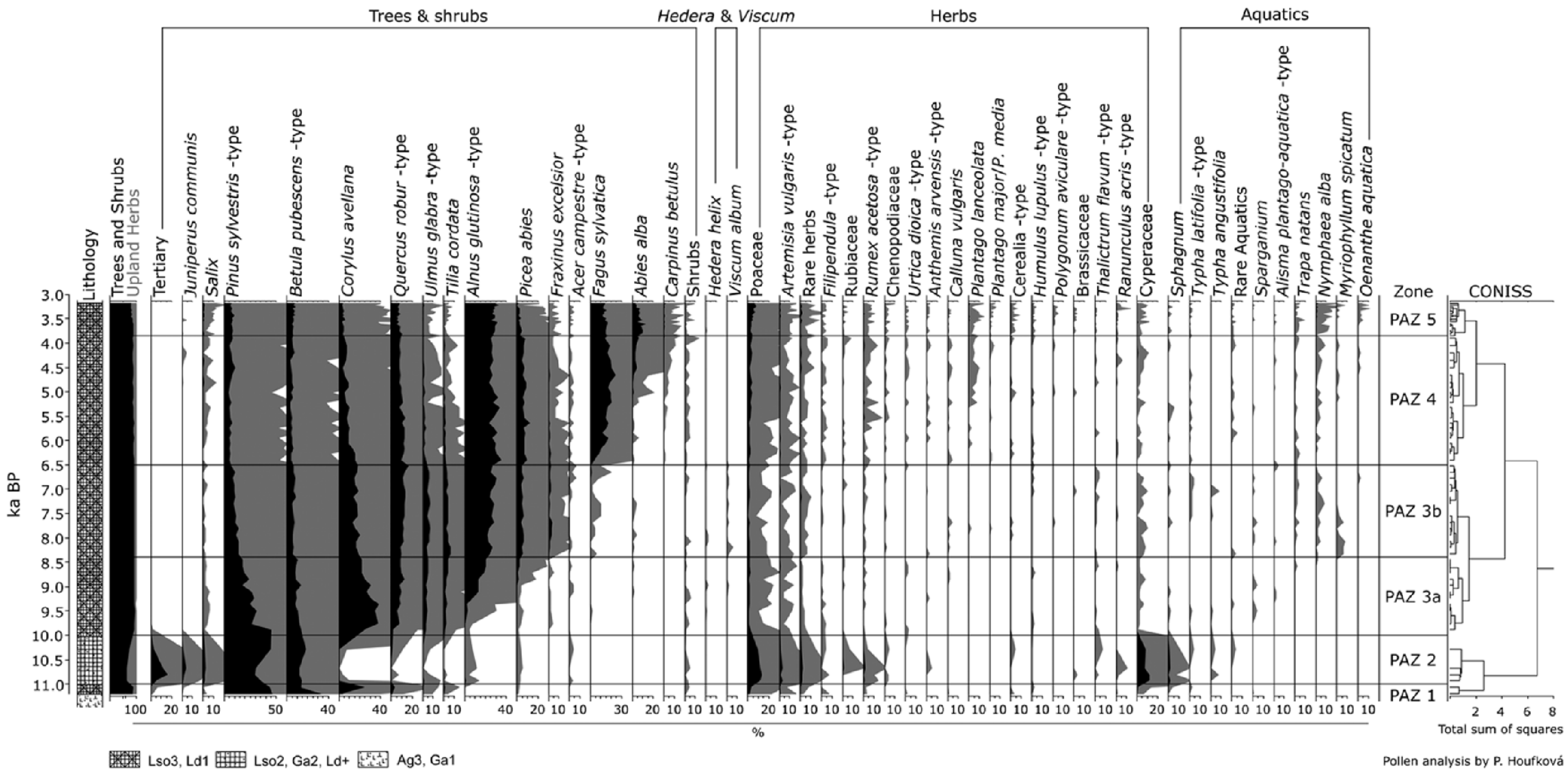
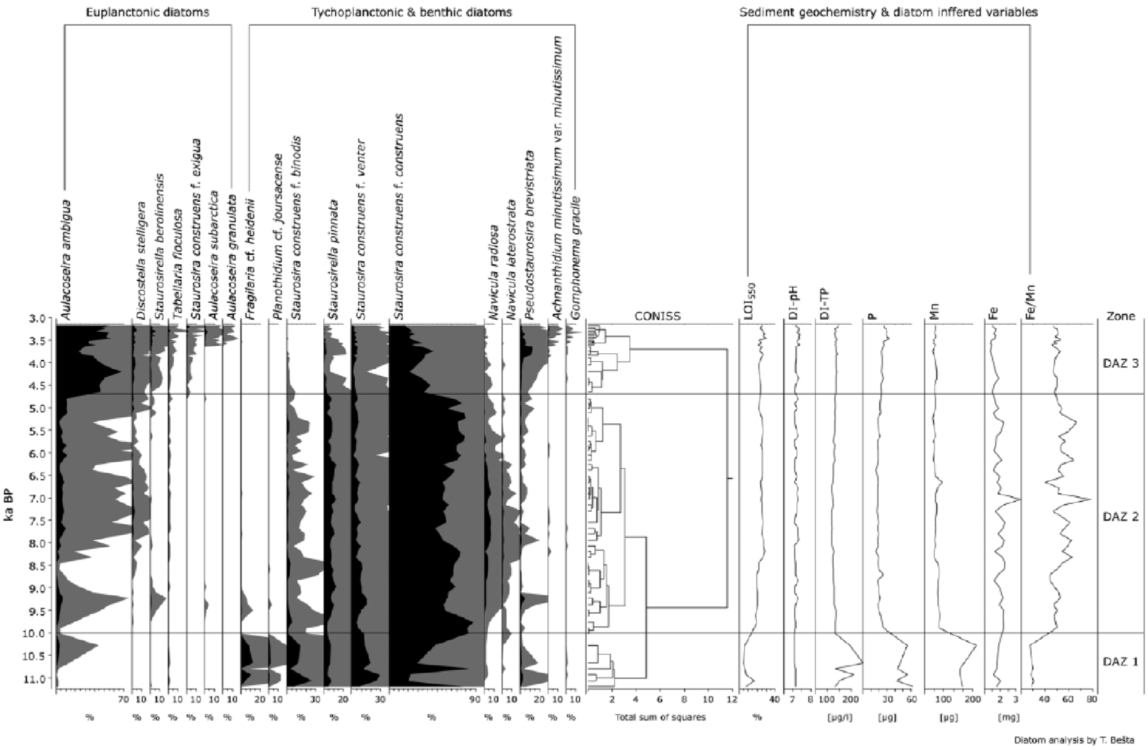


Figure 3. Pollen diagram from the core PK-1-C, Lake Komořany, Czech Republic (50.543°N, 13.544°E). The relative abundance of major pollen types is in black, and the grey area corresponds to 10-fold of the black. Pollen types with discontinuous occurrence were grouped to tertiary, shrubs, rare herbs and rare aquatics.



Diatom analysis by T. Bešta

Figure 4. Results of diatom analysis from the core PK-1-C, Lake Komořany, Czech Republic (50.543°N, 13.544°E). Relative abundance of diatom species is in black, and the grey area corresponds to 10-fold of the black. Black curves show trends in the content of organic matter, diatom-inferred pH (DI-pH) and diatom-inferred total phosphorus (DI-TP), content of selected elements (P, Mn and Fe) and the Fe/Mn ratio.

with abruptly changing diatom species composition and valve concentration. Samples dominated by the nominate form of the tychoplanktonic *Staurosira construens* alternated with samples typified by the occurrence of *Fragilaria heidenii*, a taxon preferring eutrophic saline water, along with other forms of *S. construens* (*binodis* and *venter*). Also, chrysophycean stomatocysts reached their maximum abundance.

The species composition and valve concentration were rather stable in DAZ-2 (10.0–4.8 ka BP) with the tychoplanktonic species *S. construens* var. *construens* being dominant. The epipelic *Navicula radiosa* and *N. laterostrata* occurred solely in DAZ-2. Euplanktonic species were represented by *Aulacoseira ambigua* and *Discostella stelligera*, a taxon preferring deep water. Euplanktonic taxa preferring eutrophic water (*F. heidenii* and *Staurosirella berolinensis*) were significantly abundant in 9.5–9.1 ka BP. Decreasing abundance of euplanktonic species was recorded in 9.9–9.8, 9.1–8.4 and 6.3–5.1 (4.9) ka BP. The third one was less distinct, linked with fluctuation of *D. stelligera*. A massive occurrence of euplanktonic species (*A. ambigua, D. stelligera* and *S. berolinensis*) specified DAZ-3 (4.7–3.2 ka BP). Their abundance decreased in 3.8–3.6 ka BP, which coincided with a peak in the benthic *Pseudostaurosira brevistriata.* Several euplanktonic species (*A. granulata* and *A. subarctica*) preferring eutrophic conditions occurred in 3.6–3.2 ka BP.

Geochemistry

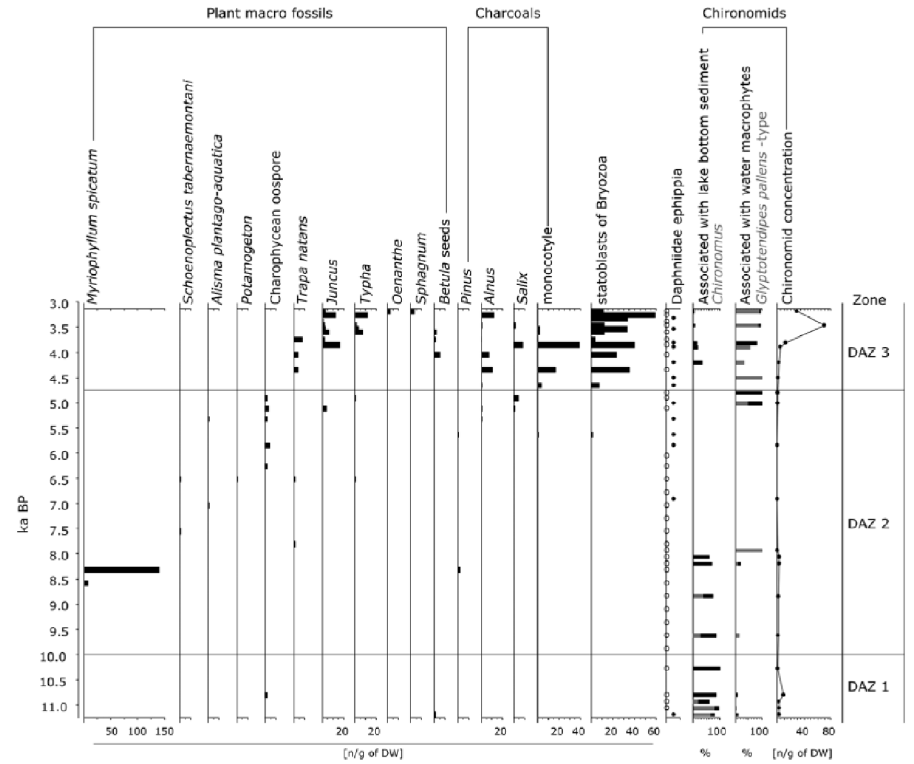
Low levels of LOI_{550} (5–8%, except of the peak at 11.1 ka BP) were recorded in samples corresponding to DAZ-1. These increased to 17–22% for the period 11.0–8.4 ka BP followed by a gradual decrease from 29% to 22% in the 8.2–3.9 ka BP period. Fluctuating levels ranging between 21% and 30% were recorded at 3.8–3.2 ka BP (Figure 4). LOI_{950} levels were generally low and stable and did not exceed 3%, which implies a negligible hard-water effect. Similar trends in sediment TP and DI-TP values (Figure 4) were confirmed by their highly significant correlation ($p < 0.001$, $R^2 = 0.51$). A lake environment sensitive to hypolimnetic oxygen (from 11.2 to 10.0 ka BP) and permanently aerobic conditions in 10.0–3.2 ka BP was detected on the basis of Fe/Mn ratios (Figure 4).

Plant macrofossil analysis

The recovered plant macrofossil spectra were rather poor (Figure 5) with a total of 12 plant species recorded. Their number ranged between 0 and 140 counts. Plant remnants were completely absent except for a few finds of charophycean oospores in DAZ-1 (11.2–10.0 ka BP). There was a distinct increase in the number of *Myriophyllum spicatum* seeds at 8.3 ka BP. Low numbers of *Trapa natans* fruits and appendices, *Alisma plantago-aquatica* and *Schoenoplectus tabernaontanii* fruits, and fruits of *Potamogeton* sp. div. and *Typha* were identified in the 8.2–4.8 ka BP period. Charophycean oospores were present in 6.4–4.9 ka BP. Charcoals of *Alnus, Salix* and unidentified monocots and remnants of *Typha, Juncus, Oenanthe, Betula* and *T. natans* were present in 4.7–3.2 ka BP.

Chironomids, cladocerans and bryozoans

A total of 25 chironomid taxa (Diptera and Chironomidae) were distinguished (Figure 5). The often poorly preserved HCs reached very low counts on average (7 HC/gDW). In DAZ-1 (11.2–10.0 ka BP), chironomids preferring eutrophic and tolerating anoxic conditions prevailed: *Chironomus anthracinus*-type, *Chironomus plumosus*-type and *Procladius*. Chironomid remains were lacking in DAZ-2 (10.0–4.8 ka BP), except for the presence of taxa associated with aquatic macrophytes at 8.3 ka BP. A gradual increase in HC concentrations (up to 70 HC/gDW) was characterized by the dominance of *Glyptotendipes pallens*-type, and members of the genus *Endochironomus* (*E. albipennis*-type, *E. impar*-type and *E. tendens*-type) in DAZ-3 (4.7–3.2 ka BP). No remains of phantom midges (Diptera: Chaoboridae) were found in the



Plant macro fossil analysis by A. Bernardová
Charcoal analysis by J. Novák
Chironomid analysis by D. Vondrák

Figure 5. Results of plant macrofossils, chironomids, cladocerans and bryozoans from the core PK-1-C, Lake Komořany, Czech Republic (50.543°N, 13.544°E). Total counts are expressed by black histograms. The presence of Daphniidae ephippia is expressed by black full dots and its absence by black empty dots. The relative abundance of chironomids was expressed by black histograms; all types were assigned to general groups with the exception of two dominant types that were plotted by grey histograms. Selected samples for chironomid analysis are visualized by black dots in column 'Chironomid concentration'.

Table 2. Correlation coefficients for four climatic variables (T_{ann}, T_W, T_C and P_{ann}) between a pollen-based reconstructed and the estimated values (R_1) as well as between the estimated and observed climate variables (R_2), according to Nakagawa et al. (2002). The reconstruction was based on pollen data from the PK-1-C profile, Lake Komořany, Czech Republic (50.543°N, 13.544°E).

Reconstructed parameter	R_1	R_2
T_{ann}	0.72	0.98
T_W	0.74	0.98
T_C	0.65	0.95
P_{ann}	0.78	0.96

sediment. Cladocerans (Crustacea: Cladocera) were recorded by counting the resting eggs of the family Daphniidae only. All eggs were identified as ephippia of *Ceriodaphnia* sp. and *Daphnia* sp. Resting eggs of freshwater bryozoans (*Cristatella mucedo* and *Plumatella* sp.) occurred in DAZ-3.

Quantitative pollen-based climate and biome reconstruction

Cool mixed forest had the highest affinity score during the whole recorded period, excluding one sample originating from PAZ-2, where a temperate deciduous forest was reconstructed. There was sufficiently high accuracy ($R > 0.99$ for temperature and $R > 0.98$ for precipitation) of the estimation of the modern climate in the best modern analogue pollen spectra. The correlation coefficients are listed in Table 2. Reconstructions based on a training set composed of data including all terrestrial pollen types provided higher R_1 in comparison with reconstructions based on a training set composed of pollen types that define PFTs. The blank space in the diagrams corresponds to samples defining PAZ-2 (11.0–10.0 ka BP), which did not have any analogues for reconstruction (Figure 6). There were eight analogues for each layer, with the exception of the layers pointing to climate shifts at 9.5–9.2 ka BP, where there were one or four analogues. The pollen-based climate reconstruction revealed six periods (Figure 6): (1) 10.0–9.2 ka BP composed of samples with a low number of analogues indicating low T_{ann}, especially T_w, (2) 9.1–6.5 ka BP corresponding to a relatively dry climate with rather stable T_{ann}, (3) 6.2–4.8 ka BP pointing to humid and warm conditions with the precipitation maximum around 5.0 ka BP, (4) 4.7–3.8 ka BP pointing to decreasing T_{ann}, (5) 3.8–3.5 ka BP corresponding to decreasing temperature and precipitation and (6) 3.5–3.2 ka BP defined by temperature increases.

Quantitative diatom reconstruction of TP and pH

The DI-pH (Figure 4) ranged from 7.1 to 7.4 and corresponded to circumneutral conditions in the whole studied sequence. DI-TP (Figure 4) ranged from 67 to 199 µg/L which indicated eutrophic–hypereutrophic conditions in the lake in DAZ-1 (11.2–10.0 ka BP), to stable mesotrophic conditions in DAZ-2 (10.0–4.8 ka BP) and to meso-eutrophic conditions in DAZ-3 (4.7–3.2 ka BP).

Discussion

Reliability of sediments used for palaeolimnological investigation

The limits of our study are linked with the nature of shallow lakes. Even though their sediments cannot offer data with the

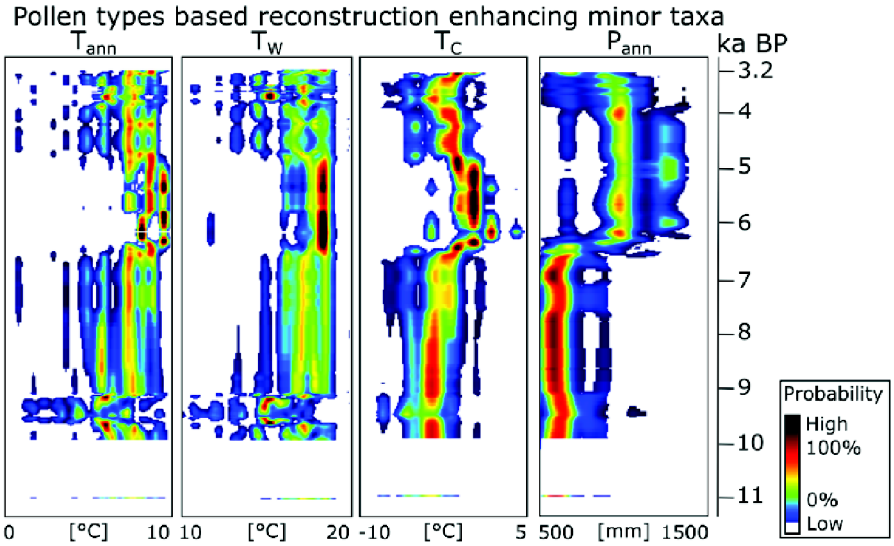


Figure 6. Climate changes of the period 11.2–3.2 ka BP around Lake Komořany, Czech Republic (50.543°N, 13.544°E), reconstructed from the pollen record excluding aquatic species from the PK-1-C core by the best modern analogue method.

resolution comparable to sediments from deep lakes (Pražáková et al., 2006; Van Raden et al., 2013) or even with the varved ones (Bronk Ramsey et al., 2012; Ojala et al., 2012; Zolitschka et al., 2015), they are sensitive to climate fluctuations and can also be of great ecological and socio-economic importance now as well as in the past (Korponai et al., 2010; Kuneš et al., 2015). The low resolution of their historical data is due to a low sedimentation rate (Gąsiorowski, 2008; Willemse, 2002), which is influenced by sediment focusing and other processes (Hilton et al., 1986). In PK-1-C, the extremely low sedimentation rate can be explained by (1) a low supply of allochthonous inorganic material as proved by the lack of sand, clay and silt on the diatom slides; (2) continuous remineralization as evidenced by the relatively low content of organic matter (LOI_{550}); and (3) sediment focusing indicated by the sedimentation rate being half of that in the littoral parts of Lake Komořany (Bešta et al., 2015; Jankovská and Pokorný, 2013). Disturbances in the stratigraphic record are difficult to detect unless an abrupt hiatus is evident in the lithological, geochemical, ^{14}C, diatom or pollen data (Whitmore et al., 1996). Based on our data, the fairly continuous deposition from 10 to 3.2 ka BP is analogous to the constant sedimentation process in lake littorals for the 9.1–4.7 ka BP period (Bešta et al., 2015) with an abrupt interruption in PAZ-2 recorded in PK-1-C. Short-term hiatuses probably may not change the interpretations of our time resolution (~50–150 yr/sample). Another limit comes from the use of bulk sediment for AMS ^{14}C dating. Any hard-water effect was of minor importance since $LOI_{950} < 3\%$ suggests a negligible content of carbonates in the sediment. Moreover, Lake Komořany lacks environmental factors which would influence AMS ^{14}C dating of soft water sediments (Björck and Wohlfarth, 2001). Factors causing an offset between AMS ^{14}C dates of terrestrial macrofossils and bulk sediment, such as increased input of allochthonous material (Gąsiorowski, 2008), major sediment redistribution (Whitmore et al., 1996) or oxygen deficiency (Barnekow et al., 1998), were documented in PK-1-C only in the early-Holocene, and the corresponding ^{14}C date was excluded from the deposition model. Although most circumstances support a negligible reservoir effect (Willemse, 2002), the chronological interpretations were made with an awareness of possible errors.

Development in early-Holocene

Lake-level shifts often forced by climate changes (Eusterhues et al., 2002; Finsinger et al., 2010; Kalis et al., 2003; Magny et al., 2009, 2013) are recorded in Lake Komořany due to the different ages of the start and end of sedimentation of the lake deposits at different locations (Bešta et al., 2015; Jankovská and Pokorný, 2013; Losert, 1940). The start of sedimentation in the PK-1-C section is dated to ca. 11.2 ka BP (Table 1), which is synchronous with warming after the 11.4-ka event recorded in the Greenland DYE-3, GRIP and NGRIP ice cores (Kobashi et al., 2008; Rasmussen et al., 2007, 2014) tentatively equal to the 'Preboreal Oscillation' (Hoek and Bos, 2007). This transition was linked with enhanced humidity in NW Europe (Bos et al., 2007) and possibly coincided with phases of high water levels in west-central European (WCE) lakes (Magny, 2004). The reconstructed lake-level rise in Lake Komořany coincides with an increase in *Corylus* pollen abundance (PAZ 1, Figure 3). We suggest that the warmer but also more humid phase at ca. 11.2 ka BP facilitated a spread of this thermophilous tree taxa in the area before the spread of a 'Preboreal dry phase' in CE after 11.16 ka BP (Kalis et al., 2003; Kulesza et al., 2012; Theuerkauf et al., 2014). The start of this dry period was perhaps linked to distinct redeposition events and changes in the aquatic environment (e.g. lowering of the water level and periodic desiccation) in PAZ-2 as supported by identification of some 15% of pollen grains of Tertiary origin, low pollen concentration, presence of rather damaged pollen grains (Figure 3), an outlier date of a gyttja sample (Table 1), fluctuation in diatom spectra, eutrophic–hypereutrophic conditions according to DI-TP and TP concentrations and an environment sensitive to hypolimnetic oxygen concentrations using Fe/Mn ratios (Figure 4) and chironomid analysis (Figure 5). Disturbed deposition in early-Holocene sediments is known from numerous CE lakes (Fajer et al., 2012; Losert, 1940; Ralska-Jasiewiczowa et al., 1998; Rudolph, 1926). Based on our results, we expect there was a rather warm, shallow and marshy aquatic environment with anoxic conditions from 11.0 to 10.0 ka BP. A significant change to more stable conditions was recorded in the lake environment starting at 10.0 ka BP (Figure 3 and 4), and which bordered the period of further expansion of other thermophilous tree taxa in the vicinity of Lake Komořany (Figure 3), which is in accordance with data from other CE sites (Ralska-Jasiewiczowa et al., 1998; Theuerkauf et al., 2014). The less significant decrease in temperatures was reconstructed in 9.5–9.2 ka BP (Figure 6), which is synchronous with a cool and wet phase in 9.5–9.2 ka BP and glacier advances reconstructed in the alpine region in the period from 9.6 to 9.3 ka BP (Joerin et al., 2006; Schmidt et al., 2006). A significant rise in temperature reconstructed according to a macrophysical climate model (MCM) in

Pannonian lowlands after 9.5 ka BP (Kuneš et al., 2015) may be also influenced by the Atlantic climate and connected with a 9.3-ka event described in Rasmussen et al. (2007). The reconstructed temperature shift was followed by changes in the lake environment at 9.2 ka BP (Figure 4). Halophilous diatoms were succeeded by an increased abundance of benthic ones pointing to the increased contribution of the littoral species pool to the recorded spectrum after 9.1 ka BP (Figure 4). This corresponds with the onset of lacustrine sedimentation at the site of the PK-1-CH core (Bešta et al., 2015) implying lake expansion, particularly of its extended littorals. To summarize, the influence of the Atlantic climate, especially the short-term '11.4, and 9.3 events', was probably reflected in processes in continental and lowland Lake Komořany.

Changing lake in a stable climate in 9.1–6.5 ka BP

A stable climate defined by low precipitation rates prevailed until 6.5 ka BP with lacustrine alternations at 8.4 ka BP. Even though we cannot exclude there being a shift in our dating model and that these alternations actually correspond to the '8.2-ka event', we suppose that the boundary between the early-Holocene and middle-Holocene is not reflected by any analysed proxy similar to the climate reconstructions from WCE (Litt et al., 2009). Moreover, synchronicity with the beginning of the Holocene optimum at 8.5 ka BP in the mid-northern latitudes of Europe (Litt et al., 2009) and wetter climate in Germany from 7.5 to 6.3 ka BP (Kalis et al., 2003) are not reflected by our data. Pollen of *Hedera* and *Viscum* are the only indicators of elevated temperatures in the 9.1–6.5 ka BP period.

The spread of water macrophytes in Lake Komořany at 8.4–8.3 ka BP correlates with an increased abundance of chironomid species bound to aquatic plants (Figure 5). Even though the distribution of aquatic plant taxa reflect increased temperatures (Väliranta et al., 2015) and human activities (Karg, 2006), it is often driven by the availability of suitable habitats consisting of shallow, eutrophic standing water (Schofield and Bunting, 2005). The increased abundance of aquatic species in the pollen record reflects most probably their spatial distribution and close proximity of littorals (Davis and Brubaker, 1973; Davis et al., 1971). This interpretation, along with a decrease in the contribution of littorals to the recorded diatom spectra in the 8.3–6.5 ka BP period (Figures 3 and 4), implies that the lake area was smaller in this interval. The lack of macrofossils indicates that the location of the core was not directly by the location of the lake shore during the 8.2–6.5 ka BP period (Figure 6). Correlation with a low number of poorly preserved chironomid HCs indicates mixing of the water column with the absence of anoxic conditions (Naeher et al., 2013) and transport of mixed material towards a downwind shoreline (Grelsson and Nilsson, 1991; Sarneel et al., 2014).

Climatic optimum in 6.5–4.8 ka BP

A moist and warm climate (Figure 6) corresponds with the more expanded lake area in 6.5–4.8 ka BP. This is based on our data corresponding to previously described assumptions and inferred from lithology and pollen data (Losert, 1940). Moreover, a local lack of macrophytes growing in the littorals is indicated by the increased count of *Chara* oospores (Figure 5) pointing to transparent water (Hannon and Gaillard, 1997). Our climate data are in agreement with reconstructed increased precipitation between time points at 7, 6 and 5 ka BP for a site close to Lake Komořany (Mauri et al., 2015) and in nearby lowland areas (Mondsee, 6.5–4.5 ka; Balaton, 5.6–5.0 ka BP) which peaked at 5 ka BP (Korponai et al., 2010; Swierczynski et al., 2013). But such data are not fully consistent in CE lowlands, as increased aridity has been reconstructed elsewhere (MCM, Vracov, 9.5–5.5 ka BP; multiple sites in Germany after 6.3 ka BP; Kalis et al., 2003; Kuneš et al., 2015). There was a more variable climate in WCE (Arbogast et al., 2006; Baier et al., 2004; Magny, 2004) and the alpine region (Joerin et al., 2006; Patzelt, 1977; Swierczynski et al., 2013), even though some described climate fluctuations are considered to be rather minor in the longer time horizon (Ivy-Ochs et al., 2009). But since our data are synchronous to the significant changes reconstructed in the area of a nearby Lake Vracov, based on a REVEALS estimated vegetation (e.g. increase in *Corylus* abundance), and are not reflected by the used MCM (Kuneš et al., 2015), further studies are needed.

The late-Holocene and a collapse in the landscape

Decreases in the reconstructed temperature and the lake level were initiated starting in 4.8/4.7 ka BP, before a climatostratigraphical boundary for the onset of the late-Holocene in 4.2 ka BP (Walker et al., 2012), but occur after a temperature drop in WE and WCE in 5 ka BP (Davis et al., 2003; Litt et al., 2009). The reconstructed changes temporally coincide with an event of clustering changes in European pollen diagrams identified by Giesecke et al. (2011). The drop in the Lake Komořany water level is synchronously recorded in the PK-1-CH core resulting in the cessation of gyttja sedimentation in 4.1 ka BP (Bešta et al., 2015). In PK-1-C, this water level decrease was deduced from the increased abundance of water macrophytes and littoral species in the pollen (Figure 3) and macrofossil spectra (Figure 5). Almost 100% of the chironomid species were associated with the macrophytes implying their extremely dense overgrowth (Figure 5). Two phases of reduced littorals are reconstructed for the 4.7–3.9 and 3.5–3.2 ka BP periods based on the diverse proportions of benthic and euplanktonic diatoms (Figure 4). These phases correspond to less distinct climate shifts in 3.8 and 3.5 ka BP (Figure 6). Climate deterioration starting in 3.8 ka BP corresponds with increased human impact in the region as inferred from increased AI abundance (Figure 3). Eutrophication and increased content of organic matter developed from 3.5 ka BP onwards (Figure 4). As in the case of the significant change in vegetation cover connected with the development of gradual soil acidification in 4.7 ka BP leading to a complete collapse in the sandstone landscape (Pokorný and Kuneš, 2005), we consider that the synchronously starting process of lake transgression is a multifactorial process that was not straightforwardly caused by climatic changes. We suggest that it was affected by climate, but it might also have been induced by humans with a significant time lag and connected with the ongoing deforestation in the catchment area starting from 5.5 ka BP. Even though the AP/NAP ratio remained constant, the pollen curve of *Plantago lanceolata* pointed to the expansion of dry grasslands (Poschlod and Baumann, 2010) caused by the increased influence of grazing (Behre, 1981).

Conclusion

Synchronicity in the external climate and local lacustrine changes was documented in the Holocene record of the large and shallow Lake Komořany located in a semi-continental lowland of CE. Water surface area extension reacted to short-term climate events in the early-Holocene, namely to warming after the '11.4 and 9.3 ka events'. Long-term trends in the Holocene climate, reconstructed from the pollen record of the PK-1-C core, indicate relatively dry conditions and stable mean annual temperatures between 9.1 and 6.5 ka BP and do not reflect the '8.2-ka event'. The traditionally considered 'climatic optimum' probably did not start until 6.5 ka BP, having its peak centred to the 6.3–4.8 ka BP period. The reconstructed warm and wet climate corresponded to the largest lake area. Despite a humid and warm climate, dry grasslands expanded from 5.5 ka BP onwards, thus being probably caused by human impact. One of the most significant changes was dated to 4.8/4.7 ka BP and resulted in the reduction of the lake surface area. This event was connected with a decrease in mean annual temperature. No climate changes were reconstructed at the middle-Holocene–late-Holocene boundary at 4.2 ka BP. A less distinct drop in mean annual precipitations and temperature occurred at 3.8 ka BP, along with the record of increased human impact. Further reduction in the lake area corresponded to less distinct climate changes, an increase in temperature and a decrease in precipitation at 3.5 ka BP.

Three major phases of Lake Komořany were distinguished. The character of the lake environment was rather warm, shallow, eutrophic, anoxic and marshy in the period of 11.2–10.0 ka BP. Relatively stable conditions prevailed in the period of 9.1–4.7 ka BP, pointing to the most extensive lake area possessing transparent water from 6.5 to 4.8 ka BP. The reduction of the lake area started at 4.7, continued at 3.5 ka BP and affected the trophic status.

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References

Abraham V, Kuneš P, Petr L et al. (2016) A pollen-based quantitative reconstruction of the Holocene vegetation updates a perspective on the natural vegetation in the Czech Republic and Slovakia. *Preslia* 88: 409–434.

Anderberg A-L (1994) *Atlas of Seeds and Small Fruits of Northwest-European Plant Species (Sweden, Norway, Denmark, East Fennoscandia, and Iceland) with Morphological Descriptions. Part 4, Resedaceae – Umbelliferae*. Stockholm: Swedish Museum of Natural History.

Arbogast RM, Jacomet S, Magny M et al. (2006) The significance of climate fluctuations for lake level changes and shifts in subsistence economy during the late Neolithic (4300–2400 B.C.) in central Europe. *Vegetation History and Archaeobotany* 15: 403–418.

Baier J, Lücke A, Negendank JFW et al. (2004) Diatom and geochemical evidence of mid- to late-Holocene climatic changes at Lake Holzmaar, West-Eifel (Germany). *Quaternary International* 113: 81–96.

Barnekow L, Possnert G and Sandgren P (1998) AMS ^{14}C chronologies of Holocene lake sediments in the Abisko area, northern Sweden – A comparison between dated bulk sediment and macrofossil samples. *GFF* 120: 59–67.

Battarbee RW (2000) Palaeolimnological approaches to climate change, with special regard to the biological record. *Quaternary Science Reviews* 19: 107–124.

Behre K-E (1981) The interpretation of anthropogenic indicators in pollen diagram. *Pollen et Spores* 23: 225–245.

Berggren G (1981) *Atlas of Seeds and Small Fruits of Northwest-European Plant Species (Sweden, Norway, Denmark, East Fennoscandia and Iceland) with Morphological Descriptions. Part 3, Salicaceae – Cruciferae*. Stockholm: Swedish Museum of Natural History.

Bešta T, Novák J, Dreslerová D et al. (2015) Mid-Holocene history of a central European lake: Lake Komořany, Czech Republic. *Boreas* 44: 563–574.

Bešta T, Šafránková J, Pouzar M et al. (2009) Late Pleistocene-early Holocene transition recorded in the sediments of a former shallow lake in the Czech Republic. *Hydrobiologia* 631: 107–120.

Beug H-J (2004) *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete*. München: Friedrich Pfeil.

Birks HH and Birks HJB (2006) Multi-proxy studies in palaeolimnology. *Vegetation History and Archaeobotany* 15: 235–251.

Birks HJB (2012) Overview of numerical methods in palaeolimnology. In: Birks HJB, Lotter AF, Juggins S et al. (eds) *Tracking Environmental Change Using Lake Sediments. Volume 5: Data Handling and Numerical Techniques*. Dordrecht: Kluwer Academic Publishers, pp. 19–92.

Birks HJB, Heiri O, Seppä H et al. (2010) Strengths and weaknesses of quantitative climate reconstructions based on late-Quaternary biological proxies. *The Open Ecology Journal* 3: 68–110.

Björck S and Wohlfarth B (2001) ^{14}C chronostratigraphic techniques in paleolimnology. In: Last WM and Smol JP (eds) *Tracking Environmental Change Using Lake Sediments. Volume 1: Basin Analysis, Coring, and Chronological Techniques*. Dordrecht: Kluwer Academic Publishers, pp. 205–245.

Boch R, Spötl C and Kramers J (2009) High-resolution isotope records of early Holocene rapid climate change from two coeval stalagmites of Katerloch Cave, Austria. *Quaternary Science Reviews* 28: 2527–2538.

Bonk A, Tylmann W, Amann B et al. (2015) Modern limnology, sediment accumulation and varve formation processes in Lake Żabińskie, northeastern Poland: Comprehensive process studies as a key to understand the sediment record. *Journal of Limnology* 74: 358–370.

Bos JAA, van Geel B, van der Plicht J et al. (2007) Preboreal climate oscillations in Europe: Wiggle-match dating and synthesis of Dutch high-resolution multi-proxy records. *Quaternary Science Reviews* 26: 1927–1950.

Boyle JF (2001) Inorganic geochemical methods in palaeolimnology. In: Last WM and Smol JP (eds) *Tracking Environmental Change Using Lake Sediments. Volume 2: Physical and Geochemical Methods*. Dordrecht; London: Kluwer Academic Publisher, pp. 83–142.

Bronk Ramsey C (2008) Deposition models for chronological records. *Quaternary Science Reviews* 27: 42–60.

Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51: 337–360.

Bronk Ramsey C (2014) *OxCal 4.2 Online Program*. OxCal Project web. Available at: https://c14.arch.ox.ac.uk/oxcal/OxCal.html.

Bronk Ramsey C, Staff RA, Bryant CL et al. (2012) A complete terrestrial radiocarbon record for 11.2 to 52.8 kyr B.P. *Science* 338: 370–374.

Brooks SJ, Langdon PG and Heiri O (2007) *The Identification and Use of Palaearctic Chironomidae Larvae in Palaeoecology*. London: Quaternary Research Association.

Cappers RTJ, Bekker RM and Jans JEA (2006) *Digital Seed Atlas of the Netherlands*. Eelde: Barkhuis Publishing & Groningen University Library.

Chytrý M (2012) Vegetation of the Czech Republic: Diversity, ecology, history and dynamics. *Preslia* 84: 427–504.

Davis BAS, Brewer S, Stevenson AC et al. (2003) The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Science Reviews* 22: 1701–1716.

Davis MB and Brubaker LB (1973) Differential sedimentation of pollen grains in lakes. *Limnology and Oceanography* 18: 635–646.

Davis MB, Brubaker LB and Beiswenger JM (1971) Pollen grains in lake sediments: Pollen percentages in surface sediments from southern Michigan. *Quaternary Research* 1: 450–467.

Dean WE (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition – Comparison with other methods. *Journal of Sedimentary Petrology* 44: 242–248.

Denys L (1991) *A Check-List of the Diatoms in the Holocene Deposits of the Western Belgian Coastal Plain with a Survey of Their Apparent Ecological Requirements. Volume 1: Introduction, Ecological Code and Complete List*. Berchem: Service Géologique de Belgique.

Dörfler W, Feeser I, van den Bogaard C et al. (2012) A high-quality annually laminated sequence from Lake Belau, Northern Germany: Revised chronology and its implications for palynological and tephrochronological studies. *The Holocene* 22: 1413–1426.

