



***Restitutio Ab Initio*: Direct Dating and Isotopic Evidence to Evaluate the Proxy Reliability of Intrusive Archaeobotanical Remains**

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Abstract

Recovering archaeobotanical remains from archaeological contexts often entails substantial methodological challenges. Flotation and environmental sampling routinely yield charred seeds whose cultural attribution does not necessarily correspond to the stratigraphic position or inferred chronology of the deposits in which they occur. Direct radiocarbon dating frequently exposes marked discrepancies, demonstrating that intrusive seeds may derive from much later occupations than the layers that contain them. Such materials are commonly excluded from analysis, either because they are deemed intrusive or because their taxa are not otherwise attested in the archaeological period represented by the context. We argue, however, that within multi-stratified and multi-period sites, intrusive carpological remains may, in specific cases, provide limited and context-dependent evidence for later episodes of site use, provided that their chronology and taphonomic status are independently verified by direct radiocarbon dating and, where feasible, complementary isotopic analysis. This study presents new radiocarbon and stable isotope data for charred millet grains recovered from the Gumelnița site in southeastern Romania. Two broomcorn millet (*Panicum miliaceum*) grains and one foxtail millet (*Setaria italica*) grain were directly dated, placing their presence in the second half of the 2nd millennium BC and the beginning of the 1st millennium BC. The directly dated *Setaria italica* grain is, to our knowledge, the earliest securely dated occurrence of foxtail millet in Europe; an earlier occurrence is known from Pichori in Transcaucasia, outside Europe, which remains the earliest directly dated record of foxtail millet currently known from the Caucasus. These results demonstrate that intrusive grains may provide limited chronological evidence for documenting later occupational or depositional events superimposed upon earlier archaeological layers.

Keywords Southeastern Europe · Bronze Age · Carpological ecofacts · Radiocarbon dating · Stable isotopes · Millet

Introduction

A proper understanding of past plant-body history requires correlation with archaeological contexts and chronology, an essential condition for tracking archaeological, palaeoecological, or archaeobotanical queries. By their structure and morphology, plant micro- and macro-remains preserve a wide range of information on human activities and past environments. However, their recovery depends strongly on the depositional setting and subsequent taphonomic processes. Thus, such archaeobotanical remains may occur in multiple archaeological features and survive through different preservation pathways—including waterlogging, charring, desiccation, mineralisation, or as impressions—each requiring carefully adapted sampling and collection strategies to minimise contamination and disturbance (Celant *et al.*, 2015).

The Contextual Fragility of Archaeobotanical Ecofacts

Broader site formation research confirms that both vertical and horizontal shifts of archaeobotanical macroremains often mirror the same sedimentary and disturbance processes documented for other ecofacts, including gravity-driven microstratigraphic deformation, compaction, and bioturbation, all well established in classic analyses of cultural and natural formation processes (Schiffer, 1987) and in micro-morphological studies showing vertical displacement and lateral drift of organic particles under repeated wetting, trampling, and fine scale sediment movement (Goldberg & Macphail, 2006).

Whenever subsurface remains are detected, investigators must be aware of possible disturbances and the effects these processes may have had on the distribution and patterning of the artefacts. Archaeological deposits are dynamic: a range of mechanical, biological, and anthropogenic processes can displace sediments and their constituents, including charred plant macroremains. Burrowing fauna, root growth and decay, tree throw, shrink–swell processes, freeze–thaw cycles, and slope/water-driven reworking can all alter the original horizontal and vertical position of ecofacts and artefacts, with consequences for contextual attribution and chronological interpretation (Goldberg & Macphail, 2006; Waters, 1997). Understanding these processes is essential because they shaped both horizontal and vertical distributions, complicating subsequent interpretation.

For archaeobotanical assemblages in particular, contamination through intrusion and residuality is widely recognised and has been discussed through both methodological syntheses and applied case studies. We therefore treat unexpected taxa and distributions as hypotheses to be tested—preferably by direct dating of individual grains—rather than as automatic cultural indicators (Johnson & Stegner, 1990; Pelling *et al.*, 2015; Reed *et al.*, 2022; Rossen *et al.*, 1996; Schweger, 1985; Stein, 1983; Wood & Johnson, 1978).

