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RESEARCH ARTICLE

New radiocarbon dates point to the early evolution of resilient agriculture among Central Europe's first farmers

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Abstract
The shift towards cultivating domesticated crops was a pivotal development in ecological, economic, and human behavioural systems. As agriculture expanded beyond its origins, it faced diverse environments, often unsuitable for the originally cultivated domesticates. Farmers in Central Europe had to adjust and transform their farming systems, typically cultivating only five domesticated crop species. Here, we present new archaeobotanical data comprising 7955 determined charred remains and 22 radiocarbon dates from South Bohemia. This region, with higher altitudes, colder climates, and less fertile soils, lies on the periphery of Early Neolithic settlement. Our results reveal increased crop diversity as a form of adaptation to the harsher environment that bolstered resilience against crop failure. The earliest ^{14}C-based evidence of deliberate cultivation of barley and Timopheev's wheat in the region also provides new insights into the interplay between crop diffusion, landscapes, and food choices in the Neolithic Central Europe.

Introduction

The spread of farming from centres of domestication into new biogeographic zones may have led to a loss of the original crop diversity. While the first southwest Asian farmers cultivated thirteen crop species (Zohary et al. 2012), the Linearbandkeramik (LBK, 5550–4900 BC) communities in Central Europe relied on five staple crops: two hulled wheats—einkorn (*Triticum monococcum*) and emmer (*Triticum dicoccum*), two legumes—lentil (*Lens culinaris*) and common pea (*Pisum sativu*m), and one fibre/oil plant—flax (*Linum usitatissimum*) (Kreuz et al. 2005; Colledge and Conolly 2007; Conolly et al. 2008; Kreuz and Marinova 2017; Ivanova 2020). The uniformity of Central European Early Neolithic farming may not be surprising if considered in the sociocultural context. The LBK communities are well recognized for their cultural conservatism, characterized by a high degree of uniformity in artefact production, architecture, and economic practices, especially in the early phase, which played a significant role in their swift and widespread expansion across a large territory (Shennan 2018). However, it is crucial to consider the ecological context when examining archaeobotanical data. Since the LBK populations predominantly settled in fertile lowlands of Central Europe (Brigand et al. 2022), the limited assortment might be a result of a deliberate selection of crops being well adapted to given conditions. Here we address the question of whether the uniform character of LBK agriculture signifies only a cultural homogenisation or whether it rather represents a deliberate selection of crops well adapted to conditions of fertile lowlands.

To test this hypothesis, we need to study the early farming implementation in less productive regions of Central Europe, mainly in those with ecologically demanding conditions for crop cultivation.