Dreibrodt S and Wiethold J (2015) Lake Belau and its catchment (northern Germany): A key archive of environmental history in northern central Europe since the onset of agriculture. *The Holocene* 25: 296–322.

Eusterhues K, Lechterbeck J, Schneider J et al. (2002) Late- and Post-Glacial evolution of Lake Steisslingen (I).: Sedimentary history, palynological record and inorganic geochemical indicators. *Palaeogeography, Palaeoclimatology, Palaeoecology* 187: 341–371.

Fægri K and Iversen J (1989) *Textbook of Pollen Analysis*. 4th Edition. Chichester: John Wiley & Sons.

Fajer M, Waga JM, Rzetala M et al. (2012) The Late Vistulian and Holocene evolution of Jezioro Lake: A record of environmental change in southern Poland found in deposits and landforms. *Journal of Paleolimnology* 48: 651–667.

Faria JC (2009) *Resources of Tinn-R GUI/Editor for R Environment*. Ilheus: UESC.

Finsinger W, Colombaroli D, De Beaulieu JL et al. (2010) Early to mid-Holocene climate change at Lago dell'Accesa (central Italy): Climate signal or anthropogenic bias? *Journal of Quaternary Science* 25: 1239–1247.

Fohlmeister J, Schroder-Ritzrau A, Scholz D et al. (2012) Bunker Cave stalagmites: An archive for central European Holocene climate variability. *Climate of the Past* 8: 1751–1764.

Francis DR (2001) Bryozoan statoblasts. In: Smol JP, Birks HJ and Last WM (eds) *Tracking Environmental Change Using Lake Sediments. Volume 4: Zoological Indicators*. Dordrecht: Kluwer Academic Publishers, pp. 105–123.

Fyfe RM, de Beaulieu JL, Binney H et al. (2009) The European pollen database: Past efforts and current activities. *Vegetation History and Archaeobotany* 18: 417–424.

Gaillard MJ, Sugita S, Mazier F et al. (2010) Holocene land-cover reconstructions for studies on land cover-climate feedbacks. *Climate of the Past* 6: 483–499.

Gąsiorowski M (2008) Deposition rate of lake sediments under different alternative stable states. *Geochronometria* 32: 29–35.

Giesecke T, Bennett KD, Birks HJB et al. (2011) The pace of Holocene vegetation change – Testing for synchronous developments. *Quaternary Science Reviews* 30: 2805–2814.

Grelsson G and Nilsson C (1991) Vegetation and seed-bank relationships on a lakeshore. *Freshwater Biology* 26: 199–207.

Grimm EC (1987) CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences* 13: 13–35.

Grimm EC (2011) *Tilia* (Version 1.7.16). Springfield, IL: Illinois State Museum.

Guiot J, Harrison SP and Prentice IC (1993) Reconstruction of Holocene precipitation patterns in Europe using pollen and lake-level data. *Quaternary Research* 40: 139–149.

Haas JN, Richoz I, Tinner W et al. (1998) Synchronous Holocene climatic oscillations recorded on the Swiss Plateau and at timberline in the Alps. *The Holocene* 8: 301–309.

Hannon GE and Gaillard MJ (1997) The plant-macrofossil record of past lake-level changes. *Journal of Paleolimnology* 18: 15–28.

Heiri O, Lotter AF and Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnology* 25: 101–110.

Heiri O, Tinner W and Lotter AF (2004) Evidence for cooler European summers during periods of changing meltwater flux to the North Atlantic. *Proceedings of the National Academy of Sciences of the United States of America* 101: 15285–15288.

Heiri O, Lotter AF, Hausmann S et al. (2003) A chironomid-based Holocene summer air temperature reconstruction from the Swiss Alps. *The Holocene* 13: 477–484.

Hilton J, Lishman JP and Allen PV (1986) The dominant processes of sediment distribution and focusing in a small, eutrophic, monomictic lake. *Limnology and Oceanography* 31: 125–133.

Hoek WZ and Bos JAA (2007) Early Holocene climate oscillations – Causes and consequences. *Quaternary Science Reviews* 26: 1901–1906.

Hormes A, Müller BU and Schlüchter C (2001) The Alps with little ice: Evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. *The Holocene* 11: 255–265.

Hošek J, Pokorný P, Kubovčík V et al. (2014) Late glacial climatic and environmental changes in eastern-central Europe: Correlation of multiple biotic and abiotic proxies from the Lake Švarcenberk, Czech Republic. *Palaeogeography, Palaeoclimatology, Palaeoecology* 396: 155–172.

Hurník S (1969) Příspěvek ke geologické problematice tzv. Komořanského jezera, Mostecko-Litvínovsko, Regionální studie. *Příroda* 6: 5–14.

Ivy-Ochs S, Kerschner H, Maisch M et al. (2009) Latest Pleistocene and Holocene glacier variations in the European Alps. *Quaternary Science Reviews* 28: 2137–2149.

Jankovská V and Pokorný P (2013) Reevaluation of the palaeoenvironmental record of the former Komoranske jezero lake: Late-glacial and Holocene palaeolimnology and vegetation development in north-western Bohemia, Czech Republic. *Preslia* 85: 265–287.

Joerin UE, Stocker TF and Schlüchter C (2006) Multicentury glacier fluctuations in the Swiss Alps during the Holocene. *The Holocene* 16: 697–704.

Kaiser K, Lorenz S, Germer S et al. (2012) Late Quaternary evolution of rivers, lakes and peatlands in northeast Germany reflecting past climatic and human impact – An overview. *E&G Quaternary Science Journal* 61: 103–132.

Kalis AJ, Merkt J and Wunderlich J (2003) Environmental changes during the Holocene climatic optimum in central Europe – Human impact and natural causes. *Quaternary Science Reviews* 22: 33–79.

Karg S (2006) The water chestnut (*Trapa natans* L.) as a food resource during the 4th to 1st millennia BC at Lake Federsee, Bad Buchau (southern Germany). *Environmental Archaeology* 11: 125–130.

Kobashi T, Severinghaus JP and Barnola J-M (2008) 4±1.5 °C abrupt warming 11,270 yr ago identified from trapped air in Greenland ice. *Earth and Planetary Science Letters* 268: 397–407.

Komárek J and Jankovská V (2001) *Review of the Green Algal Genus Pediastrum; Implication for Pollen-Analytical Research*. Berlin: J. Cramer.

Korponai J, Braun M, Buczkó K et al. (2010) Transition from shallow lake to a wetland: A multi-proxy case study in Zalavári Pond, Lake Balaton, Hungary. *Hydrobiologia* 641: 225–244.

Krammer K and Lange-Bertalot H (1986) *Bacillariophyceae (Naviculaceae). Süsswasserflora von Mitteleuropa*. Stuttgart: Gustav Fisher Verlag.

Krammer K and Lange-Bertalot H (1988) *Bacillariophyceae (Bacillariaceae, Epithemiaceae, Surirellaceae)*. *Süsswasserflora von Mitteleuropa*. Stuttgart: Gustav Fisher Verlag.

Krammer K and Lange-Bertalot H (1991a) *Bacillariophyceae (Achnanteaceae, Kritische Ergänzungen zu Navicula (Lineolateae) und Gomphonema. Gesamtliteraturverzeichnis Teil 1–4. Süsswasserflora von Mitteleuropa*. Stuttgart: Gustav Fisher Verlag.

Krammer K and Lange-Bertalot H (1991b) *Bacillariophyceae (Centrales, Fragilariaceae, Eunotiaceae)*. *Süsswasserflora von Mitteleuropa*. Stuttgart: Gustav Fisher Verlag.

Krause W (1986) Zur Bestimmungsmöglichkeit subfossiler Characeen-Oosporen an Beispielen aus Schweizer Seen. *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich* 131: 295–313.

Kulesza P, Suchora M, Pidek IA et al. (2012) The Holocene palaeoenvironmental changes reflected in the multi-proxy studies of Lake Słone sediments (SE Poland). *Palaeogeography, Palaeoclimatology, Palaeoecology* 363–364: 79–98.

Kuneš P, Abraham V, Kovářík O et al. (2009) Czech quaternary palynological database – PALYCZ: Review and basic statistics of the data. *Preslia* 81: 209–238.

Kuneš P, Svobodová-Svitavská H, Kolář J et al. (2015) The origin of grasslands in the temperate forest zone of east-central Europe: Long-term legacy of climate and human impact. *Quaternary Science Reviews* 116: 15–27.

Laird KR, Kingsbury MV, Lewis CFM et al. (2011) Diatom-inferred depth models in 8 Canadian boreal lakes: Inferred changes in the benthic:planktonic depth boundary and implications for assessment of past droughts. *Quaternary Science Reviews* 30: 1201–1217.

Legendre P and Legendre L (1998) *Numerical Ecology*. Amsterdam; Oxford: Elsevier.

Litt T, Schölzel C, Kühl N et al. (2009) Vegetation and climate history in the Westeifel Volcanic Field (Germany) during the past 11 000 years based on annually laminated lacustrine maar sediments. *Boreas* 38: 679–690.

Löffler H (1979) *Neusiedlersee: The Limnology of a Shallow Lake in Central Europe*. The Hague: Dr. W. Junk bv Publishers.

Losert H (1940) Beiträge zur spät- und nacheizeitlichen Vegetationgeschichte Innerböhmens. 1. Der Kommerner See. *Beihefte zum Botanischen Centralblatt* 60B: 346–394.

Ložek V (1998) Late Bronze Age environmental collapse in the sandstone areas of northern Bohemia. In: Hänsel B (ed.) *Man and Environment in European Bronze Age*. Kiel: Oetker-Voges Verlag, pp. 57–60.

MacArthur RH (1957) On the relative abundance of bird species. *Proceedings of the National Academy of Sciences of the United States of America* 43: 293–295.

Magny M (2004) Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements. *Quaternary International* 113: 65–79.

Magny M, Aalbersberg G, Bégeot C et al. (2006) Environmental and climatic changes in the Jura mountains (eastern France) during the Lateglacial–Holocene transition: A multi-proxy record from Lake Lautrey. *Quaternary Science Reviews* 25: 414–445.

Magny M, Combourieu-Nebout N, de Beaulieu JL et al. (2013) North-south palaeohydrological contrasts in the central Mediterranean during the Holocene: Tentative synthesis and working hypotheses. *Climate of the Past* 9: 2043–2071.

Magny M, Galop D, Bellintani P et al. (2009) Late-Holocene climatic variability south of the Alps as recorded by lake-level fluctuations at Lake Ledro, Trentino, Italy. *The Holocene* 19: 575–589.

Magny M, Vanniere B, de Beaulieu JL et al. (2007) Early-Holocene climatic oscillations recorded by lake-level fluctuations in west-central Europe and in central Italy. *Quaternary Science Reviews* 26: 1951–1964.

Mauri A, Davis BAS, Collins PM et al. (2015) The climate of Europe during the Holocene: A gridded pollen-based reconstruction and its multi-proxy evaluation. *Quaternary Science Reviews* 112: 109–127.

Mayewski PA, Rohling EE, Stager JC et al. (2004) Holocene climate variability. *Quaternary Research* 62: 243–255.

Mirosław-Grabowska J and Zawisza E (2014) Late Glacial–Early Holocene environmental changes in Charzykowskie Lake (northern Poland) based on oxygen and carbon isotopes and Cladocera data. *Quaternary International* 328: 156–166.

Naeher S, Gilli A, North RP et al. (2013) Tracing bottom water oxygenation with sedimentary Mn/Fe ratios in Lake Zurich, Switzerland. *Chemical Geology* 352: 125–133.

Nakagawa T, Tarasov PE, Nishida K et al. (2002) Quantitative pollen-based climate reconstruction in central Japan: Application to surface and Late Quaternary spectra. *Quaternary Science Reviews* 21: 2099–2113.

Neustupný E (1985) K holocénu Komořanského jezera. *Památky archeologické* 76: 9–70.

New M, Lister D, Hulme M et al. (2002) A high-resolution data set of surface climate over global land areas. *Climate Research* 21: 1–25.

Ojala AEK, Francus P, Zolitschka B et al. (2012) Characteristics of sedimentary varve chronologies – A review. *Quaternary Science Reviews* 43: 45–60.

Patzelt G (1977) Der zeitliche Ablauf und das Ausmass postglazialer Klimaschwankungen in den Alpen. In: Frenzel B (ed.) *Dendrochronologie und postglaziale Klimaschwankungen in Europa*. Wiesbaden: F. Steiner Verlag, pp. 249–259.

Pokorný O (1963) Komořanské jezero. *Sborník československé společnosti zeměpisné* 1: 68–70.

Pokorný P and Kuneš P (2005) Holocene acidification process recorded in three pollen profiles from Czech sandstone and river terrace environments. *Ferrantia* 44: 107–114.

Pokorný P, Chytrý M, Juřičková L et al. (2015) Mid-Holocene bottleneck for central European dry grasslands: Did steppe survive the forest optimum in northern Bohemia, Czech Republic? *The Holocene* 25: 716–726.

Poschlod P and Baumann A (2010) The historical dynamics of calcareous grasslands in the central and southern Franconian Jurassic mountains: A comparative pedoanthracological and pollen analytical study. *The Holocene* 20: 13–23.

Pražáková M, Veselý J, Fott J et al. (2006) The long-term succession of cladoceran fauna and palaeoclimate forcing: A 14,600-year record from Plešné Lake, the Bohemian Forest. *Biologia* 61: S387–S399.

Prentice IC, Guiot J, Huntley B et al. (1996) Reconstructing biomes from palaeoecological data: A general method and its application to European pollen data at 0 and 6 ka. *Climate Dynamics* 12: 185–194.

Punt W (1976) *The Northwest European Pollen Flora: Parts 1–7*. Amsterdam: Elsevier.

Punt W and Blackmore S (1991) *The Northwest European Pollen Flora: Parts 44–51*. Amsterdam: Elsevier.

Punt W and Clarke G (1980) *The Northwest European Pollen Flora: Parts 8–20*. Amsterdam: Elsevier.

Punt W and Clarke G (1981) *The Northwest European Pollen Flora: Parts 21–28*. Amsterdam: Elsevier.

Punt W and Clarke G (1984) *The Northwest European Pollen Flora: Parts 29–37*. Amsterdam: Elsevier.

Punt W, Blackmore S and Clarke G (1988) *The Northwest European Pollen Flora: Parts 38–43*. Amsterdam: Elsevier.

Punt W, Blackmore S and Hoen P (1995) *The Northwest European Pollen Flora: Parts 52–56*. Amsterdam: Elsevier.

Punt W, Blackmore S, Hoen P et al. (2003) *The Northwest European Pollen Flora: Parts 57–68*. Amsterdam: Elsevier.

Punt W, Blackmore S, Hoen P et al. (2009) *The Northwest European Pollen Flora: Part 70*. Amsterdam: Elsevier.

R Development Core Team (2010) *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Ralska-Jasiewiczowa M, Goslar T, Madeyska T et al. (1998) *Lake Gościąż, Central Poland: A Monographic Study*. Kraków: W. Szafer Institute of Botany.

Rasmussen SO, Bigler M, Blockley SP et al. (2014) A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: Refining and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews* 106: 14–28.

Rasmussen SO, Vinther BM, Clausen HB et al. (2007) Early Holocene climate oscillations recorded in three Greenland ice cores. *Quaternary Science Reviews* 26: 1907–1914.

Reimer PJ, Bard E, Bayliss A et al. (2013) Intcal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55: 1869–1887.

Řeháková Z (1983) Diatom succession in the post-glacial sediments of the Komořany Lake, North-West Bohemia, Czechoslovakia. In: Meriläinen J, Huttunen P and Battarbee RW (eds) *Paleolimnology*. Dordrecht: Springer, pp. 241–245.

Řeháková Z (1986) The postglacial history of diatom-bearing sediments of the former Lake Komořany (North-West Bohemia). *Anthropozoikum* 17: 87–134.

Rudolph K (1926) Pollenanalytische Untersuchungen im thermophilen Florengebiete Böhmens. Der Kommernsee bei Brüx. *Berichte der Deutschen Botanischen Gesellschaft* 44: 239–248.

Sarneel JM, Beltman B, Buijze A et al. (2014) The role of wind in the dispersal of floating seeds in slow-flowing or stagnant water bodies. *Journal of Vegetation Science* 25: 262–274.

Schmidt R, Kamenik C, Tessadri R et al. (2006) Climatic changes from 12,000 to 4,000 years ago in the Austrian Central Alps tracked by sedimentological and biological proxies of a lake sediment core. *Journal of Paleolimnology* 35: 491–505.

Schofield JE and Bunting MJ (2005) Mid-Holocene presence of water chestnut (*Trapa natans* L.) in the meres of Holderness, East Yorkshire, UK. *The Holocene* 15: 687–697.

Schweingruber FH, Lenz O and Eidgenössische Forschungsanstalt für Wald Schnee und Landschaft (Birmensdorf) (1990) *Mikroskopische Holzanatomie: Formenspektren mitteleuropäischer Stamm- und Zweighölzer zur Bestimmung von rezentem und subfossilem Material*. Birmensdorf: Eidgenössische Forschungsanstalt für Wald.

Speranza A, Hanke J, van Geel B et al. (2000) Late-Holocene human impact and peat development in the Černá Hora bog, Krkonoše Mountains, Czech Republic. *The Holocene* 10: 575–585.

Spurk M, Leuschner HH, Baillie MGL et al. (2002) Depositional frequency of German subfossil oaks: Climatically and non-climatically induced fluctuations in the Holocene. *The Holocene* 12: 707–715.

Stanzl B (1832) *Hydrotechnischer Lokalbefund, welcher bei der zusammengesetzten gemeinschaftlichen Kommission über das grossartige Unternehmen der Entwässerung des Kommerner Sees auf der Fürst Ferdinand v. Lobkowitz'schen Herrschaft Neudorf-Eisenberg Saazer Kreis in Böhmen unter der Oberleitung und Vorsitz des k. k. Gubernialrates und saaser Kreishauptmanns Herrn Ferdinand Wussin von dem k. k. Wasserbau-Ingenieur Herrn Bernard Stanzl zu Brüx am 16. November 1831 abgegeben wurde*. Saaz: Verlag von Peter Ritter von Schönfeld.

Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. *Pollen et Spores* 13: 615–621.

Stuchlik L (2001) *Atlas of Pollen and Spores of the Polish Neogene*. Kraków: W. Szafer Institute of Botany.

Svobodová H, Soukupová L and Reille M (2002) Diversified development of mountain mires, Bohemian Forest, Central Europe, in the last 13,000 years. *Quaternary International* 91: 123–135.

Swierczynski T, Lauterbach S, Dulski P et al. (2013) Late Neolithic Mondsee Culture in Austria: Living on lakes and living with flood risk? *Climate of the Past* 9: 1601–1612.

Szeroczyńska K and Sarmaja-Korjonen K (2007) *Atlas of Subfossil Cladocera from Central and Northern Europe*. Świecie: Friends of the Lower Vistula Society.

Theuerkauf M, Bos JAA, Jahns S et al. (2014) *Corylus* expansion and persistent openness in the early Holocene vegetation of northern central Europe. *Quaternary Science Reviews* 90: 183–198.

Tinner W and Lotter AF (2001) Central European vegetation response to abrupt climate change at 8.2 ka. *Geology* 29: 551–554.

Tinner W, Ammann B and Germann P (1996) Treeline fluctuations recorded for 12,500 years by soil profiles, pollen, and plant macrofossils in the Central Swiss Alps. *Arctic and Alpine Research* 28: 131–147.

Tolasz R, Míková T, Valeriánová A et al. (2007) *Climate Atlas of Czechia*. Olomouc: Český hydrometeorologický ústav, Univerzita Palackého v Olomouci.

Troels-Smith J (1955) *Karakterisering af løse jordarter* [Characterization of Unconsolidated Sediments]. København: I kommission hos C.A. Reitzel.

Tylmann W, Zolitschka B, Enters D et al. (2013) Laminated lake sediments in northeast Poland: Distribution, preconditions for formation and potential for paleoenvironmental investigation. *Journal of Paleolimnology* 50: 487–503.

Väliranta M, Salonen JS, Heikkilä M et al. (2015) Plant macrofossil evidence for an early onset of the Holocene summer thermal maximum in northernmost Europe. *Nature Communications* 6: 6809.

Van Dam H, Mertens A and Sinkeldam J (1994) A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands. *Netherland Journal of Aquatic Ecology* 28: 117–133.

Van Geel B (2001) Non-pollen palynomorphs. In: Smol JP (ed.) *Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators*. Dordrecht: Kluwer Academic Publishers, pp. 99–119.

Van Raden UJ, Colombaroli D, Gilli A et al. (2013) High-resolution late-glacial chronology for the Gerzensee lake record (Switzerland): δ^{18}O correlation between a Gerzensee-stack and NGRIP. *Palaeogeography, Palaeoclimatology, Palaeoecology* 391: 13–24.

Veron A, Novak M, Brizova E et al. (2014) Environmental imprints of climate changes and anthropogenic activities in the Ore Mountains of Bohemia (Central Europe) since 13 cal. kyr BP. *The Holocene* 24: 919–931.

Von Grafenstein U, Erlenkeuser H, Brauer A et al. (1999) A mid-European decadal isotope-climate record from 15,500 to 5000 years B.P. *Science* 284: 1654–1657.

Vondrák D, Prach J and Houfková P (2015) Sediments of post-glacial lakes in the Czech Republic – Unique natural archives overlooked by (Czech) limnology. In: Rádková V and Bojková J (eds) *XVII. konference České limnologické společnosti a Slovenskej limnologickej spoločnosti 'Voda – věc veřejná' – Sborník příspěvků*. Brno: ČLS and Masarykova univerzita v Brně, pp. 162–167 (in Czech with English abstract).

Wackerbarth A, Langebroek PM, Werner M et al. (2012) Simulated oxygen isotopes in cave drip water and speleothem calcite in European caves. *Climate of the Past* 8: 1781–1799.

Walker MJC, Berkelhammer M, Bjorck S et al. (2012) Formal subdivision of the Holocene Series/Epoch: A discussion paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). *Journal of Quaternary Science* 27: 649–659.

Wanner H (2011) Weather, climate, human development. From the Ice Age to the 21st century. Scientific Paper Company in Darmstadt. *Praehistorische Zeitschrift* 86: 293–294.

Wasylikowa K (1986) Analysis of fossil fruits and seeds. In: Berglund B (ed.) *Handbook of Holocene Palaeoecology and Palaeohydrology*. Chichester: John Wiley & Sons, pp. 571–590.

Whitmore T, Brenner M and Schelske CL (1996) Highly variable sediment distribution in shallow, wind-stressed lakes: A case for sediment-mapping surveys in paleolimnological studies. *Journal of Paleolimnology* 15: 207–221.

Wiederholm T (1983) *Chironomidae of the Holarctic Region: Keys and Diagnosis. Volume 1: Larvae*. Lund: Scandinavian Entomology Ltd.

Willemse NW (2002) *Holocene Sedimentation History of the Shallow Kangerlussuaq Lakes, West Greenland*. Copenhagen: Museum Tusculanum Press.

Zapletal L (1954) Zbytky Komořanského jezera. *Ochrana přírody* 9: 57–58.

Zolitschka B, Brauer A, Negendank JFW et al. (2000) Annually dated late Weichselian continental paleoclimate record from the Eifel, Germany. *Geology* 28: 783–786.

Zolitschka B, Francus P, Ojala AEK et al. (2015) Varves in lake sediments – A review. *Quaternary Science Reviews* 117: 1–41.

5.3. Paper III.

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PRIMARY RESEARCH PAPER

The oldest Czech fishpond discovered? An interdisciplinary approach to reconstruction of local vegetation in mediaeval Prague suburbs

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Abstract Wet sediments of a former water reservoir were discovered during an archaeological rescue excavation. Vegetation and environmental changes taking place in the mediaeval suburbs of Prague, Czech Republic, from the tenth to the middle of the fourteenth century were investigated. The origin and function of the water reservoir was revealed using a multi-proxy approach that combined the results of macrofossil, pollen, diatom, antracological, archaeo-zoological and sedimentological analyses. Gradual changes of the surrounding vegetation were documented. Field indicators increased in time, whereas proportions of broadleaf trees and shrubs decreased; proportions of ruderal plants increased continually. A gradual decline of semi-natural hygrophilous vegetation was accompanied by an inverse tendency in trampled vegetation. All these trends indicate an intensification of human activity around the pool. A similar intensification of anthropogenic influence is clearly visible in the development of the aquatic environment. According to the diatom composition, the base of the profile is the result of sedimentation in considerably oligotrophic conditions. A successive deterioration of water quality was documented by various organisms (diatoms, green algae, water macrophyta, fishes and intestinal parasites). The high content of dissolved nutrients, probably connected with anoxia, could have caused the disappearance of both diatoms and fishes.

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Introduction

Fish farming has a long and rich tradition in the Czech lands. The spreading of carp (and knowledge of carp breeding) was probably connected with cultural influences coming from West Europe (Makowiecki, 2001). The progressive development of fishpond building in thirteenth century further culminated in fifteenth to sixteenth centuries (Hurt, 1960; Andreska, 1987; Čítek et al., 1998). However, there are indications that some kind of artificial water reservoirs containing fishes existed here already before the introduction of the carp fishponds. Sporadic written sources (mostly chronicles and legends) mention ‘fishponds’ already in tenth to eleventh centuries. The oldest known reference is traditionally being identified with a ceased Mediaeval village called Rybník (the Czech meaning of its name is ‘the Fishpond’) once located in the area of today’s New Town of Prague. The Rybník village was first mentioned in 993 in the Donation Deed of the Břevnov Monastery, obliging that the monastery receives tithes from all fields belonging to this village (called Ribnyk in the original Latin text).

A range of palaeoenvironmental techniques was used to study sediments which were supposed to be remnants of a pool once connected with the Rybník village. Among others, diatom analysis and the presence of eggs of intestinal parasites were included in the presented research. Structure of diatom community is tightly linked with changes in aquatic environment (e.g. Battarbee, 1986) and the rate of artificial pollution has been traditionally expressed in the index of saprobity (Sládeček, 1986). The presence of eggs of intestinal parasites has been used as an indicator of pollution by faeces (Bosi et al., 2011).

Combination of several techniques, above all palynology, anthracology and analysis of plant macro-remains were used for reconstruction of both aquatic and terrestrial vegetation. These analyses already proved their reliability within the palaeoecological and archaeobotanical research (e.g. Smol et al., 2001). Each of these methods naturally has its own advantages as well as limits resulting from different source areas of material, taphonomy and different determination levels (for more details see e.g. Birks & Birks, 2006; Gaillard, 2007; Novák et al., 2012; Théry-Parisot et al., 2010); therefore, it is advisable to combine them (for some examples see Sadori et al., 2010 or Święta-Musznicka et al., 2013).

Good examples of former water reservoirs studied using multi-proxy techniques are investigations of late-Glacial to early-Holocene Lake Švarcenberk (Pokorný, 2002) or a cistern at the pre-Roman Iron Age hillfort Vladař (Pokorný et al., 2006) as well as a Holocene profile from the Řežabinec fishpond (Rybníčková & Rybníček, 1985). However, there are not many palaeoenvironmental studies dealing with Mediaeval fishponds. Several fishponds were investigated in Germany (Hellwig, 1997; Rösch, 1999, 2012). Sediments of Mediaeval fishpond Vajgar (Jindřichův Hradec, Czech Republic), established at the thirteenth century, reflect Mediaeval colonization as well as the development of the fishpond until recent times (Jankovská & Pokorný, 2002).

The study site

The foundation of the New Town of Prague in 1348 had probably posed prominent changes in the environment of the Mediaeval town’s suburbs. According to its Foundation Deed, the New Town was established in a suburban area, where ‘villages, gardens and fields had been located’. We attempt to examine what the vegetation character of these suburbs must have been like before the site changed to one of building and construction.

The New Town of Prague (as well as the Old Town of Prague) is situated on the right bank of the Vltava River (Fig. 1). The morphology and character of its original terrain, as well as its hydrology, was directly influenced by a system of several riverine terraces, deposited here within the Pleistocene. According to many archaeological records, several moist depressions and a rather dense network of brooks were evidenced in the area outside the Old Town walls (Kaštovský et al., 1999; Starec, 2005; Kašpar, 2007; Starec et al., 2012). The moist depressions were later filled in with the town’s domestic waste and likely disappeared even before the foundation of the New Town (Hrdlička, 1984, 1997). The permanently moist sediments of these features represent an optimal environment for the preservation of both plant

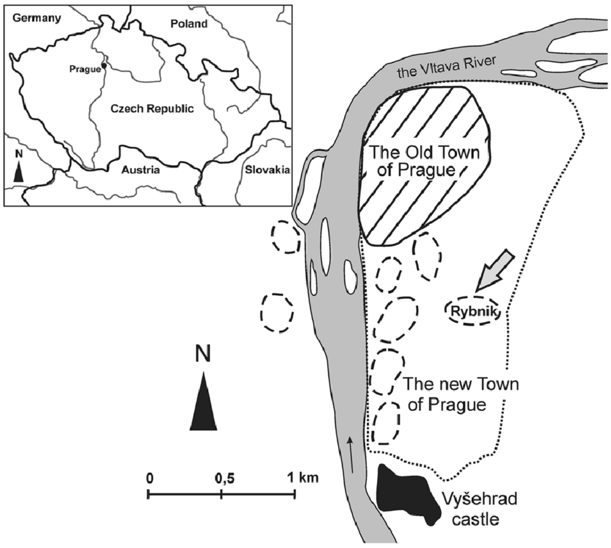


Fig. 1 Schematic representation of the surroundings of the Old town of Prague before 1348. The boundary of the New town of Prague is indicated by *dotted line*. The former settlements' positions are marked by *dashed lines*. The supposed position of Rybnik village is marked by an *arrow*. The course of the Vltava River (*grey*) corresponds to the recent situation. Redrawn according to Mencl (1969)

macrofossils and pollen grains. However, the waste origin of these deposits makes the interpretation of the performed archaeobotanical analyses difficult, as the plant assemblages represent an inseparable mixture of material from several sources.

Having the intention to reconstruct the character of the area's original vegetation, we needed to analyse a different type of sediment, namely the sediment of a water reservoir that had resulted from a natural sedimentation process. In 2009, such sediment was found during a rescue archaeological excavation in the cellar of the house V Tůních no. 1625/II (the excavation being directed by P. Starec, Prague City Museum). The formation of grey clay layers was preliminarily interpreted as the lacustrine sediments of a former pool, promising good preservation of biofacts in the waterlogged conditions. These sediments (and the pool) could have been related to the ceased Mediaeval village Rybník (see above). Archaeological evidence (Kašpar, 2003) supports the existence of the village at a location to the northwest of the investigation site between at least the eleventh and thirteenth century (Figs. 1, 2).

Our aims are to describe the vegetation of the Mediaeval Old Town of Prague's suburbs and to consider the environmental changes that have occurred

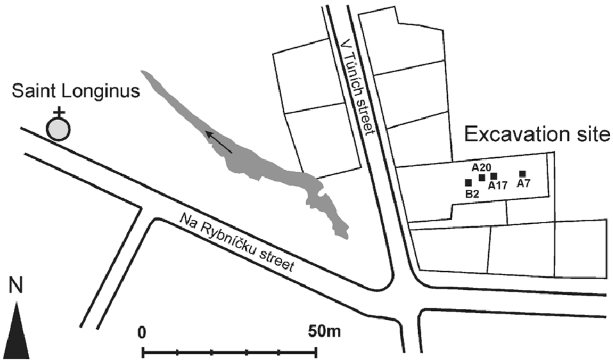


Fig. 2 Surroundings of the excavation site including positions of individual profiles mentioned in the text. The Romanesque rotunda of Saint Stephen (Saint Longinus today) represented the religious centre of the Rybnik settlement. A section of a former stream (*grey*) was documented archaeologically by Kašpar (2007). The supposed direction of the stream (according to the present-day slope direction) is shown by an *arrow*

before the mid-fourteenth century. The second aim of this study is to reveal the origin and function of the investigated water reservoir.

Materials and methods

A trench 1 m wide and approximately 1 m deep had been dug out during the reconstruction of a basement (canalisation trench) of the house V Tůních no. 1625/II. Four profiles, placed subsequently on the line of the trench, and one additional profile placed within the static test pit, were studied (for the position of individual profiles, see Fig. 2). As all the encountered sediments were waterlogged, sediment samples taken from individual layers were wet sieved to obtain biological remains (seeds, charcoal pieces, animal bones, etc.) Two sieves of 1 mm and 0.25 mm were used, sample volumes varying from 0.5 to 3 l. Fragments of wood and animal remains (bones of large- and medium-sized mammals, mussels) when encountered during the excavation were also analysed.

For a more detailed approach, a box profile one metre in length was taken within the profile A20 (the longest of the profiles investigated). Sub-samples of 1 cm^3 were taken for pollen and diatom analyses at 5 cm intervals. In the lowermost part of the profile, the sampling frequency was increased. The remaining sediment was then divided into 5-cm sections (approx. 0.5 l each) and wet sieved to obtain plant macrofossils and fish remains. Three sub-samples for radiocarbon dating were also taken from this profile. Radiocarbon (^{14}C AMS) dating was undertaken using selected *Chenopodium album* seeds by the laboratory CAIS, USA (Center for Applied Isotope Studies, University of Georgia). Calibration of radiocarbon data, based on the calibration curve IntCal 09 (Reimer et al., 2009), was performed using the application OxCal 4.1.6 (Ramsey et al., 2010).

The wet-sieved and dried material was sorted under a binocular microscope and the plant seed/fruit remains were identified in the whole volume, using both a reference collection (Department of Botany, Faculty of Science, Charles University in Prague) and determination literature (Katz et al., 1965; Cappers et al., 2006). The results of the carpological analysis were processed using the *ArboDatMulti* database programme (Kreuz & Schäfer, 2002) and became a part of the Czech archaeobotanical database CZAD (Pokorná et al., 2011). The nomenclature used in the following text was based on Kubát et al. (2002) (vascular plants) and Chytrý & Tichý (2003) (vegetation units).

Pollen grains from sub-samples (1 g) were extracted by chemical treatment according to Faegri & Iversen (1989) including boiling in 10% KOH, sieving, acetolysis and treatment in 40% HF to remove silica. *Lycopodium* spores of a known quantity were added to each sample in order to determine the absolute pollen concentration (Stockmarr, 1971). Pollen grains were counted under a light microscope at a magnification of 400–1000×. A minimum of 500 pollen determinations (where possible) were made for every sample. Taxonomic identifications followed Punt (1976), Punt & Blackmore (1991), Punt & Clarke (1980, 1981, 1984), Punt et al. (1988, 1995, 2003, 2009), and Beug (2004). The presence of non-pollen palynomorphs (e.g. intestinal parasite eggs, algal and invertebrate remains) was recorded (Komárek & Jankovská, 2001; van Geel, 2001); their quantification was related to the total pollen count. Data were processed using Tilia 1.5.12. software (Grimm, 2011). The diversity of pollen spectra was expressed using the Shannon index (Shannon, 1948).

The charcoal and wood analyses were performed only on the largest fraction of fragments (>2 mm). Charcoal pieces were identified using an episcopic interference microscope (Nikon Eclipse 80i) with a 200–500× magnification. The reference collection (Laboratory of Archaeobotany and Paleoecology in České Budějovice) was used for determination. In addition, standard identification keys were also used (Schweingruber, 1990; Heiss, 2000).

The analysis of diatoms was based on methods described by Battarbee (1986). Permanent slides were prepared using hydrogen peroxide for digestion, and Pleurax as a mounting medium (Fott, 1954). Frustules were counted using a light microscope at a magnification of 1000×. A minimum of 400 valves were counted per slide with the exception of the deepest sample where the total only reached 99 valves due to the low concentration of frustules in the sediment. Taxonomic identifications primarily followed Süsswasserflora von Mitteleuropa (Krammer & Lange-Bertalot, 1986, 1988, 1991a, b). Calculation of saprobic indices was based on values of species-specific weights and saprobic indices stated in Sládeček (1986) with corrections proposed by Marvan (unpublished).

Small fish remains (predominantly scales, pharyngeal teeth and vertebrae) recovered by wet sieving were identified using a fish skeleton reference collection (Laboratory of Archaeobotany and Paleoecology in České Budějovice) and determination literature (Baruš & Oliva, 1995; Radu, 2005; Wheeler & Jones, 2009). Fish remains were identified to the lowest taxonomic level possible. The evaluation of representative taxa was calculated using the number of identified specimens (NISP). For the determination of aquatic bivalve molluscs, Pfleger (1988) and Beran (1998) were used. An overview of the identification of mammalian bones is summarized elsewhere (Kovačiková, unpublished report).

A CONISS cluster analysis (Grimm, 1987) and determination of significant pollen accumulation zones (PAZ) based on the broken stick model (MacArthur, 1957, Legendre & Legendre, 1998) were performed using package Rioja (Juggins, 2009) in R 2.11.0 (R Development Core Team, 2010). Canonical correspondence analysis (CCA) of pollen data was realized in the package Vegan (Oksanen et al., 2010). Affiliation of the samples to particular sediment layers was used as an environmental factor. Both cluster and CCA analyses were performed on square root transformed data.

Results

General features

Three main vertically positioned zones were distinguished within the whole profile according to their sedimentary structure and the presence or absence of ecofacts indicating the aquatic environment (Fig. 3, Table 1). Zone 1 overlies the bedrock formed by the Older Palaeozoic marine sediments of the Prague Basin (Barrandien). The gradual decrease of its thickness towards the northwest implies that it could represent deluvio-fluvial sediments transported to the site from the Vinohrady terrace (the edge of this riverine terrace of Pleistocene origin is about 150 m to the southeast). Zone 2 surely represents the aquatic phase of the sedimentation (for more details see below). Zone 3 delineates a well-marked sedimentary stratification, probably the result of an outwash erosion of psammitic material and its subsequent deposition in the water reservoir.