Building on this, archaeobotanical criteria for identifying and excluding intrusive seeds emphasise the importance of taxonomic consistency, stratigraphic coherence,

and contextual patterning, since atypical distributions or taxa known to infiltrate deposits through natural disturbance often signal intrusion rather than cultural deposition (Hillman, 1981; Hubbard & Clapham, 1992; Schiffer, 1987; Veen, 1992).

Together, these findings demonstrate that vertical movement of carbonised seeds can occur independently of human behaviour, underscoring the need to integrate stratigraphic control with micro-sedimentological analysis when interpreting archaeobotanical distributions.

Millet Significance

Millets are small-seeded cereals of the Poaceae family, well suited to arid and semi-arid environments due to their exceptional drought tolerance, short growing season, and adaptability to poor soils. As C4 plants, they possess a highly efficient photosynthetic pathway that enhances carbon fixation under conditions of high temperature and low moisture. Their rapid maturation—often within 3 months—allows for a supplementary summer harvest, providing a critical buffer in years of winter crop failure (FAO, 2023).

Among the earliest domesticated species, broomcorn millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*) originated in northern China around 10,300–8700 cal BP (Liu *et al.*, 2012; Lu *et al.*, 2009; Wang *et al.*, 2017; X. Yang *et al.*, 2012; Zhao, 2011). Although millet remains have been reported in Neolithic and Eneolithic contexts across central and western Europe (Hunt *et al.*, 2008; Zohary *et al.*, 2012), radiocarbon dating has revealed that these often belong to much later periods (Motuzaite-Matuzeviciute *et al.*, 2013). A large-scale dating programme has shown that broomcorn millet likely reached Europe by the 16th century BC, with widespread cultivation occurring during the fifteenth and fourteenth centuries BC (Filipović *et al.*, 2020). The earliest securely dated presence is currently from Vinogradniy Sad in Ukraine, around the 17th century BC (Dal Corso *et al.*, 2022; Pashkevych, 2022).

In Romania, broomcorn millet has been reported at Late Neolithic and Chalcolithic sites, though these early finds are often limited and potentially intrusive, as they remain undated by radiocarbon methods (Cârciumaru, 1996; Monah, 2007). While millet was present during the Bronze Age, its widespread cultivation appears to have intensified from the Iron Age onwards, becoming common at Dacian sites with archaeobotanical evidence (Cârciumaru, 1996; Ciută, 2021; García-Vázquez *et al.*, 2025).

Current Approach

We resumed research at the eponymous Gumelnița site in Lower Danube, Romania (Fig. 1a), in 2017, focusing on the Neolithic-Chalcolithic sequences (Lazăr *et al.*, 2020). During systematic flotation of discrete 10-L sediment samples from the fills of two Chalcolithic burials (M8 and M10), we recovered three charred millet grains—an occurrence that would be chronologically anomalous if attributed to the 5th millennium BC. We therefore directly dated the individual grains and conducted