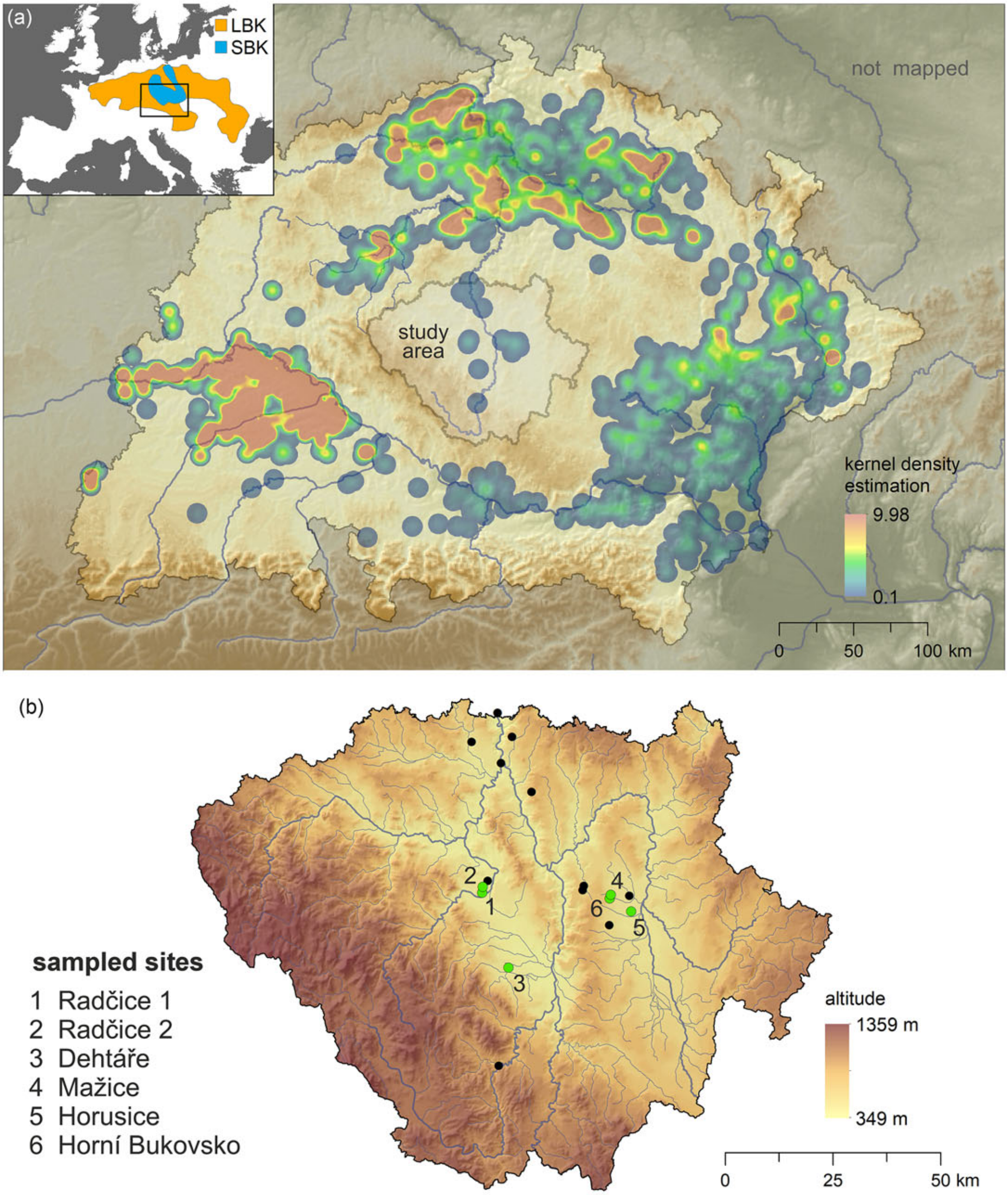

Figure 1. *The settlement context of the archaeobotanical record from South Bohemia. (a) kernel density estimation of LBK settlement sites. (b) LBK and SBK sites in the study area. Green dots represent archaeobotanically investigated sites.*

South Bohemia (Czechia) provides an ideal study setting because of a diverse landscape mosaic with elevations of above 350 metres a.s.l., less favourable soils (mostly cambic and pseudogley; Chábera et al. 1985), cooler climate (when compared to neighbouring lowlands), strong seasonality of temperatures, and rather moist summers (Supplementary Text 1). In the Early Neolithic, the region stood out as a distinctive (inner) periphery of the LBK settlement area with significantly less intensive occupation (Figure 1) and delayed colonization. While the initial wave of LBK diaspora reached the surrounding lowlands in the 54th century BC (Jakucs et al. 2016; Shennan 2018), it was postponed here ca. 150 years (Vondrovský et al. in press). The settlements here were far apart and isolated from the surrounding lowland zones (see Figure 1). Towards the end of the LBK period, there was a steep decline in the already sparse occupation, with very few settlements persisting beyond 5000 BC when the region witnessed the emergence of the Middle Neolithic Stichbandkeramik culture (SBK, 5000–4500 BC).

Our study bridges a knowledge gap caused by a scarcity of archaeobotanical data from peripheral regions of the Central European LBK settlement zone (Vondrovský and Chvojka 2021). Before our project, hardly any archaeobotanical and radiocarbon data on the Neolithic in the region were available. The situation has changed through our numerous archaeological prospection surveys followed by targeted small-scale excavations (Supplementary Text 2). Given the dry conditions of the sites where only charred plant remains are preserved, a low density of archaeological plant material was expected. To overcome the obstacle of obtaining only a limited and/or unreliable dataset we applied an extremely intensive archaeobotanical sampling strategy.