Within the archaeozoological assemblage, 82.6% (NISP = 166) of the total remains ($N = 201$) have been identified as fish (the remains comprising bones, teeth and scales). Scales (both cycloid and ctenoid) and their fragments dominated (55.2% of total finds of fish remains). The identified species included tench (*Tinca tinca*), chub (*Leuciscus cephalus*), bleak (*Alburnus alburnus*) and roach (*Rutilus rutilus*). The ctenoid scales are typical of the order Perciformes. From this order, we take into consideration the following species: European perch (*Perca fluviatilis*), pike-perch (*Sander lucioperca*) or ruffe (*Gymnocephalus cernuus*). For the environmental demands of the

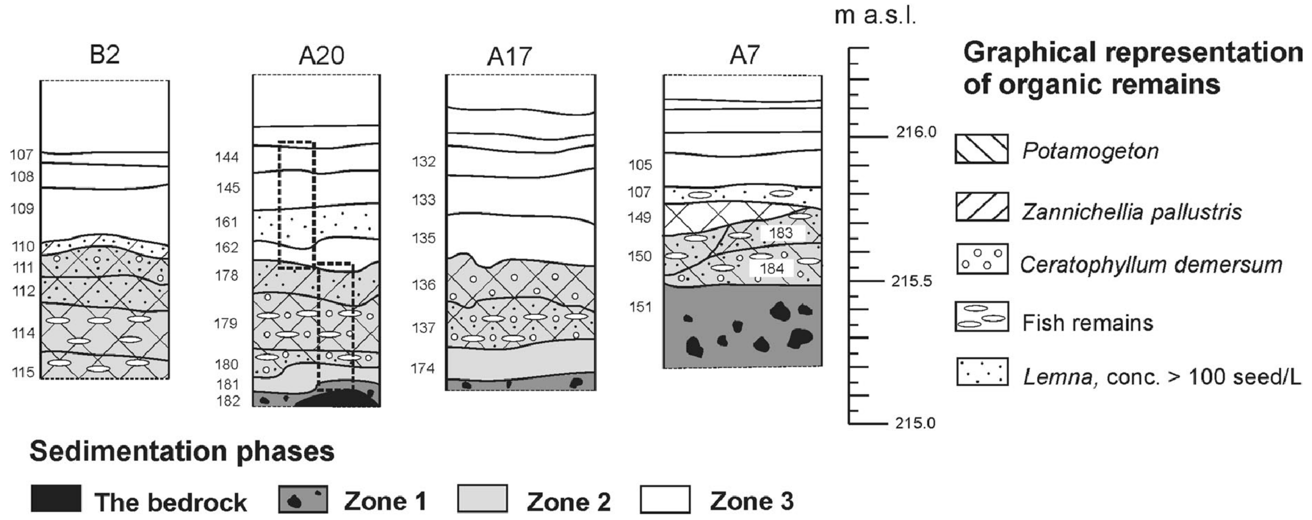


Fig. 3 Illustration of the four profiles mentioned in the text (for detailed position of the profiles see Fig. 2), with representation of organic remains indicating the aquatic phase of sedimentation. The position of sampling boxes is represented by the *two dashed line rectangles* in the profile A20

Table 1 General description of individual zones distinguished within the profile A20

Zone	Mineralogical description	Ecofacts presence
1	Sandy layers with bulky quartz and quartzite fluvial boulders	Very low concentrations of plant macro-remains and no fish remains
2	Grey dusty clays with high admixture of organic material, classified by its character and stratigraphic position as sediments of a pool with standing water	Frequent presence of various indicators of water phase: seeds of various species of aquatic plants (*Z. pallustris*, *Potamogeton* spp., *C.* and *Lemna minor/gibba*), fish remains, mussels, Cladocera, Charales, coccal green algae and diatoms
3	A thick formation consisting of sand with stripes of grey dusty clay in the upper part of the profiles	No fish remains, seeds of *Lemna minor/gibba* in much lesser quantity than in the zone 2, no other aquatic plants

fishes (and other aquatic animals identified) see Table 2.

Profile A20

The profile A20 was used for more detailed investigation because it was the longest one, and also because the zone 2 was the thickest one in this profile. For precise position of the two sampling boxes see Fig. 3. Three samples were chosen for dating using the radiocarbon method (see Table 3). The seeds of *C. album* were used in all cases. The lowermost layer of the profile was not suitable for dating because of a very low concentration of plant macro-remains (and the absence of the terrestrial ones). Therefore, the first sample was taken from the layer 180 (10 cm above the bottom). The second sample was taken from the layer 178 (40 cm above the bottom). Those two dates delimit the duration of the sedimentation of the zone 2 between the end of 10th century and the first half of 14th century. The third sample for dating was located 65 cm above the bottom (the zone 3, layer 161). This sample was chosen to determine the period of sedimentation of the thin clayey layer between the sandy layers overlaying the aquatic sediments.

Two significant pollen accumulation zones (PAZ) were determined using species with minimum abundance of 3%. On the contrary, no significant PAZ occurred if all species were included. The classification of A20 profile according to the sedimentologically defined layers was preferred, since the results of CCA analysis showed their significant ($P < 0.05$, 39.1% of total explained variability) relation to the pollen samples composition.

Layer 182

The lowermost layer was characterised by an absence of pollen grains and a very low occurrence of plant macro-remains. However, *Lemna minor/gibba*, *Zannichellia palustris* and several pieces of *Salix* branches were found here.

Layer 181

The concentration of plant macro-remains was still very low here; the pollen spectrum was composed

Table 2 The environmental demands of fishes and other aquatic animals documented archaeo-zoologically

Taxon	Characteristics
Fishes	
Rutilus rutilus roach—*Cyprinidae*	Prefers deeper water layers; young individuals stay in the shallows; the middle tolerance of oxygen dissolved in water; maximum length 40 cm
Tinca tinca tench—*Cyprinidae*	Prefers warmer parts in shallow shore zone; able to tolerate low oxygen concentrations; present in both stagnant and slow-moving water, often in pools with muddy substrates, covered with abundant vegetation; maximum length 30–63 cm
Leuciscus cephalus chub—*Cyprinidae*	Prefers indented bottoms and banks (it hides both between stones and under the undermined and overgrown shores); it tolerates slightly polluted water, if the amount of dissolved oxygen is sufficient; maximum length 60 cm
Alburnus alburnus bleak—*Cyprinidae*	Occurs near the surface (superficial fish) of both stagnant and slow-moving water, avoiding the parts overgrown by vegetation; maximum length 15–20 cm
Perciformes	Three species could be expected within this family: *Perca fluviatilis* (European perch)—lakes of all types to medium-sized streams; *Sander lucioperca* (pike-perch)—large, turbid rivers and eutrophic lakes; and *Gymnocephalus cernuus* (ruffe)—bottom parts of both lacustrine and flowing waters (depths to 85 m)
Mussels	
Anodonta/Unio mussel—*Unionidae*	Mussels of family *Unionidae* occur mostly in slow-moving watercourses of different types as well as in stagnant water
Cladocera	
Daphnia magna	Typical zooplankton of various types of stagnant water; it tolerates highly polluted water; often being found in enormous amounts (up to 2,000 individuals/L)
Daphnia pulex	In slightly polluted ponds and backwaters

Table 3 List of calibrated radiocarbon data originating from macro-remains of *Chenopodium album* separated from profile A20

Sample ID	layer	δ^{13}C, ‰	^{14}C age	±	Calibrated ^{14}C age
18_A20	180	−28.2	1060 B.P.	25	cal A.D. 945–1023
12_A20	178	−26.8	650 B.P.	25	cal A.D 1282–1362
07_A20	161	−27.5	980 B.P.	25	cal A.D .995–1154

mainly of non-arboreal pollen (NAP). Following macrophytes were documented (both macro-remains and pollen): *Alisma plantago-aquatica*, *L. minor/gibba*, *Myriophyllum spicatum* type, *Potamogeton* (*P. natans* type), *Sparganium erectum* type and *Z. palustris*. The diatom composition (*Amphora pediculus*, *Gomphonema sarcophagus*, *G. angustatum* s.l., *Cymbella aspera*, *Navicula radiosa* s.l. and *Planothidium frequentissimum*) indicates clean water (the index of saprobity equates to 1.2). Among the water algae, Charales, *Pediastrum simplex* and *Tetraedron minimum* were found. The resting eggs of Rotifers appeared here in low quantities, as well as ephippia of *Daphnia* cf. *pulex*.

Among pollen of the terrestrial plants the family Poaceae dominated. Anthropogenic indicators (e.g. crops and numerous ruderal species) as well as grazing indicators (*Plantago lanceolata* and *Calluna vulgaris*) were recorded in the pollen spectrum. The arboreal/non-arboreal pollen ratio (AP/NAP) equals 25%; charcoal of *Quercus* and small *Salix* branches were recorded.

Layer 180

The radiocarbon date from this layer has been calibrated and the resulting interval is A.D. 945–1023 (see Table 3). The layer shows an increasing concentration of macro-remains and pollen of aquatic macrophytes (*Ceratophyllum demersum, Lemna* and *Potamogeton*); green algae (*T. minimum, P. simplex* and *Scenedesmus*) were also abundant here. Fish bones and scales were found in high quantities (e.g. *T. tinca*, *A. alburnus* or *L. cephalus*) as well as mussel shells and ephippia of both *Daphnia magna* and *D.* cf. *pulex*. The composition of diatoms differed markedly from layer 181. Species with a low index of saprobity (*A. pediculus* and *G. sarcophagus*) remained only in minor quantities. A domination of *Stephanodiscus hantzschii*, *Amphora veneta* and *Cocconeis placentula* v. *euglypta* (species with an index of saprobity above 2), along with *Achnanthidium minutissimum*, *Hippodonta capitata*, *Lemnicola hungarica* and *Nitzschia fonticola* was recorded.

Among terrestrial plants, hygrophilous vegetation and wet meadows were indicated (e.g. *Carex*, *Juncus*, *Lysimachia vulgaris* type, *Lythrum salicaria* type, *Persicaria hydropiper*, *Ranunculus sceleratus*, *R. acris* group, *Urtica dioica* type and *Scirpus sylvaticus*). The abundance of pollen types of the family Poaceae and genus *Artemisia* decreased in contrast to the increasing percentage of anthropogenic indicators (*Polygonum aviculare*, *Chenopodium* spp., *Rumex acetosa* type and the family Brassicaceae). Aside from other cereal species, a presence of *Secale cereale* pollen was recorded. Three bones of large mammals were also found here. AP/NAP remained similar to the previous layer.

Layer 179

The layer was characterised by a high number of pollen types and a high absolute concentration of pollen grains. Also the concentration (above 500/l) of plant macro-remains and the number of determined plant species (46 taxa) reached their maximum here. *Lemna* dominated among aquatic macrophytes*; C. demersum*, *M. spicatum* type, *Potamogeton* and *Z. palustris* were abundant too. The number of fish remains (Cyprinidae and Perciformes) also reached its maximum as well as the ephippia of both *Daphnia* species. Both green algae and diatoms showed a very similar species composition to that in layer 180.

Hygrophilous plant species were also abundant here (*Bidens tripartita* type, *Eleocharis palustris* aggr., *Lycopus europaeus*, *P. hydropiper*, *P. lapathifolia*, *R. sceleratus* and cf. *Solanum dulcamara*). However, *Alisma plantago-aquatica* type and *S. erectum* type decreased in the pollen spectrum. Wet meadows were represented by *Chaerophyllum hirsutum* type, *Filipendula* type, *Juncus*, *Lychnis flos*-cuculi, *Peucedanum palustre* type, *R. acris* group, *R. flammula* group, *S. sylvaticus* and *Valeriana officinalis* type.

Field crops (*Horedeum* type, *Triticum* type, *Avena* type and *S. cereale*) and weeds as well as ruderal taxa (e.g. *Artemisia* type, *Anthemis arvensis* type, Brassicaceae, Chenopodiaceae, *P. aviculare* type and *R. acetosa* type) were documented in pollen. Abundance of Poaceae and *P. lanceolata* (grazing indicator) was recorded. Among the macro-remains, the following weeds were found: *Agrostemma githago*, *Anthemis cotula*, *Chenopodium* spp., *Polycnemum arvense*, *Thlaspi arvense* and *Valerianella dentata*. Compared to layer 180, *P. aviculare*, *C. album* and *U. dioica* macro-remains slightly increased. One seed of *Cucumis melo/sativus* and a glume of *Panicum miliaceum* were found here, as well as macro-remains of edible wild species: *Rubus idaeus*, *Rubus fruticosus* aggr., cf. *Fragaria*, *Sambucus nigra* and *Corylus avellana*.

Tree species composition in the pollen spectrum remained similar to the previous layer; however, *Fraxinus* type and *Acer* type appeared here. Besides, occurrence of rare taxa such as *Prunus* type and *Cornus mas* type was recorded. *Salix* pollen grains disappeared in contrast to many small pieces of *Salix* branches found here. This layer contained a high amount of charcoal fragments of *Quercus*, *Pinus sylvestris* and *Fagus sylvatica*. Fragments of wood of *P. sylvestris* were quite abundant and some scarce occurrences of *Abies alba* wood were also recorded.

Layer 178

The radiocarbon date from this layer is cal. A.D. 1282–1362 (see Table 3). It was still rich in both plant macro-remains and pollen types; however, the number of fish remains decreased markedly. *Lemna* and *Z. palustris* remained at comparable high concentrations as in the previous layer. On the contrary, the macro-remains of *Potamogeton* decreased rapidly. All the diatom species disappeared in this layer, as well as the green algae (with the single exception of *P. simplex*). Ephippia of *Daphnia* cf. *pulex* disappeared and the *D. magna* concentration decreased. The occurrence of parasite eggs of *Trichuris* was firstly recorded from the upper half of this layer.

Macro-remains of hygrophilous plant species decreased compared to the previous layer (both the number of species and concentration). The indicators of wet meadows nearly disappeared here, also the pollen ratio of Poaceae decreased. Among the grassland species, only those of dry grasslands (Festuco-Brometea) remained present (macro-remains of *Arenaria serpyllifolia* and *Hypericum perforatum*). On the other hand, the abundance of pollen of field crops increased, as well as *P. aviculare* type (indicator of trampled vegetation). Also the concentration of *C. album* increased markedly in this layer. Weeds were represented by *A. arvensis*, *Centaurea cyanus*, *C. ficifolium*, *Consolida ambigua* type, *Euphorbia helioscopia*, *Fumaria officinalis*, *Papaver rhoeas* type, *P. arvense*, *T. arvense* and *Stellaria media*. One seed of cf. *Vitis vinifera* and two bones from a large mammal were found here.

Layer 162

Contrarily to the previous clayey layers, this layer was characterised by a high admixture of sand. Concentration of both plant macro-remains and pollen decreased markedly here. Further, the pollen curves based on the absolute values of all woody species were lowered. However, the percentage diagram shows an increase in the AP/NAP ratio. This is based on an increase in the *Pinus* proportion in the layers with a sand admixture.

Remains of aquatic macrophytes as well as hygrophilous plants nearly disappeared in this layer (with exception of *Lemna* and *R. sceleratus*), also *Daphnia magna* and rotifers became scarce here, and only two fish bones of Cyprinidae were found. On the other hand, the macro-remains of ruderal plants increased their concentration; this trend was most prominent in *C. album*, *C. hybridum* and *Sambucus ebulus*. The composition of root crop weeds was very similar to that of layer 178, whereas the macro-remains of field weeds were very scarce. Among the NAP pollen curves, an increase in the abundance of Chenopodiaceae, *P. aviculare* type and *C. cyanus* was observed.

Layer 161

This layer differs from both the underlying and the overlaying layers in its sedimentological character. It represents a streak of grey dusty clay between shale and siliceous sands of the layers 162, 145 and 144.

Radiocarbon date (Table 3) from this layer (after calibration) is A.D. 995–1154 (for more details, see "Discussion" section). In the pollen diagram, the total number of species (pollen types) decreased compared to previous layers as well as the number of plant species in the macro-remain assemblage.

The concentration of *Lemna* macro-remains was relatively high but no other aquatic macrophytes were encountered (except for 2 achenes of *Alisma plantago-aquatica*). The following species of natural hygrophilous habitats were found here: *Carex*, *Juncus*, *Lemna*, *P. maculosa*, *R. aquatilis* group, *R. sceleratus*, *R. crispus/obtusifolius*, *S. erectum* and *Typha latifolia*.

The macro-remains concentration of *C. album* (and other species of this genus) culminated here. Composition of the macro-remains of weeds was similar to the previous layers; on the other hand, indications of weeds such as *Dipsacus fullonum* type, *Gnaphalium uliginosum* type, *Jasione montana* type, *Scleranthus annuus*, *Sedum* type, *Teucrium* and *Xanthium strumarium* type appeared among the rare species in pollen spectra. The pollen of crops, weeds and ruderals as well as of species growing on highly disturbed areas increased in abundance in this layer.

The abundance of almost all woody species in the pollen diagram decreased; however, the proportion of *Pinus* in the percentage pollen diagram increased (probably due to a sand admixture in the upper part of this layer). Among both charcoal and wood fragments, *P. sylvestris* dominated.

Layers 145 and 144

In both of these uppermost layers of the profile A20, the concentration of plant macro-remains decreased continually along with the number of determined taxa. The total number of pollen types also decreased. The only remaining aquatic species represented by macro-remains was *Lemna*, while the only remaining hygrophilous species was *R. sceleratus*. The composition of species typical for ruderal habitats was extended by *Atriplex* and cf. *Galeopsis tetrahit,* in addition to the *Chenopodium* species and *Sambucus ebulus* found also in previous layers. Among the weeds, the only remaining species were *F. officinalis* and *P. arvense* (both in gradually decreasing concentrations). *Glaucium corniculatum* appeared for the first time in layer 144; two caryopses of *S. cereale* were also found in this layer. The dominant pollen type was *P. aviculare*, followed by species of the Poaceae, Chenopodiaceae, genus *Artemisia* and *Rumex*. The pollen of crops, ruderals, weeds and species of highly disturbed sites increased in abundance. By contrast, the abundance of pollen of woody species was very low here.

Discussion

The permanently moist sediments comprise optimal conditions for the preservation of environmental information. However, the majority of wet sediments obtained until now in the city of Prague have originated chiefly from pits or wells (Opravil, 1986, 1994; Čulíková, 1987, 1998a, b, 2001a, b, 2005, 2008, 2010), which represent an inseparable mixture of material of various origins (both natural and anthropogenic). Indeed, it is difficult to find a suitable material in urban archaeology as the localities under focus are mostly completely built up. Any research of a former water reservoir located under recent buildings is rare (e.g. Hellwig, 1997; Sasaki & Takahara, 2011; Starec et al., 2012). Within the area of Prague, the only investigated wet sediments of more or less natural origin were those of the so-called Old Town defence system moat (Beneš et al., 2002) and the alluvial sediments of the Vltava River backwaters (Kozáková & Pokorný, 2007; Čulíková 2010).

Time extent of the sedimentation record

The sediments investigated by this study were dated using the radiocarbon method (see Table 3). As for the lowermost part (first 6 cm) of the investigated profile A20, there were not enough macro-remains for dating. Moreover, this material contained almost no pollen; therefore, we cannot make any conclusion concerning the age of the oldest part of the profile. The first date (from the sample located 10 cm above the bottom) corresponds approximately to the oldest known reference to the Rybník village (tenth to eleventh century). The second date (thirteenth to fourteenth century) comes from the sample located 40 cm above the bottom. This material has probably sedimented shortly before the ending of the pond existence, which could be causally related to the demise of the Rybník village after the New Town foundation in 1348. This period was characterised by an extensive building activity in the neighbourhood.

The third date (tenth to eleventh century) was obtained from the clayey layer 161, set between the sandy layers above the aquatic sediments. According to the correspondence analysis, this sample is much more similar to the samples from layer 178 than to the samples originated from the adjacent layers. Therefore, we can assume that this material was the result of redeposition of older sediment, perhaps connected with the later increased building activity at the site. Another explanation takes into consideration an outwash from some higher positions of the drainage area. Either way, this peculiar date must lead us to extreme caution when interpreting the upper half of the profile.

Still, we consider the two dates from the lower half of the profile as being plausible. They are in accordance with our expectations, the succession between them is uninterrupted, and the fragments of ceramic found between them correspond to the twelfth century. Besides, the emergence of *C. cyanus* pollen by the end of the tenth century and the gradual growth of its curve in the course of the following centuries accords with the results of other investigations in the Czech Republic (Jankovská, 1997; Kozáková et al., 2009).

Vegetation types

The classification of vascular plant species was based on the recent vegetation of the Czech Republic characterised by the diagnostic species (Chytrý & Tichý, 2003). The Following vegetational units were identified (see Table 4): aquatic vegetation, hygrophilous herbaceous vegetation, hygrophilous woodland vegetation, grassland vegetation (meadows, pastures and dry grasslands), annual vegetation of ruderalised sites, and weeds.

Aquatic vegetation

Among aquatic macrophytes, the following species were documented: *C. demersum*, *Lemna minor*, *M. spicatum*, *P. crispus*, *P.* cf. *natans* and *Z. palustris*. Classes of Lemnetea and Potametea (Nymphaeion albae, Magnopotamion and Parvopotamion) could be identified according to the diagnostic species. These are common vegetation types of standing water extending nearly all over the world. Nevertheless, the macroremains of these species are not very common in other documented archaeobotanical assemblages from Prague. For a more detailed description of the development of the water environment of this site see the following section.

Hygrophilous herbaceous vegetation

The following species of hygrophilous herbs were found: *Alisma plantago-aquatica*, *Bidens cernua*, *Bidens* cf. *tripartita*, *Butomus umbellatus*, *E. palustris*, *G. uliginosum*, *L. europaeus*, *L. salicaria*, *P. hydropiper*, *R. sceleratus*, *Rorippa palustris*, *Saggitaria sagittifolia*, *S. erectum*, *Sparganium emersum* and *T. latifolia*. Classes of Isoeto-Nanojuncetea (Eleocharition ovateae), Phragmito-Magnocaricetea (Phragmition communis and Oenanthion aquaticae) and Bidentetea tripartitae (Bidention tripartitae) could be identified according to the diagnostic species.

The species of hygrophilous vegetation culminated (both quantitatively and qualitatively) in the lower half of the profile, and showed a decreasing tendency. This trend was prominent both in the macro-remains and pollen. These plants were probably growing on sites connected immediately with the pond. Similar vegetation was detected near a backwater in Malá Strana (Kozáková & Pokorný, 2007; Čulíková, 2010). However, *Eleocharis* and *Lycopus* have been found in nearly all sites in Mediaeval Prague, including pits (Opravil, 1986, 1994; Čulíková, 1998a, b, 2001a, b, 2005, 2010).

Hygrophilous woodland vegetation

The following taxa of hygrophilous woodland vegetation were found: *Salix*, *Alnus* cf. *glutinosa*, *Aegopodium podagraria*, *C. hirsutum*, *Fraxinus exelsior*, cf. *Myosoton aquaticum* (*Cerastium fontanum* group), *R. idaeus*, *Rumex crispus/obtusifolius*, *S. nigra* and *U. dioica*. Classes of Salicetea purpureae (Salicion triandreae) and Querco-Fagetea (Alnion incanae) could be identified according to the diagnostic species.

These species were represented mostly by pollen or wood (charcoal). Only *Rumex*, *Urtica*, *R. idaeus* and *S. nigra* (edible fruits) were also found in the macroremains. This could be intepreted as a consequence of a situation when this type of vegetation was growing nearby, but not directly on the site.

Wet meadows

The following species (or pollen types) indicating wet meadows were found: *Angelica sylvestris*, *Alchemilla pentaphyllea*, *Alnus*, *Caltha palustris*, *Carex* cf. *hirta*, *Carex* cf. *pallescens*, *C. hirsutum*, *Cichorium intybus* type, *Cirsium palustre* type, *Filipendula ulmaria*, *Geranium molle* type, *Heracleum sphondylium*, *Lathyrus*, *Leucanthemum vulgare* aggr., *Lychnis flos-cuculi*, *L. vulgaris* type, *R. acris*, *R. repens*, Rubiaceae,

Table 4 Vegetation units identified according to (recent) diagnostic species (classification of plant taxa into syntaxa follows Chytrý & Tichý 2003) based on finds of macro-remains

Ecological groups	1		2			3	4					5	6	7	8			9
Syntaxa	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Aethusa cynapium	.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.
Agrostemma githago	.	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.
Ajuga cf. *reptans*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	o	+
Alisma plantago-aquatica	.	.	+	.	o	.	.	.	.	.	.	.	.	.	.	.	.	.
Anagallis arvensis	.	.	.	.	.	.	.	.	.	.	.	.	+	+	.	.	.	.
Anthemis arvensis	.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.
Anthemis cotula	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.	.
Aphanes arvensis	.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.
Arenaria serpyllifolia agg.	.	.	.	.	.	.	.	.	.	o	.	.	.	+	.	.	.	.
Atriplex sp.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.	.
Bidens cernua	.	.	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.	.
Bidens cf. *tripartita*	.	.	+	.	.	o	.	.	.	.	.	.	.	.	.	.	.	.
Bupleurum rotundifolium	.	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.
Capsella bursa-pastoris	.	.	.	.	.	.	.	.	.	.	.	.	+	+	.	.	.	.
Carex cf. hirta	.	.	.	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.
Carex cf. *pallescens*	.	.	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	.
Carex leporina	.	.	.	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.
Centaurea cyanus	.	.	.	.	.	.	.	.	.	.	.	.	.	+	.	.	.	.
Ceratophyllum demersum	o	o	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Chenopodium album agg.	.	.	.	.	.	.	.	.	.	.	.	.	+	+	.	.	.	.
Chenopodium ficifolium	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.	.
Chenopodium hybridum	.	.	.	.	.	.	.	.	.	.	.	.	+	.	.	.	.	.
Chenopodium polyspermum	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.	.
Cirsium cf. *palustre*	.	.	.	.	.	.	o	.	.	.	.	.	.	.	.	+	.	.
Dianthus armeria/deltoides	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.	.	.	.
Echinochloa crus-galli	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.	.
Eleocharis palustris agg.	.	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.	.	.
Euphorbia helioscopia	.	.	.	.	.	.	.	.	.	.	.	.	+	+	.	.	.	.
Fallopia convolvulus	.	.	.	.	.	.	.	.	.	.	.	.	+	+	.	.	.	.
Filipendula ulmaria	.	.	.	.	.	.	o	.	.	.	.	.	.	.	+	+	.	.
Fumaria officinalis	.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.
cf. *Galeopsis tetrahit*	.	.	.	.	.	.	.	.	.	.	.	.	.	+	.	.	.	.
Geranium molle/collumbinum	.	.	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	.
Glaucium corniculatum	.	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.
Herniaria glabra	.	.	.	.	.	.	.	.	o	.	.	.	.	.	.	.	.	.
Hypericum perforatum	.	.	.	.	.	.	.	.	+	o	.	.	.	.	.	.	.	.
Juncus sp.	.	.	+	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.
Lamium cf. *amplexicaule*	.	.	.	.	.	.	.	.	.	.	.	.	o	+	.	.	.	.
Lapsana communis	.	.	.	.	.	.	.	.	.	.	.	.	o	+	.	.	.	.
Lemna minor/gibba	o	+	.	o	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Leontodon autumnalis	.	.	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	.

Table 4 continued

Ecological groups	1		2			3	4					5	6	7	8			9
Syntaxa	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Leucanthemum vulgare agg.	.	.	.	.	.	.	.	o	.	.	.	.	.	.	.	.	.	.
Lychnis flos-cuculi	.	.	.	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.
Lycopus europaeus	.	.	.	o	o	+	.	.	.	.	.	.	.	.	.	+	.	.
cf. *Myosoton aquaticum*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	.	.	.
Myriophyllum cf. *verticillatum*	.	+	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Myriophyllum spicatum	.	+	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Neslia paniculata	.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.
Papaver cf. rhoeas	.	.	.	.	.	.	.	.	.	.	.	.	.	+	.	.	.	.
Persicaria hydropiper	.	.	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.	.
Persicaria lapathifolia agg.	.	.	+	.	.	+	.	.	.	.	.	.	+	+	.	.	.	.
Persicaria maculosa	.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.
Picris cf. *hieracioides*	.	.	.	.	.	.	.	.	.	+	.	.	.	.	.	.	.	.
Polycnemum arvense	.	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.
Polygonum aviculare agg.	.	.	.	.	.	.	.	.	.	.	.	o	+	+	.	.	.	.
Potamogeton cf. *natans*	.	+	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Potamogeton crispus	.	+	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Potentilla anserina	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.	.	.
Prunella vulgaris	.	.	.	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.
Ranunculus acris	.	.	.	.	.	.	o	+	.	.	+	.	.	.	.	.	.	.
Ranunculus repens	.	.	.	.	.	+	o	.	.	.	.	+	+	.	+	+	.	.
Ranunculus sceleratus	.	.	o	.	.	o	.	.	.	.	.	.	.	.	.	.	.	.
Rorippa palustris	.	.	o	.	.	o	.	.	.	.	.	.	.	.	.	.	.	.
Rubus idaeus	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	o	+
Rumex cf. *crispus*	.	.	.	.	.	.	.	.	.	.	.	.	.	+	.	.	.	.
Rumex cf. *obtusifolius*	.	.	.	.	.	.	.	.	.	.	.	.	.	.	+	.	.	.
Sambucus ebulus	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.	.
Scirpus sylvaticus	.	.	.	.	.	.	o	.	.	.	.	.	.	.	.	+	.	.
Scleranthus anuus	.	.	.	.	.	.	.	.	.	+	.	.	.	+	.	.	.	.
Setaria cf. *viridis*	.	.	.	.	.	.	.	.	.	.	.	.	+	.	.	.	.	.
Setaria pumila	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.	.
Silene cf. *viscaria*	.	.	.	.	.	.	.	.	.	+	.	.	.	.	.	.	.	o
Solanum dulcamara	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.
cf. *Sparganium erectum*	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Stachys cf. *annua*	.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.
Stellaria graminea	.	.	.	.	.	.	.	o	.	.	.	.	.	.	.	.	.	.
Stellaria media agg.	.	.	.	.	.	.	.	.	.	.	.	.	o	+	.	.	.	.
Taraxacum officinale agg.	.	.	.	.	.	.	+	.	.	.	.	+	+	+	.	.	.	.
cf. *Thalictrum flavum*	.	.	.	.	.	.	+	.	.	.	.	.	.	.	.	.	.	.
Thlaspi arvense	.	.	.	.	.	.	.	.	.	.	.	.	+	+	.	.	.	.
cf. *Typha latifolia*	.	.	.	o	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Urtica dioica	.	.	.	+	+	.	.	.	.	.	.	.	.	.	+	+	o	+
Urtica urens	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.	.

Table 4 continued

Ecological groups	1		2			3	4					5	6	7	8			9
Syntaxa	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Vaccaria hispanica	.	.	.	.	.	.	.	.	.	.	.	.	.	x	.	.	.	.
Valerianella dentata	.	.	.	.	.	.	.	.	.	.	.	.	.	o	.	.	.	.
Zannichellia palustris	.	+	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.

Ecological groups and the syntaxa relating to the various groups

1 Aquatic vegetation. A, Lemnetea; B, Potametea

2 Hygrophilous herbaceous vegetation. C, Eleocharion ovatae; D, Phragmition communis; E, Oenanthion aquaticae

3 Ruderalised hygrophilous habitats. F, Bidention tripartitae

4 Grassland vegetation (meadows, pastures and dry grasslands). G, Calthion; H, Arrhenatherion; I, Plantagini-Festucion ovinae; J, Festuco-Brometea; K, Violion caninae

5 Trampled habitats. L, Plantaginetea majoris

6 Annual vegetation of ruderalised sites. M, Chenopodietea (Fumario-Euphorbion, Sperglo-Oxalidion, Panico-Setarion)

7 Crop weeds. N, Secalietea (Caucalidion lappulae, Sherardion, Veronico politae-Taraxacion, Aphanion)

8 Hygrophilous woodland vegetation. O, Salicion triandrae; P, Alnion glutinosae; Q, Alnion incanae

9 Trees. R, Querco-Fagetea

\+ Taxon occurs in the group

o Taxon has its main occurrence in the group

x Taxon is considered to have occurred in the group in the past

R. acetosa type and *S. sylvaticus*. The class Molinio-Arrhenatheretea (Calthion) could be identified according to the diagnostic species. Also *S. graminaea*—the species with a wide ecological valence from dry to wet meadows was among the list of grassland species.

Both the macro-remains and pollen of this group showed a decreasing tendency in the profile. Many of them were also found in the backwater in Mala Strana (Kozáková & Pokorný, 2007; Čulíková, 2010), as well as in the drainage ditch of the Old Town defence system (Beneš et al., 2002), and in the Prague Castle (Kozáková & Boháčová, 2008). Moreover, the following taxa were also found in other archaeological sites in Mediaeval Prague: *Caltha palustris*, *Lychnis flos-cuculi*, *Ranunculus*, *S. sylvaticus, S. graminaea* and *Cirsium*. It is thus possible to conclude that meadows were probably quite widespread in Prague suburbs (mostly around the river and its tributaries) and the material of the meadows (hay) was also manipulated in households (or it could have been transported by animals and deposited in cesspits in the form of dung).

Dry grasslands

The occurrence of some rare pollen types (e.g. *Lychnis viscaria* type, *Anthericum* type, *Saxifraga oppositifolia* type, *Thesium* type, *Aster tripolium* type, *Helianthemum*, *Lithospermum arvense*, *Medicago lupulina* type, *Echium* type, *Teucrium* type and *Verbascum* type) in the pollen spectrum would imply that xerophilous grasslands probably developed in the close vicinity of the investigated water reservoir. The area of Prague has many places where biotopes mainly belonging to the class Festuco-Brometea could occur. These habitats were probably used as pastures in the past. The presence of grazing indicators (e.g. pollen of Poaceae, *P. lanceolata*, *C. vulgaris*, *J. montana* type; and charcoal from *Juniperus*) in the pollen spectrum would support such a scenario (Behre, 1981). Those habitats with remaining dry grassland vegetation within Prague are nowadays generally under the status of nature reserves (Dostálek & Frantík, 2008). We could suppose that such habitats were more common within the area before the New Town of Prague was established.

Annual vegetation of ruderalised sites

The following species of ruderal vegetation were found: cf. *Capsella bursa-pastoris*, *Chenopodium album* aggr., *C. hybridum*, *C. polyspermum*, *Echinochloa crus-galli*, *E. helioscopia*, *Lapsana communis*, *P. aviculare* aggr., *Setaria pumila*, *Stellaria media* aggr., and *T. arvense*. The present-day class Chenopodietea (Fumario-Euphorbion and Panico-Setarion) could be identified according to the diagnostic species.

This group of vegetation shows an increasing tendency, culminating in the upper half of the profile. It corresponds with the pollen curve of trampled vegetation indicators, and this trend is at the same time opposite to the trend of semi-natural types of vegetation mentioned above. When comparing with other sites, the macro-remains of these species are nearly ubiquitous both in archaeological sites and in natural sediments, so this vegetation probably grew inside the town and around the villages, as well as along watercourses. In contrast, perennial ruderals were very scarce on this site. Nevertheless, their particular occurrence in the Old Prague trade centre Ungelt (Opravil, 1986) indicates the different environment in the urban and trade centre of that time.

Weeds

The following weeds were found: *Anagallis arvensis*, *Aethusa cynapium*, *Agrostemma githago*, *A. arvensis*, *Aphanes arvensis*, *A. serpyllifolia* aggr., *Bupleurum rotundifolium*, cf. *Capsella bursa-pastoris* (Brassicaceae), *C. cyanus*, *Chenopodium album* aggr., *E. helioscopia*, *Fallopia convolvulus*, *F. officinalis*, *Glaucium corniculatum*, *Lapsana communis*, *Lithospermum arvense*, *Microrrhinum minus*, *Neslia paniculata*, *Papaver* cf. *rhoeas*, *P. lanceolata*, *P. major*, *P. arvense*, *P. aviculare* aggr., *Rumex crispus/obtusifolius*, *S. annuus*, *Stachys* cf. *annua*, *Stellaria media* aggr., *T. arvense* and *V. dentata*. The present-day class Secalietea (Caucalidion lappulae, Sherardion, Aphanion and Veronico politae-Taraxacion) could be identified according to the diagnostic species. However, some of these weedy species are no longer present in present-day fields, although they were very frequent in Mediaeval fields (i.e. *Agrostemma githago*, *Glaucium corniculatum*, *Bupleurum rotundifolium* and *P. arvense*).

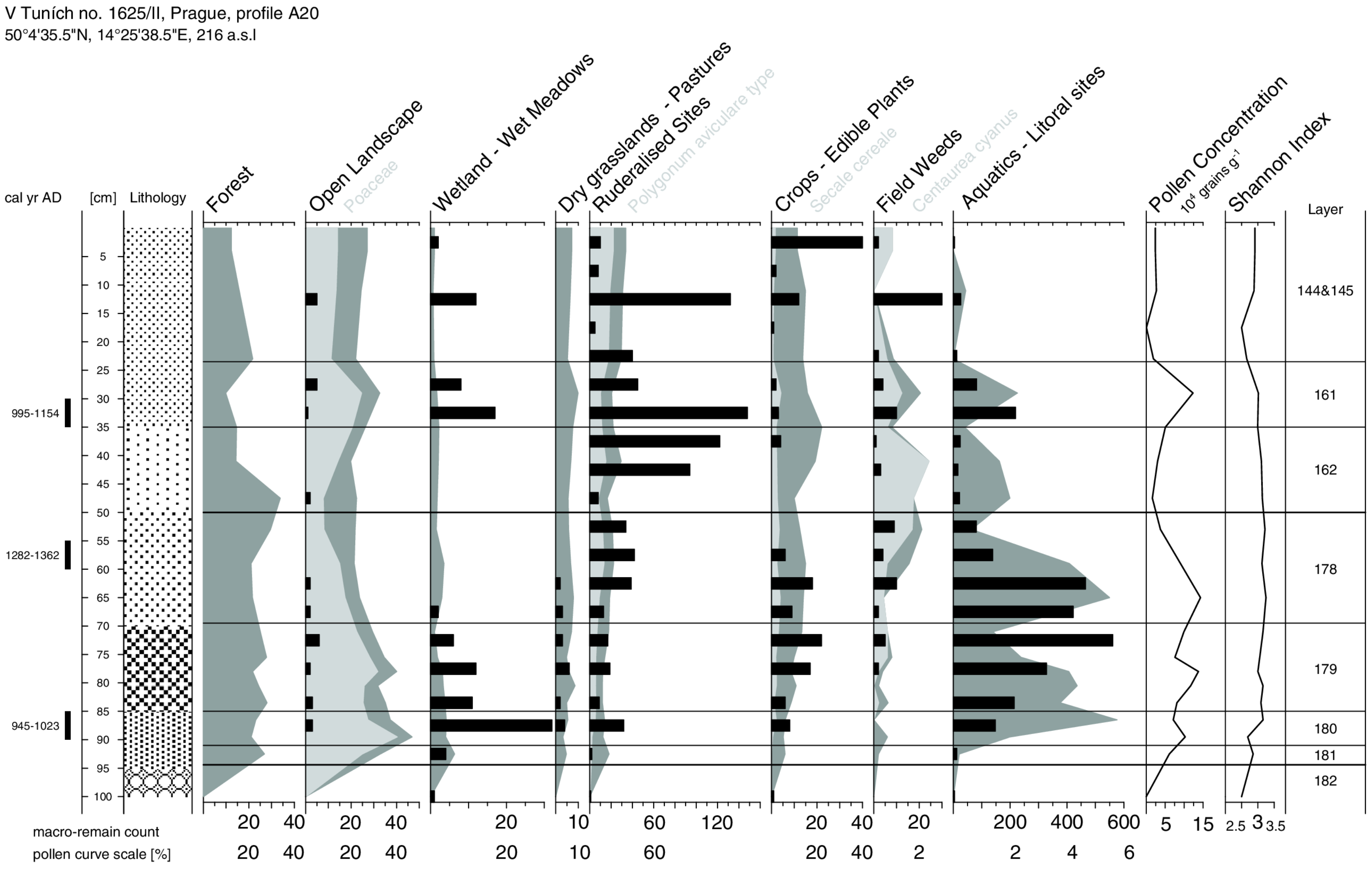
Both the number of species and quantity of weeds increased in time (both pollen and macro-remains), along with the pollen of cereals. Many of these weed species are ubiquitous in archaeological sites (*Aethusa cynapium*, *Anagallis arvensis*, *A. arvensis*, *A. serpyllifolia*, *C. cyanus*, *F. officinalis*, *Lithospermum arvense*, *Neslia paniculata*, *Fallopia convolvulus*, *S. annuus* and *V. dentata*). The possible explanation is that they frequently entered settlements along with the field products brought in. Nevertheless, some weedy species often found in cesspits were not encountered on this site (e.g. *Caucalis platycarpos*, *Galium spurium*, *Lithospermum arvense*, *Adonis aestivalis* and *Sinapis arvensis*). On the other hand, some weedy species were almost only found here (e.g. *A. cotula*, *Vaccaria hispanica* and *S. annuus*) though some of them were also encountered at Mala Strana.

