REVIEW

Review on vegetation, landscape and climate changes in the Carpathian Basin during the Neolithic and Chalcolithic period

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Abstract

The Neolithic and Copper Age (CA) of Hungary (6000–2800 cal BC) represents a meticulous construction of settlement structure, material culture, arable farming and herding techniques with at least one, but likely several reappearing population movements that brought in innovations and possibly contributed to the societal changes in this period. The last couple of decades witnessed a considerable progress in the study of concurrent vegetation, climate and landscape management changes particularly via the increased number of high-resolution pollen records, archaeobotanical and archaeological investigations, coupled with stable isotope analyses of the charred cereal assemblages. In this review we synthetize the results of these research projects and demonstrate that the Neolithic and CA landscapes of Hungary were characterised by mixed oak forest communities, and in the territory of Hungary thermophilous steppe oak forests were present in the lowland landscape that were the principal choice of early farmers represented by the Körös-Starčevo-Criş cultures. Climate modelling and climate reconstruction from these regions indicate higher than preindustrial summer mean temperatures and higher than modern summer rainfall. We demonstrate that Linear Pottery Culture was the first culture that technologically advanced to clear larger plots of land for crop cultivation purposes. The first large scale and landscape level clearance is discernible in the Hungarian pollen records in the Late Neolithic period, when population size likely reached its Neolithic maximum, both in the lowlands and the surrounding mid-mountains.

Keywords Neolithic · Vegetation change · Climate · Hungary · Pollen · Archaeobotany

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Introduction

Since the work of Willis and Bennet (Willis and Bennett 1994), the question whether Neolithic populations of the Aegean, Balkan and Carpathian (ABC zones) (Chapman and Souvatzi 2020) shaped their natural environment in a way that moved these ecosystems out from their safe operational space and influenced their natural climate-induced succession, comes up repeatedly (Magyari et al. 2012; Chapman 2018; Sümegi et al. 2020) without a satisfying unequivocal answer. According to Kaplan (Kaplan et al. 2011), subsistence required a relatively large area until about ~500 cal BC due to technological limitations (ca. 6.5 ha/capita), while the archaeological literature estimates Late Neolithic (LN) population agglomeration in the ABC zone just under 1,000 individuals in one settlement (Müller et al. 2016). The only exceptions are the LN Trypillia megasites in the Ukrainian Pontic forest steppe region, where earlier estimates suggested > 10,000 capita per settlement (Müller et al. 2016),

but recent research raised the possibility of pilgrimage or seasonal assembly as the main function of these sites with a restricted long-term settlement activity (Albert et al. 2020; Gaydarska et al. 2020). Ongoing archaeobotanical and archaeozoological work, on the other hand, attests to permanent settlement and well-developed agro-pastoral communities (Makarewicz et al. 2022). In addition, it was demonstrated (Bogaard et al. 2007, 2013, 2019) that until the invention of plough and animal traction during the 4th millennium BC, arable farming tended to be labour intensive (hoe-farming), incorporated manuring and was integrated with small-scale herding. This finding overall suggests that particularly in the Early (EN) and Middle Neolithic (MN) the visibility of small populations with relatively small fields (gardens) at site-proximity will likely remain difficult to notice using landscape level methods, such as pollen analysis. The transformation of farming from a labour-limited to a land-limited agriculture took place during the 4th millennium BC, in the Aeneolithic/Chalcolithic Period (~ Copper Age in Hungary; Bogaard et al. 2019) south of the Great Hungarian Plain (GHP) with the invention of plough and animal traction. This is the turning point, at which we expect an intensification of land use and possibly forest clearance to enlarge available arable land and possibly also pastures, the latter due to the demand to maintain larger herds. It remains however questionable when this transformation towards increased animal power use with larger arable fields became the main motivation for keeping more cattle.

According to our current knowledge, LN societies (Table 1) of the GHP (Tisza-Herpály-Csőszhalom cultures) and Transdanubia (Lengyel Culture) have not yet used plough and animal traction, but towards the end of the Aeneolithic/Copper Age (CA), people of the late Lengyel-Balaton-Lasinja and Baden cultures introduced animal traction, ploughing and wagons (Klimscha 2017), as suggested by the finding of a twin-yoked oxen copper animal statuette in northern Slovakia (Liskovská cave, Struhár et al. 2010) and numerous wagon and wheel models at Late Copper Age (LCA) Boleráz and Baden sites in Hungary (Soproni 1954; Ilon 2001; Horváth 2010; Bondár 2012, 2013). In addition to this, new archaeozoological data from 11 sites from the Balkans prove that between 6100 and 4500 cal BC there was a longer history of the use of cattle for 'light' traction (Gaastra et al. 2018). The earliest date of wagon use in the Carpathian Basin (CB) is assumed to be around the mid 4th millennium BC (~ 3500 cal BC; Bondár 2012). This inference was also supported by Țurcanu (2020) who proved that the cultures in the Balkans and the CB (Ariuşd-Cucuteni-Trypillia cultural complex) were already familiarized with animal traction before its exponential dissemination towards the end of the 4th millennium BC. In the GHP, a clear change of the material representation of prestige is discernible for the LCA at 3600/3500 cal BC, when instead of copper and gold objects in the earlier Tiszapolgár and Bodrogkeresztúr graves, the deposition of paired cattle burials and clay cart models indicate a new 'nomadic' value system (Hansen 2009). This is a

Table 1 Chronological division of the Neolithic, Copper Age and Early Bronze Age in the Carpathian Basin with respective cultures in the eastern and western part of the basin; after Parkinson (2006, p 57, Fig. 4.4), Raczky and Siklósi (2013, p 570, Fig. 7), Pusztainé Fischl et al. (2015, Fig. 1a, b) and Salisbury (2016, Table 3.1)

Chronology (BC)	Period	Cultures/groups in the Eastern Carpathian Basin (East Hungary)	Cultures/groups in the Western Carpathian Basin (West Hungary)
2800/2500–2000	Early Bronze Age	Late Nagyrév, Hatvan, Nyírség/Szaniszló	Kisapostag, Gáta-Wieselburg I
	3	Otomani I, Maros	
		Late Makó, Nyírség,	
	2	Early Nagyrév, Early Maros	Late Somogyvár/Proto Kisapostag
		Makó, Yamnaya	
	1		Somogyvár-Vinkovci, Late Vučedol/ Early Somogyvár-Vinkovci
3500–2800	Late Copper Age	Late Baden,	Vučedol, Kostolac
		Yamnaya, Early Makó	Late Baden
		Baden	Baden
		Pre-Yamnaya	
		Proto-Boleráz, Boleráz	Proto-Boleráz, Boleráz
4100–3500	Middle Copper Age	Hunyadihalom	Stab-and-drag (Furchenstich) Ornamented Pottery
4500–4100	Early Copper Age	Tiszapolgár, Bodrogkeresztúr, Ludanice	Lengyel III, Balaton-Lasinja
5000–4500	Late Neolithic	Tisza-Herpály-Csőszhalom	Lengyel I-II
5500–5000	Middle Neolithic	Alföld Linear Pottery Culture (ALPC), Bükk, Tiszadob, Szakálhát, Esztár	Transdanubian Linear Pottery Culture (TLPC), Zseliz, Sopot-Bicske
6000–5500	Early Neolithic	Körös	Starčevo

sharp turn compared to previous management practices. The Baden (3600–2800 cal BC) economic system was described by Horváth (2012) as a large animal keeping, pasturing and extensive lifestyle completed with cultivation of varying proportions within wet climatic circumstances, but not a fully nomadic lifestyle.

From the numbers above, one would expect low intensity human disturbance on the natural vegetation in general for the Neolithic and Early Copper Age (ECA), and an intensification from the LCA. And indeed, a summary by Roberts et al. (2018) using large number of pollen records from Europe (over 1,000 sites) suggested that on a landscape level, forest cover was declining progressively since ~6,000 years ago (~4050 cal BC, Chalcolithic) in the mixed temperate forest zone of Europe, and this shift could clearly be linked to agricultural expansion and technological development (Bogaard et al. 2019).

On landscape level, the impact of Neolithic forest-clearance, farming and animal husbandry is most often studied by pollen analysis using lake and mire sediments located in the vicinity of known archaeological sites (Juhász 2004; Willis 2007; Sümegi et al. 2020) or large sedimentary basins with a regional pollen source area (Willis 1997; Cserny and Nagy-Bodor 2000; Nagy-Bodor et al. 2000). Such large basin pollen records allow us, via taking into account basin size and pollen productivity, to reconstruct land cover and its changes through time (Sugita 2007).

Pollen records from Hungary are still scarce, and have not yet been fully deposited in continental or global pollen databases (such as EPD, Giesecke et al. 2014, NEOTOMA or PANGAEA, Herzschuh et al. 2022). Available data however suggest that the eastern part of the GHP, which was the main territory of the first Neolithic wave (Körös Culture) was covered by naturally semi-open warm-deciduous forest steppe with a gross estimate of forest cover around 70% (Magyari et al. 2010a). As opposed, Transdanubia and the surrounding pre-Carpathian Hill region were forested (Fig. 1), with >90% woodland cover at the onset of the Neolithic expansion (Starčevo Culture) (Juhász 2007).

Pollen records furthermore attest in nearly all cases small-scale, often fire-induced episodic clearance events in this period (Willis 1997; Magyari et al. 2012), and provide evidence for woodland management (coppicing) at site level (Gardner 2002; Magyari et al. 2012) during the MN and LN. These records also suggest occasional arable faming activities at low and mid altitudes in the neighbouring Romanian Carpathian Mts (up to 440 m a.s.l.), where cereal pollen appears as early as 7,950 cal BP/6000 cal BC (Feurdean and Tanţău 2017; Gumnipor and Stobbe 2021). Further to the north, in the mid-mountain region of eastern Hungary
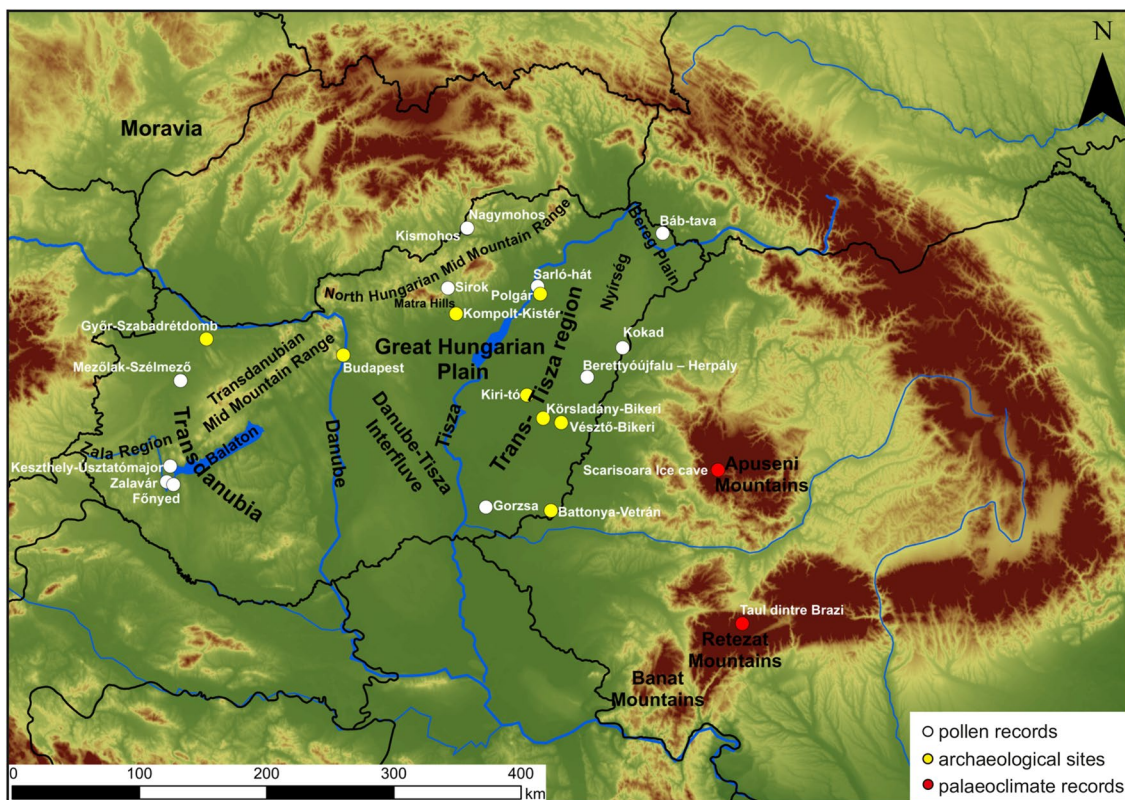

Fig. 1 Map of the Carpathian Region with the location of sites and geographical areas mentioned in the text

pollen diagrams from the Putnok Hills (300–400 m a.s.l.; Fig. 1) furthermore suggest that Neolithic farmers started to utilize this landscape already during the MN, when people of the Bükk Culture (Table 1) demonstrably used the mixed oak woodlands for hazel and elm coppicing, while populations of the Alföld Linear Pottery (ALP) Culture practiced both arable and pastoral faming in the valleys of the Putnok Hills (Magyari et al. 2001, 2012).