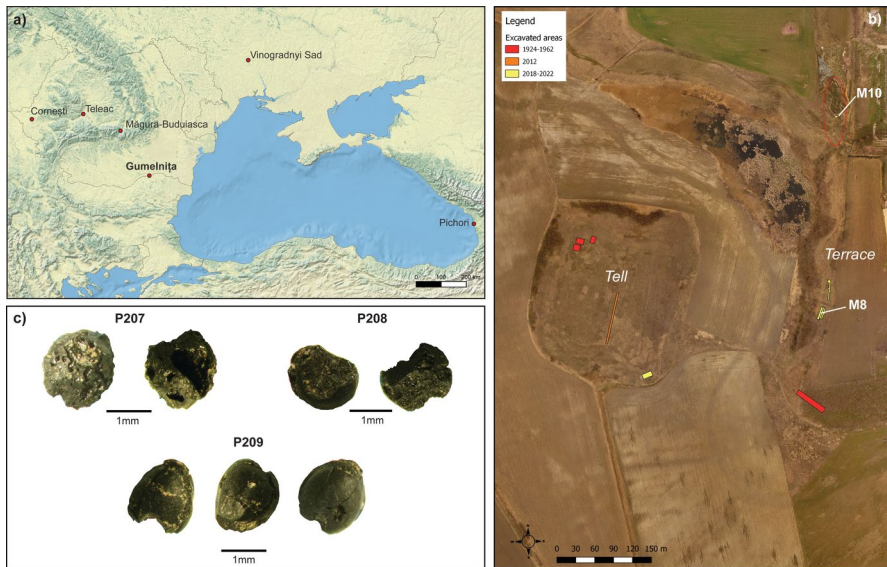


Fig. 1 **a** Location of the Gumelnița site and other sites mentioned in the text. **b** Aerial picture of Gumelnița site showing excavation areas and the location of graves M8 and M10 from which the millet grains were recovered. **c** Charred millet remains: P207 (DET 60), broomcorn millet grain in dorsal and ventral views; P208 (DET 78), foxtail millet embryo shown from two angles; P209 (DET 80), broomcorn millet grain in dorsal, lateral, and ventral views. Higher resolution images of the grains are shown at Fig. S12

exploratory stable isotope analysis on one specimen to (i) verify their intrusive status and (ii) assess whether securely dated intrusive macroremains can provide a limited, transparent proxy for later (Bronze Age/Early Iron Age) activity that is otherwise poorly documented within the excavated areas of the terrace sector.

Through this approach, we explore whether intrusive artefacts or ecofacts from adjacent archaeological horizons can, in restricted circumstances, provide limited evidence for later site use at sites investigated only partially or at low intensity. We do not treat such materials as standalone indicators of broader archaeological or palaeoecological patterns; rather, their interpretive value depends on direct dating, taphonomic assessment, and careful spatial contextualisation.

Material and Methods

The Archaeological Site

The Gumelnița site (also known as Măgura Gumelnița or Măgura Calomfirescu) is well known as the largest tell settlement north of the Danube (Fig. 1a) and as the eponymous site of the Gumelnița culture, part of the Kodjadermen–Gumelnița–Karanovo VI (KGK VI) Chalcolithic block of the late 5th millennium BC. It anchors a long tradition of archaeological research in Romania,

extending from Vladimir Dumitrescu's investigations in the 1920s to the present, within a micro-region densely occupied by contemporaneous and later sites representing multiple archaeological periods (Dumitrescu, 1924, 1925, 1966; Dumitrescu & Marinescu-Bîlcu, 2001; Lazăr, 2001; Lazăr *et al.*, 2017; Șerbănescu, 2009; Șerbănescu, 1985). The site is located in southeastern Romania (Fig. 1a), on the left bank of the Danube River, just south of the confluence of the Argeș River with its tributary, Valea Mare (García-Vázquez *et al.*, 2023; Lazăr, 2001; Lazăr *et al.*, 2017, 2020, 2021; Tafani *et al.*, 2025).

The site is composed of the Middle Chalcolithic KGK VI tell-type settlement and two pair necropolises, along with an Early Chalcolithic occupation (Boian–Vidra phase), a Late Chalcolithic cemetery (Cernavoda II culture), a Bronze Age settlement (Tei culture), and occupations corresponding to the first Iron Age and to the seventh–eleventh centuries AD (Lazăr *et al.*, 2020; Șerbănescu, 2009; Șerbănescu, 1985, 2022) (Fig. S1).

The Excavations

The excavations at Gumelnița, in disciplinary terms, have been primarily directed towards investigating and clarifying the internal stratigraphy and development of the Chalcolithic sequence (Gumelnița culture/KGK VI) at the tell settlement and its associated cemetery, while also extending research into the adjacent floodplain through coring and various forms of non-intrusive prospection (Fig. 1b). These investigations aim to reconstruct past palaeoenvironments and to correlate isotopic data from humans, fauna, and plants with the archaeological record (Lazăr *et al.*, 2017, 2020). The Chalcolithic tell and the related necropolis cover the period between 5041 and 3816 cal BC (Table S1) (Bem, 2000; García-Vázquez *et al.*, 2023; Lazăr *et al.*, 2017, 2020; Mattila *et al.*, 2023; Popescu *et al.*, 2023). They have yielded a rich sequence of palaeoecological and archaeological proxies, including evidence of mixed farming, sophisticated ceramic production, early metallurgy, and long-distance trade alongside reduced human mobility (García-Vázquez *et al.*, 2023; Lazăr, 2001; Lazăr *et al.*, 2017, 2020, 2021; Tafani *et al.*, 2025).