Environmental changes

Terrestrial vegetation

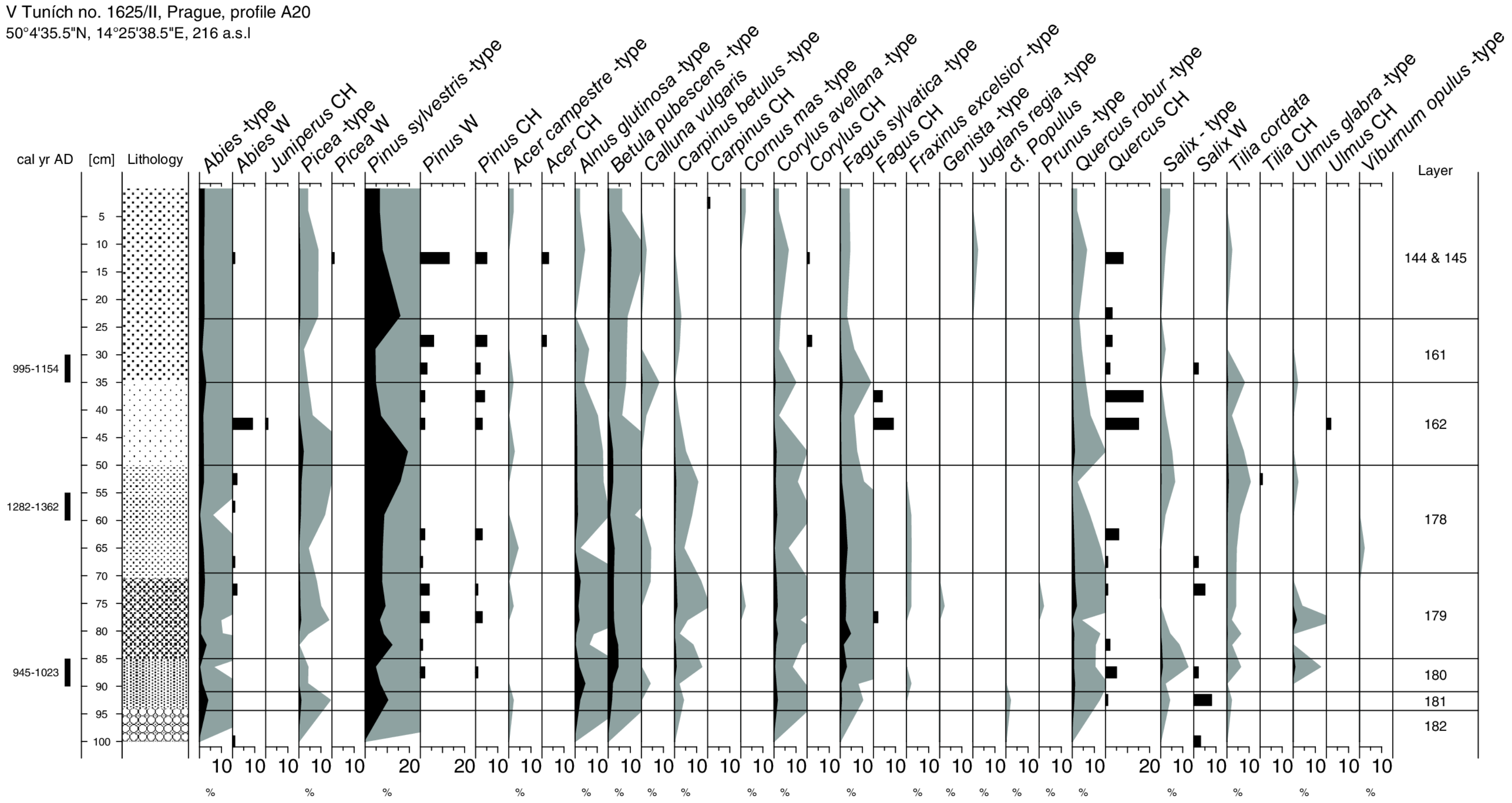
During the period between the end of tenth to approximately the middle of fourteenth century, rather extensive changes of plant species composition took place in the region of Prague. The changes observed at the investigated site clearly correspond with the general trends in landscape management reconstructed by Kozáková et al. (2009). According to this reconstruction, a fine mosaic of habitats existed in Prague before the end of twelfth century. Subsequently, the environmental diversity decreased considerably during the following centuries. This trend was explained as a result of increasing ruderalization and intensification of the land use.

In the site investigated, the field indicators (both cereals and field weeds) increased over time (Fig. 4), whereas the proportion of broad-leaf trees and shrubs decreased (Fig. 5). This trend in the pollen spectra could be interpreted as a manifestation of the gradual enlargement of land under the plough. At the same time, the proportion of ruderal plants increased continually both in the pollen and macro-remains spectra. The trend in grassland indicators is much less clear; however, this type of vegetation seems to decrease slightly with time. A gradual decline in the semi-natural hygrophilous vegetation was accompanied by an opposite tendency in trampled vegetation (*P. aviculare* and *R. acetosella*). This trend, along with the distinct increase of landscape ruderalisation, seems to indicate the gradual intensification of human



Macro-remain analysis by A. Pokorná
Pollen analysis by P. Houfková

Fig. 4 Trends in development of vegetation units (as recorded in the A20 profile) expressed by both sums of macro-remains (*histograms*) and percentage of pollen within the total pollen spectrum (*curves*). *Dark grey curves* represent total percentage of pollen types assigned to individual vegetation units; whereas the *light grey area* within the curve represent the proportion of selected pollen type within the unit. Total number of determined pollen types is expressed by the Shannon index (dimensionless quantity). The depth from the surface (*y axis*) is expressed in cm. Calibrated radiocarbon dates (cal yr AD) are plotted along the *y axis*



Pollen analysis by P. Houfková
Charcoal analysis by J. Novák

Fig. 5 Occurrence of woody plants in the A20 profile. Mixed diagram of both pollen (percentage within the total pollen spectrum expressed by curves, *grey areas* depict the same values exaggerated tenfold) and charcoal/wood (count of pieces expressed by histograms). The depth from the surface (*y axis*) is expressed in cm. Calibrated radiocarbon dates (cal yr AD) are plotted along the *y axis* activity around the water pool. A similar intensification of anthropogenic influence is clearly visible in the development of the aquatic environment of the pool, which has been documented thoroughly.

The area of Prague belongs to the Bohemian Thermophytic region, the Prague Basin subunit of the phytogeographical region called The Prague Plateau (Skalický, 1997). The potential vegetation of this site is Hercynian oak-hornbeam forest (Carpinion), acidophilous oak forest (Genisto germanicae-Quercion) and ash-alder alluvial forest (Alnenion glutinoso-incanae) (Moravec et al., 1991; Neuhäuslová, 1998). According to the results of pollen, wood and charcoal analyses, all of these types of forest vegetation were probably present in the vicinity of the study site. An analogous species composition has been recorded from other Prague Mediaeval sites (Beneš et al., 2002; Kozáková & Pokorný, 2007; Kozáková et al., 2009; Novák et al., 2012). The results originating from both charcoal and wood analyses revealed a lower number of species than the pollen analysis. Some rare shrub species (e.g. *Viburnum opulus* type, *C. mas* type and *Juglans regia* type) were recorded only through the pollen analysis. Such differences between the pollen and the charcoal/wood analyses reflect the various source areas. The species composition of charcoal fragments reflects the

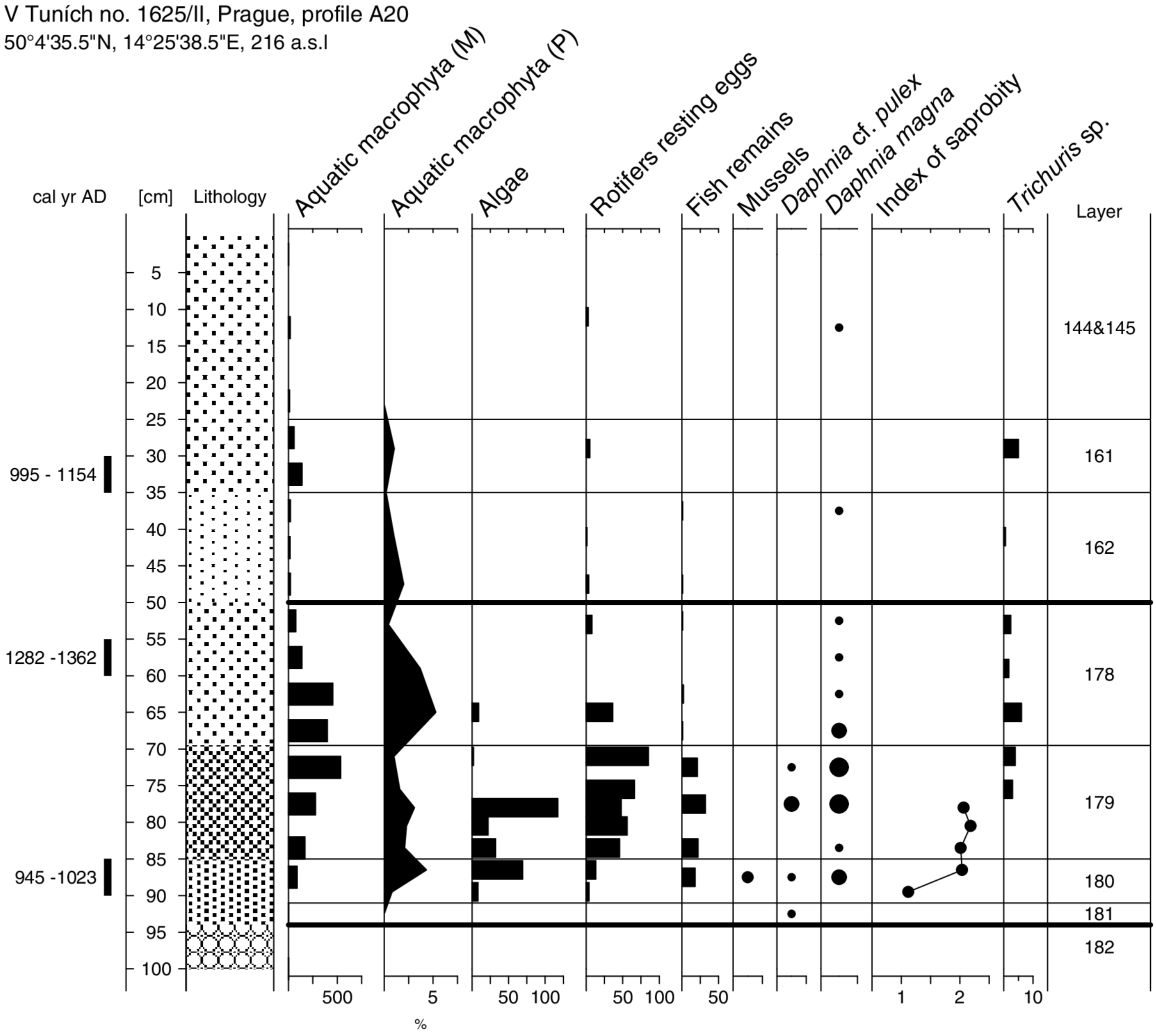


Fig. 6 Quantification of proxy data indicating the aquatic environment (as recorded in the A20 profile). The depth from the surface (*y axis*) is expressed in cm. Calibrated radiocarbon dates (cal yr AD) are plotted along the *y axis*. The count of macro-remains (macrophyta, algae, resting eggs of rotifers, *Trichuris* eggs as well as fish remains) is expressed in pieces (*x axis*). Aquatic macrophyta are represtnted by both sum of macro-remains (M) and percentage of pollen (P). Estimated abundance of mussels and *Daphnia* are plotted as *black dots*; the size of dots (small, medium and big) corresponds to the estimated quantification. The level of aquatic pollution is expressed by index of saprobity (dimensionless quantity) calculated according to diatom spectrum

use of firewood originating in close proximity of the site (Théry-Parisot et al., 2010; Novák et al., 2012). In contrast, the species composition of wood often reflects local vegetation cover, e.g. willow branches, or selectively collected construction material (fir and spruce).

Aquatic environment

Using a series of various methods, it was possible to make a detailed reconstruction of the aquatic environment of the site and its gradual changes. The changes of water quality were documented by a series of organisms: water macrophytes (*C. demersum*, *Lemna minor/gibbaI, M. spicatum*, *Potamogeton*, *Sparganium* and *Z. pallustris*), green algae (*Pediastrum simplex*, *T. minimum* and *Scenedesmus*), cladocera (ephipia of *D. magna* and *D.* cf. *pulex*), fish (Cyprinidae: *T. tinca*, *L. cephalus*, *A. alburnus, R. rutilus* and Perciformes), rotifers and diatoms of various species. On the grounds of the diatom composition, an index of saprobity was calculated—which could be used as a measure of water quality (Fig. 6).

According to the index of saprobity (1.2), the base of the profile (layers 181 and 182) was the result of sedimentation in considerably oligosaprobic conditions. The index of saprobity then gradually increased, exceeding 2 within layer 179, followed by the absolute disappearance of diatoms in layer 178. The rapid and almost synchronous decrease of green algae, diatoms and fishes in layer 178 implies that it was probably the response of aquatic organisms to some changes in the environment. The water was obviously greatly shaded by a thick layer of both *L. gibba/minor* and *P. natans*. This could explain the decrease of green algae but not also the decrease of diatoms occurring in early spring and late autumn, when summer shadowing by floating plants should be irrelevant. Alternatively, the high content of dissolved nutrients, which was probably connected with anoxia, could have been a major culprit causing the disappearance of both diatoms and fishes. Pollution of the water by organic waste (e.g. excrement) could be the principal reason for the rapid decrease in water quality. This interpretation is supported by appearance of the intestinal parasite *Trichuris* (not the human one) eggs shortly before the diatoms disappeared. Other waste indicators found in these two layers were as follows: seed of cucumber, seed of grape, pig bone and several pieces of ceramics.

According to the environmental demands of the fish (Table 2), the aquatic environment of the pond was probably rather diversified—the determined fish species occur both in *lotic* (i.e. flowing) and stagnant water (e.g. ponds and pools with muddy substrates). Tench and chub tolerate a lower amount of oxygen dissolved in water and prefer sites overgrown by vegetation. Species of the order Perciformes could occur in various types of water pools (e.g. lagoons, lakes of all types, or slow to medium flowing watercourses).

As opposed to the lower half of the profile, the intrerpretation of the upper part is much less clear. We assume that the layers 180, 179 and 178 definitely represent sedimentation in water reservoir. On the other hand, the overlying sediments (layers 162, 161, 145 and 144) are characterised by a rapid decrease in the number of remains of aquatic organisms. This could be due to a deterioration of preservation conditions. Besides, the psammitic (fine sandstone) character of the sediment of these layers implies an increased influx of material, which could be connected to an increased risk of contamination. Moreover, the possibility of the redeposition of an older material (the ^{14}C date within the layer 161, see above) should be taken into consideration.

There are two possible explanations of this phenomenon. One of the possibilities is that the material of the layer 161 is the result of redeposition of older sediment, perhaps connected to subsequent increase of building activity at the site. In that case all the materials from the upper part of the profile would be heavily contaminated. Alternatively, the older material encountered in the layer 161 could have been washed away from another location and later settled on the investigated site, similarly to the sandy sediments of the layers 162, 145 and 144—which are probably the result of an outwash from some higher positions of the drainage area. In that case the assemblages of biofacts encountered in the upper part of the profile would represent a mixture of material of both local and regional origin. Nevertheless, we suppose that the second scenario is more probable because of continuous succession of anthropogenic indicators in both macro-remains and pollen spectra. On the other hand, it is not possible to determine whether the water reservoir merely changed its character after the middle of fourteenth century or it disappeared and only a wet place with seasonal water influx remained.

Origin and function of the pond

Origin

The existence of the water reservoir is obviously related to the strong springs rising on the boundary between the permeable gravel of the Vinohrady riverine terrace and the underlying impermeable clay and bedrock (Zavřel, unpublished reports). The groundwater emerging from the base of this terrace also probably flowed inside the permeable layers of the secondary transported sands, afterwards seeping out onto the surface. In addition to that, the water from the terrace could also have flowed above the surface creating occasional small watercourses. For all these reasons the site and its near surroundings had been characterised for a long time by a high level of groundwater (Zavřel, 2009, unpublished report) and numerous wetlands and springheads (for more details to the hydrology of the New Town of Prague, see Zavřel (2006)).

The most probable explanation of the pond origin is that this naturally wet place was dammed artificially. However, this could not be proved definitively, as the supposed dam position lies outside the excavation area. Nevertheless, a 50-m section of a brook was found in the close vicinity of the investigated area (Fig. 2) (Kašpar, 2003). There could be two possible interpretations of the mutual relationship between these two features (the pond and the brook): According to the slope direction, either the brook flowed out of the pond, or the brook had no connection with the pond (in which case the pond would probably be very small).

Function

Knowledge of carp breeding and fishpond dam construction came to the Czech lands from West Europe (Makowiecki, 2001), probably with monks from Germany. Before this time, the so-called ‘vivaria piscium’, i.e. artificial water pools (stews, ‘stavy’) used for storage of captured fishes (Čítek et al., 1998), were constructed here, probably already since the eightth to ninth centuries (Andreska, 1987). Their existence in Moravia near Olomouc has been supported by a document from 1078 (Hurt, 1960). The oldest reference concerning a fishpond in Bohemia is a mention in the Chronica Bohemorum, in the part relating to the foundation of the Sázava monastery (Kosmas, 2011) in the 11th century. In 1227, the king Ottokar II of Bohemia authorized the construction of fishponds. In the fourteenth century, fish farming was already an important economic activity in the Czech lands. Since the first half of the fourteenth century, small ponds were built in the middle of each village, serving both for fish farming, and as fire water reservoirs (Čítek et al., 1998).

According to the fish species composition and the dating of the sediments, we could assume that the pond could have served for the retention of water and/or storing of fish, but not for fish breeding. During the earlier phases of the pond’s existence, the water was clean enough for drinking; however, it was later heavily contaminated by organic material. Still, it could have served as a water reservoir for various handicrafts, as, for example, brickmaking, pottery, ironworking or leather processing.

The further history of the pond remains unclear. The uppermost layers of the sedimentary sequence had been destroyed during the construction of the basement. However, the existence of three ponds belonging to a farmstead nearby was documented even in 1428 (Tomek, 1892). According to historical maps from 1791 (Herget’s plan) and from 1816 (Jüttner’s plan), this part of the New Town of Prague remained undeveloped (at least not built on) and the ground concerned was a part of some open areas or garden plots.

Conclusions

The results of this study allow the following conclusions:

1. According to the results of the environmental analyses, the material of the lower part of the profile is definitely a result of sedimentation on the bottom of a water reservoir. The duration of the water body was estimated for the period from the end of tenth century to approximately half of fourteenth century according to radiocarbon dating. Several species of freshwater fishes were determined according to bones/scales, but no remains of carp were found. Therefore, we can conclude that this was probably a kind of water reservoir containing fishes; however, it was not a typical fishpond intended for carp farming.

2. The origin of the water reservoir was connected with rich water springs having their source on the slope of the riverine terrace. The pond itself was probably constructed artificially, or alternatively a shallow natural pool could have been deepened and extended. Nevertheless, because the extent of the investigation area was too small, any remains of the dam structure were not documented.
3. The water quality was estimated according to proxy data. We assume that the water was originally relatively clean and the base of the profile was the result of sedimentation in considerably oligosaprobic conditions. However, increasing degree of organic pollution was documented in subsequent layers, caused probably by human influence (occasional waste disposal and defecation of domestic animals).
4. The character of the surrounding vegetation was reconstructed according to both pollen and macroremains data. Originally, the water body was surrounded by vegetation of semi-natural character (i.e. hygrophilous herbaceous vegetation directly on the banks as well as wet meadows, pastures and willow shrubs in the proximity). Later, gradual changes in the surrounding environment were documented. Increasing ruderalisation and intensification of human impact in closer proximity were manifested by indicators of trampled vegetation and nitrophilous plant species. Additionally, increasing proportion of cereals and decreasing proportion of trees in the pollen diagram indicated the significant changes taking place on the landscape level.

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References

Andreska, J., 1987. Rybářství a jeho tradice [Fishing and its tradition]. Státní zemědělské nakladatelství, Praha.

Baruš, V. & O. Oliva, 1995. Mihulovci (Petromyzontes) a ryby (Osteichthyes) 2 [Lampreys (Petromyzontes) and fishes (Osteichthyes) 2]. Academia, Praha.

Battarbee, R., 1986. Diatom analysis. In Berglund, B. E. (ed.), Handbook of Holocene Paleoecology and Paleohydrology. Wiley, Chichester.

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

Beneš, J., J. Kaštovský, R. Kočárová, P. Kočár, K. Kubečková, P. Pokorný & P. Starec, 2002. Archaeobotany of the Old Prague Town defence system: archaeology, macroremains, pollen and diatom analysis. Vegetation History and Archaeobotany 11: 107–119.

Beran, L., 1998. Vodní měkkýši ČR [Aquatic molluscs of the Czech Republic]. ČSOP, Vlašim.

Beug, H. J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Verlag Friedrich Pfeil, München.

Birks, H. H. & H. J. B. Birks, 2006. Multiproxy studies in palaeolimnology. Vegetation History and Archaeobotany 15: 235–251.

Bosi, G., M. Bandini Mazzanti, A. Florenzano, I. Massamba N'siala, A. Pederzoli, R. Rinaldi, P. Torri & A. M. Mercuri, 2011. Seeds/fruits, pollen and parasite remains as evidence of site function: Piazza Garibaldi–Parma (N Italy) in Roman and Mediaeval times. Journal of Archaeological Science 38: 1621–1633.

Cappers, R. T. J., R. M. Bekker & J. E. A. Jans, 2006. Digitale Zadenatlas van Nederland [Digital Seed Atlas of the Netherlands]. Barkhuis & Groningen University Library, Groningen.

Chytrý, M. & L. Tichý, 2003. Diagnostic, constant and dominant species of vegetation classes and alliances of the Czech Republic: a statistical revision. Masarykova Universita, Brno.

Čítek, J., V. Krupauer & F. Kubů, 1998. Rybnikářství [Fish farming]. Informatorium, Praha.

Čulíková, V., 1987. Zajímavý nález rostlinných makrozbytků ze středověké Prahy [An interesting find of plant macroremains from medieval Prague]. Archeologické rozhledy 39: 445–452.

Čulíková, V., 1998a. Rostlinné makrozbytky z raně středověkých sedimentů na III. nádvoří Pražského hradu [Plant macroremains from early medieval sediments in the 3rd courtyard of Prague castle]. Archaeologica Pragensia 14: 329–341.

Čulíková, V., 1998b. Výsledky analýzy rostlinných makrozbytků z lokality Praha 1 – Malá Strana, Tržiště čp. 259/III (Hartigovský palác) [Results of the analysis of plant macro-remains from the locality Prague 1-Lesser Town, Tržiště no. 259/III (Hartigovský palác palace)]. Archeologica Pragensia 14: 291–316.

Čulíková, V., 2001a. Rostlinné makrozbytky z lokality Praha 1 – Malá Strana, Malostranské nám. čp. 258/III (Lichtenštějnský palác) [Plant macro-remains from the locality Prague 1-Lesser Town, Malostranské nám. no. 258/III (Lichtenštejnský palác palace)]. Medievalia Archaeologica 3: 137–166.

Čulíková, V., 2001b. Rostlinné makrozbytky z pěti středověkých lokalit při obvodu centrální části Pražského hradu [Plant macro-remains from five medieval localities around the perimeter of the central part of Prague castle]. Medievalia Archaeologica 3: 303–327.

Čulíková, V., 2005. Rostlinné makrozbytky z raně středověké lokality Mostecká – Josefská ul. (dřevěná cesta), Praha 1 –

Malá Strana [Plant macro-remains from the early medieval site at Mostecká – Josefská str. (wooden causeway), Prague 1-Lesser Town]. Archeologica Pragensia 17: 137–169.

Čulíková, V., 2008. Ovoce, koření a léčiva z raně novověké jímky hradčanského špitálu [Fruits, spices and medicaments from the post-medieval cesspit of the hospital at Prague-Hradčany]. Archeologické Rozhledy 60: 229–260.

Čulíková, V., 2010. Středověká údolní niva Vltavy v Praze na Malé Straně (Valdštejnská čp. 154/III, Kolovratský palác) [Medieval floodplain of the Vltava river in the neighbourhood of the Lesser Town in Prague (Valdštejnská st. no. 154/111, Kolovrat palace)]. Archeologické Rozhledy 62: 72–116.

Dostálek, J. & T. Frantík, 2008. Dry grassland plant diversity conservation using low-intensity sheep and goat grazing management: case study in Prague (Czech Republic). Biodiversity 17: 1439–1454.

Fægri, K. & J. Iversen, 1989. Textbook of Pollen Analysis, 4th ed. Wiley & Sons, Chichester.

Fott, B., 1954. Pleurax, synthetická pryskyřice pro preparaci rozsivek [Pleurax, the synthetic resin for diatoms preparation]. Preslia 26: 163–194.

Gaillard, M. J., 2007. Pollen Methods and Studies – Archaeological Applications. In Elias, S. A. (ed.), Encyclopedia of Quaternary Science. Elsevier, Oxford: 2570–2595.

Grimm, E. C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers & Geosciences 13: 13–35.

Grimm, E. C., 2011. Tilia. Version 1.5.12. Illinois State Museum, Springfield.

Heiss A. G., 2000. Anatomy of European and North American woods – an interactive identification key. http://www.holzanatomie.at/.

Hellwig, M., 1997. Plant remains from two cesspits (15th and 16th century) and a pond (13th century) from Götingen, southern Lower Saxony, Germany. Vegetation History and Archaeobotany 6: 105–116.

Hrdlička, L., 1984. Nástin vývoje reliéfu historického jádra Prahy ve středověku [A sketch of the development of medieval historical centre of Prague]. Archaeologica Pragensia 5: 197–209.

Hrdlička L., 1997. Od spontánního vývoje k regulaci terénního reliéfu Starého Města pražského [From spontaneous terrain development to regulation of relief in the Old Town of Prague]. In Kubková J., J. Klápště, M. Ježek & P. Meduna (eds), Život v archeologii středověku. Archeologický ústav AV ČR, Praha, vvi: 246–252.

Hurt, R., 1960. Dějiny rybnikářství na Moravě a ve Slezsku [History of fish farming in Moravia and Silesia]. Krajské nakladatelství v Opavě, Opava.

Jankovská V., 1997. Výsledky pylových analýz z lokality: Praha 1 – Malá Strana, Tržiště 259/III [Results of pollen analysis from Lesser Town, Tržiště Street 259/III, Prague]. In Kubková J., J. Klápště, M. Ježek & P. Meduna (eds), Život v archeologii středověku. Archeologický ústav AV ČR, Praha, vvi: 299–308.

Jankovská, V. & J. Pokorný, 2002. Palaeoecology of a medieval fishpond system (Vajgar, Czech Republic). Folia Geobotanica 37: 253–273.

Juggins S., 2009. Rioja: analysis of Quaternarry science data, R package version 0.5-6. http://cran.r-project.org/web/packages/rioja/index.html.

Kašpar, V., 2003. Rotunda sv. Longina a osada Rybník na Novém Městě pražském [St. Longin's Rotunda and the Rybnik village in the New Town of Prague]. Gorgoneion 1: 15–42.

Kašpar V., 2007. Politických vězňů čp. 913/II. In Dragoun, Z. (ed.), Pražský sborník historický 35, Praha: 352–353.

Kaštovský, J., P. Kočár, R. Kočárová, P. Pokorný, J. Beneš & P. Starec, 1999. Předběžné poznatky o některých vodotečích na území Starého a Nového Města pražského [Preliminary knowledge of some watercourses in the area of the New and Old Towns of Prague]. Archaeologia Historica 24: 143–151.

Katz, N. J., S. V. Katz & M. G. Kipiani, 1965. Atlas and keys of fruits and seeds occurring in the quaternary deposits of the USSR. Nauka, Academy of Science of the USSR, Moscow.

Komárek, J. & V. Jankovská, 2001. Review of the green algal genus *Pediastrum*. Implication for pollen-analytical research. Gebrüder Borntraeger Verlagsbuchhandlung, Berlin.

Kosmas, 2011. Kronika Čechů [Chronicle of the Bohemians]. Hrdina K, Bláhová M (translation). Argo, Praha.

Kozáková, R. & I. Boháčová, 2008. Přírodní prostředí Pražského hradu a jeho zázemí v raném středověku – výpověď pylové analýzy sedimentů ze III. nádvoří [Environment of Prague Castle and its vicinity – notice of pollen analysis from Early Medieval sediments from the 3rd courtyard]. Archeologické Rozhledy 60: 547–564.

Kozáková, R. & P. Pokorný, 2007. Dynamics of the biotopes at the edge of a medieval town: pollen analysis of Vltava river sediments in Prague, Czech Republic. Preslia 79: 259–281.

Kozáková, R., P. Pokorný, J. Havrda & V. Jankovská, 2009. The potential of pollen analyses from urban deposits: multivariate statistical analysis of a data set from the medieval city of Prague, Czech Republic. Vegetation History and Archaeobotany 18: 477–488.

Krammer, K. & H. Lange-Bertalot, 1986. Bacillariophyceae (Naviculaceae). In Ettl, H., J. Gerloff, H. Heinig & D. Mollenhauer (eds), Süsswasserflora von Mitteleuropa 1. Gustav Fischer Verlag, Stuttgart.

Krammer, K. & H. Lange-Bertalot, 1988. Bacillariophyceae (Bacillariaceae, Epithemiaceae, Surirellaceae). In Ettl, H., J. Gerloff, H. Heinig & D. Mollenhauer (eds), Süsswasserflora von Mitteleuropa 2. Gustav Fischer Verlag, Stuttgart.

Krammer, K. & H. Lange-Bertalot, 1991a. Bacillariophyceae (Achnanteaceae, Kritische Ergänzungen zu Navicula (Lineolateae) und Gomphonema Gesamtliteraturverzeichnis). In Ettl, H., J. Gerloff, H. Heinig & D. Mollenhauer (eds), Süsswasserflora von Mitteleuropa 4. Gustav Fischer Verlag, Stuttgart.

Krammer, K. & H. Lange-Bertalot, 1991b. Bacillariophyceae (Centrales, Fragilariaceae, Eunotiaceae). In Ettl, H., J. Gerloff, H. Heinig & D. Mollenhauer (eds), Süsswasserflora von Mitteleuropa 3. Gustav Fischer Verlag, Stuttgart.

Kreuz, A. & E. Schäfer, 2002. A new archaeobotanical database program. Veget Hist Archaeobot 11: 177–179.

Kubát, K., L. Hrouda, J. Chrtek jun, Z. Kaplan, J. Kirschner & J. Štěpánek, 2002. Klíč ke květeně České republiky [Field guide to flora of the Czech Republic]. Academia, Praha.

Legendre, P. & L. Legendre, 1998. Numerical Ecology, 2 English ed. Elsevier, Amsterdam.

MacArthur, R. H., 1957. On the relative abundance of bird species. Proceedings of the National Academy of Sciences of the United States of America, 43: 293–295.

Makowiecki, D., 2001. Some remarks on medieval fishing in Poland. In Buitenhuis, H. & W. Prummel (eds), Animals and Man in the Past. ARC-Publicatie 41, Groningen: 236–241.

Mencl, V., 1969. Praha. Odeon, Praha.

Moravec, J., R. Neuhäusel, D. Blažková, M. Husová, J. Kolbek, F. Krahulec & Z. Neuhäuslová-Novotná, 1991. Přirozená vegetace území hlavního města Prahy a její rekonstrukční mapa [Natural vegetation of the capital city Prague and its reconstruction map]. Academia, Praha.

Neuhäuslová, Z. (ed.), 1998. Mapa potenciální přirozené vegetace České republiky [Map of potential natural vegetation of the Czech Republic]. Academia, Praha.

Novák, J., L. Lisá, P. Pokorný & M. Kuna, 2012. Charcoal analyses as an environmental tool for the study of Early Medieval sunken house infills in Roztoky near Prague, Czech Republic. Journal of Archaeological Science 39: 808–817.

Oksanen J., F. G. Blanchet, R. Kindt, P. Legendre, R. B. O'Hara, G. L. Simpson, P. Solymos, M. H. Stevens & H. Wagner, 2010. Vegan: Community Ecology Package. R package version 1.17-2. http://cran.r-project.org/web/packages/vegan/index.html.

Opravil, E., 1986. Rostlinné makrozbytky z historického jádra Prahy [Plant macro-remains from the historical centre of Prague]. Archaeologica Pragensia 7: 237–271.

Opravil, E., 1994. Příspěvek k poznání rostlinných makrozbytků ze staré Prahy [A contribution to the knowledge of plant macro-remains from historical Prague]. Archeologické Rozhledy 46: 105–114.

Pfleger, V., 1988. Měkkýši [Molluscs]. Artia, Praha.

Pokorná, A., D. Dreslerová & D. Křivánková, 2011. Archaeobotanical Database of the Czech Republic, an Interim Report. IANSA 1: 49–53.

Pokorný, P., 2002. A high-resolution record of Late-Glacial and Early-Holocene climatic and environmental change in the Czech Republic. Quaternary International 91: 101–122.

Pokorný, P., N. Boenke, M. Chytráček, K. Nováková, J. Sádlo, J. Veselý, P. Kuneš & V. Jankovská, 2006. Insight into the environment of a pre-Roman Iron Age hillfort at Vladař, Czech Republic, using a multi-proxy approach. Vegetation History and Archaeobotany 15: 419–433.

Punt, W., 1976. The Northwest European Pollen Flora, Vol. I. Elsevier, Amsterdam.

Punt, W. & G. C. S. Clarke, 1980. The Northwest European Pollen Flora, Vol. II. Elsevier, Amsterdam.

Punt, W. & G. C. S. Clarke, 1981. The Northwest European Pollen Flora, Vol. III. Elsevier, Amsterdam.

Punt, W. & G. C. S. Clarke, 1984. The Northwest European Pollen Flora, Vol. IV. Elsevier, Amsterdam.

Punt, W., S. Blackmore & G. C. S. Clarke, 1988. The Northwest European Pollen Flora, Vol. V. Elsevier, Amsterdam.

Punt, W. & S. Blackmore, 1991. The Northwest European Pollen Flora, Vol. VI. Elsevier, Amsterdam.

Punt, W., S. Blackmore & P. P. Hoen, 1995. The Northwest European Pollen Flora, Vol. VII. Elsevier, Amsterdam.

Punt, W., S. Blackmore, P. P. Hoen & P. J. Stafford, 2003. The Northwest European Pollen Flora, Vol. VIII. Elsevier, Amsterdam.

Punt, W., S. Blackmore, P. P. Hoen & P. J. Stafford, 2009. The Northwest European Pollen Flora, Vol. IX. Elsevier, Amsterdam.

R Development Core Team, 2010. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.

Radu, V., 2005. Atlas for the Identification of Bony Fish Bones from Archaeological Sites. Editura Contrast, Bucuresti.

Ramsey, B. C., M. Dee, S. Lee, T. Nakagawa & R. Staff, 2010. Developments in the calibration and modelling of radiocarbon dates. Radiocarbon 523: 953–961.

Reimer, P. J., M. G. L. Baillie, E. Bard, A. Bayliss, et al., 2009. IntCal09 and marine09 radiocarbon age calibration curves, 0–50,000 years Cal BP. Radiocarbon 514: 1111–1150.

Rösch, M., 1999. Ein Pollenprofil aus dem ehemaligen Fischweiher des Herzogs von Württemberg bei Nabern, Stadt Kirchheim/Teck, zur Kenntnis der Kulturlandschaftsgeschichte des Späten Mittelalters und der Frühen Neuzeit im Vorland der Schwäbischen Alb. In Fundberichte aus Baden-Wurttemberg. Konrad Theiss Verlag, Stuttgart: 741–778.

Rösch, M., 2012. Die Weiher des UNESCO-Welterbes Kloster Maulbronn als wirtschafts- und umweltgeschichtliche Archive. In Archologische Ausgrabungen in Baden-Wurttemberg. Konrad Theiss, Stuttgart: 71–75.

Rybníčková, E. & K. Rybníček, 1985. Paleogeobotanical evaluation of the Holocene profile from the rezabinec fishpond. Folia Geobotanica & Phytotaxonomica 20(4): 419–437.

Sadori, L., A. M. Mercuri & M. Mariotti, 2010. Reconstructing past cultural landscape and human impact using pollen and plant macroremains. Plant Biosystems 144(4): 940–951.

Sasaki, N. & H. Takahara, 2011. Late Holocene human impact on the vegetation around Mizorogaike Pond in northern Kyoto Basin, Japan: a comparison of pollen and charcoal records with archaeological and historical data. Journal of Archaeological Science 38: 1199–1208.