The aim of this paper is to summarize vegetation, land cover and climate changes in Hungary between 10,000 and 4,800 cal BP (ca. 8,050–2850 cal BC) with the help of eight pollen records from the region. The questions we seek answer for are threefold: What was the natural environment Neolithic and CA/Chalcolithic people met with in the CB? What was their impact on a landscape level? Did any of the socioeconomic transformations detected in the archaeological record coincide with marked changes in climate as inferred by biological, stable isotope proxies and climate models?

We also focus on the period of LN tell abandonment in the GHP and the subsequent spread of small farmsteads during the ECA. Here the questions we discuss are related to the causes and consequences of tell abandonment (Parkinson et al. 2002; Gyucha et al. 2013).

In this regard, the study by Hoakman-Sites and Giblin (2012) is particularly stimulating. They examined N- and C-isotopes in LN and ECA human and animal bones and found that N isotopic values remained relatively constant from the LN through the CA. They were however significantly enriched compared to EN and MN samples (Giblin et al. 2013). These enriched N isotopic values indicated that animal protein was an important component in the diet from the LN on, or there was a further increase in manuring. More animal fats were only present in pottery from the MCA and LCA, indicating an increase in the level of animal product use in the MCA. This study overall found that at the time when settlement patterns, burial practices, etc. were altered, the data do not support similar drastic shifts in animal management practices. Frequent climate changes, with periodic return of cool/wet conditions has been invoked to at least partially explain changes in the MCA and LCA economies particularly in Transdanubia, where an increased reliance on animal husbandry has been inferred from the scarcity of crop remains, the few house remains at settlements and the clear development of cattle husbandry at that time (Horváth 2012). Water level fluctuations in both Lake Balaton and the Central European alpine lakes were associated with periodic lakeshore pile dwellings in drier periods followed by site abandonments in wet periods characterised by decreased solar activity (Magny 2004; Magny and Haas 2004; Arbogast et al. 2006; Magny et al. 2006; Schöll-Barna et al. 2012). These data suggest that during the MCA and LCA (~Hypsithermal/Neoglaciation

transition) frequent alteration of the climate might have caused more frequent crop failures that facilitated innovative and adaptive plant and animal husbandry solutions and aided technological development. We will also review available records on this question in this paper.

Pollen and archaeobotany inferred natural vegetation of the Carpathian Basin before and during the Neolithic and Chalcolithic/Copper Age

In the eastern CB both the Trans-Tisza and the Danube-Tisza interfluve (Fig. 1) regions are characterized by a multitude of riverbeds formed by the Danube and Tisza rivers and their tributaries that have been meandering in the Holocene and left behind a dense palaeochannel network (Borsy and Félegyházi 1983; Gillings 1997, 2007a; Gábris 1998). Most of them accumulated Holocene lake and mire sediments often with satisfactory pollen preservation, but in many cases with sedimentary hiatuses. It is also common that the records do not cover the entire Holocene (Buczkó et al. 2009). Along with pollen records from large tectonic and landslide basins, these palaeochannel pollen records are valuable and can be used to reconstruct the Holocene vegetation dynamics in the CB landscape. In the following section, we will summarize Neolithic and CA vegetation changes using eight pollen records from Hungary. Table 2 gives details of these sites with important information on the original publications, geographical position, catchment size, time resolution of the Neolithic and CA sections of the records and the number of radiocarbon dates used for age-depth modelling of these records.

In brief, Sarló-hát is probably the best-studied and highest-resolution pollen record that is coming from the palaeo-channel of the river Tisza in north-east Hungary. The oxbow lake was separated from the main river around 11,400 cal BP, and sediment accumulation has been continuous in it since then. At the core location ~ 7 m thick lake sediment was obtained. In scope of the Upper Tisza Project (Chapman et al. 2010) systematic archaeological field walking was done in this area, and excavation of several Neolithic and Bronze Age sites has been done in this region in the early 2000s, in connection with the M3 motorway construction (Raczky and Anders 2008; Raczky et al. 2011). Báb-tava is another oxbow lake in the Bereg-Plain, in north-west Hungary (Fig. 1). Currently occupied by a wooded *Sphagnum*-bog with birch trees, this is a protected site, from which a ~ 5 m long sediment core was obtained in 1998 and studied for pollen by Magyari et al. (2008). The pollen record represents the last 7,800 years. Given the remote location of this oxbow lake with limited archaeological survey in this potentially forested corner of the GHP, the original study

Table 2 Geographical characteristics, dating details and time resolution of the pollen records discussed in the paper; analysts' full names are *EM* Enikő Magyari, *AG* Adam Gardner, *KJW* Kathrine J. Willis, *IJ* Imola Juhász, *ZSM* Zsófia Medzihradszky, *RCS* Réka Csorba

Site name	Site type	Latitude Longitude	Elev (m)	Core length (cm) age interval (cal BP)	No. ^{14}C dates	Resolution between 10–4.8 kyr cal BP	Analyst	Coring year	References
Sarló-hát (SH-WOOD)	Palaeochannel fen	47° 58′ 01″ 21° 10′ 09″	86	698 0–11,400	14 AMS, plant macro	142	EM	2003	Magyari et al. 2010a, 2012b
Báb-tava (BT-1)	Infilled oxbow lake, *Sphagnum* bog	48° 11′ 09″ 22° 28′ 5 9″	107	510 0–7,800	4 bulk	58	EM	1998	Magyari et al. 2008
Sirok	Wooded *Sphagnum* bog	47° 55′ 48.6″ 20° 11′ 08.4″	200	450 c. 0–10,000	5 bulk	36–113	AG	1995	Gardner 1999, 2002
Kismohos	Wooded *Sphagnum* bog	48° 24′ 40″ 20° 24′ 30″	306	886 0–14,600	13	119	KJW	1995	Willis et al. 1997, 1998
Nagy-mohos	*Sphagnum* bog	N48°20′ 20″ E:20° 25′ 30″	297	430 0–27,000	13	80	EM	1995, 1997	Magyari et al. 1999, 2014
Zalavár (Zalavári-1)	Shallow lake	46° 40′ 00.8″ 17° 13′ 06.2″	106	380 1,000–11,500	8 AMS	158	IJ	c. 1994	Juhász 2007
Keszthely-Úsztató-major	Lakeshore swamp	46° 45′ 46″ 17° 13′ 30″	110	480 2,000–12,000	11 bulk	95	ZSM	?	Medzihradszky 2001b; Szántó and Medzihradszky 2004
Hódmező-vásrhely Gorzsa (Kéró-ér)	Infilled palaeochannel	46° 19′ 7″ 20° 17′ 20″	82	0–2,000 6,900–9,600	10 AMS, plant macro	106	EM, RCS	2021	This paper

showed archaeological site numbers in 50 km radius of the lake. Kismohos and Nagymohos are wooded *Shpagnum*-bogs located near to each other in landslide basins in the North-Hungarian Putnok Hills (Fig. 1). Their altitude is around 300 m, the distance between the two bogs is about 500 m, but still their formation time and pollen catchment area differs. Kismohos was formed ~ 15,000 years ago via a landslide, and until the Middle Ages its pollen record is continuous (Willis et al. 1998). Its north–south orientation with a shading steep eastern slope and its small size (1 ha) results in a cool microclimate and small catchment size. Both peatbogs are also fed by springs, their vegetation is transitional between bogs and fens. Nagymohos is larger (1.65 ha), it has been formed ~ 27,000 years ago by a landslide (Magyari et al. 1999, 2014). However, sediment accumulation has not been continuous in this basin. A hiatus is observed between 15,000 and 9,000 cal BP (Magyari et al. 2001). Furthermore, peat cutting in the Iron Age removed layers younger than 6,000 years. The Neolithic is however well-represented. Sirok peat bog is located in the eastern fringe of the Mátra Hills (Fig. 1). It was originally

studied for pollen by Gardner (1999, 2002) and the site has been revisited for plant macrofossil analysis by Jakab et al. (2004). Approximately 4 m moss peat accumulated in this landslide basin since 10,000 cal BP. Peat accumulation has been continuous and Gardner (1999) found evidence for CA coppicing around the site. Zalavár is a palaeochannel in the vicinity of Lake Balaton in Transdanubia (Fig. 1). It has been studied for pollen in scope of the PhD work of Imola Juhász (Juhász et al. 2001; Juhász 2007). The pollen record is continuous between ~ 11,500 and 1,000 cal BP. We also mention briefly the pollen record of Keszthely-Úsztatómajor (Medzihradszky 2001a; Szántó and Medzihradszky 2004), which is located on the northwestern shore of Lake Balaton in Transdanubia (Fig. 1). This pollen record comes from the lakeshore wetland zone of Lake Balaton and provides a continuous pollen record for the period 12,000–2,000 cal BP. Finally, we also present the pollen record of a recently cored palaeochannel from SE Hungary. Hódmezővásárhely-Gorzsa (Fig. 1) comes from the vicinity of a LN tell site with the same name (Horváth 2020). The meander is located in the southwestern corner of the tell. We obtained a 500 cm long

Fig. 2 Pollen percentage diagram of core SH-WOOD, Sarló-hát, ▶
Tiszagyuláháza, north-east Hungary; percentages of selected terrestrial pollen taxa are plotted against age (cal BP) and depth; microcharcoal accumulation rates, palynological richness, reconstructed biomes and steppe indicator pollen frequencies are also shown; *EN*
Early Neolithic, *MN* Middle Neolithic, *LN* Late Neolithic, *ECA* Early
Copper Age, *MCA* Middle Copper Age, *LCA* Late Copper Age, *AP*
arboreal pollen, *NAP* non-arboreal pollen; crossed circles at the left of
the diagram mark the positions of the.[14]C dates; palynological richness was calculated using rarefaction analysis in which the minimum
terrestrial pollen sum was 500 (E$_{(T500)}$)

core from the Kéró-ér meander in 2021. AMS ^{14}C dates and
the Bacon age-depth model of this site are presented in ESM
Table S1 and Fig. S5.

Probably the best studied of these records is the Sarló-hát
meander in the Polgár-Tiszagyuláháza region in the GHP
(Fig. 1, Magyari et al. 2010a, b, 2012). Its high-resolution
pollen diagram is supported by a robust age-depth model
based on 12 AMS ^{14}C measurements (Magyari et al. 2010a,
2012; Magyari 2011). In the Early Holocene (EH) part of
this record (11,400–10,250 cal BP/9450–8300 cal BC, Fig. 2),
pollen from woody plants accounts for only 40–55% of the
terrestrial pollen assemblage suggesting a wooded steppe
environment. Deciduous trees were already present and
dominant: *Betula pendula* (tree birch), *Salix* spp. (willow),
Ulmus spp. (elm), *Fraxinus excelsior/F. angustifolia* (ash),
Corylus avellana (hazel), *Quercus robur*-type (deciduous
oak) and *Tilia* (linden). Pines (*Pinus* diploxylon-type) also
accounted for 20%, suggesting that *P. sylvestris* (Scots pine)
was probably still present on the sandy surfaces, but no
longer had significant cover in the area. Near the riverbed,
softwood groves (low floodplain forest) with *Salix* species
and hardwood groves (high floodplain forests) have already
formed composed of *Fraxinus excelsior,* likely also *F. angustifolia* ssp. *pannonica*, *Quercus* and *Ulmus*. The characteristic of the period, which is evident in several pollen diagrams
east of the Danube, is the high frequency of elm trees in the
woody vegetation. Low, open-structure forest patches similar to the recent continental Ukrainian forest-steppe were
inferred based on this pollen composition (Fig. 2).