Methods

Excavations and sampling

We chose small-scale excavation with very intensive sampling and detailed recording of spatial and contextual data for all artefacts and samples. The chronology of each archaeological feature was determined based on material culture and/or radiocarbon dating of plant macrofossils. Features were dated and classified to the LBK, SBK, and Neolithic. The latter category includes either LBK or SBK cultures, without the possibility of further differentiation. Detailed descriptions of the sites are provided in Supplementary Text 2.

In Radčice 1 and Mažice sites, features were sampled totally, meaning that 100 % of their infill was taken for archaeobotanical analysis. The samples (analytical units) were collected in a 50 × 50 cm grid and 5 cm arbitrary spits. After the evaluation of the approach's effectiveness, the strategy was modified. At Radčice 2, Dehtáře, and Horní Bukovsko 10 L of sediment were collected from each 10 cm thick layer within the same grid. An exception is the Horusice site excavated as a rescue campaign triggered by motorway construction. Samples of 10 to 20 L were collected in a 1 × 1 m grid and 10 cm thick spits.

Recovery from deposits, taxa identification, and counting of the plant remains

A total of 2162 samples (25,572 L of sediment) were processed using a flotation machine, with a 0.25 mm mesh for floating remains and a 1 mm mesh to capture heavy fractions (cf. Pearsall 2015). Both, light and heavy fractions yielded charred plant remains. All were sorted and identified using low-power stereomicroscopes, identification keys, and reference collections available at the Laboratory of Archaeobotany and Palaeoecology at the University of South Bohemia and the Department of Archaeology at Constantine the Philosopher University in Nitra. M. Ptáková, V. Komárková, T. Šálková, and M. Hajnalová carried out the identification of plant macrofossils. Images were taken with a Keyence VHX 7000 digital microscope.

Due to suboptimal preservation conditions, each cereal fragment (grain or chaff) was attributed a numerical value of one. Determined taxa denoted as "cf." were merged with the corresponding taxonomic categories for further calculations or statistical evaluation. The relative importance of individual crops is evaluated by considering their abundance (number of remains per analytical unit) and frequency (percentage of analytical units where they are found).

Radiocarbon dating of the plant remains

In total, 22 charred plant macrofossils were dated by the AMS method in the Czech Radiocarbon Laboratory (CRL) and Poznan Radiocarbon Laboratory (Poz). Samples were pretreated with an

Table 1. Diversity in the archaeobotanical crop dataset from 6 Neolithic sites in South Bohemia (see Supplementary Table 1 for further details on the dataset). a, determined crop taxa, their quantity and frequencies in samples

Crop		Counts	Total	Frequency (%)
Triticum monococcum	Grain	287	996	27.9
Triticum monococcum	Glume base	11	32	1.1
Triticum monococcum/dicoccum	Grain	47	80	4.6
Triticum dicoccum	Grain	304	851	29.6
Triticum dicoccum	Glume base	8	10	0.8
Triticum timoheevii	Grain	98	134	9.5
Triticum timopheevii	Glume base	7	11	0.7
Triticum aestivum/compactum/turgidum	Grain	9	9	0.9
Triticum sp.	Grain	187	340	18.2
Hordeum vulgare	Grain	80	220	7.8
Cerealia	Grain	712	4736	69.3
Cerealia	Glume base	5	7	0.5
Lens culinaris	Seed	2	2	0.2
Pisum sativum	Seed	63	84	6.1
Leguminosae sativae	Seed	86	148	8.4
Linum usitatissimum	Seed	39	295	3.8

acid-alkali-acid method, followed by combustion and graphitisation. The resulting dates were corrected for isotopic fractionation using $\delta^{13}C$ and calibrated in OxCal v.4.4 software using the IntCal20 calibration curve (Bronk Ramsey 2009; Reimer et al. 2020).

Results and discussion

We secured an assemblage of 2162 flotation samples, i.e., 25,572 L of archaeological sediment from six Early and Early-to-Middle Neolithic settlement sites and resulted in the recovery of 8605 carbonized determined plant macrofossils. Of these, 92.4% (n = 7955) are remains of domesticated plants (Supplementary Tables 1 and 2).