Shannon, C. E., 1948. A mathematical theory of communication. The Bell System Technical Journal 27: 379–423.

Schweingruber, F. H., 1990. Anatomie europäischer Hölzer [Anatomy of European woods]. Paul Haupt, Bern.

Skalický V., 1997. Regionálně fytogeografické členění [Regional-phytogeographical zoning]. In Hejný S. & B. Slavík (eds), Květena České republiky 1 [Flora of the Czech Republic 1]. Academia, Praha, pp 103-121.

Sládeček, V., 1986. Diatoms as indicators of organic pollution. Acta Hydrochimica et Hydrobiologica 145: 555–566.

Smol, J. P., H. J. Birks & W. M. Last, 2001. Tracking Environmental Change Using Lake Sediments. Data Handling and Numerical Techniques, Vol. 5. Kluwer Academic Publishers, Dordrecht.

Starec, P., 2005. Z příspěvků archeologie ke studiu vodních poměrů v historickém jádru Prahy [Archaeological contribution to the knowledge about watercourses in the historical centre of Prague]. Documenta Pragensia 24: 39–46.

Starec, P., P. Houfková & A. Bernardová, 2012. A contribution to the knowledge of natural conditions of Nové Město – excavations in Panská Street No. 1308/II. Staletá Praha 28: 149–164.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores 13: 615–621.

Święta-Musznicka, J., M. Latałowa, M. Badura & A. Gołembnik, 2013. Combined pollen and macrofossil data as a source for reconstructing mosaic patterns of the early medieval urban habitats e a case study from Gdańsk, N. Poland. Journal of Archaeological Science 40: 637–648.

Théry-Parisot, I., L. Chabal & J. Chrzavzez, 2010. Anthracology and taphonomy, from wood gathering to charcoal analysis. A review of the taphonomic processes modifying charcoal assemblages in archaeological contexts. Palaeogeography, Palaeoclimatology, Palaeoecology 291: 142–153.

Tomek, V. V., 1892. Dějepis města Prahy I [History of the town of Prague]. Řivnáč, Praha.

van Geel, B., 2001. Non-pollen Palynomorphs. In Smol, J. P., et al. (eds), Tracking Environmental Change Using Lake Sediments. Terrestrial, Algal, and Siliceous Indicators, Vol. 3. Kluwer Academic Publishers, Dordrecht.

Wheeler, A. & A. K. G. Jones, 2009. Fisches. Cambridge University Press, Cambridge.

Zavřel, J., 2006. Geologická problematika archeologického poznání Nového Města pražského [Contribution of geology to the archaeological knowledge of the New Town of Prague]. Archaeologica Pragensia 18: 245–261.

5.4. Paper IV.

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Origin and development of long-strip field patterns: A case study of an abandoned medieval village in the Czech Republic

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ABSTRACT

Long-strip and terraced fields systems form significant elements of the current cultural landscape. When evaluating their significance, it is necessary to determine their origins and to further specify their development. However, archeological researchers have encountered problems in dating field systems that were exposed to intensive agriculture in the 20th century AD. In this study, we describe a combination of approaches used to confirm the current landscape's High Medieval origin of the long-strip terrace-like field system of the former village of Malonín, which is located in the Bohemian Forest Mts., Czech Republic. The methods employed are radionuclide dating, geographic information system (GIS)-based reconstruction using old maps, historical documents, and archeological and palaeobotanical records. Our study evaluated the historical significance of field boundaries in the form of hedgerows, which have stabilized the pattern of the agricultural landscape since medieval times. The results of this study provide a basis for further land use planning and for conserving the cultural landscape.

1. Introduction

Long-strip field systems and terraced field systems form agricultural landscapes showing a diverse morphology of fields and field boundaries. These systems reflect diverse recent and historical management based on local terrain typologies (Denevan, 2001; Fleming and Ralph, 1982; Matzat, 1988; Mitchell, 1990). Terraced slopes (Stanchi et al., 2012), terraced paddy fields (Iiyama et al., 2005) and hedgerow network landscape known as *bocage* (Baudry et al., 2000; Groot et al., 2010) have recently been subjected to conservation and careful management in recognition of their environmental and aesthetic value. Maintained field boundaries in the form of stone-walled terraces and hedgerows contribute to long-term soil conservation (Oshunsanya, 2013), improve topsoil retention (Goodman-Elgar, 2008), and reduce runoff and intense erosion (Bayer and Beneš, 2004; Seeger and Ries, 2008). Shelterbelts and hedgerows have been shown to be artificial linear features that enhance species biodiversity (Cornulier et al., 2011; DeClerck et al., 2010; Harvey et al., 2005; Le Cœur et al., 2002; Pulido-Santacruz and Renjifo, 2011; Staley et al., 2012). In addition, present plant communities are influenced by the past land use of a particular landscape patch (Karlík and Poschlod, 2009). Field boundaries are a prominent indicator of former arable land use in recent grasslands or forests (Hejcman et al., 2013).

The establishment of a particular field system is generally difficult to date (Bevan and Conolly, 2011; Frederick and Krahtopoulou, 2000; Petersson, 1999), though in some cases ancient origins have been determined (Denevan, 2001; Gibson, 2001; Iriarte et al., 2010; Krahtopoulou and Frederick, 2008; Malpass, 1987). Archeological dating of artifacts is often the main source for assessing the age of terraced fields, but this information embraces rather long time intervals. Historical documents and maps are restricted by limited availability of sources. The combination of these sources with environmental methods (Kosňovská et al., 2011; Sasaki and Takahara, 2011), archeological dating of artifacts and physical age determination based on ^{14}C data (Bronk Ramsey, 2009), ^{210}Pb concentrations for sediment layers younger than 150 years, and the discrete stratigraphic chronomaker ^{137}Cs peaks derived from atomic bomb testing in 1963–1964 AD and the Chernobyl accident in 1986 AD (Appleby, 2008; Gunten et al., 2009; He and Walling, 1997; Sanchez-Cabeza and Ruiz-Fernández, 2012) provide other powerful tools (Fernández Mier et al., 2014; Follain et al., 2009; Schoorl et al., 2004a,b; Wakiyama et al., 2010).

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In various areas of the world, field systems have created specific patterns, each with its own historical origin. In the Czech Republic, a specific landscape mosaic is shaped by field systems of neighboring villages (Černý, 1979; Gojda, 2000). A field system originally belonging to a single High Medieval village is called “pluzina” in the Czech language. As this is a regionally specific phenomenon, the term pluzina has been adopted in English language scientific literature (Sklenicka et al., 2009). Each pluzina consists of a number of individual fields, long parallel plots with a minimum of transversal separators, which are connected with individual farmsteads in the village. From the 13th century AD, most of the High Medieval field structures were organized into long, narrow parallel plots mainly in response to the new, single direction tillage technology (Bayer and Beneš, 2004). According to the local geomorphology, the field boundaries can take the form of terraces, mounds, or clearance walls (Fleming and Ralph, 1982; Kuna and Tomášek, 2004), while some boundaries are also defined by hedgerows. Although the structural attributes have frequently been preserved, the hedgerow network was massively reduced in the 20th century AD due to the intensification of agriculture and further extensification of land management (Molnárová, 2008; Sklenicka et al., 2009).

The objective of this study is to reconstruct and date the changes in the pluzina field pattern of the deserted former village of Malonín, which is currently characterized by the presence of a well-preserved abandoned long-strip field system with a terrace-like morphology.

Using the combination of the dating approaches mentioned above, we attempt to answer the following questions:

1) How old is the field system in the study site?
2) Is the dating of the field system using written resources, pottery chronology, and radiocarbon methods consistent?
3) Was the field system established when the village was being established, and was it stable during the centuries that followed?

2. Material and methods

2.1. A description of the study site

The study was conducted within the 216 ha area of the former village of Malonín, situated in the cadastral area of the village of Frantoly, Prachatice region, in the foothills of the Bohemian Forest, Czech Republic (Fig. 1). The elevation of the study site ranges from 660 to 735 m. The mean annual temperature is 5–6 °C, and the mean annual precipitation is about 700 mm.

Previous archeological excavations carried out in the built-up former village area determined that its origin was High Medieval (Beneš, 1995), coinciding with the settlement activity in the region in the second half of the 13th century AD (Boháč, 1983; Profous, 1951). This is further in accordance with data on the colonization of other marginal areas in the Czech Republic (Klápště, 2005; Sláma, 1976; Žemlička, 2002). No

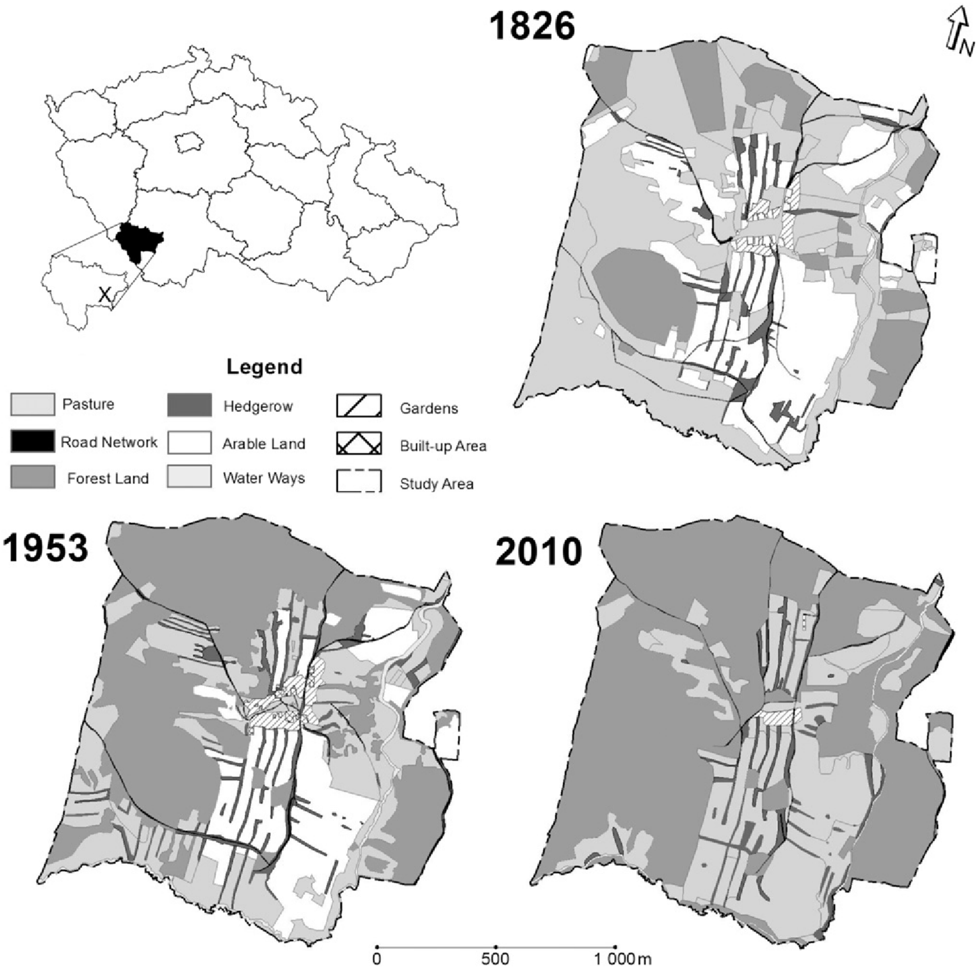

Fig. 1. Location of the former Malonín village within the Czech Republic (14.079 E, 48.971 N). The dark area marks the Prachatice region, the study site is marked as X. Land cover maps of the Malonín area originate from 1826, 1953, and 2010. Dominant soils are Dystric Cambisols.

records of prehistoric settlement activity were detected at the study site. Relatively low settlement density has been reconstructed throughout the region (Parkman, 2003a,b, 2004). We assumed that we are dealing with the first distinctive change to the local landscape pattern, which took place during High Medieval times.

The study site was characterized by the presence of sediments containing well-preserved macro-botanical remnants suitable for radiocarbon analysis. The background geology is composed of Moldanubian Massif granulites. In the lower parts of the slopes, these rocks are covered by colluvial deposits. The lowermost parts of the valley bottom are composed of bedded alluvial deposits from the Chrobolský Stream, consisting of gravely, sandy, and locally clayey or silt loam deposits, including organic charcoal-rich layers. Dystric Cambisols, with a high skeletal content in parts deeper than 30 cm, are typical soils in the study area. The alluvial zone is dominated by Eutric Fluvisols (Czech Geological Survey, 2013). The current vegetation is characterized as a mosaic of grasslands, hedgerows, and forests (Figs. 1, 2).

2.2. History of the study site

The settlement activity in the region started in the second half of the 13th century, and was characterized by several waves of building activity. The closest village to the study site, Frantoly, situated 2 km north of the site, was founded in 1315 AD (Boháč, 1983; Profous, 1951). The first written record of the village of Malonín comes from 1349 AD. By this year, the village had already been in existence for some time.

The village was not damaged by the Thirty Years War in 1618–1648 AD (Doskočil, 1953–1954). In Malonín, there were four farmsteads with land ownership greater than 4.5 ha, eight farmsteads with less than 4.5 ha, and one cottage with some small land ownership, according to the landholding registry from 1654 AD. The tax registry refers to 73 cows, 30 sheep, 17 pigs and arable fields suitable for *Secale cereale* cropping (Doskočil, 1953–1954). The same number of farmsteads as in 1654 AD corresponds with the data in the Stable Cadastre in 1826 AD (Fig. 1).

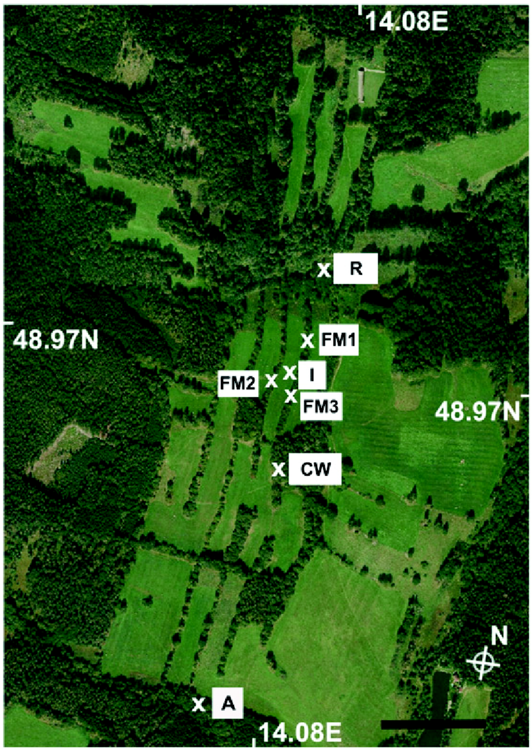

Fig. 2. Aerial map from 2010 of the area of the former Malonín village. White crosses correspond to the series of test pits in the north-southwards direction: (R) water reservoir on the village square, (FM1–FM3) field margins, (I) inner part of the field, (CW) clearance-wall and (A) alluvium. Dominant soils are Dystric Cambisols, the alluvial zone is dominated by Eutric Fluvisols. Used scale bar — 300 m.

According to local records (Chronicle of Frantoly, 1945–1954), 14 buildings and 2 remote settlements were located in Malonín in 1945 AD. All inhabitants were German speaking, and all were resettled in February 1946 AD. Some of the houses were demolished, and the remaining nine houses were settled by invited Slovak farmers from Romania in April 1946 AD. The arable land gradually became grassland, the number of inhabitants decreased, and in 1954 AD only five houses remained. The ruins of the houses were completely demolished in 1956–1957 AD. After the early 1950s AD, the grasslands were used as cattle pastures by the local cooperative farm, and some grasslands were reforested.

2.3. Data collection

In the deserted village, we selected the village square water reservoir and the most typical farmstead (no. 3.), with the former fields ending in the adjacent alluvium of the Chrobolský Stream. Since our aim was to combine ^{14}C data with the chronology based on the archeological record, the character of the excavation was defined as a set of archeological test pits.

The distribution of the test pits was selected on the basis of a geographic information system (GIS)-based analysis of old maps and aerial photographs (Zímova et al., 2013; Fig. 2), and also on the basis of on-the-ground experience at the site (Millican, 2012). We selected (a) the water reservoir on the village square (R), (b) the inner part of a former field (I), (c) the former field margins (FM1-FM3), which took the form of steps more than one meter in height (Fig. 3a,b), (d) a field margin in the form of a 0.6 m high clearance-wall (CW) built from stones removed from the former arable field (Fig. 3c), and (e) the alluvium (A) in the most remote part of the village (Fig. 2, Table 1).

The soft sediment thoroughly saturated with water in the former village square water reservoir was cored. All other samples were collected from profiles revealed in the test pits (Table 1). Soil and sediment samples were taken from the bottom layers. In the case of the test pits, archeological material was recovered from each 10 cm layer. To follow the topology of the decline of the terrain, the test pits situated in the field margins were classified into three sectors (Fig. 3b). The first sector corresponded to the change in the terrain level between two fields, and the compact excavated profile reflected a change in depth of more than one meter. Two other sectors were shallower. Since the FM1 recovered profile was well preserved and compact (Fig. 3a), an additional soil sample for ^{14}C dating was recovered (Figs. 3a, 5). Two further test pits were placed in the field margins (FM2 and FM3) and data was collected in a similar manner. A 20 m long segment more distant from the village center was differentiated from the rest of the field margin by the presence of a stone wall.

The test pit in the clearance-wall reached a total depth of 100 cm. This inner part was classified as the first sector. The depth on its two sides reached 50 cm beneath the current level of the terrain (Fig. 3c). Two sides of the pit were then classified as two more sectors. The upper part of the profile was composed of large stones and formed a loose stratigraphy. The 18-cm-thick soil layer buried beneath the stones was mainly intact (Table 1).

2.4. Archeological artifacts

Potsherds distributed as manuring scatters were collected from all test pits from layers 10 cm in depth (Table 1) located in the inner part of the field, in the field margins, in the clearance-wall, and in a trench in the alluvium. To collect all the artifacts, soil from each mechanical

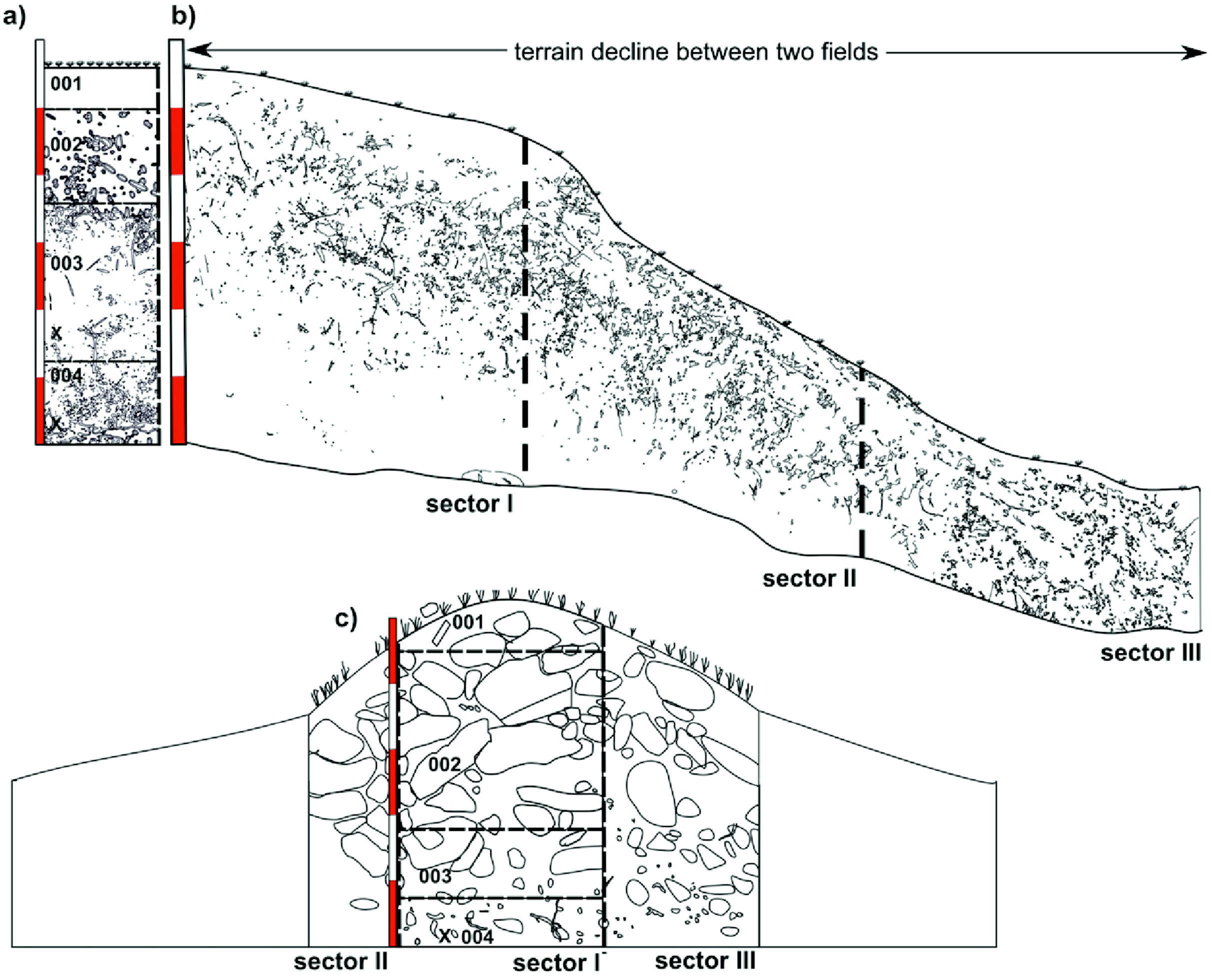

Fig. 3. Scheme of the field margin (FM1) and the clearance-wall (CW) arrangement, Malonín, Bohemian Forest Mts., the Czech Republic. Used scale bars fit to both axes, each part corresponds to 20 cm. a) Revealed profile in the front side of the FM1 test pit. Soil samples which provided the material for radiocarbon analysis were taken from the 003 and 004 layers and their location is marked with X. b) Side view of the FM1 test pit defined by the gradual terrain decline between two adjacent field terraces. c) Side view of the CW test pit. The revealed profile was situated in the middle of the test pit. Soil samples which provided the material for radiocarbon analysis were taken from layer 004 and their location is marked with X.

layer was sieved using a 2 mm mesh. Sherds were then sorted into typology classes according their fabric (Klápště, 2002; Nekuda and Reichertová, 1968; Salač, 1998; Vařeka, 1998), reflecting approximate chronological periods (see Fig. 4). Ordinary sherds were added to the probable period, but were listed as a separate group.

2.5. Radiocarbon dating

Macro-botanical remnant analysis was carried out in order to obtain suitable material for radiocarbon dating (Birks and Birks, 2000). Sediment samples (100 mL) were washed through 0.25 mm sieves.

Table 1
Position, coordinates, and sampling descriptions of each test pit/core in the former Malonín village, Bohemian Forest Mts., the Czech Republic.

Test pits/core	Coordinates	Altitude [m.a.s.l.]	Distance from the intravilan [m]	Total depth [cm]	Sector size [m]	Number of sectors
R	14.0799050 E 48.9717397 N	720	Village center	91	Core	–
FM1	14.0797169 E 48.9704600 N	736	21	118	1 × 1	3
FM2	14.0791172 E 48.9697828 N	743	209	140	1 × 1	3
FM3	14.0796672 E 48.9696000 N	736	234	150	1 × 1	3
I	14.0794361 E 48.9701358 N	740	177	35	1 × 1	1
CW	14.0793369 E 48.9681619 N	728	800	100	1 × 1	3
A	14.0781369 E 48.9636900 N	660	1400	80	1 × 1	1

Fig. 4. 3D scan of a sherd in manuring scatters typical for the 14th century AD found in field margin test pit (FM1) in Malonín, Bohemian Forest Mts., the Czech Republic (14.0797169 E, 48.9704600 N). Each part of used scale bar corresponds to 1 cm.

Macro-botanical remnants were picked out and identified according to Anderberg (1994), Berggren (1981) and Cappers et al. (2006). Accelerator Mass Spectrometer (AMS) ^{14}C dating of 8 macrofossil samples was carried out in the CAIS laboratory, USA. When possible, macro-botanical remnants of the same origin (charred needles of *Abies alba*) were used. The ^{14}C data were calibrated to calendar ages using the OxCal 4.2 online application (Bronk Ramsey, 2009) based on the IntCal 13 (Reimer et al., 2013) calibration curve.

2.6. Recent soil dating

A compact profile was taken from the field margin test pit (FM1) and was stored at 4 °C until it was opened. Sediment samples were taken at precise positions along the profile. Gamma-decay counts of radionuclide concentrations (^{210}Pb, ^{226}Ra, ^{137}Cs) were measured in the CEN Radiochronology Laboratory, Canada, using the High-Purity Germanium detector (HPGe). The excess lead-210 (^{210}Pb$_{ex}$) activity was assessed by subtracting the ^{226}Ra value from the total ^{210}Pb, assuming that supported ^{210}Pb is in secular equilibrium with ^{226}Ra. However, the negative ^{210}Pb$_{ex}$ values from the lower part of the profile indicated that equilibrium was not established due to the loss of some ^{222}Rn from the soil through evaporation and washing. We adjusted the final ^{210}Pb$_{ex}$ value by estimating the fraction of ^{222}Rn lost from the soil using the standard emanation coefficient of 0.3, as suggested by Du and Walling (2012).

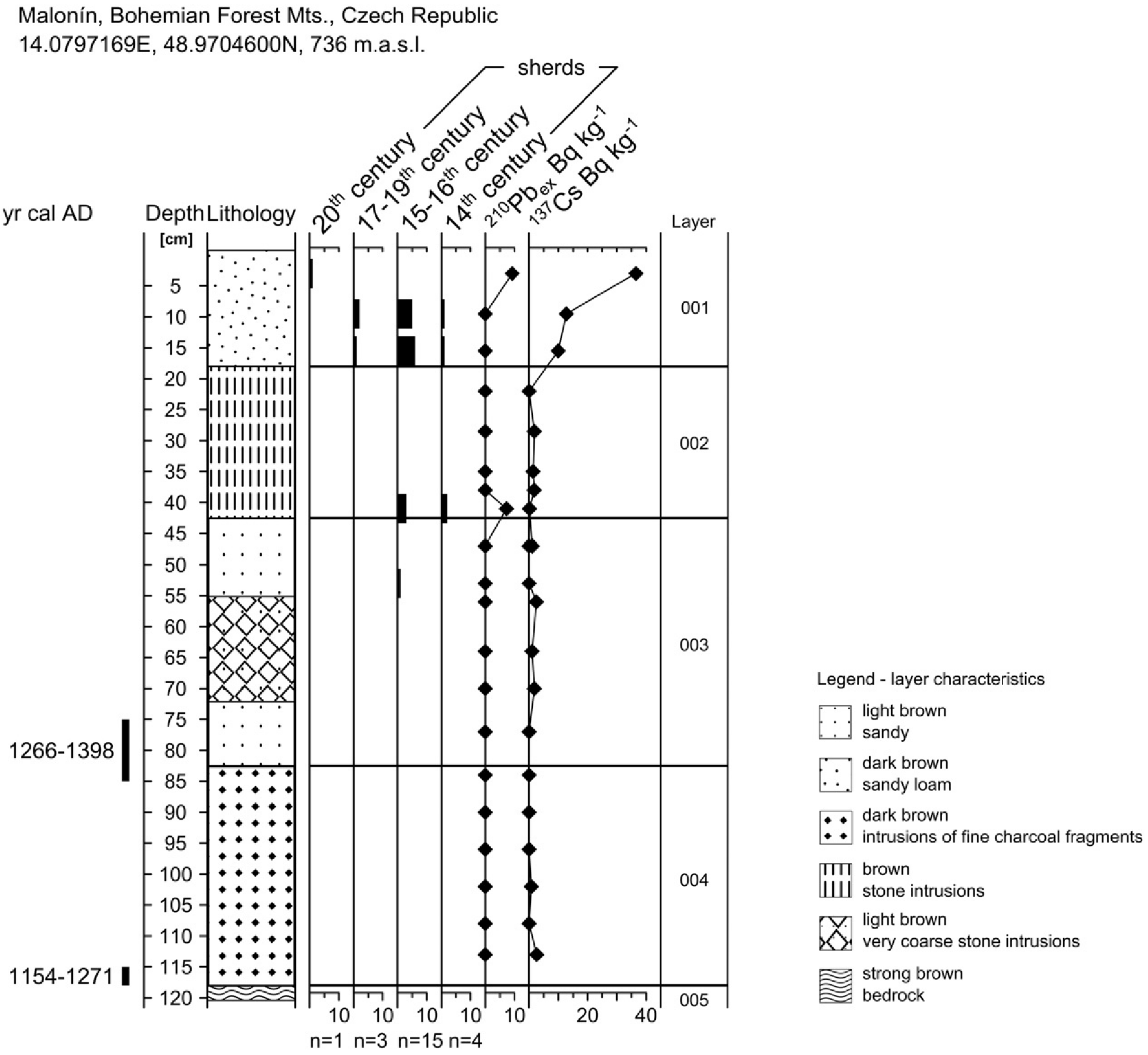

Fig. 5. Distribution of sherds in manuring scatters in the field margin test pit FM1, sector I, is given by black histograms. n — indicates total number of sherds of each chronological category excavated within the pit. Calibrated radiocarbon dates are plotted along the diagram. Chronology is given in years AD. Concentrations of ^{210}Pb$_{ex}$ and ^{137}Cs are given by the black line with the dots representing the measured values. The recovered profile was characterized by layers marked as 001–005 following the principles of archeological stratigraphy. The individual layers were composed of soil transferred from arable fields with intrusions of pottery fragments (001, 002, 003), stones (002, 003), and fine charcoal fragments (004) resulting from direct human activity.

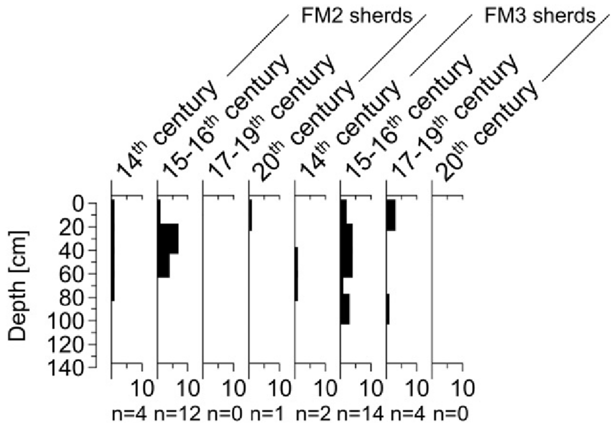

Fig. 6. Distribution of sherds in manuring scatters is given by black histograms in field margin test pits (FM2, FM3), sector I. n — indicates total number of sherds of each chronological category excavated within whole test pit. Chronology is given in years AD. Position of FM2 test pit was located in undisturbed part of field margin (14.0791172 E, 48.9697828 N). Stratigraphy was analogous as in FM1 test pit. Position of FM3 test pit reflected the locus of hedged field margin characterized by the presence of stone wall (14.0796672 E, 48.9696000 N).

3. Results

3.1. Archeological artifacts

The vertical distribution of the sherds in field margin test pit FM1 is presented in Fig. 5. The spectrum of sherds covered the time horizon from the 14th century until the 20th century AD, and the typological distribution in particular layers reflected the time horizon of the layer deposition. Similar results were obtained from field margin pit FM2. The record of the sherds differed in field margin pit FM3 (Fig. 6). A mixture of sherds from each interval (14th, 15th–16th, 17th–19th, 20th century AD) was recovered in all layers of the test pit originating from the inner part of the field.

We discovered only three sherds from the clearance-wall test pit; one sherd dated to the 14th century AD was recorded in the 50-to-60 cm depth interval, and two sherds dated to the 15th–16th century AD were recorded in bottom layer (90–100 cm). No sherds were discovered in the alluvium.

Table 2
List of radiocarbon dates originating from macro remnants separated from given soil sample, Malonín, Bohemian Forest Mts., the Czech Republic. The quoted uncalibrated dates (^{14}C age) and their intervals (±) were given by CAIS laboratory in radiocarbon years before 1950 (years BP), using the ^{14}C half-life of 5568 years. Each interval of calibrated date (year cal AD) using the OxCal 4.2 online application was stated with its probability (%).

Test pits/core	Sample ID (UGAMS#)	Layer and/or depth	^{14}C age, years BP	±	Year cal AD	%
R	12302	87–91 cm	Modern	–	Modern	–
FM1	12298	003/73–83 cm	670	45	1266–1332	51.2
					1337–1398	44.2
	12299	004/115–118 cm	830	35	1059–1063	0.4
					1154–1271	95
FM2	17267	004/140 cm	820	30	1165–1265	95.4
FM3	17268	004/150 cm	340	25	1472–1637	95.4
CW	12300	004/100 cm	240	50	1489–1604	21.9
					1610–1694	33.6
					1727–1813	29.7
					1918–1955	10.2
	13082	004/100 cm	Modern	–	Modern	–
A	12301	72 cm	660	25	1279–1319	47.5
					1352–1391	47.9

GPS location of study site is 14.079 E, 48.971 N.

3.2. Radiocarbon dating

Charred needle remains of *A. alba* were recovered in test pit FM1 and in test pit A. No charred remains were present in the samples originating from the water reservoir and the clearance-wall, so subfossil seeds of *Scleranthus anuus* and *Fragaria vesca* were used. As intensive soil mixing was recognized in the test pit located in the inner part of the field on the basis of the distribution of the sherds, the recovered sample was not submitted to further analysis. The bottom layer (004) in field margin FM1 was dated to 1154–1271 year cal AD, and the upper layer (003) was dated to 1266–1398 years cal AD. The ^{14}C date originating from the charred fragment of caryopsis (probably of *Hordeum*) obtained from the bottom layer (004) of FM2 was calibrated to 1165–1265 years cal AD. The charred Fabaceae seed ^{14}C date recovered from the bottom layer (004) of FM3 fitted to the 1472–1637 years cal AD interval. The probability distribution of ^{14}C date from the bottom layer (004) of the clearance-wall exhibited a multimodal character (sample ID 12300 in Table 1). To achieve a more precise dating, a second ^{14}C date was obtained from the same layer. For this purpose, a ten times greater amount of soil (1 L) was used. The charred *Sambucus nigra* seed used for this radiocarbon analysis was of modern origin (sample ID 13082 in Table 1). The organic layer (charred needle of *A. alba* from a depth of 72 cm) at the base of the Chrobolský Stream alluvium was dated to the interval 1279–1391 year cal AD. Results originating from a subfossil *S. anuus* seed separated from the organic sediment indicated the modern origin of the base of the water reservoir (Table 2).

3.3. Recent soil dating

Soil samples taken along field margin test pit FM1 showed extremely low concentrations of all measured radionuclides. Almost all values were within the range of the counter background. ^{210}Pb$_{ex}$ was absent in almost all samples, and there was a concentration of 9.2 Bq kg^{-1} without the use of a correction factor at a depth of 3 cm. The ^{210}Pb$_{ex}$ values from the lower part of the profile were negative, so the emanation coefficient of 0.3 was used. The coefficient increased the value to 17.2 Bq kg^{-1} at a depth of 3 cm. Increased ^{137}Cs concentrations were recorded in soil layers up to a depth 15 cm. The concentrations were very low and almost constant at depths from 20 to 120 cm (Fig. 5).

4. Discussion

4.1. Origin and development of the field system

The accumulation of charred organic material at the base of the revealed field margin profile FM1 dated to the interval 1154–1271 year cal AD was directly connected with human activities. It preceded the first written record of colonization of the region, which dates from 1349 AD (Profous, 1951). Relatively frequent finds of charred needles of *A. alba*, a shade-tolerant climax tree species, indicate that the area was forested directly before the establishment of the village and the long-strip terraced fields. The first step of the newly-arrived farmers, prior to the introduction of arable farming, was probably slash-and-burn. The excavated field margin profiles were very compact, so we assume that the plant remnants had not migrated through the established soil layers in recent times, but had been buried at the time when the soil layer accumulated. According to Frederick and Krahtopoulou (2000), radiocarbon dating of organic inclusions in buried soil does not necessarily date the establishment or the use of a terraced field. However, the use of multiple ^{14}C dating could specify the process of soil accumulation more precisely (Dreibrodt et al., 2013; Jansen et al., 2013; Robin et al., 2013; Schroedter, et al., 2013). In the case of the terrace-like field margin studied here, the gradual accumulation of soil could be taken into consideration. For test pit FM1, the ability to determine two separate layers dated to 1154–1271 and 1266–1398 years cal AD can provide support for a scenario of this type. However, it is also possible that these layers do not represent two distinct periods of time, as the soil may have been mixed by the settlers. If this is what happened, the accumulation is likely to have taken place rather abruptly between 1266 and 1271 AD. One way or another, our results suggest that some prominent human activity affecting the local landscape took place between 1154–1271 AD, at least 78 years before the first mention of the village in written sources (1349 AD). This is supported by the dating of the charred material originating from FM2. A fragment of charred caryopsis (probably *Hordeum*) was dated to 1165–1265 years cal AD suggesting possible agricultural activity at that time. Large amounts of charcoal residues document increased fire activity in the area. The resulting deforestation probably led to increased erosion and to the formation of the alluvium of the Chrobolský Stream, which has an 8-cm-thick organic charcoal-rich layer on the basis. Radiocarbon analysis of charred organic material originating from this bottom layer of the Chrobolský Stream alluvium dated these massive changes in landscape use to the interval 1279–1391 year cal AD and is clearly connected with the existence of the village of Malonín. Malonín was first mentioned in written resources in 1349 AD (Profous, 1951). This date is supported by data originating from archeological excavations previously carried out in the center of the village, which revealed the existence of a 14th century AD settlement (Beneš, 1995).

The presence of 14th century AD sherds at a depth of 55 cm, above the layer characterized by the intrusion of stones, documents the presence of humans and inclusions of farmland manure suggests the existence of fertilized arable fields (Beneš, 1996; Schofield, 1991). The presence of a small amount of 14th century AD sherds may have been caused by the fragmentation of ceramics in acid soils, a phenomenon described by Beneš (1998). The simultaneous occurrence of sherds originating from the periods of the 14th century and the 15th–16th centuries AD at a depth of 50 cm may correspond with a change in the accumulation rate connected with different land use in the 15th–16th century AD. The interval of 1472–1637 years cal AD, originating from the charred Fabaceae seed from the hedgerow segment characterized by the presence of a stone wall, may imply that the field boundaries were maintained in good conditions and were repaired. This statement is supported by the presence of a mixture of sherds dated to various time horizons at the base of FM3. The ceramic record provides evidence of the maintenance of fields during the 17th and 19th centuries AD, as mentioned in written sources and as shown in old Stable Cadastre maps (1826 AD). In addition, the occurrence of 14th to 20th century AD sherds recorded in all layers of the test pit in the inner part of the field provides evidence of the use of tillage, i.e., a land use involving intensive soil mixing.