Biom reconstruction furthermore suggested (Fig. 2) the
presence of a cool mixed forest-steppe largely due to the
presence of *Picea abies* (Norway spruce). Spruce is present
in all Early Holocene EH) lowland pollen records in East
Hungary, even in the south GHP and Nyírség region (see
the Hódmezővásárhely-Gorzsa pollen record on Fig. 3), suggesting that these needle leaved trees survived into the EH
from the Late Glacial period, likely in the North-Hungarian
mid-mountains and in the Bereg Plain (Magyari et al. 2008;
Pató et al. 2020), when needle leaved forests were dominant.
However, the structure of the EH forest-steppe in the GHP
cannot be inferred from pollen data. We can only use modern
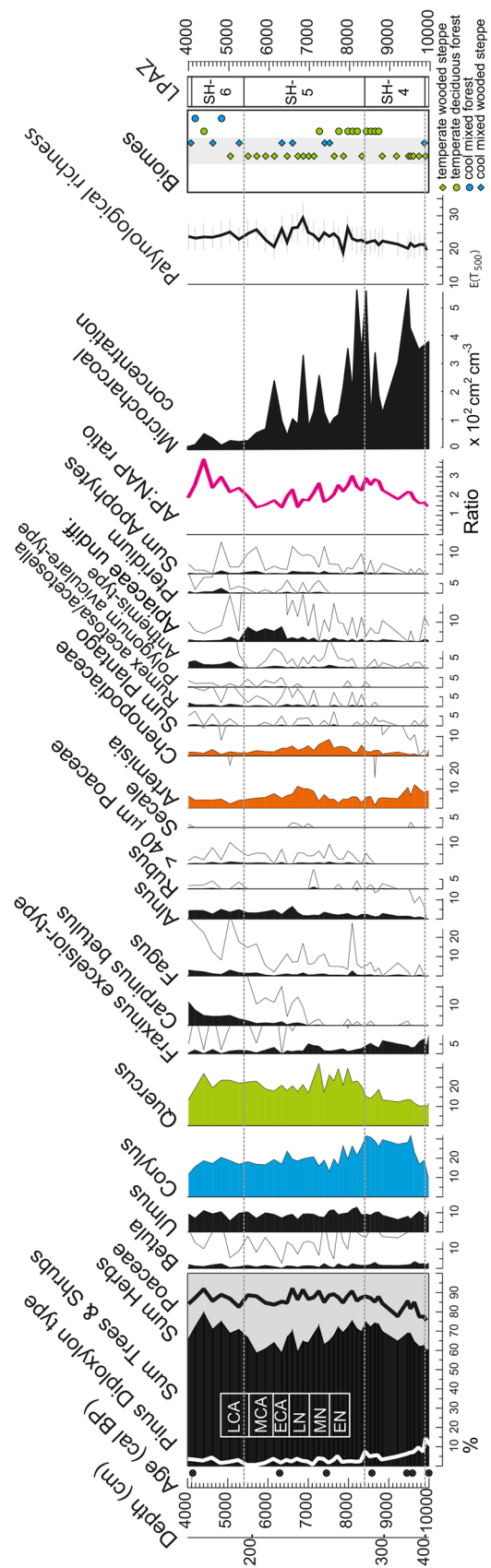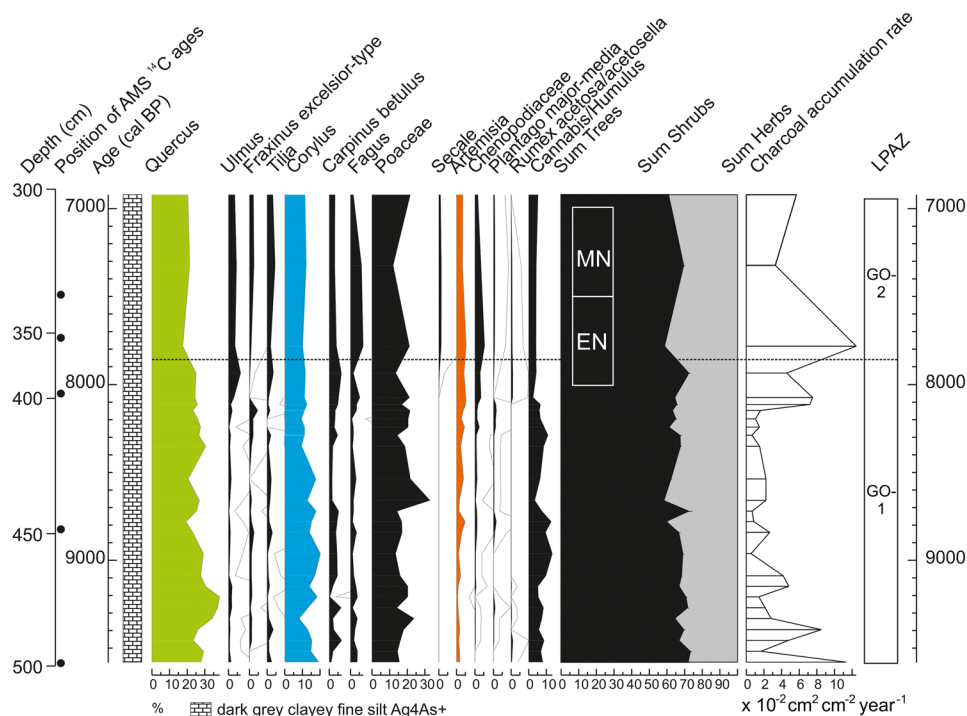analogues and the soil maps of the area, assuming that the

Fig. 3 Relative frequency diagram of selected pollen types for the early and mid-Holocene from Hódmezővásárhely-Gorzsa palaeochannel, SE Hungary; for site locations see Fig. 1, for radiocarbon dates and age-depth model see ESM Table S1 and Fig. S5

forests may have been patchy, in the form of closed groups of trees in the floodplain, while the loess-mantled Pleistocene river terraces were savannah like (see also Sümegi 2012).

Pollen from tall herbs were abundant in these EH pollen records suggesting the presence of floodplain wet grasslands. Important features of the Sarló-hát pollen diagram (Fig. 2) and several other pollen records from this period (e.g. Kokad; Feurdean et al. 2019; Vincze et al. 2019, see Fig. 1) ares the high microcharcoal accumulation rates that indicate frequent woodland fires (Fig. 3; see also Magyari et al. 2010a; Feurdean et al. 2012, 2020; Finsinger et al. 2014; Carter et al. 2020). This phenomenon was observed in the eastern parts of the CB as well as in the Carpathians and clearly indicate the increased continentality of the EH climate with warmer than present summer temperatures driven by insolation and the related frequent prevalence of droughts.

About 10,250 years ago (~ 8200 cal BC), a significant change in the pollen assemblages was observed in eastern Hungary. In the Sarló-hát pollen sequence (Fig. 2), the proportion of trees increased moderately, mainly *Quercus robur*-type and *Fraxinus excelsior/F. angustifolia*, but also *Corylus avellana* after 8,250 cal BP (~ 6200 cal BC). Steppe indicator herbs decreased (Poaceae, *Artemisia*), but still reached 10–15% (Fig. 2). This short transitional period lasted until 7,900 cal BP (~ 5950 cal BC), and was characterised by an increase in mixed *Quercus* and *Corylus* woodland cover in the floodplain and in the loess and sand areas of the floodplain. The role of *Corylus* is ambiguous

in the absence of analogues, but it was probably a canopy component of mid-mountain and high floodplain forests. Deciduous forest steppe was the typical vegetation in the GHP (see biomes on Fig. 3) at his time, which directly precedes the Neolithic in East Hungary.

Between 7,900 and 5,400 cal BP (5950–3450 cal BC) the proportion of herb pollen was still relatively high (25–42%), and steppe taxa reached 12% (Figs. 2 and 3). Overall, this suggests that the landscape of the northern (represented by Sarló-hát) and southern GHP (represented by Hódmezővásárhely-Gorzsa) was semi-open in this period. The first Neolithic farmers arrived in the eastern CB at this time (Körös Culture: 7,950 cal BP/~6000 cal BC, Oross and Siklósi 2012; Porčić et al. 2020). Continental steppes have survived in the landscape. Biomes reconstructed based on pollen are temperate deciduous forest and forest steppe in the northern GHP (Fig. 2). *Qercus robur*-type, *Ulmus*, *Tilia* and *Corylus* played the most important role in the composition of forests at that time. It is important to note, however, that both in terms of the dominant woody taxa and proportions, pollen diagrams can be significantly biased due to the different pollen production and dispersal rates of the pollen types (Sugita 2007). Biom reconstruction partially eliminates this effect (Fig. 2) and so does the REVEALS modelling that ideally gives us more precise representation of woodland cover at landscape level if several small sites are combined (Sugita 2007). Here we used the pollen productivity estimates of the Moravian Plateau (Kuneš et al. 2019) in combination with a recent European compilation for cereals (Githumbi

et al. 2022) (see ESM Table S2), but only combining the pollen records of three small sites in the northern GHP and North-Hungarian mountains. Therefore, these REVEALS based land cover estimates can be biased. In Transdanubia we use a single large site, Zalavár (Fig. 4). The REVEALS model based regional vegetation cover estimates attest to 80–83% forest cover in NE Hungary and about 60% forest cover in the area of Sarló-hát (Fig. 4; ESM Fig. S3). Oak forest steppe landscape dominated in the eastern GHP, and forest cover was > 80% in the Bereg Plain and in the North-Hungarian mountains (based on Kismohos and Báb-tava, see ESM Figs. S1–S2). Furthermore, the REVEALS model based vegetation reconstruction suggests that cereal cultivation had relatively small, but in a few cases demonstrable effect on total forest cover during the Neolithic (see Kismohos and Zalavár in ESM Figs. S1 and S5) with maximum 10% decrease in forest cover. Furthermore, both anthropogenic indicator and cereal pollen are present even at the mid-mountain sites (Figs. 8–9; ESM Figs. S1–S5), but their share in the vegetation was low suggesting that Neolithic populations had local vegetation modifying effects that are more visible in the fully forested western Hungary and in the NE Hungarian mid-mountains, where cereal cultivation was possible only after forest clearance. If we compare these REVEALS-based land cover estimates with the European gridded estimates of Githumbi et al. 2022 and Serge et al. 2023, we see that for the Neolithic and CA period these estimates agree well for NE Hungary (~ 20% open land), but other regions of the country have no data. If we compare our CA (4500–3800 cal BC) REVEALS-based forest cover reconstruction with the Lower Danube area (Feurdean et al. 2021), there forest cover was considerably less, around 55%. Note, however, that this reconstruction used a different PPE data set (ESM Table S2). The application of these PPEs would result in lower forest cover in Hungary as well.

A fortunate situation is the case of Polgár-Tiszagyulaháza (Fig. 1) due to the intensive research of the Neolithic and CA population in the area and the remains of MN and LN settlements belonging to the ALP and Csőszhalom cultures (Raczky et al. 2007; Raczky and Anders 2008). Recent excavations yielded rich macrocharcoal assemblages from these sites (Moskal-del Hoyo 2013; Moskal-del Hoyo et al. 2018). This area represents one rare case where forest composition obtained by pollen and macrofossils of accurately dated samples can be directly compared. In Fig. 5, we compare the percentage distributions of woody taxa based on pollen and charcoal over two time horizons, 7450–6950 cal BP (5500–5000 cal BC, MN) and 6950–6450 cal BP (5000–4500 cal BC, LN). What is striking at first glance for the MN period, is the large difference in the representation of *Corylus* between the pollen and charcoal-based forest composition. *Corylus* dominates the pollen assemblages, but it is rare in the charcoal record suggesting its overrepresentation in the pollen records, or its avoidance as firewood. This latter interpretation is however less likely, as in many other sites further west *Corylus* was often used as firewood during the Neolithic (Kreuz 1992).

In the charcoal assemblages, the relative frequency of *Quercus* and Rosaceae shrubs/trees is higher, and the frequency of *Cornus* spp. (dogwoods) reaches 10%. This comparison suggests that oak forests dominated the floodplain forest steppe landscape between 7,250 and 6,950 cal BP (5300–5000 cal BC, MN). *Cornus mas* (Cornelian cherry) was likely an important element of these forests. Its fruits were reported from the MN and LN archaeological sites at Polgár and several other Neolithic sites in Hungary (Gyulai 2010). This species is an important component of sub-Mediterranean wooded steppe forests today in the Serbian Great Plain, the Thracian Great Plain in Bulgaria and in the northwestern part of Turkey where in many wooded steppe associations it occurs in the company of sub-Mediterranean oak species (*Quercus frainetto, Q. cerris, Q. pubescens* and *Q. infectoria*) (Horvat et al. 1974; Bohn et al. 2004). Together with the sporadic presence of

Fig. 4 Pollen-based land cover reconstruction on the basis of eastern and western Hungarian pollen records using the REVEALS model of Sugita (2007), the pollen productivity estimates of Kuneš et al. (2019) from the Moravian Upland and the combined European pollen productivity estimates (PPE) of Githumbi et al. (2022); pollen data were recalculated to even age intervals (200 yrs); PPE values and the description of the method is provided in ESM Method and Table S2; for further abbreviations see Fig. 2
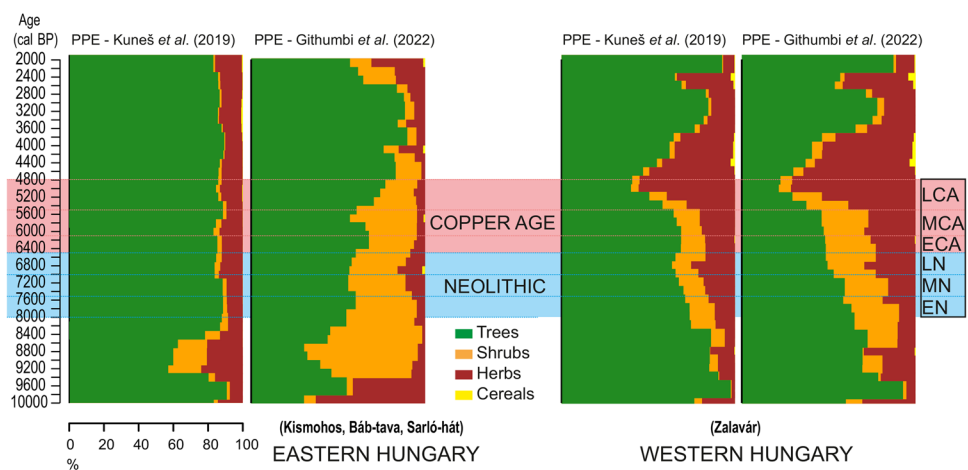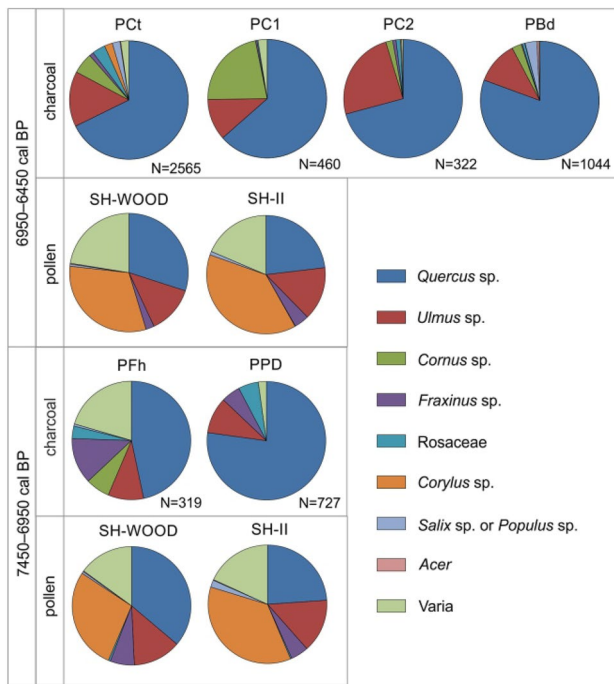
Fig. 5 Pie-charts of tree pollen relative frequencies from the Neo-lithic layers of SHWOOD, Sarló-hát, Tiszagyulaháza-Polgár region, Hungary (left panel), and relative frequencies of charcoal assemblages collected from Neolithic archaeological sites (MN and LN) in the vicinity of Polgár, NE Hungary (*PFh* Polgár-Ferenci hát, *PPD* Polgár-Piócási-dűlő, *PCt* Polgár-Csőszhalom tell, *PC1* Polgár-Csőszhalom 1, *PC2* Polgár-Csőszhalom 2, *PBd* Polgár-Bosnyák-domb); charcoal data were originally published by Moskal-del Hoyo 2013, pollen data by Magyari et al. 2012 and pollen-charcoal data comparison by Moskal-del Hoyo et al. 2018