In 2018, in the terrace sector, following a report by our colleagues from the Oltenița Museum (Romania), we identified an illegally excavated area in the vicinity of an abandoned pig farm, c. 340 m north of the zone where we were conducting archaeological excavations in the Chalcolithic cemetery) (Fig. S2). This recent pit measured roughly 110×30 m at the time of our observation (June 2018). However, the analysis of satellite imagery (Google Earth/Google Maps) indicated that it had been used as a source of fill for a longer period (Lazăr *et al.*, 2019, 2020) (Fig. S3). Crucially, in 2015, our colleagues from the Oltenița Museum had already documented several disturbed and partially destroyed features by this borrow pit, attributed to the Chalcolithic and Bronze Age sequences; among these was at least one complete crouched burial ascribed to the Gumelnița culture (Șerbănescu, 2022).

In this area, we carried out an initial survey, including drone flights and geo-spatial mapping, followed by targeted fieldwork (Frujină *et al.*, 2020; Lazăr *et al.*, 2017, 2019, 2020, 2021); Stal *et al.*, 2022, 2024). This led to the identification of

several archaeological features: some preserved in an uncut profile, others situated in a zone where the mechanical excavation had been halted (Fig. S4), leaving a stepped surface between the contemporary ground level (0) and the base of the borrow pit (c. 2.8–3.8 m), at approximately 1.4–1.9 m depth. Our excavations in this sector brought to light a series of archaeological features attributed mainly to the Chalcolithic sequence (including burial M10 (Fig. S5), which was radiocarbon dated (Table S1)). The first batch of broomcorn millet grains analysed in this study derives from this context (Table S2). The second assemblage of archaeobotanical macro-remains comes from the Chalcolithic burial M8 (Table S2; Fig. S6), which was uncovered in the main area of investigation of the cemetery.

The methodological protocol applied in this sector—combining microstratigraphic excavation, Harris Matrix recording (Fig. S7), with the systematic flotation of pit and grave fills (Figs. S13–S14)—enabled the recovery of a range of micro-artefacts, bone fragments, and archaeobotanical remains. Each sediment sample was collected in a separate plastic bag, with a standard size (10 L) for each bag (with absolute coordinates measured) (Table S2).

Archaeobotanical Remains

Plant remains were recovered during the 2017–2019 excavations at the Gumelnița site (Lazăr *et al.*, 2017, 2020, 2021) from sediment samples collected from the grave fills. Photographs of the relevant grave infill stratigraphic sequences and sampling positions are shown in Figs. S13–S14 to support the taphonomic interpretation. Each 10-L sample was processed by machine-assisted flotation in the Bioarchaeology Department of the ‘Vasile Pârvan’ Institute of Archaeology. The flotation samples were sorted and examined under a stereomicroscope (Optika ST-50LED), and the botanical macroremains were identified using standard reference atlases (Bojňanský & Fargšová, 2007; Jacomet, 2006; Schoch *et al.*, 1988).

A wide variety of plant taxa has been recorded from Chalcolithic contexts at the site, including both settlement and funerary features, with most remains originating from the tell (Lazăr *et al.*, 2017, 2020, 2021). Cereals constitute the most diverse and abundant category, comprising both wild and domesticated species in the 2018 campaign (Table S3).

Broomcorn and foxtail millet grains were recovered through sediment flotation from two Chalcolithic graves M8 and M10 (Table 1 and Table S3; Figs. S5–S6). The graves themselves are securely dated (Table S1) to the second half of the 5th millennium BC (García-Vázquez *et al.*, 2023; Lazăr *et al.*, 2020). Because the presence

Table 1 Context for broomcorn and foxtail millet grains recovered from the Gumelnița site

Lab ID	Code—context	Species
P207	DET 60—M8	<i>Panicum miliaceum</i>
P208	DET 78—M10	<i>Setaria italica</i>
P209	DET 80—M10	<i>Panicum miliaceum</i>
GUM-122	DET 80—M10	<i>Panicum miliaceum</i>

of millet in such early contexts is exceptional—and would, if taken at face value, imply an implausibly early appearance of these crops in the region—we selected three grains (P207–P209; Fig. 1c and Fig. S12) for direct AMS radiocarbon dating to clarify their contextual placement and true chronology. Where two grains were recovered from the same flotation sample (DET 80; Table 1), one specimen (P209) was dated and the second (GUM-122) was analysed for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ as an exploratory indicator of cultivation conditions, explicitly recognising the limitation of single-grain replication.