Historical maps from 1826 AD depict the existence of a field boundary in the second part of the field. The rather loose structure of the clearance-wall probably allowed the transport of recent plant remnants through the wall to its bottom layers, and it is therefore not possible to date the establishment of the boundary directly.

The dating of modern soil layers using $^{210}Pb_{ex}$ and ^{137}Cs radionuclides together with findings of ceramics has contributed to the reconstruction of recent accumulation processes in field margins. Radionuclides $^{210}Pb_{ex}$ and ^{137}Cs are delivered as wet or dry atmospheric deposition to the soil surface, where they rapidly become associated with organic matter and clay-sized mineral particles. They are redistributed across the landscape mainly by soil transport and erosion (Mabit et al., 2014). Measurements of $^{210}Pb_{ex}$ and ^{137}Cs activities served above all as a negative control. We assumed that in case of abrupt material transport to the field edge in recent times, concentrations of both radionuclides increase in all samples. A gradual increase in their concentrations would imply gradual accumulation of the soil at the field edge in the course of the last 100–150 years. Zero concentrations of $^{210}Pb_{ex}$ contradict the genesis of the terrace entirely during last 100–150 years, and near a surface peak of ^{137}Cs followed by a decrease near to zero suggests that the profile comprises undisturbed soil (Matisoff, 2014). After fundamental changes in land use throughout the landscape unit, as recorded in written sources due to abandonment of the village and transformation of the arable land into pastures, there was very low soil accumulation in the field margins. The abandonment of the village is also recorded in the sediments in the water reservoir. The sediment accumulated after the village was abandoned, when the water reservoir ceased to be cleaned. Its bottom layer was dated to modern times on the basis of ^{14}C analysis. Since the macro-botanical remnants spectrum that was recovered reflected agricultural activity, the sediment probably originated from the early 1950s AD.

4.2. Significance of the landscape structure from the historical point of view, and future conservation of the landscape

Using the multi-proxy approach, we demonstrate that the current structure of the long-strip field landscape originates from the High Medieval period, and that the pluzina field pattern carries the historical memory of the landscape. At the present time, the hedgerows preserve plant species that are rarely found in the region. They do not occur in the surrounding forests or in the grasslands (e.g., *Corydalis cava*, *Digitalis grandiflora* and *Lilium martagon*). In addition, in the present-day form of the field patterns there are also secondary grasslands, providing a habitat that makes the main contribution to the total number of species and exhibits the highest species density in the Bohemian Forest Mts. area (Prach et al., 1996). The regional diversity pool is thus bound to all elements of the historic pluzina landscape pattern. Pastures or meadows were established on the former arable fields, and these parts can be considered as long-term deforested parts of the landscape. This statement can be supported by the results of an experimental study that drew attention to the enormous efforts connected with the removal of shrubs from terraced fields treads (Palmer et al., 2010). From the point of restoration management, exceptional cases of the spontaneous establishment of woody communities in old fields should be taken into consideration (Jírová et al., 2012). We suggest that maintaining deforested parts in combination with maintaining the pluzina hedgerows can improve habitat availability and conserve biodiversity by following the historical pattern of the landscape. Preserving this pattern could serve to maintain the connectivity of the habitat mosaic (Zimmermann et al., 2011), and could have a similar effect in conservation management as the widely used methods of establishing fence lines and nearby uncultivated patches in agricultural landscapes (Nicholls and Altieri, 2013) or temporary abandoned areas in grasslands (Šumpich and Konvička, 2012).

5. Conclusions

In this study we present for the first time a detailed multi-proxy analysis of field systems in the Czech Republic in order to decipher their origin. Our approach involved combining information from various sources, i.e., historical documents and maps, chronologies based on dating of archeological artifacts, ^{14}C data, and the measurement of ^{210}Pb and ^{137}Cs activities. This analysis demonstrates that the present-day fields pattern around the former village of Malonín were formed in the High Middle Ages and preceded the first written record of human impact in this area. Written records must therefore be taken with caution for dating the establishment of field systems. The field system in Malonín was formed within a relatively short period of time, and reflects the transformation of medieval society. The High Medieval origin of the field system corresponds with information about the colonization process in other marginal areas of the Czech Republic. We hypothesize that the current-day landscape pattern around Malonín, which reflects the medieval landscape, is representative for many other villages in marginal areas of Central Europe that originated in the Middle Ages. Preservation of these landscape units will conserve both the long-term historical pattern as well as the high biodiversity that is typical for these fragmented landscapes.

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References

Anderberg, A.L., 1994. Atlas of Seeds and Small Fruits of Northwest-European Plant Species With Morphological Descriptions. Swedish Museum of Natural History, Stockholm.

Appleby, P.G., 2008. Three decades of dating recent sediments by fallout radionuclides: a review. The Holocene 18, 83–93.

Baudry, J., Bunce, R.G., Burel, F., 2000. Hedgerows: an international perspective on their origin, function and management. J. Environ. Manag. 60, 7–22.

Bayer, T., Beneš, J., 2004. Medieval terraced fields in the Bohemian Forest as a hydropedological phenomenon and problem of landscape archaeology. Archeol. Rozhl. 56, 139–159.

Beneš, J., 1995. Výzkumy archeologického pracoviště Prachatického muzea v roce 1995. Zlatá stezka. Sborník Prachatického muzea 2, pp. 159–165 (in Czech).

Beneš, J., 1996. The synanthropic landscape history of the Šumava Mountains (Czech side). Silva Gabreta 1, 237–241.

Beneš, J., 1998. Ceramics, ploughzone and relief. Field research into settlement activity near the village of Kozly (NW Bohemia). Archeol. Rozhl. 50, 170–191.

Berggren, G., 1981. Atlas of Seeds and Small Fruits of Northwest-European Plant Species With Morphological Descriptions. Swedish Museum of Natural History, Stockholm.

Bevan, A., Conolly, J., 2011. Terraced fields and Mediterranean landscape structure: an analytical case study from Antikythera, Greece. Ecol. Model. 222, 1303–1314.

Birks, H.H., Birks, H.J.B., 2000. Future uses of pollen analysis must include plant macrofossils. J. Biogeogr. 27, 31–35.

Boháč, P., 1983. Územní rozsah majetku vyšehradského proboštství na Prachaticku v 13.-14. století. Hist. Geogr. 21, 337–370 (in Czech).

Bronk, Ramsey C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51, 337–360.

Cappers, R.T.J., Bekker, R.M., Janset, J.E.A., 2006. Digital Seed Atlas of the Netherlands. Groningen Institute of Archaeology and the Deutsches Archäologisches Institut, Groningen.

Černý, E., 1979. Zaniklé středověké osady a jejich plužiny. Metodika historicko-geografického průzkumu v oblasti Drahanské vrchoviny. Academia, Praha (in Czech).

Chronicle of Frantoly, 1945–1954. Book nr. 205, State Regional Archive in Prachatice. Kronika obce Frantol (in Czech).

Cornulier, T., Robinson, R.A., Elston, D., Lambin, X., Sutherland, W.J., Benton, T.G., 2011. Bayesian reconstitution of environmental change from disparate historical records: hedgerow loss and farmland bird declines. Methods Ecol. Evol. 2, 86–94.

Czech Geological Survey, 2013. http://mapy.geology.cz/website/geoinfo/.

DeClerck, F.A.J., Chazdon, R., Holl, K.D., Milder, J.C., Finegan, B., Martinez-Salinas, A., Imbach, P., Canet, L., Ramos, Z., 2010. Biodiversity conservation in human-modified landscapes of Mesoamerica: past, present and future. Biol. Conserv. 143, 2301–2313.

Denevan, W.M., 2001. Cultivated Landscapes of Native Amazonia and the Andes. Oxford Geographical and Environmental Studies SeriesOxford University Press, Oxford.

Doskočil, K., 1953–1954. Popis Čech r. 1654: souhrnný index obcí, osad a samot k berní rule: rekonstrukce ztracených částí ruly, hlavní změny statků do r. 1779, seznam majitelů deskových statků, mapy krajského rozdělení Čech, komunikací a Kladska v době ruly. Státní pedagogické nakladatelství, Praha (in Czech).

Dreibrodt, S., Jarecki, H., Lubos, C., Khamnueva, S.V., Klamm, M., Bork, H.-R., 2013. Holocene soil formation and soil erosion at a slope beneath the Neolithic earthwork Salzmünde (Saxony-Anhalt, Germany). Catena 107, 1–14.

Du, P., Walling, D.E., 2012. Using ^{210}Pb measurements to estimate sedimentation rates on river floodplains. J. Environ. Radioact. 103, 59–75.

Fernández Mier, M., Fernández, J.F., Alonso González, P., Antonio López Sáez, J., Pérez Díaz, S., Hernández Beloqui, B., 2014. The investigation of currently inhabited villages of medieval origin: agrarian archaeology in Asturias (Spain). Quat. Int. 346, 41–55.

Fleming, A., Ralph, N., 1982. Medieval settlement and land use on Holne Moor, Dartmoor: the landscape evidence. Mediev. Archaeol. 26, 101–137.

Follain, S., Walter, C., Bonté, P., Marguerie, D., Lefevre, I., 2009. A-horizon dynamics in a historical hedged landscape. Geoderma 150, 334–343.

Frederick, C.D., Krahtopoulou, A., 2000. Deconstructing agricultural terraces: examining the influence of construction method on stratigraphy, dating and archaeological visibility. In: Halstead, P., Frederick, C.D. (Eds.), Landscape and Land Use in Postglacial Greece. Sheffield Academic Press, Sheffield, pp. 79–94.

Gibson, S., 2001. Agricultural terraces and settlement expansion in the highlands of early Iron Age Palestine: is there any correlation between the two? In: Mazar, A. (Ed.), Studies in the Archaeology of the Iron Age in Israel and Jordan. Sheffield Academic Press, Sheffield, pp. 113–146

Gojda, M., 2000. Archeologie krajiny. Academia, Praha (in Czech).

Goodman-Elgar, M., 2008. Evaluating soil resilience in long-term cultivation: a study of pre-Columbian terraces from the Paca Valley, Peru. J. Archaeol. Sci. 35, 3072–3086.

Groot, J.C.J., Jellema, A., Rossing, W.A.H., 2010. Designing a hedgerow network in a multifunctional agricultural landscape: balancing trade-offs among ecological quality, landscape character and implementation costs. Eur. J. Agron. 32, 112–119.

Gunten, L., Grosjean, M., Beer, J., Grob, P., Morales, A., Urrutia, R., 2009. Age modeling of young non-varved lake sediments: methods and limits. Examples from two lakes in Central Chile. J. Paleolimnol. 42, 401–412.

Harvey, C.A., Villanueva, C., Villacís, J., Chacón, M., Muñoz, D., López, M., Ibrahim, M., Gómez, R., Taylor, R., Martinez, J., Navas, A., Saenz, J., Sánchez, D., Medina, A., Vilchez, S., Hernández, B., Perez, A., Ruiz, F., López, F., Lang, I., Sinclair, F.L., 2005. Contribution of live fences to the ecological integrity of agricultural landscapes. Agric. Ecosyst. Environ. 111, 200–230.

He, Q., Walling, D.E., 1997. The distribution of fallout ^{137}Cs and ^{210}Pb in undisturbed and cultivated soils. Appl. Radiat. Isot. 48, 677–690.

Hejcman, M., Karlík, P., Ondráček, J., Klír, T., 2013. Short-term medieval settlement activities irreversibly changed forest soils and vegetation in central Europe. Ecosystems 16, 652–663.

Iiyama, N., Kamada, M., Nakagoshi, N., 2005. Ecological and social evaluation of landscape in a rural area with terraced paddies in southwestern Japan. Landsc. Urban Plan. 70, 301–313.

Iriarte, J., Glaser, B., Watling, J., Wainwright, A., Birk, J.J., Renard, D., Rostain, S., McKey, D., 2010. Late Holocene neotropical agricultural landscapes: phytolith and stable carbon isotope analysis of raised fields from French Guianan coastal savannahs. J. Archaeol. Sci. 37, 2984–2994.

Jansen, D., Lungershausen, U., Robin, V., Dannath, Y., Nelle, O., 2013. Wood charcoal from an inland dune complex at Joldelund (Northern Germany). Information on Holocene vegetation and landscape changes. Quat. Int. 289, 24–35.

Jírová, A., Klaudisová, A., Prach, K., 2012. Spontaneous restoration of target vegetation in old-fields in a central European landscape: a repeated analysis after three decades. Appl. Veg. Sci. 15, 245–252.

Karlík, P., Poschlod, P., 2009. History or abiotic filter: which is more important in determining the species composition of calcareous grasslands? Preslia 81, 321–340.

Klápště, J., 2002. Archeologie středověkého domu v Mostě (čp. 226). Mediaevalia archaeologica 4. Archeologický ústav AV ČR, Ústav archeologické památkové péče severozápadních Čech; Most, Praha (in Czech).

Klápště, J., 2005. Proměna českých zemí ve středověku. Nakladatelství Lidové noviny Praha, (in Czech).

Kosňovská, J., Houfková, P., Kovář, D., 2011. Lannova street, České Budějovice, based on archaeobotanical analyses and historical sources. Archeologické Výzkumy v Jižních Čechách 24, 263–280 (in Czech).

Krahtopoulou, A., Frederick, C., 2008. The stratigraphic implications of long-term terrace agriculture in dynamic landscapes: polycyclic terracing from Kythera Island, Greece. Geoarchaeology 23, 550–585.

Kuna, M., Tomášek, M., 2004. Povrchový průzkum reliéfních tvarů. In: Kuna, M. (Ed.), Nedestruktivní archeologie. Academia, Praha (in Czech).

Le Cœur, D., Baudry, J., Burel, F., Thenail, C., 2002. Why and how we should study field boundary biodiversity in an agrarian landscape context. Agric. Ecosyst. Environ. 89, 23–40.

Mabit, L., Benmansour, M., Abril, J.M., Walling, D.E., Meusburger, K., Iurian, A.R., Bernard, C., Tarján, S., Owens, P.N., Blake, W.H., Alewell, C., 2014. Fallout ^{210}Pb as a soil and sediment tracer in catchment sediment budget investigations: a review. Earth Sci. Rev. 138, 335–351.

Malpass, M., 1987. Prehistoric agricultural terracing at Chijra in the Colca Valley, Peru: preliminary report I. In: Denevan, W.M., Mathewson, K., Knapp, G.W. (Eds.), Pre-Hispanic Agricultural Fields in the Andean RegionB.A.R. International Series. Archaeopress, Oxford, pp. 45–66.

Matisoff, G., 2014. ^{210}Pb as a tracer of soil erosion, sediment source area identification and particle transport in the terrestrial environment. J. Environ. Radioact. 138, 343–354.

Matzat, W., 1988. Long strip field layouts and their later subdivisions — a comparison of English and German cases. Geogr. Ann. Ser. B Hum. Geogr. 70, 133–147.

Millican, K., 2012. The outside inside: combining aerial photographs, cropmarks and landscape experience. J. Archaeol. Method Theory 19, 548–563.

Mitchell, F., 1990. The Shell Guide to Reading the Irish Landscape. Country House, Dublin.

Molnárová, K., 2008. Landscape studies long-term dynamics of the structural attributes of hedgerow networks in the Czech Republic — three case studies in areas with preserved medieval field patterns. J. Landsc. Stud. 1, 113–127.

Nekuda, V., Reichertová, K., 1968. Středověká keramika v Čechách a na Moravě. Moravské museum, Brno (in Czech).

Nicholls, C.I., Altieri, M.A., 2013. Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review. Agron. Sustain. Dev. 33, 257–274.

Oshunsanya, S.O., 2013. Spacing effects of vetiver grass (*Vetiveria nigritana* Stapf) hedgerows on soil accumulation and yields of maize–cassava intercropping system in Southwest Nigeria. Catena 104, 120–126.

Palmer, C., Colledge, S., Bevan, A., Conolly, J., 2010. Vegetation recolonisation of abandoned agricultural terraces on Antikythera, Greece. Environ. Archaeol. 15, 64–80.

Parkman, M., 2003a. Osídlení Prachaticka v raném středověku. Archeologické Výzkumy v Jižních Čechách 16, 129–194 (in Czech).

Parkman, M., 2003b. Osídlení Prachaticka v pravěku a rané době dějinné Diploma thesis, FF MU, Brno (in Czech).

Parkman, M., 2004. Doba bronzová na Prachaticku. Popelnicová pole a doba halštatská. Příspěvky z VIII. konference, České Budějovice 22. - 24. 9. 2004. Archeologické výzkumy v jižních Čechách - Supplementum 1, pp. 413–428 (in Czech).

Petersson, M., 1999. Ancient fields excavated. Eur. J. Archaeol. 2, 57–76.

Prach, K., Štech, M., Beneš, J., 1996. Secondary grasslands — a neglected component of biodiversity in the Šumava Mts. Silva Gabreta 1, 243–247.

Profous, A., 1951. Místní jména v Čechách vol. III (M-Ř). Nakl. Československé akademie věd, Praha (in Czech).

Pulido-Santacruz, P., Renjifo, L.M., 2011. Live fences as tools for biodiversity conservation: a study case with birds and plants. Agrofor. Syst. 81, 15–30.

Reimer, P.J., et al., 2013. IntCal13 and Marine13 Radiocarbon Age calibration curves 0––50,000 years cal BP. Radiocarbon 55, 1869–1887.

Robin, V., Knapp, H., Bork, H.-R., Nelle, O., 2013. Complementary use of pedoanthracology and peat macro-charcoal analysis for fire history assessment: illustration from Central Germany. Quat. Int. 289, 78–87.

Salač, V., 1998. Keramika jako archeologický pramen. Archeol. Rozhl. 50, 7–15 (in Czech).

Sanchez-Cabeza, J.A., Ruiz-Fernández, A.C., 2012. ^{210}Pb sediment radiochronology: an integrated formulation and classification of dating models. Geochim. Cosmochim. Acta 82, 183–200.

Sasaki, N., Takahara, H., 2011. Late Holocene human impact on the vegetation around Mizorogaike Pond in northern Kyoto Basin, Japan: a comparison of pollen and charcoal records with archaeological and historical data. J. Archaeol. Sci. 38, 1199–1208.

Schofield, A.J., 1991. Interpreting Artefact Scatters: Contributions to Ploughzone Archaeology. Oxbow Monograph 4. Oxbow Books, Oxford.

Schoorl, J.M., Boix Fayos, C., de Meijer, R.J., van der Graaf, E.R., Veldkamp, A., 2004a. The ^{137}Cs technique applied to steep Mediterranean slopes (Part I): the effects of lithology, slope morphology and land use. Catena 57, 15–34.

Schoorl, J.M., Boix Fayos, C., de Meijer, R.J., van der Graaf, E.R., Veldkamp, A., 2004b. The ^{137}Cs technique applied to steep Mediterranean slopes (Part II): landscape evolution and model calibration. Catena 57, 35–54.

Schroedter, T.M., Dreibrodt, S., Hofmann, R., Lomax, J., Müller, J., Nelle, O., 2013. Interdisciplinary interpretation of challenging archives: charcoal assemblages in Drina Valley alluvial and colluvial sediments (Jagnilo, Bosnia and Herzegovina). Quat. Int. 289, 36–45.

Seeger, M., Ries, J., 2008. Soil degradation and soil surface process intensities on abandoned fields in Mediterranean mountain environments. Land Degrad. Dev. 501, 488–501.

Sklenicka, P., Molnarova, K., Brabec, E., Kumble, P., Pittnerova, B., Pixova, K., Salek, M., 2009. Remnants of medieval field patterns in the Czech Republic: analysis of driving forces behind their disappearance with special attention to the role of hedgerows. Agric. Ecosyst. Environ. 129, 465–473.

Sláma, J., 1976. Příspěvek k vnitřní kolonisaci raně středověkých Čech. Archeol. Rozhl. 19, 433–445 (in Czech).

Staley, J.T., Sparks, T.H., Croxton, P.J., Baldock, K.C.R., Heard, M.S., Hulmes, S., Hulmes, L., Peyton, J., Amy, S.R., Pywell, R.F., 2012. Long-term effects of hedgerow management policies on resource provision for wildlife. Biol. Conserv. 145, 24–29.

Stanchi, S., Freppaz, M., Agnelli, A., Reinsch, T., Zanini, E., 2012. Properties, best management practices and conservation of terraced soils in Southern Europe (from Mediterranean areas to the Alps): a review. Quat. Int. 265, 90–100.

Šumpich, J., Konvička, M., 2012. Moths and management of a grassland reserve: regular mowing and temporary abandonment support different species. Biologia 67, 973–987.

Vařeka, P., 1998. Proměny keramické produkce vrcholného a pozdního středověku v Čechách. Archeol. Rozhl. 50, 123–137 (in Czech).

Wakiyama, Y., Onda, Y., Mizugaki, S., Asai, H., Hiramatsu, S., 2010. Soil erosion rates on forested mountain hillslopes estimated using ^{137}Cs and ^{210}Pb$_{ex}$. Geoderma 159, 39–52.

Žemlička, J., 2002. Počátky Čech královských 1198–1253. Proměna státu a společnosti. Nakladatelství lidové noviny, Praha (in Czech).

Zimmermann, K., Fric, Z., Jiskra, P., Kopeckova, M., Vlasanek, P., Zapletal, M., Konvicka, M., 2011. Mark-recapture on large spatial scale reveals long distance dispersal in the Marsh fritillary, *Euphydryas aurinia*. Ecol. Entomol. 36, 499–510.

Zímová, K., Pospíšil, L., Janovská, V., Karlík, P., Houfková, P., Bumerl, J., Molnárová, K., Beneš, J., Bernardová, A., 2013. Pluzina development analysis of an abolished village Malonín in Prachatice region. Acta Pruhoniciana 104, 27–37 (in Czech).

5.5. Paper V.

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ORIGINAL ARTICLE

The dynamics of a non-forested stand in the Krušné Mts.: the effect of a short-lived medieval village on the local environment

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Abstract

Medieval vegetation–human–climate interactions were studied from a sediment profile situated in the centre of a short-lived medieval village located above 800 m a.s.l. on the ridge of the Krušné Mts., NW Bohemia, Central Europe. Analyses of pollen, seeds/fruits, micro- and macro-charcoals, diatoms and concentrations of microelements in connection with written sources revealed a significant human-induced deforestation in the second half of the 14th century. This deforestation occurred sooner than supposed and the area did not revert after AD 1347 as elsewhere in Europe. Arable fields probably enabled basic self-sustaining cultivation of winter cereals even at such elevations in the climatically favourable years of the Medieval Warm Period. The village presumably collapsed due to a combination of weather fluctuations at the onset of the Little Ice Age, simultaneous socioeconomic stagnation in the Czech Lands and exploitation of the surrounding forest. The dynamics of wet stand vegetation and Calthion palustris montane wet meadows were driven by fluctuating human and grazing impacts. Annual and biennial herbaceous species that peaked after village abandonment were rapidly replaced by *Filipendula ulmaria* and *Salix* stands. The secondary forest developed towards *Picea* stands. Only later, mesic montane meadows of medium tall grasses combined with *Meum athamanticum* and mountain dry pastures developed on nutrient poor patches.

Keywords Bioarchaeology · Deserted medieval village · Environmental reconstruction · Peripheral mountain area · Central Europe · Succession

Introduction

The phenomenon of short-lived, deserted medieval villages has been documented all across Europe, but especially in Central Europe (CE) including the Czech Lands (CL) (Nocuń et al. 2016; Čapek and Holata 2017). Medieval demographic and economic growth is often associated with the rather moderate climate fluctuations during the epoch conceptualized as the Medieval Warm Period (MWP) (Büntgen et al. 2011). The large degree of abandonment in the Late Medieval Period followed climate deterioration during the Little Ice Age (LIA) as evidenced in studies from northern countries such as Iceland (Gissel et al. 1981), Scandinavia (Fredskild 1988) and Greenland (Sveinbjarnardóttir 1992), as well as in the English village Wharram Percy (Hoskins 1988). However, at the same time settlements were abandoned also in traditional settlement areas with a more favourable climate where socio-economic, institutional, cultural and demographic trends outweighed climatic causes (Alfonso 2007; Kitsikopoulos 2011).

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Settlements most prone to abandonment were typically situated on the periphery of a particular country. In the CL, these were foremost the border mountain areas, including the Krušné Mts. The major colonization of their ridge (Fig. 1) is dated to the High Medieval Age around the middle of the 13th century AD, succeeding the major colonization in the Bohemian traditional settlement area dated to the 12th and 13th centuries (Klápště 2016). These regions were settled mostly due to mining activities and glassworks (Kenzler 2012; Černá and Klír 2014), (Fig. 1b). The spread of industrial activities corresponded with the era of prosperity that culminated during the reign of Charles IV (AD 1344/1348–1378) and was also synchronized with the MWP, which occurred from AD 1260–1380 in CL according to interpretations of historical documents (Brázdil and Kotyza 1995). This was contrary to other parts of Europe, where the Black Death killed almost half of the population (Brázdil and Kotyza 1995; Büntgen et al. 2011). Decreased industrial activity took place during a period historians call the "Late Medieval" Crisis which affected all aspects of society (Maur 1989; Schuster 1999). In the CL, the social instability continued into the 15th century AD culminating in the Hussite wars in AD 1419–1434, the interregnum in AD 1439–1453 and the Bohemian–Hungarian war in AD 1468–1478.

Human activities and climate influence vegetation cover in general (Gaillard et al. 2010). The European pollen record revealed massive deforestation during the MWP with the exception of the rise in forested usable land after the Black Death in AD 1347 (Kaplan et al. 2009). Similarly, the woodland ratio decline was documented from traditional settlement areas in CL (e.g. Kozáková et al. 2009, 2014; Pokorná et al. 2014) and less often in its marginal areas (Kozáková et al. 2015). The available pollen studies from the Krušné Mts. documented major man-made deforestation in the Late Subatlantic period (Jankovská et al. 2007) and no sooner than AD 1500–2000, based on the REVEALS model averaged over NW Bohemia (Abraham et al. 2016).

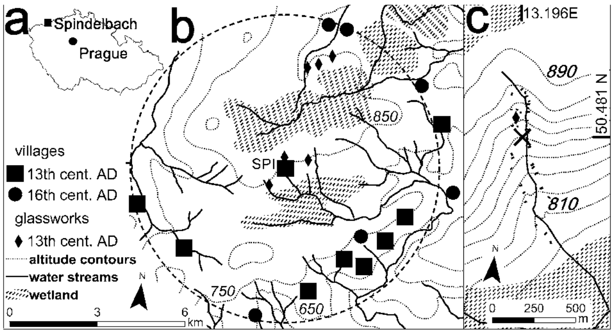


Fig. 1 (a) Location of the former village of Spindelbach in the Ore Mts., NW Bohemia is indicated by a filled square. (b) Scheme of colonization in a 5 km radius of Spindelbach (SPI filled square) due to industrial activity. Glassworking that preceded the establishment of villages in the area of Spindelbach and Jilmová is dated to the first half of the 13th century AD (marked as filled diamond). A boom in ore mining was connected with establishment of villages in the 13th century AD (marked as black filled square). The next wave of village establishment occurred no sooner than in the middle of the 16th century (marked as filled circle). Only Spindelbach was abandoned in the middle of the 15th century AD. (c) A plan of Spindelbach. The cross indicates the location of the core SPI-1

In fact, herbaceous communities occupied a significant part of CL vegetation cover according to an estimate of anthropogenic land cover change from AD 1250–1600 (Gaillard et al. 2010). These non-forested biotopes included a variety of types ranging from rural urban habitats (Pokorná et al. 2018) to xerophylous grasslands reconstructed in the area of medieval Prague or in the Most basin (Opravil 1969; Pokorná et al. 2014). Even though some of them probably persisted locally during the whole Holocene (e.g. dry grasslands in the northern part of CL) (Pokorný et al. 2015), some of them originated due to human induced deforestation (Houfková et al. 2015). However, understanding of the fine-scale spatial structure of past herbaceous vegetation often remains neglected (Szabó et al. 2017). Based on the knowledge of their modern analogues, we assume that non-forest biotopes exhibited rather high dynamics. The changing intensity of human pressure especially leads to rapid changes in species diversity, as documented in abandoned meadows (Hájková et al. 2010). A rather rapid succession from annual and biennial herbs to perennial grasslands and shrubs was observed in upland villages abandoned after the Second World War in the Czech borderlands (Jehlík 1971). Our study of these dynamics focused on the area of the former village Spindelbach, composed nowadays of wet stands and Calthion palustris montane wet meadows.

Spindelbach village

Spindelbach was a medieval village located at 800–880 m a.s.l. (50.480N, 13.196E) on the ridge of the Krušné Mts. The village topography corresponds to the structure of a so called "forest village" (Waldhufendorf), a typical village type documented on many sites in the uplands near the border of the Czech Republic and Germany. According to an archaeological survey and excavation, the village was founded in the second half of the 13th century AD and abandoned completely around AD 1450 (Hylmarová et al. 2013; Klír 2016). In the written sources, the village of Spindelbach was first mentioned in AD 1356 and for the last time in AD 1481 (Profous 1951). However, it was supposed to be already deserted in AD 1481 (Klír 2016). After AD 1490, its toponym only referred to a fishpond, a forest and meadows (Profous 1951).

Although written sources did not mention the means of subsistence for Spindelbach directly, the settlement form, relicts of agricultural terraces and artefacts found during the archaeological excavation of one of the medieval farmsteads give evidence that cereal production and animal husbandry were important parts of the village economy (Hylmarová et al. 2013). Based on archaeological findings of various tools in Spindelbach as well as analogies from across contemporaneous sites in CE, subsistence agriculture production was seasonally supplemented by market non-agricultural activities, such as forest crafts, the carrying trade, and service for the mining industry (Klír 2016).

Present vegetation of the sampling site

The slopes of the Krušné Mts. are today mainly covered by beech forests. Their supramontane belt is formed mainly by spruce forests while minerotrophic mires and bogs occur on the plateaux (Chytrý 2012). Dominant vegetation, according to floristic evidence, includes several plant associations in particular stands: Montio-Cardaminetea with *Montia fontana, Carex canescens* and *C. rostrata, Deschampsia caespitosa* and *Galium palustre* by springs or in slow-moving water stands with a low calcium content, Calthion palustris with *Cirsium palustre, Carex nigra, C. panicea* and *Juncus effusus* on wet meadows on acidic soils, and spruce alder carrs (Alnion incanae with *Picea abies, Alnus glutinosa, Calamagrostis villosa* and *Viola palustris*). The mean summer temperature ranges from 10 to 11 °C, and the mean annual total precipitation from 800 to 1,000 mm year^{-1} based on the 40-year average according to the Czech Hydrometeorological Institute (Tolasz et al. 2007).

The study

We used pollen and macrofossil analyses to reconstruct the plant cover dynamics, diatom analysis for inferring changes in the aquatic environment and geochemistry for tracking mining activities at the medieval site with short-term settlement that developed in the MWP and ceased in the LIA. Our aims were: (1) to provide evidence about woodland species dynamics prior to medieval colonization and specify trends in local deforestation in the Krušné Mts. during the MWP/LIA; (2) to specify the vegetation background and reconstruct the dynamics of local vegetation cover driven by the established medieval village Spindelbach; and (3) to describe the vegetation succession after its collapse.

Materials and methods

Fieldwork and sampling

The main core (SPI-1) was taken in a shallow depression located in the central part of a wet meadow just in the centre of the abandoned village Spindelbach (50.4829333N, 13.1941667E), approximately 50 m from a nearby brook. The site is permanently wet due to a high groundwater level. There is a low bank just below the coring site, which partly prevents water leaching from the depression, however, it is not clear whether the bank was of natural or artificial origin. The lithological description was based on Troels-Smith (1955). The complete profile was sampled for pollen and other analyses (micro-charcoals, geochemistry and macro remains) at 3 cm intervals. Diatom analysis was performed on selected levels.

Radiocarbon dating

Accelerator Mass Spectrometry (AMS) ^{14}C dating of four samples was performed on subfossil seeds in the Center for Applied Isotope Studies, USA (CAIS) and Poznań Radiocarbon Laboratory, Poland (PRL). A Poisson-process deposition model (Bronk Ramsey 2008) with one postulated event per centimetre ($k=1$ in the depth interval of 82–33 cm, Bronk Ramsey and Lee 2013) was constructed using the OxCal 4.3.2 online application (Bronk Ramsey 2009) based on the IntCal 13 (Reimer et al. 2013) calibration curve.

Pollen and micro-charcoal analysis

Sediment samples of 1 cm^3 were boiled in potassium hydroxide, sieved, acetolyzed and treated with hydrofluoric acid according to Fægri and Iversen (1989). A known quantity of *Lycopodium* spores were added to each sample to determine the total pollen concentration (TPC) (Stockmarr 1971). Pollen was counted under a Nikon Eclipse 80i light microscope (LM) at a magnification of 400–1,000×. A minimum of 500 pollen grains were determined in each sample. Taxonomic identifications followed Beug (2004), Punt et al. (1976–2009). Plant stomata were calculated as percentages of the total pollen sum (Sweeney 2004). Only dominant pollen types are displayed in the pollen diagram; trees and shrubs were grouped according to Gaillard (2013).

Microcharcoal abundance was estimated by LM using a *Lycopodium* spore standard (Stockmarr 1971). Micro-charcoal types were classified according to Umbanhowar and McGrath (1998). The origin of spheroidal microcharcoals was determined according to Griffin and Goldberg (1979) and Rose (2001).

Geochemistry

The near total element concentration was measured after energy-dispersive-X-ray-fluorescence analysis (ED-XRF) with a portable Delta Professional ED-XRF analyser (PXRF) by Olympus InnovX, with Soil Geochem measurement mode (Kalnicky and Singhvi 2001; Hürkamp et al. 2009). The samples used for this analysis were dried at 40 °C for 13 h. All measurements were performed for 1 min with 30 s of a 10 kV beam and 30 s of a 40 kV beam. The used PXRF model gives data as weight ppm. The quality of the device measurements was successfully tested by BAS Rudice Ltd. on 55 reference materials (e.g. SRM 2709a, 2710a, 2711a, OREAS 161, 164, 166, RTC 405, 408). Data were standardized using measured Sr values.

Diatom analysis

Organic matter from sediment samples was removed using cold H_2O_2 for several days (Houk 2003). Diatom valves were counted from Pleurax (Fott 1954) mounted permanent slides under an Olympus BX 51 light microscope at 1,000 × magnification. Diatom taxonomic determination was based on central European floras (Krammer and Lange-Bertalot 1986, 1988, 1991a, b). At least 100 valves were counted in each sample. The diatom inferred trophic state (TID) was calculated with Omnidia 5.1 software using values published in Rott et al. (1999). Typical species habitats were determined according to Denys (1991), and their pH preferences according to van Dam et al. (1994).

Macro-fossil analysis

Sediment was wet-sieved in the laboratory using sieves of a 0.25 mm minimal mesh size. The dried material was sorted under a binocular microscope and seeds, fruits, wood and charcoal remains were identified according to Katz et al. (1965), Schweingruber (1990), Cappers et al. (2006) and using the reference collections of the Department of Botany, Faculty of Science, Charles University and the Laboratory of Archaeobotany and Paleoecology in České Budějovice. The results were further processed using the *ArboDatMulti* database programme (Kreuz and Schäfer 2002; Pokorná et al. 2011). The charcoal and wood analyses were performed using a Nikon Eclipse 80i episcopic interference microscope on fragments larger than 2 mm. The nomenclature of vascular plants used in the following text follows Kubát et al. (2002).

Diagrams and statistics

Stratigraphic diagrams were created using Tilia 1.5.12. (Grimm 2011). The relative abundances of dominant pollen types and diatom species were plotted in black solid silhouettes, using a grey extension for ten times exaggeration. Counts of macrofossils and wood/charcoals were transformed to a unified volume of 1 l and plotted in black histograms. The significance of the pollen, diatom, macrofossil and geochemical accumulation zones based on CONISS (Grimm 1987) were determined using the broken stick model (MacArthur 1957; Legendre and Legendre 1998) and calculated in R 2.11.0 (R Development Core Team 2010) and Tinn-R 2.3.5.2 (Faria 2009).

Results

Sedimentary record

The base of the profile (SP-1) was composed of sand, probably in connection with alluvial sedimentation of the nearby brook, whereas the overlying sediment (82–30 cm) is mainly organogenic. The homogenous sedimentation was interrupted by a layer of sand/silt admixture (30–15 cm), whereas the uppermost layer (15–0 cm) was formed mainly by sphagnum peat (Table 1).

Radiocarbon dating

A Bayesian model based on four ^{14}C dates provided detailed chronology for the SPI-1 core (Table 2; Fig. 2). The maximum and minimum standard deviations (σ) for the calculated levels were 35 and 11 years, respectively.