another sub-Mediterranean shrub, *Cotinus coggygria* (smoke tree), in the charcoal record, these findings indicate that in this mid-Holocene period, the elevated chernozem covered loess terraces of the GHP were likely characterized by sub-Mediterranean oak forest steppes. This also indicates a warmer environment than today, which is in good agreement with higher summer insolation, increasing winter insolation, and higher values for the chironomid-inferred July mean temperature reconstruction for this period (Tóth et al. 2015). An interesting phenomenon is that a large number of *Cornus* sp. charcoal pieces and *C. mas* fruits from the EN and MN period have also been found in Neolithic sites along the Danube to the south (Marinova et al. 2013). Based on these data, it is likely that the EN farmers followed the ecozone of thermophilic sub-Mediterranean oak forest-steppes that was likely their main habitation zone during the EN and it reached into the northern part of the GHP (Moskal-del Hoyo et al. 2018).

Comparing the pie charts for the LN period between 6,950–6,450 years (5000–4500 cal BC, Fig. 5), similar

conclusions can be drawn as for the MN period, with the difference that the relative frequency of *Fraxinus* sp. charcoal and pollen are even lower in this period. Although the difference is not significant, it may indicate an increasingly open, shrubby landscape in the vicinity of the LN settlements, and an overexploitation of *Quercus-Ulmus-Fraxinus* woodland and the increasing shortage of the best firewood in the vicinity of the settlement (Kreuz 1992).

The Sarló-hát pollen profile also suggested that available moisture, and with it the water level of the oxbow lake, increased after 6,400 cal BP/~ 4450 cal BC (Magyari et al. 2010a, 2012) (see the percentage increase of Apiaceae in Fig. 2) that broadly coincides with the rapid disappearance of the LN tell sites in the GHP and the onset of a more dispersed settlement structure during the ECA. This, and several other proxy records from the region, suggest that the fade of Neolithic lifestyle can likely be connected to summer cooling and rapid available moisture increase around 6,400–6,200 cal BP (4450–4250 cal BC, see e.g. Magyari et al. 2009; Buczkó et al. 2012; Tóth et al. 2015). At the same time, a gradual increase can be observed in the proportion of both *Carpinus betulus* (hornbeam) and *Fagus sylvatica* (beech) pollen in the GHP (Fig. 2, ESM Figs. S2–S4), which change is even more pronounced in the two pollen records of the North-Hungarian mid-mountains at Sirok (Gardner 2002) and Kismohos (Willis et al. 1997, 1998).

From the Danube beyond the Danube: differences and similarities in the early and mid-Holocene vegetation succession of the two regions

Several new pollen records have been published from Trans-danubia in recent decades, some of which cover most of the Holocene (Zalavár, Keszthely-Úsztatómajor, Főnyed, Mezőlak-Szélmező, Fig. 1) (Medzihradszky and Járai-Komlódi 1996; Nagy-Bodor et al. 2000; Medzihradszky 2001a, b, 2005; Juhász et al. 2001; Juhász 2004, 2007; Juhász and Szegvári 2007; Szántó and Medzihradszky 2004; Ilon et al. 2006). Figure 6 shows the most important woody and herb taxa of the Zalavár pollen profile (near Lake Balaton, Fig. 1) along a linear age-depth model. Comparing this with the pollen diagrams of East Hungary, a number of important inferences can be made about the similarities and differences in the Neolithic and CA vegetation dynamics of the EH and MH and the human impact in the two areas.

All pollen records from Transdanubia show the sustained high representation of *P. sylvestris* in the EH. *Pinus* declined suddenly in all Transdanubian pollen records around 8,650 cal BP (6,700 cal BC; Fig. 6), which precedes the arrival
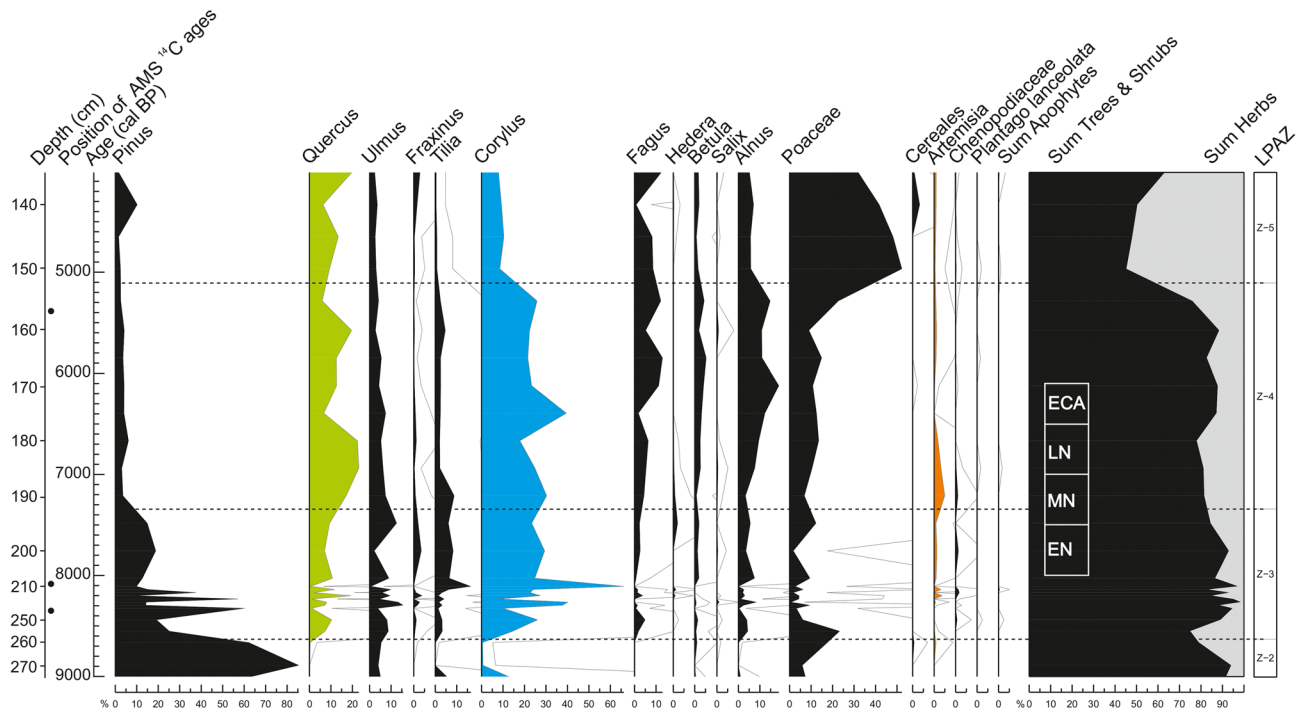
Fig. 6 Relative frequency diagram of selected pollen types for the early and mid-Holocene from Zalavár, W Hungary (Juhász 2007); for site location see Fig. 1; *LPAZ* local pollen assemblage zones; for further abbreviations see Fig. 2

of the Starčevo group to Transdanubia around 8,000 cal BP/6050 cal BC (Bánffy 2019, 2020) by ~ 650 years. Notable is that the northward expansion of the Starčevo group from Greece to Kosovo and Serbia took place during and just after the time of the 8.2 kyr climate event, when the Balkan areas became drier (Weninger et al. 2009, 2014; Weninger and Harper 2015; Krauß et al. 2018) and the impact of dry summers and prolonged winters was also seen in the South Carpathians (Pál et al. 2016), and in East Hungary (Magyari et al. 2012). Neolithic settlers in Transdanubia arrived in a landscape that was dominated by *Quercus* spp., *Corylus avellana*, *Ulmus* spp., *Fraxinus* spp. and *Tilia* spp. In the vicinity of Lake Balaton, the spread of *Fagus sylvatica* began at this time. If we perform quantitative vegetation reconstruction using REVEALS at the Zalavár site (Fig. 4; ESM Fig. S4) then we see that at the onset of the Neolithic, the Transdanubian landscape had ~ 85% forest cover, which is higher than the GHP (60%) and equals with the North-Hungarian mountains (Fig. 4; ESM Figs. S1–S5). Forest cover declined progressively during the Neolithic and by the end of the Neolithic (6,400 cal BP/ ~ 4450 cal BC) it decreased to 70–75%, which was followed by weak reforestation during the ECA and MCA (until 5,400 cal BP/ ~ 3450 cal BC). A major decline in forest cover took place afterwards, at the onset of the LCA Baden Culture period and continued into the Bronze Age (80 → 45%) (Fig. 4; ESM Fig. S4). The relative frequency of *F. sylvatica* increased

to 10% by the end of the Neolithic in Transdanubia. According to Medzihradszky (2005) significant *Fagus* stands developed after 8,600 cal BP in some places (possibly in the Transdanubian mid-mountain range and in the Zala region, see Fig. 1).

Within the period corresponding to the Atlantic chronozone, the Transdanubian pollen diagrams show an important local pollen assemblage zone boundary between 7,300–6,900 cal BP (5350–4950 cal BC) (Fig. 7). At this time, diversified changes in forest composition took place, the most striking common feature of the Transdanubian pollen diagrams is the increase in the relative abundance of Poaceae (grasses) and the increase in *Alnus glutinosa*-type (alder). Both processes may indicate a local change in the vicinity of the studied basins associated with hydroseral succession and an increasing human impact during the Neolithic. *Fagus sylvatica* declined in the diagrams of Keszthely-Úsztatómajor and Lake Balaton from 6,900 cal BP/4950 cal BC (Medzihradszky 2005), but it increased in other places (e.g. Zalavár, Fig. 6, ESM Fig. S4). At the same time, in some pollen diagrams in northeastern Hungary (e.g. Sirok, Báb-tava) a pollen assemblage zone boundary is also present (Fig. 7) that can likely be connected to Neolithic forest transformation processes in this region (coppicing, Gardner 1999). This inference is also supported by increased rate-of-change values that could be connected to human induced terrestrial vegetation change (Fig. 7). Overall, we can say that
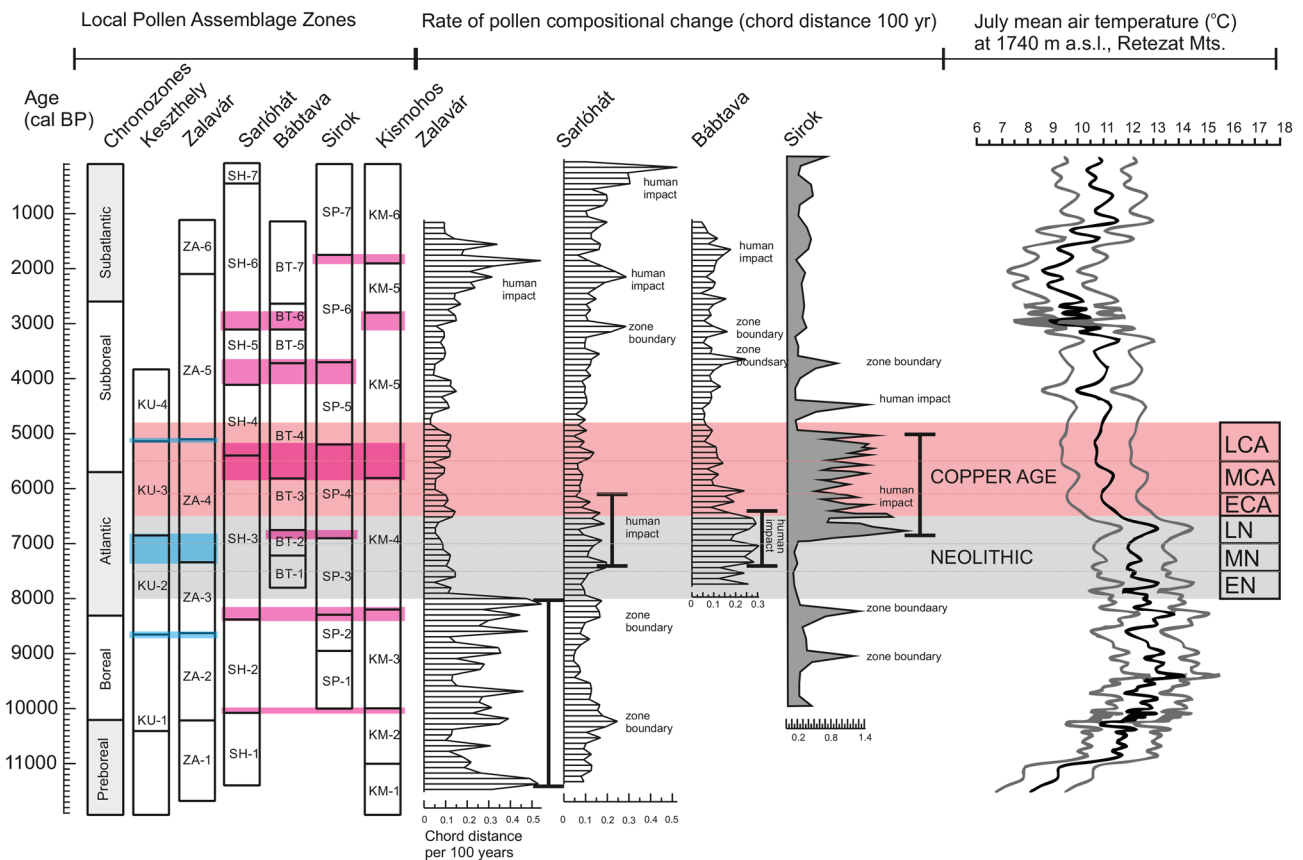
Fig. 7 Local pollen assemblage zones defined using statistical methods (mainly optimal splitting by information content) in north-east Hungarian and Transdanubian pollen records (for site location see Fig. 1), and the rate of pollen compositional change using chi2 statistics (rate-of-change analysis; Bennett and Humphry 1995); pollen counts were recalculated to even age-interval (100 yr) to make the results comparable (except for Sirok which was redrawn from Gardner 2002 and shown as filled grey curve); in the right panel, chironomid-based July mean air temperature reconstruction is displayed for the Retezat Mts (South Carpathians, Romania) originally published by Tóth et al. (2015); the confidence interval of the reconstruction is also shown; time periods with increased rate of pollen composition change were analysed and on the basis of the pollen taxa involved were either interpreted as resulting from human impact or macroclimate change induced secular vegetation change; blue and pink stripes highlight temporally coincident pollen assemblage zone boundaries; for further abbreviations see Fig. 2