The recovered plant macrofossils are extremely fragmented and distorted due to the high charring temperatures. Most finds represent undeterminable fragments of cereal grains (Table 1). Among identified specimens, the majority belong to einkorn (*Triticum monococcum*) and emmer (*Triticum dicoccum*), occurring in similar abundances but are also accompanied by barley (*Hordeum vulgare*) and "new type" wheat *Triticum timopheevii*. Additional crop diversity is provided by lentil (*Lens culinaris*), pea (*Pisum sativum*), and flax (*Linum usitatissimum*) (Table 1). Cereal spectra are the same for LBK and SBK, only the proportions of individual crops vary slightly. Due to the state of preservation differentiation between hulled (*Hordeum vulgare* var. *vulgare*) and naked (*Hordeum vulgare* var. *nudum*) forms of barley was problematic; nevertheless, both are present, although the naked variety is sporadic (Figures 2 and 3).

The plant remains come from the fills of sunken features (representing secondary or tertiary contexts) and must have been charred elsewhere. The assemblage exhibits a predominance of cereal grains, the extremely low density of finds with an average value of 0.3 items (0.7 after excluding negative samples) per liter of archaeological deposit, and the prevalence of weed seeds associated with the final stages of crop processing (Hillman 1984; Jones 1984). Chaff and weed seeds eliminated in early processing stages are extremely rare. Although they are less likely to survive charring (Boardman and Jones 1990) and/or redeposition, they might have followed different taphonomic pathways and did not enter archaeological deposits in charred form (Fuller et al. 2014)

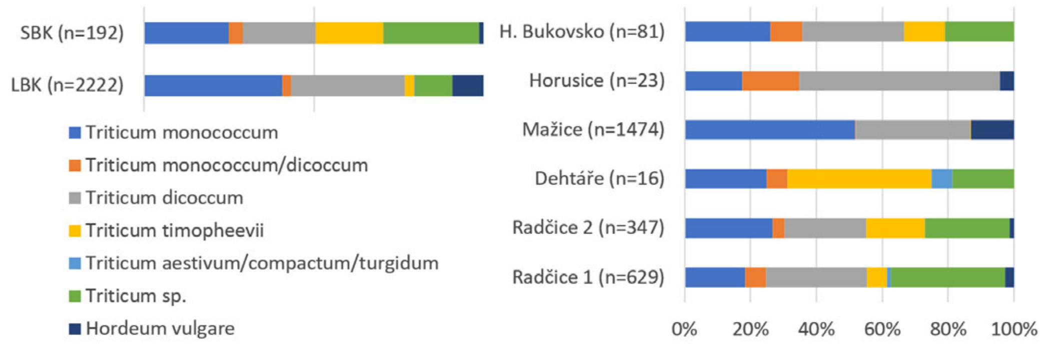

Figure 2. *Relative quantities of determined cereal taxa for the LBK and SBK contexts (left); relative quantities of determined cereal taxa for the individual sites (right).*

Twenty-two well-preserved cereal grains were radiocarbon dated by the AMS radiocarbon method. The results confirmed the previous chronology based on artefacts and stratigraphy (Table 2, Figure 3). Nineteen measurements are in accordance with the absolute chronology of the LBK culture in Bohemia set between ca. 5400 and 4950 cal BC (Jakucs et al. 2016; Riedhammer 2018). The three measurements from the Radčice 2 site are in accordance with the established chronological timeframe of the SBK period in Bohemia, estimated from ca. 4950 to 4500 cal BC (Řídký et al. 2019; Riedhammer 2018). Most importantly, of these, six caryopses of *Hordeum vulgare* and three caryopses of *Triticum timopheevii* were directly dated and respectively confirm their Early and Early-to-Middle Neolithic origin. Furthermore, we assume that these crops were part of the same economy as einkorn and emmer. The chronological homogeneity of fourteen measurements related to caryopses from LBK contexts determined to species level was tested by consistency test and outlier analysis using the OxCal notation Outlier_Model("General",T(5),U(0,4), "t"). At the 5% significance level, the results proved the statistical consistency (T = 19.5; T(5%) = 22.4; df = 13) and no outliers in the dataset. Test sensitivity is, however, limited by the radiocarbon curve plateau at 5200–5000 cal BC.