Pollen analysis

Pollen and spores were well preserved with 124 pollen types and groups recorded in total. Three significant pollen accumulation zones (PAZ) based on the relative abundance of pollen types were separated (Figs. 3, 4). Monolete spores of ferns decreased from 38 to 6% in PAZ1

Table 1 Stratigraphy of the profile SPI-1, Spindelbach. Abbreviations according to Troels-Smith (1955)

Depth (cm)	Abbreviation	Description
0–15	$Tb^0 4$	*Sphagnum* peat
15–18	$Tb^1 3$ Ga1	Clayish mud with *Sphagnum*
18–27	Gs3 $Tb^1 1$ Th+	Silty mud with sand and *Sphagnum* admixture
27–30	Ga2 $Tb^1 1$ $Th^1 1$	Silty mud with *Sphagnum* admixture
30–66	Sh4 Dl + Dh+	Washed-in silty sediment, rich in organic detritus
66–82	Sh3 Dl1 Dh+	
Base	Gs4	Sand

Table 2 Radiocarbon dates from the Spindelbach SP-1 core

Lab. no.	Depth (cm)	^{14}C years (BP)	Cal. years (AD)	Dated material (subfossil seeds)
Poz-78065	33–36	325 ± 30	1530–1601	*Scirpus sylvaticus, Carex* sp., *Stellaria* sp., *Cirsium/Carduus* sp.
UGAMS#17269	51–54	380 ± 25	1453–1481	*Carex* sp.
Poz-78066	63–66	635 ± 30	1377–1398	*Ranunculus acris/repens*
UGAMS#13074	78–82	580 ± 40	1303–1336	*Montia fontana*

The calibration was based on a Poisson-process deposition model (Bronk Ramsey 2008) with one postulated event per cm ($k = 1$) within 95.4% confidence interval (Bronk Ramsey and Lee 2013)

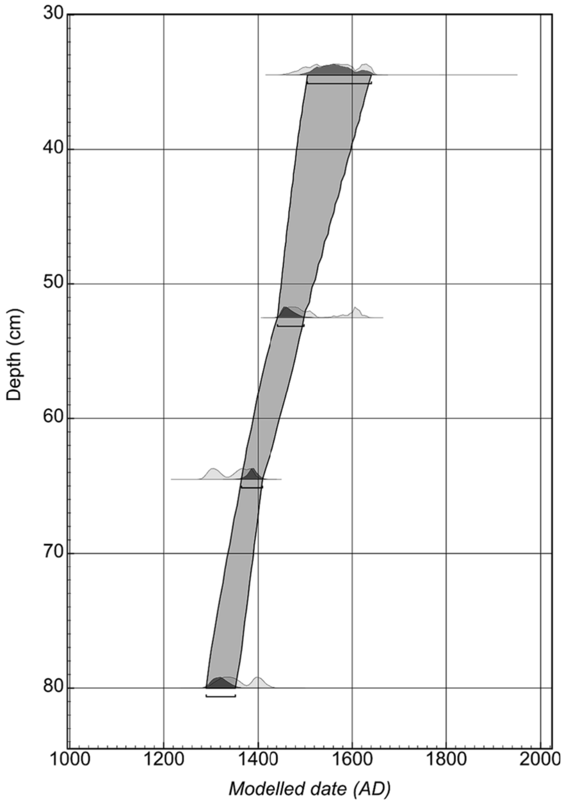


Fig. 2 A Poisson-process deposition model (Bronk Ramsey 2008) with one postulated event per cm ($k = 1$ for depths 82–33 cm, Bronk Ramsey and Lee 2013) based on the IntCal 13 (Reimer et al. 2013) calibration curve. The model was calculated and figure created in the OxCal 4.3.2 online application (Bronk Ramsey 2009)

(84–51 cm). The arboreal pollen (AP) ratio composed of pollen of particularly shade tolerant species (*Fagus sylvatica, Abies alba* and *Picea*) decreased from 46 to 11%. Non-arboreal pollen (NAP) gradually increased above 79%, mostly due to an increase in the abundance of pollen of the Poaceae family (above 38%). Pollen of cereal species (*Secale cereale, Triticum, Panicum, Avena* and *Hordeum*) increased from the 1–2% recorded in its first subzone to 2–4% recorded in the second. Grazing indicators (e.g. *Rumex acetosella, Juniperus, Calluna vulgaris*), ruderal species (e.g. Chenopodiaceae), and weeds (e.g. *Anagallis arvensis, Centaurea cyanus*) followed a similar trend. Species occurring in wet stands (e.g. *Montia, Chrysosplenium*) and meadows (e.g. *Caltha palustris, Chaerophyllum hirsutum, Valeriana dioica*) were also recorded.

At the boundary of PAZ1 and 2, the abundances of *Anthemis arvensis*-type and Brassicaceae pollen increased up to 10% and 11%, respectively. The ratio of *Salix* pollen reached 46% in PAZ2 samples (51–24 cm). Species of wet meadows increased in abundance, with the pollen of *Filipendula* reaching 11%. Cereals, weeds, ruderals and nitrophilous species decreased, while the abundance of *Picea* pollen slightly increased. Aquatic species, such as *Lythrum salicaria, Thalictrum flavum* and *Typha latifolia*, were represented as rare pollen types. In PAZ3 (24–0 cm), AP (*Picea, Alnus glutinosa, Corylus avellana, Tilia cordata, Ulmus, Fraxinus excelsior* and *Sorbus*) increased in abundance, while pollen of Cyperaceae, cf. *Glyceria, Vaccinium* and *Sphagnum* spores were recorded. The ratio of cultivated plants, weeds, and grazing indicators increased. A low but continuous abundance of *Meum athamanticum* and *Sanguisorba officinalis* was recorded. The uppermost layers were distinguished by the presence of the *Ambrosia* pollen type.

Charcoal and micro-charcoal analysis

In the zone corresponding to PAZ 1, *Picea* charcoal concentration was estimated at above 1,000 nl^{-1}. In the corresponding samples, the concentration of microcharcoal of wood origin peaked ca. 244×10^3 ng^{-1}. Then, almost no charcoal, with only 18 nl^{-1} of *Fagus* charcoal, was recorded in the 45–48 cm layer with microcharcoal concentration remaining below 10^5 ng^{-1}. A slight increase of microcharcoal concentration to ~ 10^5 ng^{-1} was measured at the end of PAZ 2 (24–33 cm). In the 78–82 cm layer, almost 2% of charcoal was classified as small (area 100–200 µm) and spheroidal (length/width ratio 1–2). Spheroidal carbonaceous particles (SCPs) reached up to 5% by the end of PAZ 3 (Fig. 3).

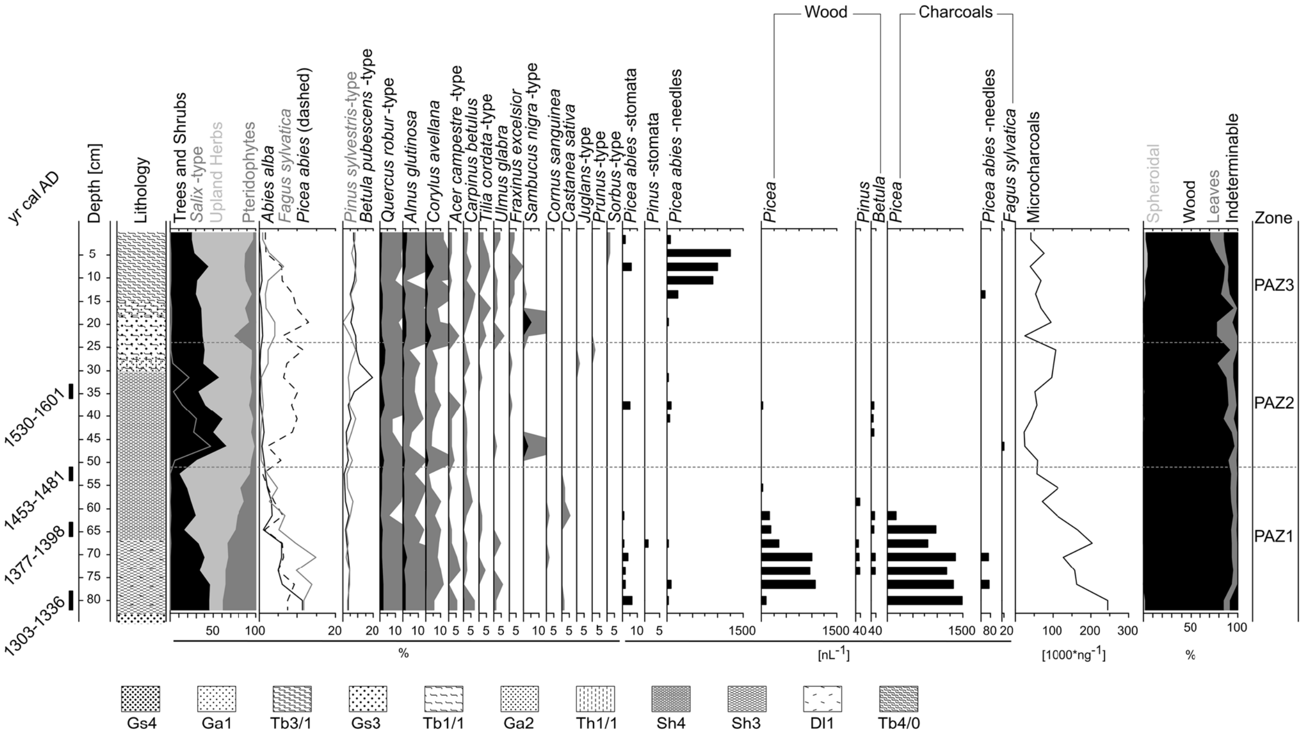


Fig. 3 Trends in tree species composition and fire activity based on pollen, macrofossil, charcoal and microcharcoals recorded in the core SPI-1, Spindelbach, Ore Mts. (50.4808494N, 13.1957847E). The grey area corresponds to a tenfold increase in relative abundance of selected species over the black. Plant stomata are displayed by black histograms as percentages of the total pollen sum. Total counts of macro fossils and charcoals are expressed by black histograms. Microcharcoal concentration is displayed as a black curve. In the final column the relative abundance of micro-charcoal types is distinguished by black/grey ratios

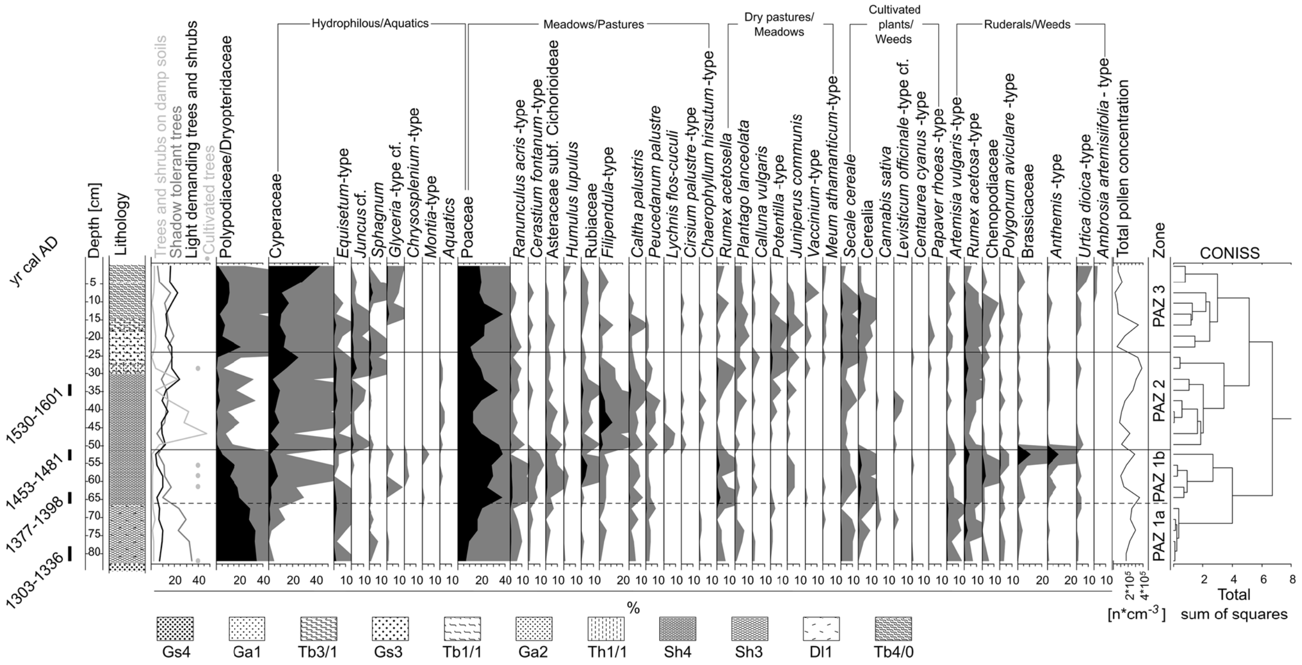


Fig. 4 Pollen diagram from the core SPI-1. The relative abundance of major pollen types is in black, the grey area corresponds to a tenfold increase over the black. Aquatic pollen types with discontinuous occurrence were grouped as Aquatics. The presence of cultivated trees is expressed by grey filled dots. Trees and shrubs were grouped according to Gaillard (2013)

Geochemistry

Two significant accumulation zones (GAZ) were separated (Fig. 5). A low concentration of elements was measured in the first cluster (GAZ 1), yet Rb, K and Zr concentrations were about four times higher than in the second one. There, Ca, S and Fe concentrations increased, followed by P, Pb, Cu and As. In GAZ 2, the concentrations of Si, Ag, Th, Cd, U and Mo increased. The increased concentrations of Al, K and Rb corresponded to the lithological unit Gs3 Tb^{1}1 Th+. The uppermost part had samples with increased concentrations of P, As, Cu, Al, Y, Zn, Ag, Th, Cd, U and Mo.

Diatom analysis

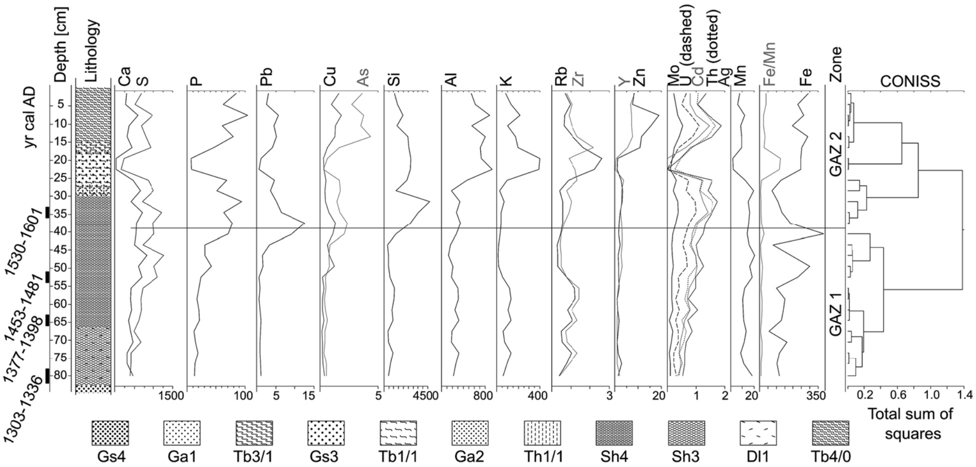
Generally, the abundance of diatom valves was low and valves were frequently damaged. Three significant zones were separated (Fig. 6). In DAZ 1 (82–54 cm), benthic taxa of relatively low aquatic trophic status dominated (*Pinnularia* sp., *Gomphonema* cf. *productum* and *Encyonema silesiacum*). Taxa tolerant to enhanced osmotic pressure, caused either by dessication or high aquatic salinity, were present at the boundary with DAZ 2 (e.g. *Aulacoseira italica*). Although absolutely low (TID = 1.2–1.4), TID in this zone reached the highest value in the profile. The species composition corresponded to circumneutral aquatic conditions (pH ~ 7). In DAZ 2 (47–27 cm), species demanding clean water and exhibiting TID = 1.2–0.9 dominated. Benthic taxa (*Fragilariforma virescens* and *Eunotia incisa*) dominated, while tychoplanctonic taxa were present (e.g. *Aulacoseira distans* and *Tabellaria flocculosa*), but species tolerant to dessication were no longer present. The steep decrease of the trophic state in the 45–47 cm sample (TID = 0.9) was caused above all by the dominance of *E. incisa*. A shift to more acidic conditions was evidenced by the dominance of acidophilic taxa (pH 6–7). The diatom community composition corresponded to the existence of a shallow aquatic body without external loading of nutrients. In DAZ 3 (27–0 cm), the aquatic environment showed dystrophic conditions characteristic of peat bog establishment. Benthic acidobiontic species typical of peat bogs (*E. exigua, E. bilunaris* and *E. tenella*) with pH optimum lower than six dominated. This is further evidenced by the decrease of TID (~ 0.9) and the proportion of tychoplanctonic species.

Macro-fossil analysis

Seeds/fruits were well preserved, mostly by waterlogging, and only rarely by charring. Three significant zones (MAZ) were separated (Fig. 7). In total, 36 taxa (species or genera) were determined according to their seeds/fruits (for detailed descriptions of selected taxa see Fig. 7).

In MAZ 1 (82–57 cm), wet stands were evidenced by the presence of *Montia fontana* and *Glyceria fluitans*. At the same time, grassland species, such as *Prunella vulgaris, Rumex crispus/obtusifilius, Ranunculus acris/repens* and *Caltha palustris*, were common in this zone. The upper part of MAZ1 corresponded to PAZ 1b and was characterized by species common to pastures (*Rumex acetosella*) and human activities (*Raphanus raphanistrum, Stellaria media, Spergula* cf. *arvensis* and *Polygonum arenastrum*). The development of wet meadows on acidic soils was reconstructed mainly in MAZ 2 (57–12 cm), based on the presence of *Lychnis flos-cuculi, Cirsium/Carduus, Viola* sp., *Juncus* sp. and *Scirpus silvaticus*. *Fragaria* seeds occurred at the depth of 30 cm. Both cone scales and needles of *Picea abies* were found in MAZ 3 (12–0 cm).

Fig. 5 Results of geochemical analysis from the core SPI-1. Curves show trends in the content of selected elements and the Fe/Mn ratio



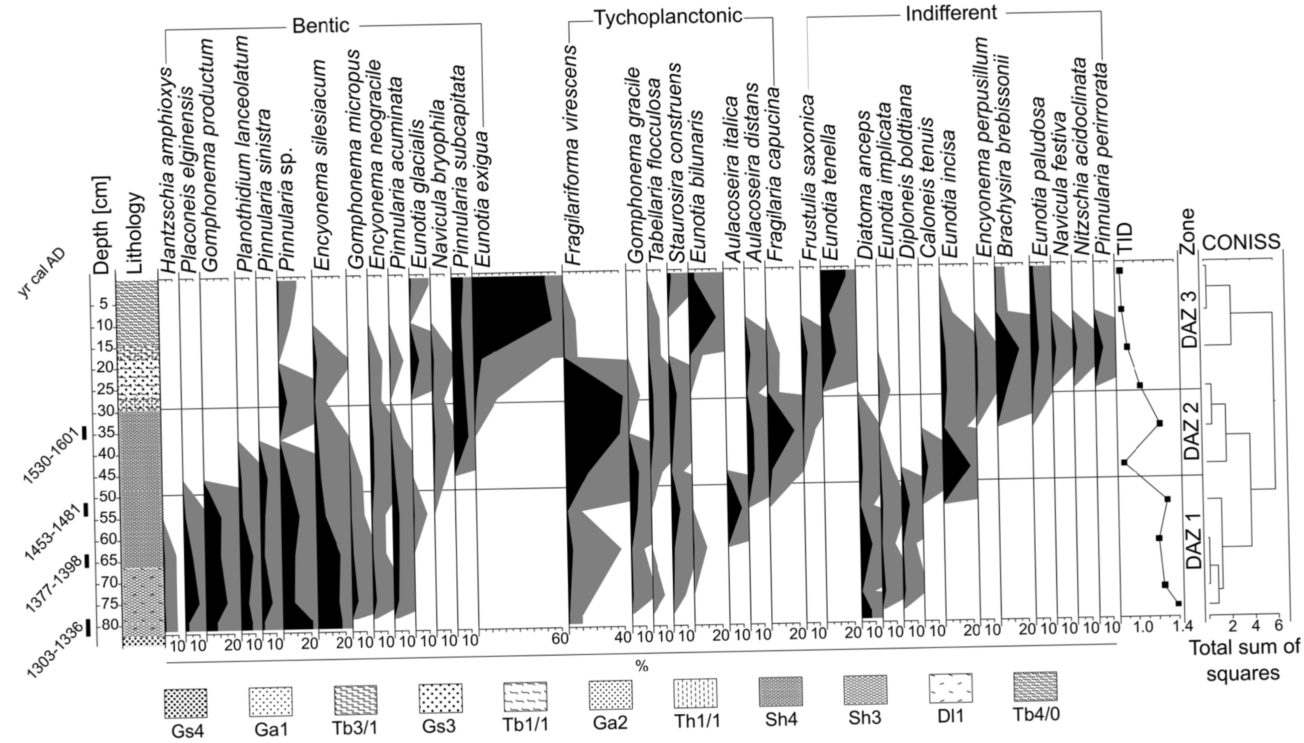


Fig. 6 Results of diatom analysis from the core SPI-1. Relative abundance of diatom species is in black, the grey area corresponds to a tenfold increase over the black. Black dots correspond to the reconstructed diatom inferred trophic state (TID)

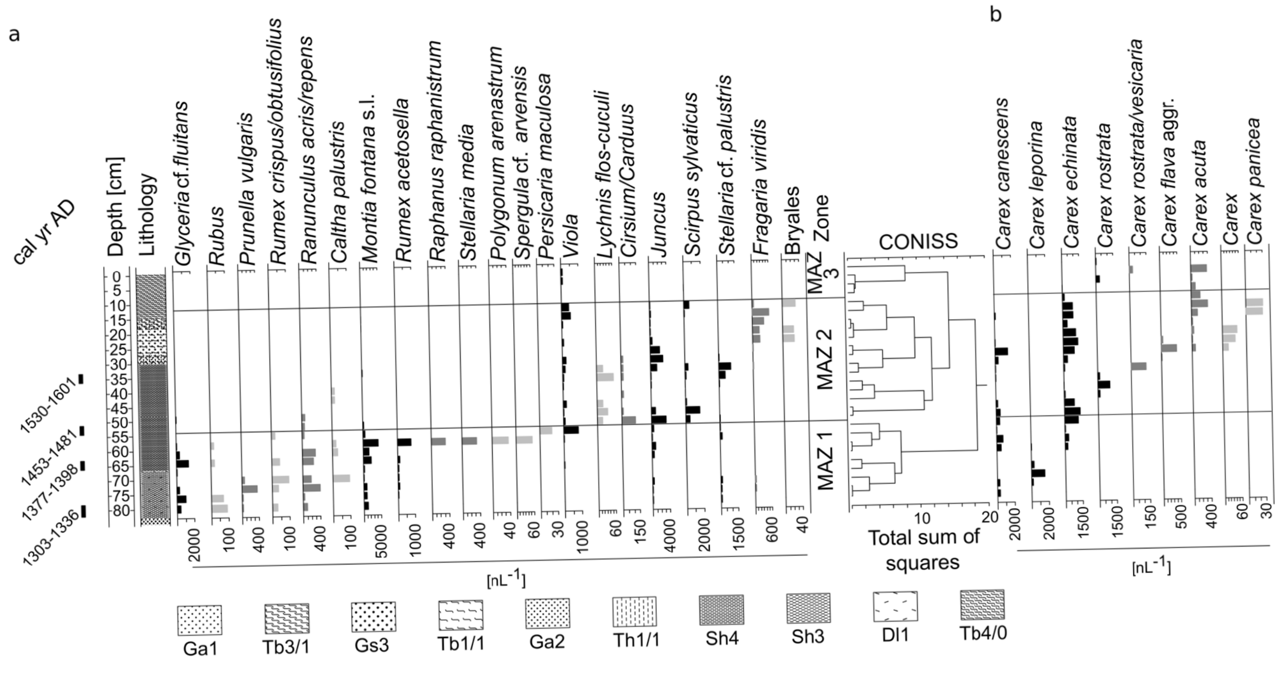


Fig. 7 **a** Results of plant macro fossils from the core SPI-1. **b** Specifies *Carex* species. Total counts are expressed by histograms. Black histograms correspond to counts in thousands, dark grey in hundreds, and light grey in tens

Discussion

Core stratigraphy and genesis of the sediment

Although the diatom species indicate an aquatic environment within the entire profile (with the exception of *Aulacoseira italica* at 54 cm, a species tolerant of desiccation) (Fig. 6), the lack of macrofossils of aquatic macrophyta makes the genesis of the sediment (limnic or semi-terrestrial) uncertain (Fig. 7). An admixture of hygrophyllous species was present in the pollen data (*Montia, Chrysosplenium, Lythrum salicaria, Thalictrum flavum* and *Typha latifolia*), however, with the exception of very rare pollen grains of *Myriophyllum spicatum* (in PAZ 2), no aquatic macrophyta were documented (Fig. 4). Still, the diatom composition suggests a minimum external loading of nutrients. Therefore, we could expect that the organic material analysed represented a local signal of the immediate surroundings of the coring site.

The methods used in our study differ in the spatial extent of their source area. Diatoms solely indicate the local environment around the core. Also, macro remains (seeds/fruits and macro charcoals) are generally of rather local origin (mostly up to several metres). Microelements are, on the contrary, airborne, so that they could be transported from greater distances, as for example Zn, Cd and As in the uppermost layers of the profile (Fig. 5) originated probably from brown coal fuelled power plants, located in the adjacent lowland since the AD 1980s. The increased concentration of some elements could, therefore, be connected with ore mining up to several km distant from the core (the concentrations would be much higher if the mining was local).

The pollen signal is the most difficult to interpret. It could be partly of local origin (vegetation of the coring site) or it may cover the area of the whole village with its farmed land. At the same time, some pollen grains could be of a regional origin, i.e. coming from forests and farmsteads placed several km away. Besides, pollen grains from very long distances could be admixed sporadically (e.g. thermophilous species from lowlands), however, this does not seem to be the case for our data, which lacked thermophilous species. Another complication is that species differ in their pollen dispersion abilities. A good example is the pollen of various cereals. Rye is a wind-pollinated cereal and its pollen was therefore of a regional origin, whereas the other cereals are cleistogamic, therefore their pollen was more likely of a local origin.

Palaeoecological record from the wet stand in Spindelbach

The wet stand was situated in the village centre (Fig. 1c). The village was founded in the AD 1350s according to historical evidence (Profous 1951). However, the oldest buildings located in the lower part of the village may have already been built in the second half of the 13th century AD according to archaeological evidence (Klír 2016). This is in correspondence with the obtained ^{14}C data, because the sedimentary record exhibiting human influence is primarily dated to the 14th and 15th centuries AD (Table 2; Figs. 2, 3, 4). Plant remnants recorded in the studied sediment reflect the colonization pictured in Fig. 1c, but the sediment is not older than about AD 1300 based on the calibrated ^{14}C intervals (Table 2; Fig. 2). We assume the sedimentological record reflects:

1. The period lasting ~70 years when the settlement was being established in the first half of the 14th century defined by the first lithological unit and PAZ 1a (82–66 cm);
2. Existence of a fully developed village from AD 1370–1450 as defined by PAZ 1b (66–51 cm);
3. The collapse horizon during the period AD 1450–1480 (54–51 cm);
4. Succession in the abandoned village area (51–30 cm);
5. A hiatus implied by sand admixture reflecting up to a 3 centuries long period (30–15 cm);
6. A subrecent epoch (15–0 cm), (Figs. 3, 4).

Since no significant PAZ is determined between (1) and (2), PAZ 1 likely reflects human activity driving a rather gradual process of forming the fully functional village. Period (4) may have lasted from the AD 1480s to the 1540s. This conclusion is, besides the deposition model (Fig. 2), based on an assumption that the increased human activity recorded at the site was connected to another village, Výsluní, established nearby in the AD 1540s. The hiatus is implied by the PAZ2/3 boundary (21–24 cm) and is also strongly indicated by a fluctuation in the total pollen concentration (TPC) (Magyari et al. 2014), which increases up to 385×10^3 grains per cm^3 and is followed by a decrease to less than 50×10^3 grains per cm^3. The comparison of cluster analysis and outlined settlement periods is given in the ESM.

Development of plant cover at the site

Reclamation of the area

The dominance of pollen from the shade tolerant climax tree species *Fagus, Abies* and *Picea*, and fern spores indicates the broader area was forested at the beginning of the 14th century (Fig. 3). Nevertheless, the recorded percentages of AP (~46%) and fern spores (~35%), *Picea* charcoal concentration reaching > 1,000 nl^{-1}, and the increased concentration of wood microcharcoal (Fig. 3) may reflect previous local glassworks activity (Fig. 1) (Černá and Klír 2014). In particular, *Picea* wood together with ferns were among the key materials in glassmaking (Cílová and Woitsch 2012). The increased charcoal concentrations may already coincide with a local slash-and-burn strategy as some houses with an agricultural background were being established in the lower part of the village by that time (Klír 2016). This accumulation of charcoal was rather caused by direct local human influence than by frequent fires resulting from droughts that were documented in CL in the 14th century (Brázdil et al. 2013). Mining activities had started in other parts of the Krušné Mts. as early as 250 BC (Veron et al. 2014) and the broader area was concurrently colonized due to mining (Fig. 1). However, there was no detection of increased local heavy metal concentrations in our study indicating the absence of mining activity in this particular area (Fig. 5). The composition of the macrofossil spectrum implies that locally there was development of a light-demanding wet stand vegetation (Fig. 7), which was supplied by slowly moving water with circumneutral aquatic conditions, relatively low aquatic trophic status (Fig. 6) and low calcium content (Fig. 5). Calthion palustris montane wet meadows occurred in the wet canopy openings around the springs and/or, to a lesser extent, in partially shaded places of the alluvial zone of the upper stream (Balátová-Tuláčková 1981; Hájková et al. 2010), (Figs. 3, 4).

Local deforestation in the Krušné Mts.

Generally in CE, the trend of a distinct deforestation during MWP in the 11th and 12th centuries was somewhat reversed due to European population decline after the Black Death in AD 1347 (Kaplan et al. 2009; Poschlod 2015). However, these trends do not correspond with those reconstructed by us in the Krušné Mts. The most significant decrease of the AP below 12% was recorded in the second half of the 14th century in the studied region (Fig. 3). As another five mining villages were established in a 5 km radius of Spindelbach, such a human-induced deforestation likely affected the structure of tree species composition in the broader area (Fig. 1b). The dominant tree species composition prior to colonization of the area is in correspondence with the REVEALS estimates for NW Bohemia for a chronozone dating from 3000 BC–AD 1500, in which major deforestation was not predicted until the second half of the last millennium (Abraham et al. 2016). The decline in *Abies* and *Picea* pollen abundance in PAZ 1a was followed by that of *Fagus* in PAZ 1b (Fig. 3), and their TPCs showed the same trend. This may indicate that *Fagus* could grow at lower elevations, more distant from the village than stands of coniferous trees and thus were cut later (Hicks 2006). Because a fluctuating sedimentation rate (Seppä and Hicks 2006) can be assumed for our sediment sample, we did not reconstruct further details regarding the actual tree cover based on annual pollen accumulation rates (van der Knaap 2009; van der Knaap et al. 2010). The decline of tree pollen abundance equalled or even outweighed that reconstructed in the Czech lowlands in the High Medieval Times (Kozáková et al. 2014; Pokorná et al. 2014). The decrease in the AP to 11% at the depth of 52 cm (Fig. 3) probably reflects intense use of wood for industrial activity as mining progressed in the broader area. An enormous amount of *Picea* and *Fagus* wood was also usually consumed to produce the ash that was used in the glassmaking process (Cílová and Woitsch 2012). In addition, the samples possessing low values of AP correspond to a period of severe winters recorded in CL in the AD 1430s–1450s and 1480s (Brázdil and Kotyza 1995), which may have contributed to enhanced wood consumption.

Even though *Picea* was later restored, *Fagus* and *Abies* never achieved their former abundances (Fig. 3). We assume that the distribution of newly spreading tree species was determined by several factors in the several decades after Spindelbach was fully abandoned in the AD 1480s (Giesecke et al. 2007). These factors possibly included:

1. *Picea* spreading naturally as a pioneer tree on newly cleared forest stands and its being favoured by humans because of its obvious advantages;
2. Climate limitations driving the recruitment of seedlings. Contrary to young *Picea* trees (Schuster and Oberhuber 2013), *Fagus* growth and its seedling distribution may not be favoured by low summer precipitation, or late spring and early autumn frosts (van Hees 1997; Jump et al. 2006). *Abies* growth was found to be even more sensitive to summer droughts than *Fagus* (Cailleret and Davi 2011). Low summer precipitation amounts were reconstructed in CL during the first half of the 16th century AD including long-lasting droughts in AD 1540 (Brázdil et al. 2013; Dobrovolný et al. 2015). On the contrary, wet years were on average reconstructed in the second half of the 16th century AD (Dobrovolný et al. 2015). This trend was however related to the prolonged winters connected to late spring and early autumn frosts starting about AD 1540 and reaching a 30-year long cold period in AD 1569–1598 (Brázdil and Kotyza 2000; Dobrovolný et al. 2010);
3. Physiological differences of the participating tree species influencing their propagation and current pollen production. For example, *Fagus* lacks a persistent seed bank as it sprouts (Pickett and McDonnell 1989). The

noted pollen production may have resulted from e.g. different flowering maturity ages (Giesecke and Bennett 2004; Hicks 2006; Bradshaw et al. 2010);
4. The different spatial distributions of the trees in the Krušné Mts. as a result of past local management around Spindelbach may have favoured a succession on abandoned pastures toward *Picea* stands while *Fagus* was possibly still exploited at lower altitudes, as other villages were not abandoned (Fig. 1b).

Economy and population of the village of Spindelbach

Spindelbach was established outside the traditional settlement regions in an area that is very marginal for agricultural production in terms of the short-fallow cultivation systems that were typical for high and late medieval CE (e.g. Kenzler 2012; Klápště 2016). Its long strip fields covered a roughly estimated area of 640 ha and were analogous to medieval field systems described in other parts of CL (Houfková et al. 2015) or Europe (Matzat 1988; Kenzler 2012). Calthion palustris montane wet meadows, a vegetation formation indicating grazing (Behre 1981), represented a significant part of the surrounding vegetation cover (Fig. 4). Thus, livestock breeding must have contributed a major part of the local agricultural production (Figs. 4, 7). We demonstrated that cereal pollen types dominated by *Secale cereale* and *Triticum* sp. reached above 4% of relative pollen abundance in the layers corresponding to the village's existence (Fig. 4). Archaeobotanical studies from a nearby medieval village at a similar altitude proved the processing of cereals imported from warmer regions, which resulted in enhanced cereal pollen concentrations (Kočár et al. 2014). However, such pollen spectra also included enhanced proportions of thermophilous weeds such as *Agrostemma githago* or *Centaurea cyanus*. In contrast, the Spindelbach profile, although having higher total pollen counts, did not contain weed pollen except for *Centaurea cyanus* recorded only at the very end of the settlement (Fig. 4). This implies winter cereals were locally cultivated on arable land. As cereals usually covered 1/3–1/2 of medieval long strip fields, we assume that the corresponding 200–300 ha could have yielded the cereals needed for the subsistence of the estimated local 25 concurrently living families (Beck 2004). The establishment of Spindelbach coincided with the MWP, which in CL is delimited to AD 1260–1380 according to interpretation of narrative sources (Brázdil and Kotyza 1995). Therefore, we speculate that climate conditions prevailing in the 14th century may have enabled self-sustaining cultivation using winter cereals at the site. In the village centre, wet stand vegetation persisted, although the representation of seeds and pollen of particular species fluctuated (Figs. 4, 7), possibly in response to human/livestock pressure. However, this potential artificial pressure was not recorded in the aquatic environment since no eutrophication of the wet stand, based on diatom index TID (Fig. 6) or total phosphorus (TP) concentration (Fig. 5), was detected. The colonization of the site had at least two detectable impacts: (1) macrofossil and sedimentological data that demonstrated a gradual silting up of the sedimentation basin; and (2) deforestation and cereal growth is evidenced in the pollen diagram. These changes were not rapid, but led to radical and until nowadays irreversible changes, e.g. in the above described tree species composition.

Succession after the collapse of the local settlement

The collapse

Spindelbach was last mentioned in the historical records in AD 1481 (Profous 1951). However, based on the archaeological excavations, some farmsteads were already abandoned around the middle of the 15th century (Hylmarová et al. 2013; Klír 2016). A collapse horizon is reflected in the plant fossil spectrum followed by succession on abandoned buildings and in their adjacent areas (Figs. 3, 4, 7). The desertion of Spindelbach was likely not forced as low fire activity is indicated in the corresponding layers (Fig. 3). We speculate that the Spindelbach desertion resulted from a combination of unfavourable factors: (1) agrarian depression and decrease in the regional mining/industrial activity, followed by a lower demand for work forces, very probably coincided as demonstrated in other industrial parts of the CL in the 15th century; (2) gradual exploitation of the forest culminating in this period might have led to the lack of fire wood. This can be seen in the charcoal and wood values which already decline before the tree pollen minimum (Fig. 3); (3) extreme weather variability was reconstructed showing dry summers peaking in the AD 1480s and severe winters particularly in the AD 1430s–1450s and 1480s (Brázdil and Kotyza 1995). Weather fluctuations could have had a stronger effect on the local agricultural system due to the fact that Spindelbach was located just at the edge of the winter cereal cultivation zone, being more than 100 m a.s.l. higher than the other co-established villages. Examples of unfavourable weather conditions leading to site-specific village abandonment have been very well described at the onset of the LIA, as in case of Wharram Percy in England (Hoskins 1988).

Immediate succession

The plant fossil spectrum reflected village abandonment and ongoing succession analogous to modern evidence documented in the area of abandoned villages in Northern Bohemia in the AD 1960s, where the initial successional phase typically lasted up to 4 years after village abandonment

(Jehlík 1971). This event was probably recorded in the upper layers of PAZ 1 and MAZ 1 (Figs. 4, 7). Seeds of annual and biennial herbaceous species, such as *Raphanus raphanistrum*, reached hundreds of finds l^{-1}, whereas cereal pollen decreased. The wet stand was restored and densely covered by *Montia fontana* probably due to decreased grazing (Figs. 4, 7). The slightly enhanced calcium content may correspond to its leaching from village ruins (Fig. 5). Calthion palustris montane wet meadows persisted, but did not contribute to the same extent and with the same species composition (Figs. 4, 7). This was influenced especially by decreased grazing documented by a decrease in the relative pollen abundance and macro fossil concentration of all indicator species (Figs. 4, 7) (Behre 1981), and a decrease in reconstructed TID (Fig. 6). The slightly increased ratio of pollen of *Urtica dioica*-type (and also its TPC) and seeds of *Rumex crispus/obtusifolius* were documented in the following layers, rapidly replaced by the onset of *Filipendula ulmaria* and *Salix* stands. Pollen of *Sambucus racemosa/nigra*, and *Acer campestre*-type contributed. Stands of high sedges, such as *C. rostrata*, developed locally, as indicated by the presence of its fossil seeds (Fig. 7). Occasionally, some previously planted herbs, like *Levisticum officinale*, persisted (Fig. 4). *Picea* was restored relatively soon according to both its increasing TPC and percentage in the pollen spectrum (Fig. 4). The development of a secondary forest that in general significantly differed from the ancient one in areas of abandoned villages (Vojta 2007) is further implied by the increase in *Betula* pollen abundance (Fig. 3). Simultaneously, further expansion of the Calthion wet meadows (Fig. 4) took place on the unforested stands, since the need for wood persisted in the region. This probably corresponded to the era after the AD 1540s, when mining activity developed around the newly established settlement Výsluní located 3 km to the southeast (Fig. 1b) (Hofmann 1939). Iron ore mining was implied by the increased concentrations of Fe and Si. Mining of silver ores is implied by the increased Ag concentration together with increased concentrations of Pb, Cu, As, Mo, Cd, U and Th (Fig. 5). This finding has its analogy in the nearby Zvonící potok valley where ore remnants containing 46.6% Fe, 26.3% Si and 0.3% Mn were detected from the still preserved mining tunnels (Kratochvíl 1953).