the Neolithic land-use reached such an extent that between 7,500–6,900 cal BP (5550–4950 cal BC; MN) local pollen zone boundaries occur in several Hungarian pollen profiles.

Archaeobotanical and archaeozoological evidence on crop farming, grazing and gathering and anthropogenic indicators in pollen diagrams—what forms of land-use activities they suggest?

Summarizing Holocene pollen records from the GHP, Magyari et al. (2012) found that agriculture and woodland clearance was relatively small-scale in the earliest Neolithic in Eastern Hungary; there were signs of expanding scale of mixed farming during the MN and strong evidence for extensive landscape alterations with enhanced pasturing and mixed farming in the LN and ECA. The main vegetation exploitation techniques in the alluvial plains of the GHP were selective tree felling (mainly *Quercus*), coppicing (mainly *Corylus* and *Ulmus*) (Magyari et al. 2012) and woodland clearance to establish grazing pastures and small scale crop farming as demonstrated on the example of the Nagymohos pollen records covering the Neolithic period in Hungary in Fig. 8. In the MN (7,300–7,000 cal BP, 5350–5050 cal BC), *Corylus* and *Ulmus* coppicing were practiced by the Neolithic settlers as suggested by the short term decreases of their pollen representation typical when short-coppice cycles are applied (Waller et al. 2012), while pastoral activities and associated woodland clearance was distinguished in the LN both in the GHP and Transdanubia (6,800–6,500 cal BP, 4850–4550 cal BC; Juhász et al. 2001; Magyari et al. 2012a).

According to the state-of-the-art view (Fairbairn 1992, 1993; Bogaard et al. 2007, 2013, 2019; Gyulai 2010, 2012; Moskal-del Hoyo 2013; Kenéz et al. 2014; Moskal-del Hoyo et al. 2018; Kreuz et al. 2020a, b), Neolithic and CA communities in the CB cultivated a patchwork of small garden plots, where they have grown a variety of cereal grains, as well as pulse crops, such as lentils and peas that needed to be harvested by hand. In the earliest phase of the Neolithic (Körös) their fields were likely no bigger than 12 ha, and their sites were occupied no longer than three generations (100–120 years, Bogaard 2005). Mass findings of charred crops are extremely rare likely due to more careful handling of the cereals or due to the comparatively smaller scale of Neolithic production and processing within the settlements (Kreuz et al. 2020a, b). Regarding the soils that have been used for farming, chernozems, brown soils and alluvial soils (fluvisols) were all demonstrated to have been in use during the Neolithic and CA (Fairbairn 1992, 1993; Sümegi 2012; Kenéz et al. 2014). A recent GIS-based analysis of site location and soil maps modifies this general notion by pointing out a strong preference of the EN population for hydromorphic meadow soils and a medium preference for alluvial soils (with particular preference of the Körös population for salt affected soils; Kempf 2020, 2021). Recent loess soil maps to be invoked to discuss this question further, as they have shed new light on the soil development (Lehmkuhl et al. 2021). They show that the Tisza floodplain is widely covered with a mosaic of loess and loess derivates (e.g. clayey loess, alluvial loess, sandy loess) and not of merely fluvial deposits. The preference moved towards hydromorphic meadow soils during the MN, and a distinct shift towards skeletal

soil and brown soil preference can be observed in the LN suggesting the use of deforested plots. Kempf comes to the conclusion that Neolithic farmers avoided chernozem and sandy soils as these were characterised by low groundwater level and increased water permeability (Kempf 2021). As demonstrated by the archaeobotanical studies (Bogaard et al. 2007; Gyulai 2010, 2012; Kreuz et al. 2020a, b), the dominant cereals were *Hordeum* (barley) and the glume wheats *Triticum dicoccum* (emmer) and *T. monococcum* (einkorn). *Triticum aestivum/durum* (free-threshing wheat), *Lens culinaris* (lentil) and *Pisum sativum* (green pea) were weakly represented in the EN sites. Although *Panicum miliaceum* (broomcorn millet) was also found sporadically (e.g. Gyulai 2012), a recent project on AMS ^{14}C dating of millet remains from Europe proved that these sporadic Neolithic finds are younger, and redeposited (Filipović et al. 2020). Compared with the Balkan sites, legumes are underrepresented in Hungary, and *Cicer arietinum* (chickpea) has not been found, overall suggesting a narrower crop spectrum for unknown reasons (Bogaard et al. 2007). This labour-limited egalitarian society underwent modest technological development during the Neolithic. In agreement with the pollen records dating to the EN, charcoals of *Quercus* sp., *Ulmus* sp., *Fraxinus* sp., *Corylus* sp., *Acer* sp., *Cornus* sp., *Rhamnus catharticus* (European buckthorn), *Populus/Salix* (poplar/willow) and *Prunus* sp. (plum/cherry) were recovered from this period in the GHP (Moskal-del Hoyo 2010, 2013; Gyulai 2012) confirming the presence of high floodplain and gallery forests in the Holocene alluvium and steppe oak forests in the Pleistocene loess mantled levee surfaces that formed islands during the biannual floods in the landscape

Fig. 8 Relative frequency diagram of selected pollen types for the early and mid-Holocene from Nagymohos, NE Hungary (Magyari et al. 2001, 2010b); for site location see Fig. 1; number of settlements in 50 km radius of the site is displayed on the right side of the diagram; palynological richness was calculated using rarefaction analysis in which the minimum terrestrial pollen sum was 300 ($E_{(T300)}$); for further abbreviations see Fig. 2
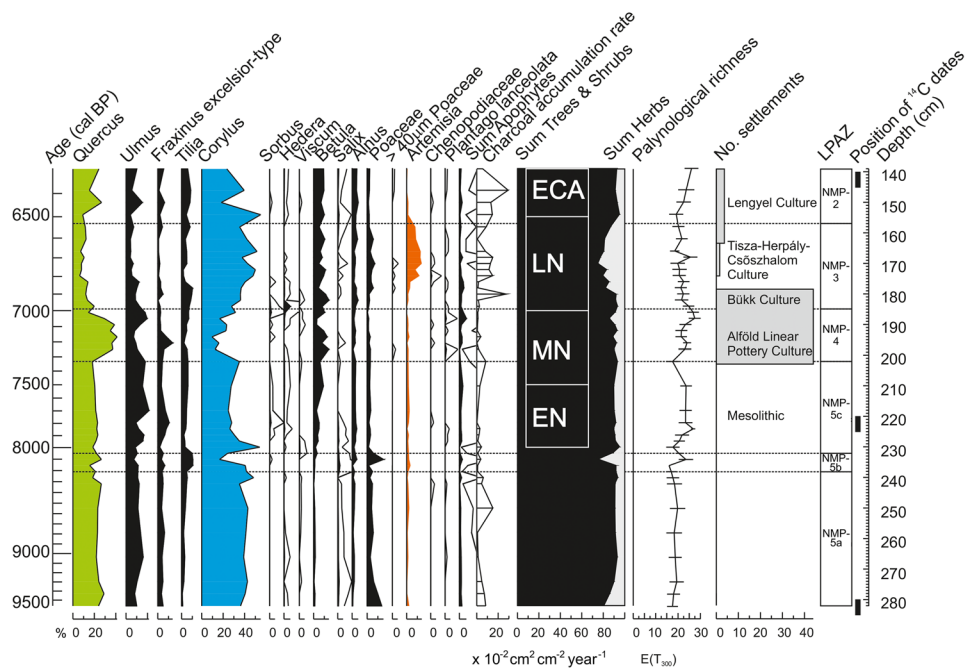
(Sümegi 2012). During the MN (ALP; Bükk Culture), barley, einkorn and emmer were still dominant in the charred crop assemblages with a wider spectrum of crops (*Linum usitatissimum*, flax and *Papaver somniferum*, opium poppy), weeds, and a clear indication for the exploitation of forested areas in Transdanubia where predominantly brown earth soils were used for crop farming for which forest parcels had to be cleared first. Note that the cultivation of *P. somniferum* was also demonstrated at Neolithic sites in Czechia (Vostrovská et al. 2020), but direct ^{14}C dating has not been done on these seeds in this region, unlike in SW Europe (Salavert et al. 2020). *Agrostemma githago* (common corncockle), *Setaria* cf. *italica* (foxtail millet) and *Bromus tectorum* (downy brome) were found, in addition other brome grass species, *Galium spurium* (false cleavers), *G. aparine* (cleavers) and *Chenopodium album* (fat-hen) (Gyulai 2010), the latter likely also collected as a cereal substitute (Behre 2008; Mueller-Bieniek et al. 2020). Also characteristic in all phases of the Neolithic both in the GHP and Transdanubia was the presence of wetland plants. Several sites recorded the collection (either deliberate or accidental) of wetland plants (*Schoenoplectus lacustris*, *Sparganium erectum*, *Carex elata*, *C. vulpina*, *C. hirta*, *Rumex hydrolapathum*, *Chara* sp.*, Eleocharis palustris, Polygonum minus, Trapa natans, Potamogeton* sp.). This also attests to the exploitation of the seasonally flooded meander-shore wetlands, but according to the current view, Neolithic crop fields were positioned on the higher lying flood-free chernozem indicated by abundant *Stipa* sp. (feather grass) findings (Kreuz et al. 2020b) and brown soil covered ecozones, in direct proximity to the settlements (< 1 km or < 500 m) with autumn sowing (Bogaard et al. 2013). There is however no direct evidence that cereals were grown together with *Stipa*. What we can confidently argue from its presence is the presence of open grasslands of steppic character near human settlements. The above mentioned GIS-based soil preference analysis also contradicts with *Stipa* being an indicator of chernozem cultivation, and so one key question for future research is to reconcile this discrepancy. The question arises, what is the source of the frequent charred *Stipa* sp. findings, if they are not coming from the garden plots themselves? In one of his early works, Fairbairn (1992) argued for risk management and a dual siting of fields during the MN and LN: in the seasonally flooded alluvium and also in the higher-lying Pleistocene loess-covered levees. An alternative explanation can be the strong tessellation of the landscape that leads into the classification of these island-like glacial elevated levee surfaces as meadow soils. Since Kempf (2021) mentions these elevated palaeolevees as low groundwater table and thus highly vulnerable locations for permanent garden plots, this alternative explanation seems unlikely. It also remains an open question whether the meadow soil covered areas of Kempf (2021) were forested at the onset of the EN. Their

relatively high ground water table, and the pollen diagrams themselves suggest that they were likely covered by high floodplain forests, at least partially.