These two species—barley and Timopheev's wheat—provide unusual diversity in the otherwise conventional crop spectrum. Both occur in most of the studied sites (Figure 2). Their occurrence in assemblages of cleaned crops, with proportions surpassing ten per cent of identified cereal finds at one location for barley and three locations for Timopheev's wheat, suggests that they were intentionally grown as crops.

Barley was one of the Neolithic founder crops and a key component of the Neolithic package of domesticated crops through which the new economy spread (not only) to Europe. However, the archaeological evidence of barley cultivation in Early Neolithic Central Europe is very sporadic, and its status as an LBK crop in its own right has been surrounded by ambiguity. Consequently, its finds are often viewed as either intrusive or grown unintentionally as a weed admixture in wheat fields (Bogaard 2004; Bogaard et al. 2017; Filipović et al. 2020; Ivanova 2020; Ivanova et al. 2018; Kočár and Dreslerová 2010; Kreuz 2012; Kreuz et al. 2005; Salavert 2011;). Although barley became a significant staple in Central Europe in the Middle and Late Neolithic, its occasional presence increased during the late phase of the LBK (Herbig et al. 2013; Kreuz and Marinova 2017). This delayed adaptation of barley is not yet fully understood (Kreuz et al. 2005). However, the peripheries might have played a significant role as a potential source of crop diversity for their subsequent expansion.

Based on our directly dated finds, we argue that barley cultivation in the LBK of Central Europe might have been an adaptation to higher altitude, lower quality soils, and/or harsher climatic conditions of peripheral regions settled during the second wave of neolithisation. Barley seems a suitable choice since it is highly resilient and capable of thriving in challenging environments where other crops struggle to grow (Newton et al. 2011). According to genetic evidence, Central and Northern Europe is an area where a variety of barley that does not respond to changes in daylight length, allowing it to