Further development

The whole area was negatively affected during the Thirty Years' War (AD 1618–1648), with Výsluní being burned down in AD 1640 (Crkal 2015). A pond named Spindelbach was mentioned in historical documents even in the 16th and 17th centuries AD, but its location has not been further specified (Crkal and Černá 2009). No pond was mapped after the second half of the 18th century AD. We did not record any war events, because fire activity did not increase in the sediment layers corresponding to further development at the site (Fig. 3). More likely, this epoch is part of a hiatus, which is implied by the sedimentological and geochemical evidence in the 30–15 cm layers. In these layers, sand and gravel admixed to acidic soil probably due to erosion (Fig. 5). This acidity was reconstructed based on diatom species preferring a pH lower than six (Fig. 6). Moreover, the obtained diatom spectrum indicates a low aquatic trophic status based on TID values (Fig. 6). This implies the occurrence of disturbed, rather acidic and nutrient poor habitats in the respective layers. This is in accordance with the observed vegetation changes. Mesic montane meadows of medium tall grasses combined with *Meum athamanticum*, mountain dry pastures (Violion caninae), and heathland vegetation developed in the surrounding landscape (Fig. 4), while the wet stand persisted at the sampling site. The huge quantity of *Viola* seeds (Fig. 7) belonged very likely to *Viola palustris* living directly on the wet stand. These nutrient poor patches were further disturbed by grazing animals (Figs. 4, 7). Layers in the 15–0 cm depth already correspond to a sub-recent period, as indicated by the presence of the *Ambrosia* pollen type, SCPs, and the increased concentration of trace elements, above all of Zn, Cd and As (Figs. 3, 4, 5). This probably corresponds to a peak in the emission of fly-ash and adsorbed trace elements recorded in the AD 1980s that originates from brown coal fuelled power plants located in the adjacent lowland (Fott et al. 1998). Diatom species composition reconstructed the dystrophic conditions characteristic for establishment of a peat bog (Fig. 6), corresponding to the described sub-recent *Sphagnum* growth in LU7 (15–0 cm).

Conclusions

Vegetation structure gradually but completely changed during human exploitation of the mountain peripheral areas of CL during the High Middle Ages in the 13th and 15th centuries AD. Establishment of the short-lived medieval village Spindelbach above 800 m a.s.l. in the Ore Mts. reflected the socio-economic trends in the second half of the 13th century and was probably connected with the favourable climate conditions recorded in the AD 1260s–1380s in CL (Brázdil and Kotyza 1995). Direct short-termed human impact was enhanced by ore mining in the broader area. Intense human pressure, together with climate conditions, irreversibly changed the woodland structure favouring *Picea* stands that have persisted until today. Even at such elevations, arable fields probably enabled a self-sustaining cultivation of winter cereals for the local inhabitants in good years during the MWP. Development of wet Calthion meadows driven by local grazing was reconstructed at least since the 14th century. However, Spindelbach was soon abandoned in the AD 1450s–1480s. Its desertion corresponded to an epoch of economic and demographic stagnation, overexploitation of the surrounding forests and an era of severe weather recorded in CL in the AD 1430s–1450s and 1480s (Brázdil and Kotyza 1995). Successional trends after the abandonment of the local settlement and diminished grazing were comparable to their modern analogues described in Jehlík (1971) and Balátová-Tuláčková (1981). These have been validated independently over time and in the prevailing climate.

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References

Abraham V, Kuneš P, Petr L et al (2016) A pollen-based quantitative reconstruction of the Holocene vegetation updates a perspective on the natural vegetation in the Czech Republic and Slovakia. Preslia 88:409–434

Alfonso I (2007) Rural history of medieval European societies: trends and perspectives. The medieval countryside, vol 1. Brepols, Turnhout

Balátová-Tuláčková E (1981) Phytozönologische und synökologische Charakteristik der Feuchtwiesen NW-Böhmens. Rozpravy ČSAV, Řada matematických a přírodních věd 91:1–91

Beck R (2004) Unterfinning: Ländliche Welt vor Anbruch der Moderne. C. H. Beck, München

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

Beug H-J (2004) Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Pfeil, München

Bradshaw RHW, Kito N, Giesecke T (2010) Factors influencing the Holocene history of *Fagus*. For Ecol Manag 259:2,204–2,212

Brázdil R, Kotyza O (1995) History of weather and climate in the Czech lands I: period 1000–1500. Zürcher Geographische Schriften, vol 62. Geographisches Institut ETH, Zürich

Brázdil R, Kotyza O (2000) History of weather and climate in the Czech Lands IV: utilisation of economic sources for the study of climate fluctuation in the Louny Region in the fifteenth–seventeenth centuries. Masaryk University, Brno

Brázdil R, Dobrovolný P, Trnka M et al (2013) Droughts in the Czech Lands, 1090–2012 AD. Clim Past 9:1,985–2,002

Bronk Ramsey C (2008) Deposition models for chronological records. Quat Sci Rev 27:42–60

Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. Radiocarbon 51:337–360

Bronk Ramsey C, Lee S (2013) Recent and planned developments of the program OxCal. Radiocarbon 552:720–730

Büntgen U, Tegel W, Nicolussi K et al (2011) 2500 years of European climate variability and human susceptibility. Science 331:578–582

Cailleret M, Davi H (2011) Effects of climate on diameter growth of co-occurring *Fagus sylvatica* and *Abies alba* along an altitudinal gradient. Trees Struct Funct 25:265–276

Čapek L, Holata L (2017) General overview of medieval settlement research in the Czech Republic: emergence and development of the field, main issues and adoption of landscape context. Revista ArkeoGazte Aldizkaria 7:267–320

Cappers RTJ, Bekker RM, Jans JEA (2006) Digital seed atlas of the Netherlands. Groningen archaeological studies, vol 4. Barkhuis Publishing, Eelde

Černá E, Klír T (2014) The settlement of the Ore Mountains in the Later Middle Ages and Early Modern Period. The context and objectives of interdisciplinary research. In: Boháčová I, Sommer P (eds) Medieval Europe in motion. In honour of Jan Klápště. Institute of Archaeology of the CAS, Prague, v.v.i., Praha, pp 105–118

Chytrý M (2012) Vegetation of the Czech Republic: diversity, ecology, history and dynamics. Preslia 84:427–504

Cílová Z, Woitsch J (2012) Potash—a key raw material of glass batch for Bohemian glasses from 14th–17th centuries? J Archaeol Sci 39:371–380

Crkal J (2015) Výsluní. In: Urban M (ed) Horní města Krušných hor. Fornica Publishing, Sokolov, pp 300–319

Crkal J, Černá E (2009) Nové objevy v Krušných horách–zaniklé středověké sklárny na k. ú. Výsluní, okr. Chomutov. Archaeol Hist 34:503–521

Denys L (1991) A check-list of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements. 1. Introduction, ecological code and complete list. Service Géologique de Belgique 246:1–41

Dobrovolný P, Brázdil R, Kotyza O, Valášek H (2010) Extreme summer and winter temperatures in the Czech Lands after A.D. 1500 and their Central European context. Geografie 115:266–283

Dobrovolný P, Rybníček M, Kolář T et al (2015) A tree-ring perspective on temporal changes in the frequency and intensity of hydroclimatic extremes in the territory of the Czech Republic since 761 AD. Clim Past 11:1,453–1,466

Fægri K, Iversen J (1989) Textbook of Pollen analysis, 4th edn (revised by Fægri K, Kaland PE, Krzywinski K.), Wiley, Chichester

Faria JC (2009) Resources of Tinn-R GUI/editor for R environment. UESC, Ilheus

Fott B (1954) Pleurax, synthetická pryskyrice pro preparaci rozsivek. Preslia 26:163–194

Fott J, Vukic J, Rose NL (1998) The spatial distribution of characterized fly-ash particles and trace metals in lake sediments and catchment mosses: Czech Republic. Water Air Soil Pollut 106:241–261

Fredskild B (1988) Agriculture in a marginal area—South Greenland from the Norse Landnam (A.D. 985) to the present (A.D. 1985). In: Birks HH, Birks HJB, Kaland PE, Moe D (eds) The cultural landscape—past, present and future. Cambridge University Press, Cambridge, pp 381–393

Gaillard MJ (2013) Pollen methods and studies, archaeological applications. In: Elias SA, Mock CJ (eds) Encyclopedia of quaternary science, 2nd edn. Elsevier, Oxford, pp 880–903

Gaillard MJ, Sugita S, Mazier F et al (2010) Holocene land-cover reconstructions for studies on land cover-climate feedbacks. Clim Past 6:483–499

Giesecke T, Bennett KD (2004) The Holocene spread of *Picea abies* (L.) Karst. in Fennoscandia and adjacent areas. J Biogeogr 31:1,523–1,548

Giesecke T, Hickler T, Kunkel T et al (2007) Towards an understanding of the Holocene distribution of *Fagus sylvatica* L. J Biogeogr 34:118–131

Gissel S, Juttikkala E, Österberg E, Sandnes J, Teitsson B (1981) Desertion and land colonization in the Nordic countries c. 1300–1600: comparative report from the Scandinavian research project on deserted farms and villages. Almqvist & Wiksell International, Stockholm

Griffin JJ, Goldberg ED (1979) Morphologies and origin of elemental carbon in the environment. Science 206:563–565

Grimm EC (1987) CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Comput Geosci 13:13–35

Grimm EC (2011) Tilia. Version 1.7.16. Illinois State Museum, Springfield

Hájková P, Hájek M, Blažková D et al (2010) Meadows and mesic pastures. In: Chytrý M (ed) Vegetation of the Czech Republic 1: grassland and heathland vegetation. Academia, Praha

Hicks S (2006) When no pollen does not mean no trees. Veg Hist Archaeobot 15:253–261

Hofmann F (1939) Geschichtes Memorandum über die Freie Bergstadt Sonnenberg. Erzg., Sudetengau

Hoskins W (1988) The making of the English landscape. Hodder and Stoughton, London

Houfková P, Bumerl J, Pospíšil L et al (2015) Origin and development of long-strip field patterns: a case study of an abandoned medieval village in the Czech Republic. Catena 135:83–91

Houk V (2003) Atlas of freshwater centric diatoms with a brief key and descriptions, part 1: Melosiraceae, Orthoseiraceae, Paraliaceae and Aulacoseiraceae. Czech Phycol Suppl 1:1–27

Hürkamp K, Raab T, Volkel J (2009) Two and three-dimensional quantification of lead contamination in alluvial soils of a historic mining area using field portable X-ray fluorescence (FPXRF) analysis. Geomorphology 110:28–36

Hylmarová L, Klír T, Černá E (2013) Iron objects from the defunct village of Spindelbach, Krušné Hory Mountains. Results of metal detecting. Archaeol Hist 38:569–609

Jankovská V, Kuneš P, van der Knaap WO (2007) 1. Fláje–Kiefern (Krušné Hory Mountains): Late Glacial and Holocene vegetation development. Grana 46:214–216

Jehlík V (1971) Die Vegetationsbesiedlung der Dorftrümmer in Nordböhmen. Eine Studie über synanthrope Vegetation und Flora. Rozpravy Československé akademie věd 81. Academia, Praha

Jump AS, Hunt JM, Martinez-Izquierdo JA, Penuelas J (2006) Natural selection and climate change: temperature-linked spatial and temporal trends in gene frequency in *Fagus sylvatica*. Mol Ecol 15:3,469–3,480

Kalnicky DJ, Singhvi R (2001) Field portable XRF analysis of environmental samples. J Hazard Mater 83:93–122

Kaplan JO, Krumhardt KM, Zimmermann N (2009) The prehistoric and preindustrial deforestation of Europe. Quat Sci Rev 28:3,016–3,034

Katz N, Katz S, Kipiani M (1965) Atlas and keys of fruits and seeds occuring in the quaternary deposits of the USSR. Academy of Science of the USSR, Nauka, Moscow

Kenzler H (2012) Die hoch- und spätmittelalterliche Besiedlung des Erzgebirges: Strategien zur Kolonisation eines landwirtschaftlichen Ungunstraumes. Habelt, Bonn

Kitsikopoulos H (2011) Agrarian change and crisis in Europe, 1200–1500. Routledge research in medieval studies. Routledge, New York

Klápště J (2016) The archaeology of Prague and the medieval Czech lands. Studies in the archaeology of medieval Europe. Equinox Publishing, Sheffield, pp 1100–1600

Klír T (2016) Research of deserted Medieval villages conducted by the Institute of Archaeology at Charles University in Prague. In: Nocuń P et al (eds) Wieś zaginiona. Stan i perspektywy badań. Monografie i materiały MGPE 5. Muzeum "Górnośląski Park Etnograficzny w Chorzowie", Chorzów, pp 17–59

Kočár P, Kočárová R, Petr L et al (2014) Pflanzenreste aus den hochmittelalterlichen Bergbaustandorten im Erzgebirge. Archeomontan 29:119–135

Kozáková R, Pokorný P, Havrda J, Jankovská V (2009) The potential of pollen analyses from urban deposits: multivariate statistical analysis of a data set from the medieval city of Prague, Czech Republic. Veg Hist Archaeobot 18:477–488

Kozáková R, Pokorný P, Mařík J et al (2014) Early to high medieval colonization and alluvial landscape transformation of the Labe valley (Czech Republic): evaluation of archaeological, pollen and macrofossil evidence. Veg Hist Archaeobot 23:701–718

Kozáková R, Pokorný P, Peša V et al (2015) Prehistoric human impact in the mountains of Bohemia. Do pollen and archaeological data support the traditional scenario of a prehistoric "wilderness"? Rev Palaeobot Palynol 220:29–43

Krammer K, Lange-Bertalot H (1986) Bacillariophyceae. 1. Teil: Naviculaceae. In: Ettl H, Gerloff J, Heinig H, Mollenhauer D (eds) Süsswasserflora von Mitteleuropa, vol 2/1. Gustav Fischer, Stuttgart

Krammer K, Lange-Bertalot H (1988) Bacillariophyceae. 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In: Ettl H, Gerloff J, Heinig H, Mollenhauer D (eds) Süsswasserflora von Mitteleuropa, vol 2/2. Gustav Fischer, Stuttgart

Krammer K, Lange-Bertalot H (1991a) Bacillariophyceae. 4. Teil: Achnanteaceae, Kritische Ergänzungen zu *Navicula* (Lineolateae) und *Gomphonema*. Gesamtliteraturverzeichnis Teil 1–4. In: Ettl H, Gerloff J, Heinig H, Mollenhauer D (eds) Süsswasserflora von Mitteleuropa, vol 2/4. Gustav Fischer, Stuttgart

Krammer K, Lange-Bertalot H (1991b) Bacillariophyceae. Teil 3: Centrales, Fragilariaceae, Eunotiaceae. In: Ettl H, Gerloff J, Heinig H, Mollenhauer D (eds) Süsswasserflora von Mitteleuropa, vol 2/3. Gustav Fischer, Stuttgart

Kratochvíl F (1953) Zpráva o geologickém mapování a rudních výskytech v okolí Výsluní u Chomutova. Unpublished report, Geofond Praha, p P5042

Kreuz A, Schäfer E (2002) A new archaeobotanical database program. Veg Hist Archaeobot 11:177–180

Kubát K, Hrouda L, Chrtek J (2002) Klíčke květeně České republiky. Academia, Praha

Legendre P, Legendre L (1998) Numerical ecology. Elsevier, Amsterdam

MacArthur RH (1957) On the relative abundance of bird species. Proc Natl Acad Sci USA 43:293–295

Magyari EK, Kuneš P, Jakab G et al (2014) Late Pleniglacial vegetation in eastern-central Europe: are there modern analogues in Siberia? Quat Sci Rev 95:60–79

Matzat W (1988) Long strip field layouts and their later subdivisions—a comparison of English and German cases. Geogr Ann B 70:133–147

Maur E (1989) Ein Beitrag zur demographischen Problematik Böhmens in vorhussitischer Zeit (1346–1419). Acta Universitatis Carolinae–Philosophica et historica. Stud Hist 34:7–71

Nocuń P, Przybyła-Dumin A, Fokt K (2016) Wieś zaginiona. Stan i perspektywy badań. Monografie i materiały MGPE 5. Muzeum "Górnośląski Park Etnograficzny w Chorzowie", Chorzów

Opravil E (1969) Synantropní rostliny dvou středověkých objektů ze SZ Čech. Preslia 41:248–257

Pickett STA, McDonnell MJ (1989) Seed bank dynamics in temperate deciduous forest. In: Leck MA (ed) Ecology of soil seed banks. Academic Press, San Diego, pp 123–147

Pokorná A, Dreslerová D, Křivánková D (2011) Archaeobotanical database of the Czech Republic, an interim report. IANSA 2:49–53

Pokorná A, Houfková P, Novák J et al (2014) The oldest Czech fishpond discovered? An interdisciplinary approach to reconstruction of local vegetation in mediaeval Prague suburbs. Hydrobiologia 730:191–213

Pokorná A, Kočár P, Novák J et al (2018) Ancient and Early Medieval man-made habitats in the Czech Republic: colonization history and vegetation changes. Preslia 90:171–193

Pokorný P, Chytrý M, Juřičková L et al (2015) Mid-Holocene bottleneck for central European dry grasslands: did steppe survive the forest optimum in northern Bohemia, Czech Republic? Holocene 25:716–726

Poschlod P (2015) Geschichte der Kulturlandschaft. Ulmer, Stuttgart

Profous A (1951) Místní jména v Čechách. Jejich vznik, původ, význam a změny III. Nakl. Československé akademie věd, Prague

Punt W et al (1976–2009) The Northwest European Pollen Flora (NEPF) Vol I (1976), Vol II (1980), Vol III (1981), Vol IV (1984) Vol V (1988), Vol VI (1991), Vol VII (1996), Vol VIII (2003), Vol IX (2009). Elsevier, Amsterdam

R Development Core Team (2010) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Reimer PJ, Bard E, Bayliss A et al (2013) Intcal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55:1,869–1,887

Rose NL (2001) Fly-ash particles. In: Last WM, Smol JP (eds) Tracking environmental change using lake sediments. Physical and geochemical methods, vol 2. Kluwer Academic Publisher, Dordrecht, pp 319–349

Rott E, Pipp E, Pfister P et al (1999) Indikationslisten für Aufwuchsalgen in österreichischen Fliessgewässern, Teil 2: Trophieindikation. Bundesministerium für Land- und Forstwirtschaft, Wien

Schuster P (1999) Die Krise des Spätmittelalters. Zur Evidenz eines sozial- und wirtschaftsgeschichtlichen Paradigmas in der Geschichtsschreibung des 20. Jahrhunderts Hist Z 269:19–55

Schuster R, Oberhuber W (2013) Age-dependent climate-growth relationships and regeneration of *Picea abies* in a drought-prone mixed-coniferous forest in the Alps. Can J For Res 43:609–618

Schweingruber FH (1990) Mikroskopische Holzanatomie. Formenspektren mitteleuropäischer Stamm- und Zweighölzer zur Bestimmung von rezentem und subfossilem Material, vol 3. Aufl. Eidgenössische Anstalt für das Forstliche Versuchswesen, Birmensdorf

Seppä H, Hicks S (2006) Integration of modern and past pollen accumulation rate (PAR) records across the arctic tree-line: a method for more precise vegetation reconstructions. Quat Sci Rev 25:1,501–1,516

Stockmarr J (1971) Tablets with spores used in absolute pollen analysis. Pollen Spores 13:615–621

Sveinbjarnardóttir G (1992) Farm abandonment in medieval and post-medieval Iceland: an interdisciplinary study. Oxbow Books, Oxford

Sweeney CA (2004) A key for the identification of stomata of the native conifers of Scandinavia. Rev Palaeobot Palynol 128:281–290

Szabó P, Kuneš P, Svobodová-Svitavská H et al (2017) Using historical ecology to reassess the conservation status of coniferous forests in Central Europe. Conserv Biol 31:150–160

Tolasz R, Míková T, Valeriánová A, Voženílek V (2007) Climate atlas of Czechia. Czech Hydrometeorological Institute, Prague

Troels-Smith JA (1955) Karakterisering af løse jordarter (Characterization of unconsolidated sediments). Danmarks Geologiske Undersøgelse 3:1–73

Umbanhowar CE, McGrath MJ (1998) Experimental production and analysis of microscopic charcoal from wood, leaves and grasses. Holocene 8:341–346

Van Hees AFM (1997) Growth and morphology of pedunculate oak (*Quercus robur* L) and beech (*Fagus sylvatica* L) seedlings in relation to shading and drought. Ann Sci For 54:9–18

Van Dam H, Mertens A, Sinkeldam J (1994) A coded checklist and ecological indicator values of freshwater diatoms from The Netherlands. Aquat Ecol 28:117–133

Van der Knaap WO (2009) Estimating pollen diversity from pollen accumulation rates: a method to assess taxonomic richness in the landscape. Holocene 19:159–163

Van der Knaap WO, van Leeuwen JF, Svitavská-Svobodová H et al (2010) Annual pollen traps reveal the complexity of climatic control on pollen productivity in Europe and the Caucasus. Veg Hist Archaeobot 19:285–307

Veron A, Novak M, Brizova E, Stepanova M (2014) Environmental imprints of climate changes and anthropogenic activities in the Ore Mountains of Bohemia (Central Europe) since 13 cal. kyr BP. Holocene 24:919–931

Vojta J (2007) Relative importance of historical and natural factors influencing vegetation of secondary forests in abandoned villages. Preslia 79:223–244

6. Curriculum vitae

Name and Title: Petra Marešová, Mgr. (equivalent to MSc.)
Born: 29. 3. 1984 in Teplice (Czech Republic)

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Education
December 2021–2022: doctoral study resumed
2015–2021: doctoral study paused due to two maternity leaves
2009–2015: Faculty of Science, University of South Bohemia
PhD. programme: Botany, specialization in Archaeobotany and Palaeoecology
PhD. Thesis: Human impact as reflected in the pollen record, with a focus on the Middle Ages

2006–2009: Faculty of Science, University of South Bohemia
MSc. programme: Experimental biology
MSc. Thesis (research project): Houfková, P. (2009): Identification of interacting partners of Discs overgrown *in vivo*, MSc. thesis. University of South Bohemia, Faculty of Science, České Budějovice, 59 pp.

2003–2006: Faculty of Biological Sciences, University of South Bohemia
BSc. programme: General Biology
Bsc. Thesis (research project): Houfková, P. (2006): Functional analysis of methyltransferases from *Trypanosoma brucei*, BSc. thesis. University of South Bohemia, Faculty of Biological Sciences, České Budějovice, 34 pp.

Employers

since 2010: Faculty of Science, University of South Bohemia

Research interests

Focus on pollen analysis, non-pollen palynomorphs and microcharcoal analysis used in palaeocological reconstructions with reference to archaeological context.

Project and grant cooperation

Since 2021: cooperation with Nature Conservation Agency of the Czech Republic (PI of two projects)

Since 2018: Czech Ministry of Culture project NAKI DG18P02OVV060 Identification and Protection of Preserved Remains of Historical Long-stripped Fields (team member)

2013-2017: GAČR 13-08169S: Prior to the Neolithic: Contextual Analysis of Environmental Dynamics During Early Postglacial Transformation of Central Europe (team member)

2013-2015: Czech Ministry of Education, Youth and Sports, project PAPAVER, Centre for human and plant studies in Europe and Northern Africa in the postglacial period (team member)

2013-2015: GAČR 13-11193S: Holocene environmental dynamics in the Hornomoravský úval region: Key processes inducing the formation of recent landscape mosaic (team member)

2009-2012: GAČR 206/09/1564: A multi-proxy paleoecological investigation of the unique sediments from the former Komořanské jezero Lake, Most Basin, Czech Republic (team member)

Student grants from the Student Grant Agency of the Faculty of Science:

2008: SGA2008/006 (solver)

2007: SGA2007/007 (solver)

2006: SGA2006/005 (co-solver)

2005: SGA2005/001 (solver)

Foreign internship:

2012 - research stay at the Newcastle University, Great Britain, School of Geography, Politics and Sociology, Prof. T. Nakagawa

Publications

Salaš, M., Šálková, T., **Houfková, P.**, Kmošek, M. (2020) An Urnfield period metal hoard from Babí lom ridge near Svinošice (south Moravia) and the contribution of its culturally-chronological semantic and environmental contex, *Archeologické rozhledy,* LXXII: 26-66.

Tichá, A., Bešta, T., Vondrák, D., **Houfková, P.**, Jankovská, V. (2019) Nutrient availability affected shallow-lake ecosystem response along the Late-Glacial/Holocene transition, *Hydrobiologia*, 846: 87-108.

Houfková, P., Horák, H., Pokorná, A., Bešta, T., Pravcová, I., Novák, J., Klír, T. (2019) The dynamics of a non-forested stand in the Krušné Mts.: the effect of a short-lived medieval village on the local environment, *Vegetation History and Archaeobotany*, 28: 607-621.

Chvojka, O., Menšík, P., **Houfková, P.**, Šálková, T. (2018) On the issue of rib hoards from an Early Bronze Age settlement context: The hoard from Kucer in south Bohemia from the perspective of archaeology and archaeobotany, *Archeologické Rozhledy,* 70:195-238.

Abraham, V., Novák, J., **Houfková, P.**, Petr, L., Dudová, L. (2017) A Landscape Reconstruction Algorithm and pedoanthracological data reveal Late Holocene woodland history in the lowlands of the NE Czech Republic, *Rewiev of Paleobotany and Palynology,* 244: 54-64.

Kysela, J., Bursák, D., **Houfková, P.**, Šálková, T. (2017) Stebno-Nouze: pozoruhodný laténský depot z Podbořanska, *Archeologické Rozhledy,* LXIX: 74-108. (in Czech)

Houfková, P., Bešta, T., Bernardová, A., Vondrák, D., Pokorný, P., Novák, J. (2017) Holocene climatic events linked to environmental changes at Lake Komořany Basin, Czech Republic, *Holocene*, 27: 1132-1145.

Novák, J., Abraham, V., **Houfková, P.**, Kočár, P., Vaněček, Z., Peška, J. (2017) History of the Litovelské Pomoraví woodland (NE Czech Republic): A comparison of archaeo-anthracological, pedoanthracological, and pollen data, *Quaternary International*, 463: 352-362.

Novák, J., Abraham, V., Kočár, P., Petr, L., Kočárová, R., Nováková, K., **Houfková, P.**, Jankovská, V. & Vaněček, Z. (2017) Middle- and upper Holocene woodland history in central Moravia (Czech Republic)

reveals biases of pollen and anthracological analysis, *Holocene,* 27: 349-360.

Šálková T., Hiltscher T., Novák J., **Houfková P.**, Kovačiková L (2017) Bioarcheologická anaýza polykulturní lokality Písek -AISIN II (okr. Písek) z roku 2014, *Archeologické výzkumy v jižních Čechách,* 30: 185-211. (in Czech)

Šálková T., **Houfková P.** (2017) Organické materiály jako součást depotů kovových artefaktů, in Chvojka et al. (eds.) *Nové české depoty doby bronzové.* České Budějovice, Praha, Plzeň: Jihočeská univerzita v Českých Budějovicích, Archeologický ústav AV ČR, Západočeské muzeum v Plzni. 195-197. (in Czech)

Hošek, J., Prach, J., Šída, P., **Houfková, P.**, Vondrák, D., Lisá, L., Pokorný, P., Chvojka, O., Dohnal, J. (2016) Sedimentární vývoj pozdně glaciálních jezer u Veselí nad Lužnicí, *Geoscience Research Reports,* 49: 157-164. (in Czech)

Chvojka, J., John, J., Thomovái, Z., Bezděk, A., Bumerl, J., Dudáček, K., **Houfková, P.**, Kovačiková, L., Kovář, D., Šálková, T. (2016) Bošilecký poklad. České Budějovice: Jihočeská univerzita v Českých Budějovicích, 175 pp. (in Czech)

Houfková, P., Bumerl, J., Pospíšil, L., Karlík, P., Beneš, J., Bernardová, A., Hrabalíková, M., Janečková Molnárová, K., Hejcman, M. (2015) Origin and development of long-strip field patterns: A case study of an abandoned medieval village in the Czech Republic, *Catena,* 135: 83-91.

Čapek, L., Chvojka, O., Kodýdková, K., Beneš, J., **Houfková, P.**, Myšková, E. (2015) Středověká odpadní jímka domu čp. 7 v Krajinské ulici v Českých Budějovicích ve výsledcích rozboru artefaktů a environmentálních analýz, *Archeologické výzkumy v jižních Čechách,* 28: 227-252. (in Czech)

Hlásek, D., **Houfková, P.,** John, J., Novák J., Šálková T. (2015) Všemyslice – Kozí vrch. Nové poznatky o hradišti z počátku střední doby bronzové, výsledky multidisciplinárního výzkumu, *Archeologie západních Čech,* 9: 96-121. (in Czech)

Hlásek, D., Chvojka, O., Šálková, T., Fröhlich, J., **Houfková, P.,** Kovačiková, L., Majer, A., Menšík, P., Michálek, J., Netolický, P., Novák, J., Pavelka, J., Petřík, J., Sosna, D. (2015) Vrcovice. Hradiště z počátku střední doby bronzové. *Archeologické výzkumy v jižních Čechách*. Supplementum 10. České Budějovice: Jihočeské muzeum v Českých Budějovicích, 320 pp. (in Czech)

Šálková, T., **Houfková, P.,** Jiřík, J., Kovačiková, L., Novák, J., Pták, M., Bešta, T., Čejková, A., Myšková, E. (2015) Economy and Environment of a Medieval Town Reflected in Wells Backfill in Písek, Bakaláře Square (South Bohemia, Czech Republic), *Interdisciplinaria Archaeologica, Natural Sciences in Archaeology,* 4: 63-82.

Šálková, T., Bezděk, A., Březinová, H., Farkašová, K., **Houfková, P.,** Chvojka, O., John, J., Koník, P., Kovačiková, L., Michálek, J., Novák, J., Pavelka, J., Šuláková, H., Bešta, T., Myšková, E., Weiter, L., Zronek, P. (2015) Bioarchaeological reconstruction of the funeral rite – case study based on organic material from the Hallstatt Period tumulus at the site Zahrádka (South Bohemia, Czech Republic), *Památky archeologické,* 106: 95-135.

Vondrák, D., Prach, J., **Houfková, P**. (2015): Sediments of postglacial lakes in the Czech Republic – unique natural archives overlooked by (Czech) limnology, in Rádková, V., Bojková, J. (eds.): *XVII. konference České limnologické společnosti a Slovenskej limnologickej spoločnosti „Voda – věc veřejná“ - Sborník příspěvků. Mikulov 29.6.-3.7.2015*, Brno: ČLS a Masarykova univerzita v Brně. 162-167. (in Czech with English abstract)

John, J., **Houfková, P.** (2014) Laténský depot z Holubova, *Archeologické výzkumy v jižních Čechách*, 27: 181-192. (in Czech)

Hlásek, D., **Houfková, P.**, Kovačiková, L., Majer, A., Novák, J., Pavelka, J., Bešta, T., Šálková, T. (2014) The Use of Environmental Methods for Studying the Fortification, Economic System and Natural Environment of a Hillfort from the Beginning of the Middle Bronze Age at Vrcovice, Czech Republic, *Interdisciplinaria archaeologica, Natural Sciences in Archaeology,* V: 31-47.

Prostředník, J., Hadacz, R., **Houfková, P.**, Novák, J. (2014) Bioarcheologický výzkum skalní dutiny Velbloud v Klokočských skalách, *Archeologie ve středních Čechách*, 18: 114-145. (in Czech)

Pokorná, A., **Houfková, P.**, Novák, J., Bešta, T., Kovačiková, L., Nováková, K., Zavřel, J., Starec, P. (2014) The Oldest Czech Fishpond Discovered? An Interdisciplinary Approach to Reconstruction of Local

Vegetation in Mediaeval Prague Suburbs, *Hydrobiologia*, 730: 191-213.

Zímová, K., Pospíšil, L., Janovská, V., Karlík, P., **Houfková, P.**, Bumerl, J., Molnárová, K., Beneš, J., Bernardová, A. (2013) Analýza vývoje plužiny zaniklé obce Malonín na Prachaticku, *Acta Pruhoniciana,* 104: 27-37. (in Czech)

Beneš, J., Pták, M., Dobisíková, M., Hojerová, H., **Houfková, P.,** Kutílková, P., Parkman, M., Šálková, T., Žďárský, E. (2012) Výzkum Hradiště Na Jánu v Netolicích v krajinných, antropologických, genetických a artefaktuálních souvislostech: Zpráva za sezónu 2011, *Archeologické výzkumy v jižních Čechách,* 25: 265-277. (in Czech)

Starec, P., **Houfková, P.,** Bernardová, A. (2012) Příspěvek k poznání přírodních podmínek Nového Města – výzkum v Panské ulici čp. 1308/II, *Staletá Praha* 28/2: 102-117. (in Czech)

Houfková, P., Bernardová, A., Nováková, K., Novák, J. (2011) Závist by Sepekov: Vegetation dynamics of a fir stand and alder carr during the Late Holocene. In Chvojka O. et al., (eds.) Osídlení doby bronzové v povodí říčky Smutné v jižních Čechách, *Archeologické výzkumy v jižních Čechách, Supplementum 8.* České Budějovice, 328-333. (in Czech)

Kosňovská, J., **Houfková, P.** Kovář, D. (2011) Lannova street, České Budějovice, based on archaeobotanical analyses and historical sources, *Archeologické výzkumy v jižních Čechách* 24: 263-280. (in Czech)

Novák, J., Bernardová, A., Bešta, T., **Houfková, P.** & Jankovská, V. (2011) The littoral part of the Komořany Lake from a paleoecological perspective, *Severočeskou přírodou*, 42: 83-88. (in Czech)

Selected conference contributions

Houfková, P., Bernardová A., Novák J., Horák J. (2014) Complex of mountain mires located in the Ore mountains, Central Europe: its origin and development. *Culture, Climate and Environment Interactions at Prehistoric Wetland Sites*, Bern, Switzerland. (poster presentation)

Uhrová, K., **Houfková, P**., Beneš, J. (2013) Late Glacial vegetation development of the South Bohemian Basin, Czech Republic. *Pollen*

Monitoring Programme 9th International Meeting, Prague, Czech republic. (poster contribution)

Houfková, P., Novák, J., Bernardová, A. (2013) Fire history and vegetation dynamics recorded in sediment of the Komořany lake, Czech republic. *56th Symposium of the International Association for Vegetation Science (IAVS 2013)*, Tartu, Estonia. (poster presentation)

Houfková, P., Pták, M., Jiřík, J., Kodýdková, K., Vaněček, Z., Stehlíková, E., Baudyšová, J., Majer, A., Bešta, T., Komárková, V., Beneš, J., Divišová, M., Šálková, T. (2013) Archeobotanical evidence of human impact within the area of Pisecke mountains, Czech Republic, *6th Conference of The International Workgroup for Palaeoethnobotany*, Thessaloniki, Greece. (poster contribution)

Bernardová, A., **Houfková, P.**, Novák, J., Chvojka, O., Nováková, K. (2013) Of alder and man. *6th Conference of The International Workgroup for Palaeoethnobotany*, Thessaloniki, Greece. (poster contribution)

Houfková, P., Bešta, T., Bernardová, A., Jankovská, V., Valentová, D., Lisá, L., Novák, J. (2012) Multi-proxy paleoecological study of the profile PK-1-C from the former Komořany Lake, Czech Republic. *12th International Palaeolimnology Symposium*, Glasgow, Great Britain. (poster presentation)

Bešta, T., Novák, J, Jankovská, V., Lisá, L, **Houfková, P.**, Bernardová, A., Dreslerová, D., Valentová, D., Tátosová, J., Vondrák, D. (2013) Vývoj Komořanského jezera ve světle nových informací ze zachráněných profilů. *9th Conference of Enviromnental Archaeology*, České Budějovice (oral presentation)

Pospíšil, L., **Houfková, P.,** Bumerl, J., Karlík, P., Beneš, J., Zímová, K., Janovská, V., Molnárová, K., Bernardová, A. (2013) Vývoj historické plužiny s agrárními terasami ve světle interdisciplinárního přístupu. *9th Conference of Enviromnental Archaeology*, České Budějovice (oral presentation)

Bešta, T., Novák, J., Jankovská, V., Lisá, L., **Houfková, P.,** Bernardová, A. (2012) Multi-proxy resarch of the exploited former lake, Lake Komořany, Czech Republic. *12th International Palaeolimnology Symposium*, Glasgow, Great Britain. (poster contribution)

Jiřík, J., Pták, M., Šálková, T., **Houfková, P.,** Kovačiková, L. (2012) Archaeological Excavation at the Bakaláře Square in Písek (South Bohemia): Medieval and Early Modern Water Management. *22. Treffen: Archäologische Arbeitsgemeinschaft Ostbayern /West- und Südböhmen /Oberösterreich*, Attersee – Mondsee, Austria. (oral presentation)

Myšková, E., **Houfková, P.**, Kočár, P., Cymbalak, T., Ditrich, O. (2012) Palaeoparasitological findings at an archaeological locality in Prague, Národní třída. *8th Conference of Enviromnental Archaeology*, Praha. (poster presentation)

Houfková, P., Pokorná, A., Bešta, T., Kovačiková, L., Nováková, K., Starec, P. (2011) The oldest Czech medieval pond, Prague. *Environmental Archaeology of Urban Sites*, Gdansk, Poland. (poster presentation)

Pedagogical activity

2017: Imaging in bioarchaeology (selected lectures)

2015–2016: Archaeobotany + Archaeobotany for archaeologists (selected lectures)

2012–2016: Introduction to environmental archaeology (selected lectures)

2012: Field work for biologist (selected lectures)

2011–2015: Archaeological field work (selected lectures)

2011–2015: Palynology (assistance with selected seminars)

2015–2017: co-supervisor of the Msc. thesis: Pravcová, I. (2017) Holocene fire dynamics in the upper parts of the Ore Mountains with the focus on the Middle Ages

2013–2015 co-supervisor of the Bsc. thesis: Trávníková, K. (2015) Human impact recorded by pollen analysis in sediments of Netolicko region

2011–2012 supervisor of the Bsc. thesis: Uhrová, K. (2012) Palaeoecological study of a site near the Černiš fish pond (České Budějovice, Czech Republic).

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