Manuring was common, and labour intensive management of the plots was demonstrated (Bogaard et al. 2007). If we look at how the species spectrum of the forests broadened by the study of MN and LN charcoal and seed assemblages, several summaries have been published by Gyulai (2010, 2012), Náfrádi et al. (2015) and Moskal-del Hoyo (2010, 2013; Moskal-del Hoyo et al. 2018). These attest to taxonomically diverse mid-Holocene oak dominated forests with a wider species spectrum in the GHP than in SW Transdanubia. In the GHP the LN tree and shrub species spectrum included, on top the MN species, *Quercus pubescens* (downy oak), *Fraxinus excelsior* (common ash), *Carpinus betulus* (European hornbeam), *Ostrya carpinifolia* (European hop-hornbeam), *Cotinus coggygria* (European smoke tree), Maloideae, *Viburnum opulus* (guilder rose), *Euonymus* (spindle) and *Frangula alnus* (alder buckthorn) pointing to the presence of oak-dominated wooded steppe, secondary forests, forest edge communities, and the exploitation of high-floodplain forests. Furthermore, the sub-Mediterranean character of the steppe oak forest was demonstrated by the presence of *Cornus mas*, *Cotinus coggygria* and *Ostrya carpinifolia* as we discussed above. If we look at the connection of this mid-Holocene oak steppe forest community, then it likely represents the predecessor of the modern sub-Mediterranean-subcontinental thermophilous *Quercus cerris* (bitter oak) and *Q. frainetto* (Balkan oak) forests of SE and E-Central Europe (Bohn et al. 2004) that were demonstrably the preferred habitats of Neolithic settlers (Krauß et al. 2018). The representation of *C. avellana* decreased at all sites during the MN and LN. In Transdanubia, on the other hand, the EN Starčevo phase was characterised by *Quercus* dominance, while during the MN and LN (Linear Pottery Culture, Sopot and Lengyel Culture groups) *Fagus* sp., *Fraxinus* sp., *Ulmus* sp. and *Alnus* sp. were found in addition to *Quercus. Corylus* was missing from these assemblages. These results suggest that the Subatlantic and Subalpine southwestern borderland of Hungary, where annual rainfall exceeds 700 mm today, as opposed to the 450–550 mm rainfall of the GHP (Bihari et al. 2018), alder carr and mixed *Quercus-Acer-Fagus* woodlands developed by the MN, in agreement with the findings of the Zalavár pollen record (Figs. 4 and 6, ESM Fig. S4; Juhász 2007). This landscape was also covered by closed forest, and the pollen record indicated forest clearance between 7,800 and 6,600 cal BP (5850–4650 cal BC) in agreement with the growing Neolithic population of Transdanubia. The appearance of *Fagus* in the *Quercus-Tilia-Ulmus* dominated mid-mountains of East Hungary was also demonstrated by Bácsmegi (2014) during the LN (Lengyel occupation phase). This picture has changed

dramatically during the ECA, when the very few sites studied by archaeobotanical and archaeozoological methods attested to a decreasing dependence on arable farming (Gyulai 2010) and an increased importance of animal husbandry. Nearly all publications explain this change in subsistence economy as a reaction to the deterioration of the climate, with cooler and wetter summers. While during the EN, caprines (sheep and goat) were dominant in the domesticated animal spectrum (Bartosiewicz 2012), cow and pig gained increased importance towards the LN (Bartosiewicz 2005; Bácsmegi 2014). The species spectrum of crop plants has however changed little in the CA, even though this inference is based on the study of very few sites, since very few sites are known from the Boleráz and Baden periods where systematic archaeobotanical studies were made. Exceptions are the ECA Vésztő-Bikeri and Körösladány-Bikeri sites, where Kasper (2003) and Yerkes et al. (2021) did systematic collection and analyses of archaeobotanical material. *Hordeum vulgare* (hulled barley) and *H. vulgare* var. *nudum* (naked barley) were the most common, followed by *Triticum dicoccum* and *T. monococcum*. A similar species spectrum characterized the Banat region to the SE (Fischer and Rösch 2004) and the ECA Battonya-Vetrán site (Fig. 1, Goldman and Szénászky 2012). *Panicum miliaceum* was also found in a relatively large number at Bikeri, but these seed remains were not dated, therefore their Neolithic origin requires further confirmation. The authors suggested that in the sotheastern GHP it became a more frequently grown staple crop during the CA, possibly due to its desirable traits (poor soil and extreme weather tolerance, spring sowing) (Yerkes et al. 2021), but as we noted above, a recent study came to the conclusion that it was not cultivated in eastern central Europe prior to the Bronze Age (Filipović et al. 2020). Very few seeds of *Lens culinaris*, *Lathyrus sativus* (grass pea), *Cicer arietinum* (chickpea), *Pisum* sp. and *Vicia ervilia* (bitter vetch) were also found suggesting their cultivation. Since *C. arietinum* has not been found in CB Neolithic sites, Bikeri provided the earliest evidence for *C. arietinum* cultivation in the CB. *Cornus mas*, *Fragaria vesca* (wild strawberry), *Prunus* sp. (wild plum), *Vitis sylvestris* (wild grape) and *Corylus avellana* were also identified in longhouse-related contexts at Bikeri suggesting the collection of these fruits from the steppe oak and floodplain forests. Interestingly, the publication of Yerkes et al. (2021) is the first to mention the possible intensification of cereal cultivation at Körösladány-Bikeri (ECA Tiszapolgár Culture). They argue that crop farming may have been fostered by the introduction of ox-drawn ard ploughing. Note however, that the use of ard could not be evidenced by archaeological objects at this site. An important element of their economy was resource management that included the production of insurance crops. The authors also argued that crop farming has not lost its importance in the ECA; the Bikeri site suggested

that dispersed farmsteads likely produced surplus cereals, as the density of charred remains was higher, particularly at Körösladány-Bikeri, in comparison to GHP Neolithic sites. As we demonstrated above, and will discuss below, this inference is not supported by the Kiri-tó pollen diagram located just 35 km northwest of this site (Fig. 1, Willis 2007), but similar continuity in land use can be seen at Sirok in the North-Hungarian mid-mountains (Fig. 7). Other Hungarian pollen records, however, do show reforestation in the ECA, and increased land use in the MCA and LCA (Kismohos, Sarló-hát, Zalavár; ESM Figs. S1–S5). Looking at the faunal assemblage from this site, an equal importance of caprine, cattle and pig characterise it, suggesting mixed-herding. Steppic mammals, *Mustela eversmanni* (steppe polecat) and *Bos primigenius* (aurochs) confirm the presence of steppe habitats (Nicodemus et al. 2021). The authors concluded that increased reliance on cattle farming cannot be demonstrated. If we look however at the age of these two ECA sites (Gyucha et al. 2021), the median age of theoccupation onset (6480.5 cal BP, 4530.5 cal BC) falls very close or even precedes to the abandonment of LN sites (e.g. Berettyóújfalu-Herpály Fig. 8.11. in Gyucha et al. 2021), while the latest phase of occupation was dated to 6,200 cal BP (4250 cal BC), suggesting ~ 270 year of habitation and so multiple generations. Nonetheless, the authors argue that the transition at this site to the ECA occurred at 6,410 cal BP/ ~ 4460 cal BC (Gyucha et al. 2021).

If we look at how crop husbandry practices has changed during the CA in various parts of Hungary, we see that the great majority of sites, where archaeobotanical study was made, come from Transdanubia or Central Hungary, and they represent the late Lengyel, Ludanice, Bodrogkeresztúr, Boleráz and Baden cultures (Gyulai 2010). From the general low quantity of seeds found at these sites, Gyulai (2010) argued a reduction in arable farming and the increasing importance on animal husbandry in the first half of the CA, and generally the development of a nomadic and pastoral lifestyle. This change was connected to climate change (Gyulai 2010). The production of *Hordeum* (dominant), *T. dicoccum*, *T. monococcum*, *T. compactum* (club wheat), *T. spelta*, *C. arietinum*, and *P. miliaceum* (not dated, questionable) was inferred, which is a similar species spectrum like in the Neolithic. Individual sites usually recorded only two or three different types of cereals and were often associated with aquatic and marsh vegetation elements (e.g. *Schoenoplectus lacustris*) suggesting the utilization of wild resources as cereal substitutes. According to Gyulai (2010), the cool and rainy climate of the ECA and MCA improved in the LCA. He found a wide crop spectrum at the LCA Boleráz sites (Győr-Szabadrétdomb, Fig. 1) associated with wild plants (Kompolt-Kistér, Fig. 1), such as *Corylus avellana*, *Prunus spinosa* (sloe), *Cornus* sp. and *Vitis sylvestris*. Fermentation of *Vitis* and *Cornus* was

assumed on the basis of their large quantities. Even though the number of sites during the LCA Baden period increased, botanical assemblages were only studied in two cases up to 2,010, both sites are in Budapest. Baden people used animal traction for ploughing (Horváth 2010, 2012). It is therefore striking that our knowledge on their crop spectrum is very limited in Hungary. The production of *Hordeum vulgare*, *T. dicoccum*, *T. monococcum* was demonstrated so far, and the surprisingly abundant roasted fragments of *Quercus* and *Fagus* acorns (Gyulai 2010) suggesting their consumption as cereal substitutes. In Slovakia, much more archaeobotanical work was done on Baden sites that overall suggested a very wide plant spectrum (*T. monococcum*, *T. dicoccum*, *T. spelta*, *T. aestivum/durum*, *H. vulgare*, *V. ervilia*, *Pisum sativum*, *Linum usitatissimum*, *Cornus mas* and *Corylus avellana*, Hajnalova 2007). Even with the increasing number of sites studied for the Neolithic and CA, the question how ox-ploughing during the Baden period, and the presumed increased area of arable farming changed the weed flora and the spectrum of cereals remain elusive to answer (Hajnalova 2007). What we see from these data, is that the cereal and weed spectrum remained quite stable during this period, and so far no changes in the Baden weed spectrum was found, which was explained by the sustained tall harvest (Fairbairn 1993; Hajnalova 2007).

Some more recent studies furthermore do not support a large-scale increase in the consumption and use of animal protein and fat during the CA in the GHP, even though an increase in animal fats confirmed by lipid residue analysis of ceramic vessels is detectable during the MCA (Hoekman-Sites and Giblin 2012). The authors concluded that livestock management remained small-scale during the Neolithic and CA and dairy use was minimal. This finding would suggest that the scarcity of plant remains at CA sites is rather a taphonomical or household management issue (Yerkes et al. 2021) and do not reflect the decreasing importance of crop farming. This inference was also corroborated by the stable isotope study of Gamarra et al. (2018). They found that Neolithic and CA individuals relied mostly on terrestrial C_3 plant resources, and the consumption of animal protein has increased in the Bronze Age only in the GHP. If we move north-west of Hungary into Moravia, where a detailed study on land use change, climate change and Neolithic-Eneolithic population dynamics has recently been conducted (Kolář et al. 2018), we see that there the period between 5,950–4,950 cal BP (4000–3000 cal BC), which includes the Baden occupation in Moravia, was characterised by population decline that was however associated with an increase in the cover of secondary forest components (*Corylus* and *Betula*). This was interpreted as a possible sign of swidden (or extensive slash-and-burn) cultivation or forest grazing associated with frequent burning of the forest floor. Deployment of new land exploitation techniques in this area

was explained by decreasing summer temperatures (from 5,700 cal BP, ~3750 cal BC) and increasing precipitation (from 5,450 cal BP, ~3500 cal BC); data derived from climate modelling.

In order to see how these societies exploited the land on a landscape level, anthropogenic indicator pollen types and pasture indicator herbs were summed using 6 pollen records from the GHP, North-Hungarian mid-mountains and Transdanubia and are presented on Fig. 9.

The six well dated pollen records are Zalavár (Fig. 6, ESM Fig. S4, Juhász 2007), Kismohos (ESM Fig. S1, Willis et al. 1998), Nagymohos (Fig. 8, Magyari et al. 2001), Báb-tava (ESM Fig. S2, Magyari et al. 2008), Hódmezővásárhely-Gorzsa (Fig. 3, this study) and Sarló-hát (Fig. 2, ESM Fig. S3, Magyari et al. 2012a). In addition, we refer to Sirok (Gardner 2002), Ecsegfalva-Kiri-tó (Willis 2007) (for locations see Fig. 1). Only two of them, Ecsegfalva-Kiri-tó and Hódmezővásárhely-Gorzsa, come from within 1 km of excavated Neolithic sites (Willis 2007).