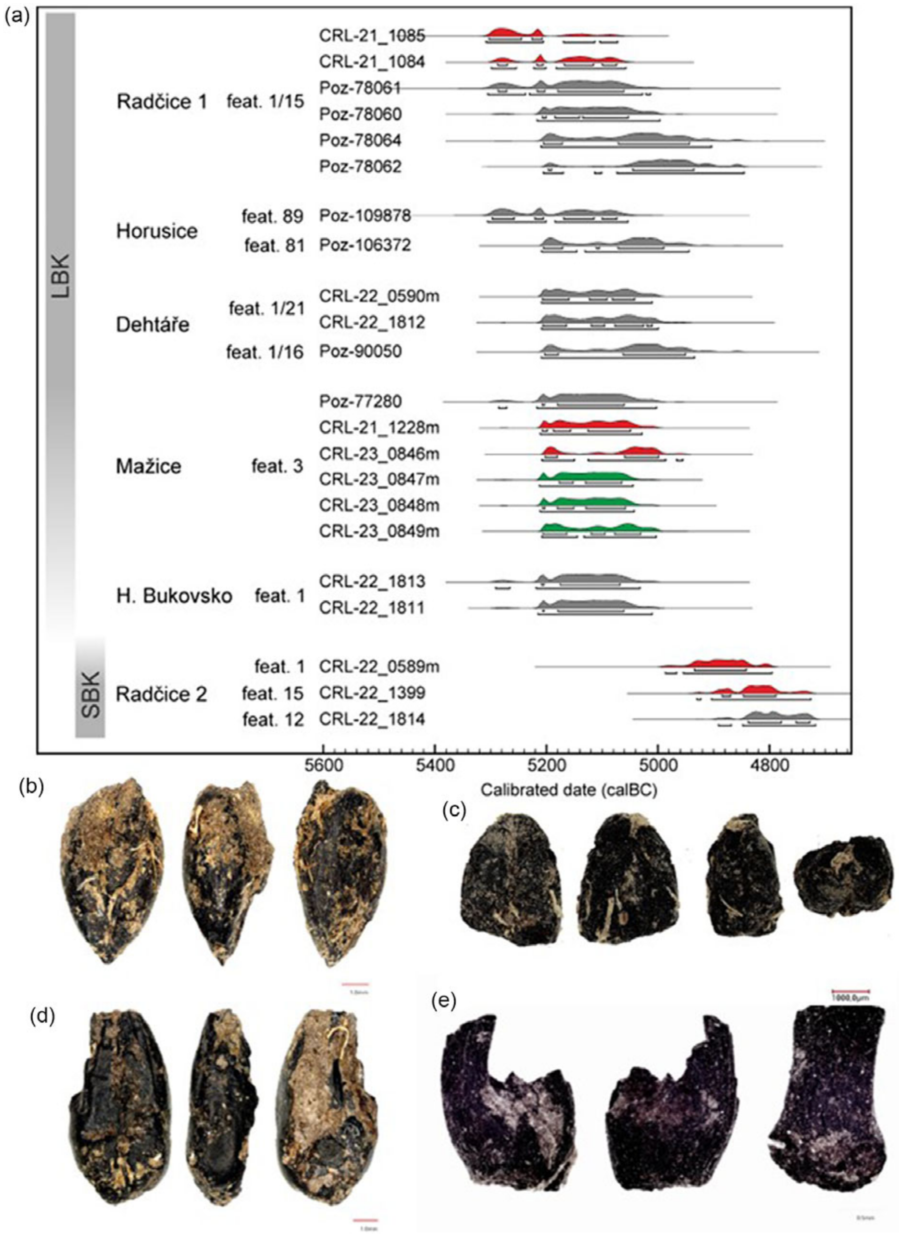

Figure 3. *Archaeobotanical remains and radiocarbon dating. (a) Multiplot of calibrated radiocarbon measurements. Barley grains (red), Timopheev's wheat grains (green). Calibrated using OxCal v.4.4 software and the IntCal20 calibration curve (Table 2). (b) charred grain of Hordeum vulgare var. vulgare. (c) charred grain of Hordeum vulgare var. nudum (d) charred grain of Triticum timopheevii. (e) charred spikelet fork of Triticum timopheevii.*

flower later and avoid late frosts, better suited for cultivation in northern latitudes, is presently predominant. Since no direct genetic evidence is available from archaeological material, it is impossible to pinpoint the date when photoperiod non-responsive barley genotypes were introduced to Central Europe (Jones et al. 2012, 2013; Lister et al. 2009).

Table 2. *Overview of samples dated by the radiocarbon (AMS) method. Results were calibrated in OxCal v.4.4 software using the IntCal20 calibration curve (Bronk Ramsey 2009; Reimer et al. 2020)*

Site	Feature no.	Depth (cm)	Sampled taxa	Lab number	^{14}C age (BP)	cal BC (95.4%)
Radčice 1	1/15	5–10	*Hordeum vulgare*	CRL-21_1085	6249 ± 28	5308 (74.3%) 5206 5170 (14.8%) 5114 5104 (6.3%) 5072
	1/15	10–15	*Hordeum vulgare*	CRL-21_1084	6220 ± 26	5299 (17.4%) 5254 5223 (11.5%) 5202 5183 (66.6%) 5058
	1/15	35–40	*Triticum dicoccum*	Poz-78061	6210 ± 50	5306 (17.1%) 5238 5230 (77.7%) 5028 5022 (0.7%) 5014
	1/15	0–5	*Triticum dicoccum*	Poz-78060	6170 ± 40	5217 (95.4%) 4997
	1/15	40–45	*Triticum monococcum/dicoccum*	Poz-78064	6110 ± 50	5210 (95.4%) 4904
	1/15	15–20	*Cerealia*	Poz-78062	6080 ± 40	5206 (7.8%) 5170 5114 (0.9%) 5102 5074 (86.8%) 4846
Horusice	89	—	*Linum usitatissimum*	Poz-109878	6230 ± 40	5306 (42.2%) 5201 5185 (53.3%) 5054
	81	—	undetermined	Poz-106372	6120 ± 35	5209 (23.7%) 5146 5131 (71.8%) 4945
Dehtáře	1/21	30–40	*Cerealia*	CRL-22_0590m	6156 ± 27	5210 (95.4%) 5011
	1/21	10–20	*Triticum monococcum*	CRL-22_1812	6146 ± 32	5209 (95.4%) 5000
	1/16	10–15	*Triticum sp.*	Poz-90050	6110 ± 40	5210 (95.4%) 4935
Mažice	3	5–10	*Triticum diccoccum*	Poz-77280	6180 ± 40	5286 (1.8%) 5272 5218 (93.7%) 5003
	3	20–25	*Hordeum vulgare*	CRL-21_1228m	6164 ± 26	5212 (95.4%) 5029
	3	15–20	*Hordeum vulgare*	CRL-23_0846m	6125 ± 23	5209 (26.6%) 5150 5126 (67.7%) 4987 4968 (1.2%) 4956
	3	15–20	*Triticum timopheevii*	CRL-23_0847m	6179 ± 23	5214 (95.4%) 5046
	3	5–10	*Triticum timopheevii*	CRL-23_0848m	6174 ± 23	5212 (95.4%) 5044
	3	0–5	*cf. Triticum timopheevii*	CRL-23_0849m	6148 ± 23	5209 (34.6%) 5146 5134 (60.9%) 5004