As we see on Fig. 9, pasture cover increased considerably around Nagymohos, Zalavár and Sarló-hát during the LN suggesting forest clearance and the establishment of pasture for grazing that are visible at landscape level during this period. This phenomenon appeared both in the lowland and mid-mountain area, despite the natural semi-openness of the lowland landscape (see also AP:NAP ratios). We also see that primary cultural indicators (PI: Cereals and dicotyledonous crops) and cultural indicators (CI) are present in some records already before the Neolithic (Zalavár, Sarló-hát, Nagymohos) confirming pre-Neolithic natural presence of Cerealia pollen (originating from cereal species and a limited number of native wild grasses; Behre 2007) and *Plantago lanceolata* (ribwort plantain), but PI indicators appear or increase at Kismohos, Nagymohos, Sarló-hát and Hódmezővásárhely-Gorzsa only at the Neolithic suggesting relatively small-scale arable farming at landscape level. We also see from the AP:NAP ratios that forests were closed in the northeast GHP (Bereg Plain: Báb-tava; Figs. 1 and 10), in the mid-mountains and in southern Transdanubia (>10 values of AP:NAP ratio). However, both the Sarló-hát and Hódmezővásárhely-Gorzsa pollen records suggest that the GHP was semi-open during the Neolithic. It is also clear from the AP:NAP ratio decrease of the north-east Hungarian Kismohos hill site that there was considerable deforestation during the LN. We can also see from the AP:NAP ratios and the REVEALS based land-cover estimates that that forest cover increased at the end of the Neolithic (Fig. 4; ESM Figs. S1–S5). During the ECA most sites were characterised by diminishing human impact on the natural vegetation (except Sirok) suggesting a decrease in land use and likely also in population size.
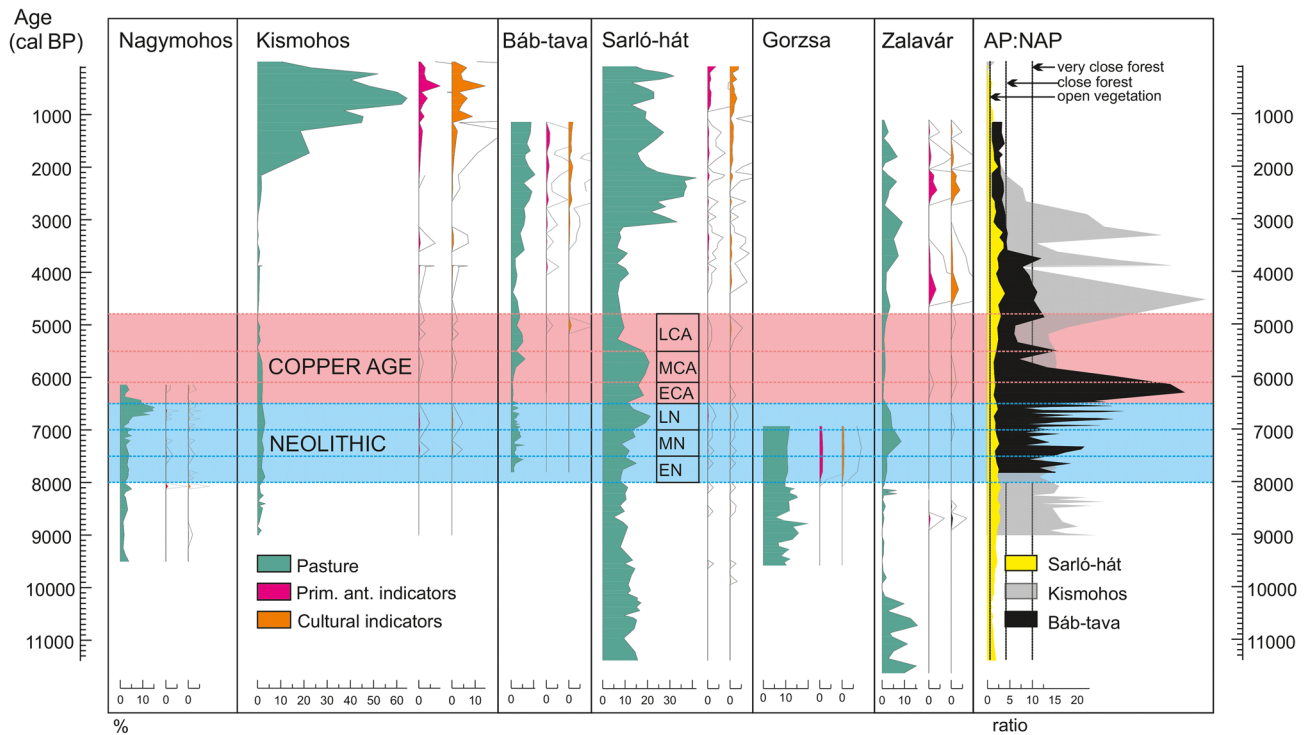
Fig. 9 Relative frequencies of pasture indicator herbs (green; for taxa included see Magyari et al. 2012), primary anthropogenic indicators (pink) and cultural indicators (orange; for taxa lists see Deza-Araujo et al. 2020) in Holocene pollen records from the Carpathian Basin, Hungary; changes in the ratio of arboreal and non-arboreal pol-

len along age are also shown in the right of the Fig. for three sites; AP:NAP > 10, very closed forest; 4–10, closed forest (at 4, first relevant vegetation openings); < 1, open vegetation; for further abbreviations see Fig. 2
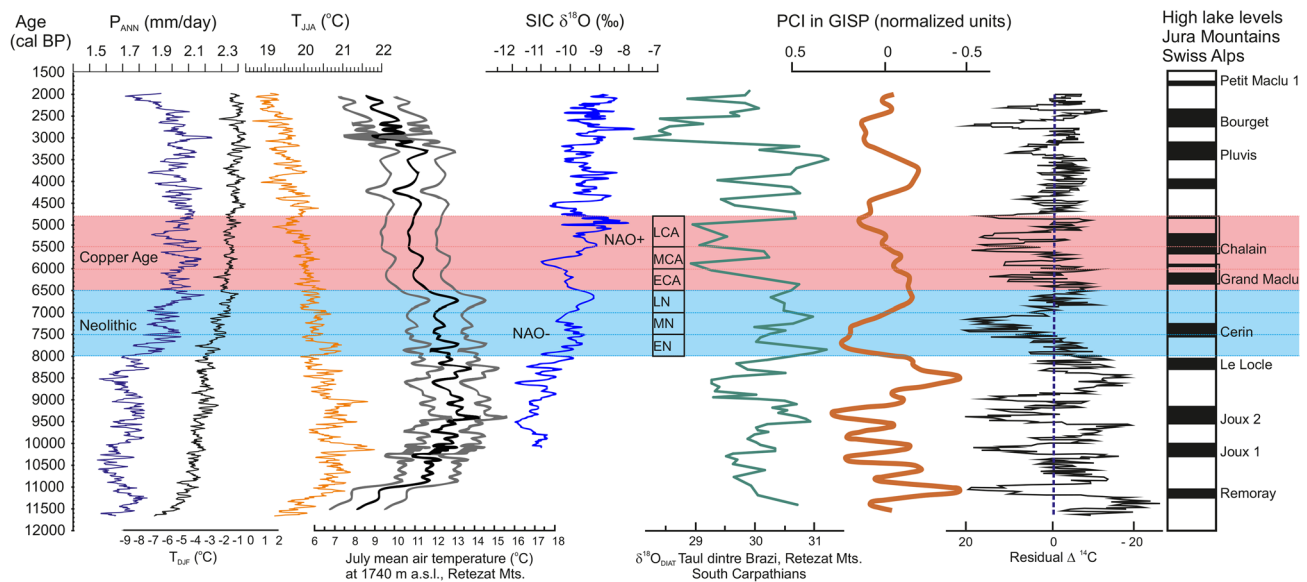
Fig. 10 Holocene climate records from modelling experiments (CCSM3, Liu et al. 2009; Fordham et al. 2017), chironomid-based July mean temperature reconstruction (Tóth et al. 2015), Scarisoara ice cave δ18O (Perşoiu et al. 2017), Lake Brazi alpine lake sediment diatom δ18O records (Magyari et al. 2013), the Polar Circulation

Index (Mayewski et al. 1997), the residual Δ14C curve (Stuiver et al. 1998) and high lake level phases of west-central European alpine lakes (Magny 2007); P_{ANN} annual precipitation, T_{JJA} summer mean temperature, T_{DJF} winter mean temperature, *NAO* North Atlantic Oscillation; for further abbreviations see Fig. 2

Although not represented in Fig. 9, Ecsegfalva-Kiri-tó in the GHP is an oxbow lake that has been studied for pollen and various geochemical proxies by Willis (2007) (Fig. 1). Since a Körös site has been fully excavated in its vicinity, its pollen record is one of the rare examples, where local human impact could be studied directly. At this site small-scale, but intensive garden cultivation with autumn sowing, year-round occupation, labour-intensive farming, manuring, weeding, small-scale herding (sheep dominated), caprine raising for meat and milk were all documented (Bartosiewicz 2007; Bogaard et al. 2007; Craig et al. 2007; Pearson and Hedges 2007). The setting has been modelled as a mosaic of wooded and open patches (Gillings 2007b; Willis 2007) with occupation starting at 7,800 cal BP (~5850 cal BC) and a duration of 70–80 years (Bartosiewicz 2007). Organic N levels in the oxbow lake sediment pointed to eutrophication of the Kiri-tó during the Körös period, possibly an effect of fertilisation of the surrounding slopes (Willis 2007). The pollen record suggested limited exploitation and change of the local environment during the Körös occupation period. The lack of significant clearance of the landscape suggested that there was already enough open land available on the floodplain for arable farming. But intensification in land use, significant forest clearance and cereal production was found during the MN ALP occupation phase, and a shift from sheep to cattle breeding (Bartosiewicz 2007). When we look at the ECA layer, we see that evidence for cereal production disappeared, and the site seem to have been depopulated in this period leading to a temporary decrease in land use, similarly to some other site in the GHP.

Overall, available pollen records from Hungary support the archaeobotanical evidence for a short-term forest recovery, decrease in land use and possibly also decreased reliance on crop husbandry during the ECA that is however not ubiquitous. Deforestation is most clearly demonstrable in Transdanubia and in the North-Hungarian mid-mountains in the LCA Baden period again, overall suggesting that the Boleráz and Baden cultures cleared more forest than the preceding Neolithic cultures, and in these areas pastoral farming intensified (or changed its character) during the LCA.

The relationship between climate and societal change

The climate of Hungary is determined by its geographical position. The country is situated in the northern temperate climate zone with the dominance of westerly winds and equal effects of three climatic zones: oceanic, continental and Mediterranean. This triple climatic influence causes frequent alteration of different climatic years with 1.5 °C

variability in July mean temperatures and about 3 °C variability in February mean temperatures (1,981–2,010 average) (Bihari et al. 2018). 84% of the country is below 200 m a.s.l., so the effect of the neighbouring mountains (mainly the Carpathians) is prominent. The annual mean temperature is 10–11 °C (1,981–2,010 average), with slightly lower values in Transdanubia and in the mid-mountain regions. The warmest period of the year is late July and early August. Summer mean temperatures increase towards the centre of the basin, the country wide average is 21.2 °C (1,981–2,010 average) (Bihari et al. 2018). Transdanubia is 1–1.5 °C cooler, while in the SE corner of the country July mean temperature reaches 22 °C. Overall the Transdanubian region is under stronger influence of the Atlantic and Mediterranean air masses, its climate is temperate-continental with Atlantic influence (C_{bfx} according to the Köppen classification system) (Réthy 1933), while Eastern Hungary is strongly continental with warm temperate-continental climate (C_{afx} and C_{bfx} according to Köppen), where increased influence of the Siberian air masses is present during the winter, and diminishing influence of the westerly flows during the summer. The mid-mountains are characterised by colder winters (< -3 °C January mean, D_{bfx} according to Köppen) (Réthy 1933). Differences in the western and eastern parts of the country are even more visible in the climate regions map of Péczely (1957) that categorizes the heat and water supply of regions based on the average temperature during the vegetation period and the aridity index (Bihari 2021). Differences between the western and eastern part of the country suggest that in case of climate change the Transdanubian region likely respond similarly to the eastern and Dinaric Alps, while Eastern Hungary may show similar changes with the eastern Carpathian Mts. The lowlands of Hungary have very few direct quantitative and independent (not pollen based) palaeoclimate records, mainly Holocene lake level records (Jakab et al. 2004; Magyari et al. 2009). For this reason, in the following discussion we use palaeoclimate records from the Alps and Carpathians as well.

Figure 10 summarizes climate modelling results from the Community Climate System Model ver. 3 (CCSM3) from the TRaCE21ka experiment (Liu et al. 2009, 2014) and several biological and isotope proxy derived quantitative climate reconstruction from the eastern Carpathian Mts. This model has a latitude – longitude resolution of ~3.75° in the atmosphere, re-gridded using bilinear interpolation to a spatial resolution of 2.5×2.5° (~277×277 km). Here we show the relevant grid cell summer mean (T_{JJA}), winter mean (T_{DJF}) temperature and annual rainfall (P_{ANN}) data covering Eastern Hungary as obtained from the PaleoView software (Fordham et al. 2017). In addition, pollen- and chironomid-based summer mean temperature (T_{JJA}) reconstructions are

shown from a South Carpathian alpine lake record (Tóth et al. 2015) and various other climate proxy records.

CCSM3 for the Neolithic shows a stepwise increase in annual rainfall at the onset of the Neolithic, which is driven mainly by an increase in summer precipitation (Liu et al. 2009). The average value for the Neolithic is 720 mm/yr (1.973 mm/day) that exceeds considerably the modern value (~ 550–600 mm/yr). Winter mean temperatures (T_{JFB}) increase gradually over this period (from −3.5 to −2.2 °C) likely in association with the winter insolation increase. On the other hand, we see an opposite decrease in summer mean temperatures (T_{JJA}) at the onset of the Neolithic; the model suggests that at 7,700 cal BP July mean temperature decreased from 21 to 20 °C, but overall the Neolithic was characterised by stable summer mean temperatures that were slightly lower than Early Holocene summer temperatures, and ~ 1 °C higher than the pre-industrial modern values of the same grid cell (not shown on Fig. 10, but note that the grid cell average encompasses the hill region as well). So, the major change that might have helped the northward spread of arable farming at the Neolithic onset was winter warming, which supported the success of autumn sowing. We can come to the same inference if we look at the trends in the chironomid-based summer mean temperatures of the South Carpathian Mts. (Fig. 10). One major difference is however apparent between the modelled and reconstructed summer temperatures. This occurs at the end of the Neolithic, around 6,500 cal BP (4550 cal BC), when the chironomid-based reconstruction shows a 2 °C decrease (1 °C without the 6.7 kyr peak), while the model fails to capture this significant cooling. If we look at the pollen compositional and biome changes displayed on Fig. 2 and ESM Figs. S1–S5, we see that climate change at the end of the Neolithic was accompanied by a considerable terrestrial vegetation change (onset of *Carpinus* pollen increase in the east and *Carpinus-Fagus* in the west of Hungary, wetland pollen compositional change, further increase in *Quercus*, decline in *Corylus* at some sites) corroborating the onset of a macroclimate change at this time in Hungary, similarly to other areas of Europe, the Near East and North Africa (Clarke et al. 2016). In addition, if we compare these results with the lake-level record of the Jura Mountains, the northern French pre-Alps, and the Swiss Plateau (Magny 2004, 2007) (Fig. 10), these show the onset of three high lake-level periods (Gand Maclu I-II and Chalain), the first of which starts at 6,400 cal BP (~ 4450 cal BC). These were explained by ocean circulation changes (McManus et al. 2004) and the consequent displacement of Atlantic Westerly Jet, which determines the latitudinal extension of the Hadley cell and the mid-latitude storm tracks, to more Central European latitudes that increased rainfall in these areas. Phases of higher lake level coincided with an increase in annual precipitation, a decrease in summer temperature and

a shortening of the growing season in this area. Even though, Hungary lies much further to the east of this area, therefore the trajectories of climate change are not necessarily in the same direction (see discussion below), the reorganization of the atmospheric circulation patterns at the LN/ECA transition is supported by these lake level records.

Figure 10 shows a comparison of the palaeoclimate records with the Polar Circulation Index (PCI) established from the GISP2 ice core chemical series (Mayewski et al. 1997) and the atmospheric ^{14}C residual series (Stuiver et al. 1998). The PCI is thought to provide a relative measure of the average size and intensity of polar atmospheric circulation, increased values of which increase the possibility of cold outbreaks from the north towards the south in the continental interior of Eurasia. The radiocarbon curve considered as a proxy record of past changes in solar activity. Noticeable is that the LN/ECA transition solar activity decreased and fluctuated considerably during the CA, while the PCI was at minimum with gradual increase throughout the CA.

The Scarisoara Ice cave $\delta^{18}O$ record (Perşoiu et al. 2017) (Fig. 10) was interpreted as a North Atlantic Oscillation (NAO) proxy that over the Neolithic period shows a NAO-dominated climate mode with an abrupt and temporary shift to NAO+ dominance around 6,700 cal BP (4750 cal BC). This shift coincides with a small positive annual precipitation anomaly in the CCSM3 climate model and a short-lived July mean temperature increase in the South Carpathians inferred by the Lake Brazi chironomid record (Fig. 10). Overall, during NAO+ years (with a deeper than usual Icelandic Low and/or stronger than usual Azores High) the westerlies carrying moisture are deflected northward, resulting in drier conditions in eastern central Europe between November and April (Bojariu and Paliu 2001; Bartholy et al. 2009; Perşoiu et al. 2017). This seems to have happened during the LN accompanied by warm summers. At the end of the Neolithic, around 6,500 cal BP (4550 cal BC), the opposite trend is observed however. A considerable shift to NAO-mode (with a shallower than usual Icelandic Low and/or weaker than usual Azores High) takes place. During NAO-mode the westerlies carry more moisture from the North Atlantic towards southeastern Europe, in addition westerlies also reach eastern central Europe via a southern pathway across the Mediterranean Sea (Perşoiu et al. 2017). At the same time, several South Carpathian alpine lakes recorded increasing lake levels (Buczkó et al. 2018) that together with the NAO- shift suggest precipitation increase during winter and early spring. This change coincides with the July mean temperature decrease in the chironomid-based record of the South Carpathians (Fig. 10) (Tóth et al. 2015). Summer cooling in Hungary is also supported by other proxy based reconstructions (Gulyás and Sümegi 2011) arguing that at the transition to the ECA, moisture availability increased

in eastern central Europe following the winter dry period. As we mentioned above, with NAO- mode the westerlies carry more moisture towards southeastern Europe causing increased winter precipitation (Bojariu and Paliu 2001; Bartholy et al. 2009; Perşoiu et al. 2017). This, combined with summer cooling and the regular intrusion of Siberian air masses between 6,200–5,000 cal BP/4250–3050 cal BC (Weninger and Harper 2015), overall suggest that the ECA climate of eastern central Europe was variable with periodic extreme cold intrusions in spring. A major change in atmospheric circulation patterns and moisture source at the LN/ECA transition is also supported by the diatom δ^{18}O record of Lake Brazi, an alpine lake in the South Carpathian Mts. (Fig. 10) (Magyari et al. 2013). Its diatom valve based oxygen isotope ($\delta^{18}O_{DIAT}$) record principally reflects the oxygen isotope composition of the spring precipitation, as diatom blooms occur mainly in spring and early summer. Hence, changes in $\delta^{18}O_{DIAT}$ were interpreted as seasonal scale changes in the amount of spring precipitation. Low O-isotope values occurred during LN/ECA transition and throughout the CA. This change was interpreted as an increase in spring precipitation at that time that likely had an impact on arable farming practices together with the noticed summer cooling and spring frost events.

Well-dated δ^{18}O and δD records from mid-Holocene stalagmites have been studied in increasing number from Hungary in the recent decades (Demény et al. 2013, 2021; Kern et al. 2019). By modelling the principles between the modern precipitation and stable isotope values in these carbonates, geochemists argue that Hungarian δ^{18}O and δD records principally reflect changes in the moisture source areas. These studies overall pointed to a lengthy interval between 6,000–5,500 cal BP (4050–3550 cal BC; ~ MCA by the classical terminology) when a predominant Mediterranean moisture source was identified suggesting the southward displacement of storm tracks in this period. This finding is in good agreement with a major reorganisation of the atmospheric circulation in the same period as suggested by the NAO related proxies (Magyari et al. 2013; Perşoiu et al. 2017) on Fig. 10.

Finally, stable isotope and geochemical studies on the sediments of Lake Balaton and mussel shells of *Unio pictorum* from its lakeshore CA settlement provided valuable insight into the CA climate of Transdanubia (Schöll-Barna et al. 2012; Pálfi et al. 2021). These studies found considerable negative excursions in the δ^{13}C and δ^{18}O values of the studied bivalve shells around 5,310 cal BP (~ 3360 cal BC) that pointed to a short wet-cold interval in the transitional phase of the CA settlement (prior to the classical Baden occupation). This short term rapid cooling event has been connected to the well-known 5.3 ky cold event detected at several sites in Europe (Schöll-Barna et al. 2012). The authors furthermore argued for a possible

North-Atlantic storm track dominance in this period. When this short term cooling event is examined in the context of a larger age interval in the biogenic carbonate sediments of Lake Balaton, then a slightly different picture emerges. In the δ^{13}C and δ^{18}O curves of the Holocene well dated sediment sequence from the Szemes Sub-basin of the lake, 5,500–4,800 cal BP (3,550–2850 cal BC; ~ LCA) is characterised by higher δ^{13}C and δ^{18}O values suggesting an overall increase in summer evaporation that can arise from lower summer precipitation, or a combination of low summer precipitation and increased summer temperatures (Pálfi et al. 2021). The 5.3 ky BP reversal is intercalated to this lengthier dry summer interval. Since the CCSM3 climate model indicates decreasing summer temperatures during the CA, the main driver of this δ^{13}C and δ^{18}O increase was likely the low summer precipitation of this period that coincided with more frequent lakeshore dwellings both at Lake Balaton and in the French and Swiss Alps (Arbogast et al. 2006).

Overall, this synthesis suggests that at the onset and end of the Neolithic period the macroclimate of Hungary changed, and particularly the unprecedented LN tell abandonments appear coincident with the climatic proxy inferred increase in spring precipitation (Buczkó et al. 2018) and sharp decrease in summer temperatures (Fig. 10; Tóth et al. 2015). The conditions of subsistence were likely influenced by these changes in macroclimate. The Neolithic was characterised by relatively stable July temperature (Fig. 10), and despite the higher than present summer rainfall (Fig. 10), the associated higher then present (~ 1 °C) mean summer temperatures resulted in generally low lake levels in Hungary that are most likely connectable to the intensive evaporation of the summer months. In Hungary, several small lakes are characterised by sedimentary hiatuses in the Neolithic period (Jakab et al. 2004; Magyari et al. 2009).

During the first half of the CA several palaeoclimate proxy records implicate summer cooling and intensified spring precipitation in the Carpathians and shift to more Mediterranean moisture source (Fig. 10; Tóth et al. 2015; Perşoiu et al. 2017; Buczkó et al. 2018). All records agree in the relatively frequent oscillation of the CA climate and a major reorganisation of the atmospheric circulation in Europe during this period (Fig. 10; Clarke et al. 2016).

Conclusions

As demonstrated by this summary, Neolithic and CA communities exerted well visible changes in their natural environment, but their activity was periodic, followed by abandonment and forest recovery.

We demonstrated that the Neolithic and CA landscapes of Hungary were characterised by mixed oak forest

communities, and thermophilous steppe oak forests were present in the lowland landscape that were the principal choice of the early farmers represented by the Körös-Starčevo-Criş cultures. Climate modelling and climate reconstruction from these regions indicate higher than preindustrial summer mean temperatures and higher than modern summer rainfall. For these reasons, even though the common notion of this period is the stability, but in fact early farmers had to cope with a summer-dry environment that was very likely spotted with seasonal drought in Hungary, which was more expressed east of the Danube.

Steppe oak forests had a low-built character that can be regarded as non-analogue associations in which several *Quercus* species were present and mixed with *Acer*, *Rhamnus*, *Cornus mas*, *Cornus* sp. and other deciduous shrubs. *Ulmus* and *Corylus* were very likely more abundant in the high floodplain forests. Even though charcoal assemblages are similar in taxonomic composition from the east of Hungary to the south of Germany (Kreuz et al. 2020a, b), their relative frequency distribution and species level composition is different suggesting the western Linear Pottery Culture developed and adopted to a different ecozone, probably best called the sub-continental mixed deciduous oak forest of Southern Germany (Kreuz et al. 2020a, b). Western Hungarian (Trasdanubian) vegetation was more like this, and the Danube formed an important border between these two climatically and floristically different parts of Hungary.

ALP was the first culture that technologically advanced to clear larger forest areas for crop cultivation purposes, but given the small size of their plots/gardens and the low population density, their land transforming activities had locally visible effect on total forest cover. Their coppicing and arable farming activities are well detectable in pollen records. The first large scale and landscape level clearance is discernible in Hungarian pollen records in the LN period, when population size likely reached its Neolithic maximum both in the lowlands and the surrounding mid-mountains.

Contrary to the generalized notion of a generally decreased reliance on crop farming during the CA, some new archaeobotanical studies particularly in the northern periphery of the CB attest to a diverse species spectrum used for crop farming during the Baden Culture period. Nonetheless, the palaeoclimate and palaeo-diet records agree in the remarkably more frequent climate fluctuations particularly in the ECA and MCA that together with the periodic 'infiltrations' of steppe nomads likely contributed to the development of a semi-nomadic lifestyle in Eastern Hungary that had a more expressed reliance on animal husbandry. This was likely parallel with the continuation of farmsteads that were situated in longer distance from one another (Parma 2017).

Nearly all Hungarian pollen records demonstrate a temporary decrease in land use during the ECA that was however followed by the regionally detectable forest clearing activity of the Baden culture. With this culture, animal traction and twin-oxen driven ard were the key technological developments that resulted in the clearance of larger areas. Pollen records from Hungary support the spread of animal-traction in the Baden period particularly in Transdanubia. In the northern part of Hungary, however, farming in the LCA remained similar to the Neolithic: the same crops and the same techniques were found suggesting aerial differences (Hajnalova 2012).

The archaeobotanical and pollen records seem to reinforce each other in that the first crop fields were likely established in naturally open or semi-open parts of the landscape, furthermore the archaeobotanical data suggest mainly stable groundwater plots that tended to be interpreted as chernozem covered (Bogaard et al. 2007). However the GIS-based research strongly argues for meadow soil preference for agriculture during the EN (Kempf 2021) admitting that hydromorphic chernozem variants likely developed from these originally meadow soils. The archaeobotanical assemblages quite often contain wetland and aquatic plants that were so far not interpreted as crop field weeds. A careful re-examination of this question is an important task of future, detailed, context-based archaeobotanical studies.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection, literature survey and data analysis were performed by EM, MM, MM, MH and PR. The first draft of the manuscript was written by EM and PR and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declarations

Competing interests Authors disclose no competing financial or non-financial interests that are directly or indirectly related to this work.

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