(*Continued*)

Table 2. (*Continued*)

Site	Feature no.	Depth (cm)	Sampled taxa	Lab number	^{14}C age (BP)	cal BC (95.4%)
Horní Bukovsko	1	20–30	*Triticum monococcum*	CRL-22_1813	6190 ± 34	5292 (3.3%) 5266 5219 (92.1%) 5032
	1	40–50	*Triticum dicoccum*	CRL-22_1811	6177 ± 32	5216 (95.4%) 5011
Radčice 2	1	30–40	*Hordeum vulgare*	CRL-22_0589m	5998 ± 28	4987 (3.3%) 4967 4955 (92.1%) 4796
	15	30–40	*Hordeum vulgare*	CRL-22_1399	5950 ± 27	4930 (1.0%) 4924 4904 (94.4%) 4726
	12	30–40	*Triticum timopheevii*	CRL-22_1814	5925 ± 30	4892 (5.1%) 4869 4848 (90.3%) 4718

Timopheev's wheat, also known as "new" glume wheat, is a distinct prehistoric cereal crop with not yet fully understood history (Czajkowska et al. 2020). Since its first identification (Jones et al. 2000) many finds have been reported from Europe and the Near East, however, finds in Neolithic Central Europe are still rare (Bieniek 2007; Bogaard 2011; Hajnalová 2007; Herbig et al. 2013; Kenéz et al. 2014; Kohler-Schneider 2003; Toulemonde et al. 2015) and it tends to represent a (scarce) contaminant/admixture of other cereal crops. The material presented here is the first in Czechia and one of the oldest in Central Europe. Although Timopheev's wheat might be underestimated in earlier works due to misidentification (Filipović et al. 2023), it is plausible that (similar to barley) its cultivation in the Early Neolithic was promoted in specific areas. This species is known to be a suitable choice for poor soils and higher altitudes and is valued for its high immunity to diseases and pests (Filipović et al. 2023; Jorjadze et al. 2013).

Although the LBK crop economy in the region appears to deviate from the well-described LBK uniformity, the SBK assemblage from South Bohemia is in line with the general broadening of crop spectra from the Middle Neolithic onwards in Central Europe (e.g. Bogaard 2004). However, the increased diversity and proportion of each cereal species varies across the study sites and may have been developed at the site level. It is also important to bear in mind the limited scope of excavation, which makes it impossible to detect variability within the settlement and explore overal patterns. To verify these trends, more extensive excavations and studies from other peripheral areas of Central Europe are required.

Conclusions

The increased variety of cultivated species in the peripheral region of South Bohemia indicates a resilient farming strategy, where planting various types of crops with different growth patterns and abilities to withstand varying conditions offers an effective buffering mechanism to overcome environmental constraints and allows for the reduction of the risk of crop failure or collapse. By use of additional cereal taxa, pioneer Central European farmers stepped out of firmly embedded cultural patterns very early on. The continuity of the same crop spectra from the Early to Middle Neolithic also suggests the establishment of local traditions in farming/culinary practices. Finally, this region and dataset provide valuable insights into the role of agricultural peripheries in the early dispersion of domesticated crops, early farmers' economies, and the multifaceted relationship between people and changing climates and environments.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/RDC.2024.84

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Competing interests declaration. The authors declare that there are no competing interests associated with this paper.

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