Radiocarbon Analysis

These efforts to obtain radiocarbon determinations from carbonised archaeobotanical macroremains form part of a broader line of research that our team has been developing over recent years (García-Vázquez *et al.*, 2025; Golea *et al.*, 2023). Three charred grains were selected for radiocarbon dating (Table 2), with analyses conducted at the LARA—Laboratory for the Analysis of Radiocarbon with AMS, University of Bern (Bern, Switzerland) and the Laboratory of Applied Nuclear Physics Department, IFIN-HH (Măgurele, Romania) (RoAMS). Sample pretreatment followed the laboratory's established protocol (Sava *et al.*, 2019). Calibrations were performed using OxCal 4.4 (Bronk Ramsey, 2009) and the IntCal20 calibration curve (Reimer *et al.*, 2020).

Stable Isotopes Analysis

One broomcorn millet grain from grave M10 (GUM-122) was selected for stable isotope analysis (Table 1). Based on previous FTIR-ATR testing of charred seeds from the Gumelnița site, only mild contamination with carbonates and nitrates was observed (García-Vázquez *et al.*, 2023), and the same pretreatment protocol was applied (Vaiglova *et al.*, 2014): 0.5 M HCl at 80 °C for 30 min (or until effervescence stopped) followed by three rinses in ultrapure water. The sample was oven-dried to a constant weight and then subjected to isotope ratio mass spectrometry (IRMS) analysis.

IRMS was conducted at the Unit of Instrumental Techniques of Analysis (UTIA) of the Research Support Services (SAI) of the University of A Coruña (UDC), Spain, using a DeltaV Advantage mass spectrometer coupled to a Flash IRMS EA IsoLink CNS analyser. Reproducibility was better than $\pm 0.2\text{‰}$ for $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, and values were calibrated against international standards. Internal precision was verified using acetanilide, yielding a standard deviation of $\pm 0.15\text{‰}$ across 10 replicates. Given the sample's weight (0.567 mg), it was analysed once. Results are expressed in delta (δ) notation. Data analysis was performed in Past 4.14 (Hammer *et al.*, 2001), with final graphical editing in Adobe Illustrator.

Results

Radiocarbon Data

The millet grains analysed in this study were recovered from the sediment fills of Chalcolithic graves (Figs. S13–S14), although their radiocarbon determinations indicate substantially later chronologies (Table 2, Fig. 2a and S8). Sample P207 was calibrated to a continuous range of 1125–818 cal BC (2σ , 95.4%). Sample P208 produced a dominant calibrated range of 1418–1107 cal BC (2σ , 93.1%), with minor additional probability at 1096–1080 cal BC (1.3%) and 1068–1056 cal BC (1.1%). Finally, sample P209 was calibrated to 1272–926 cal BC (2σ , 95.4%). These results place P208 and P209 firmly within the second half of the 2nd millennium BC, while P207 falls at the very end of the 2nd millennium or into the earliest part of the 1st millennium BC.

Stable Isotope Results

The sample GUM-122 (*Panicum miliaceum*), from M10, yielded a $\delta^{15}\text{N}$ value of 3.5‰ and a $\delta^{13}\text{C}$ value of -10.3‰ , with nitrogen and carbon contents of 2.9% and 56.2%, respectively, and a C:N ratio of 22.9 (Table 3).

Discussion

Bronze Age and Iron Age Background

Correlation of our radiocarbon results (Table 2) with the available relative chronological framework indicates the latest stages of the Tei cultural sequence align particularly well with the ^{14}C data obtained from the Gumelnița terrace, especially the samples from context M10 (P208 and P209), where foxtail and broomcorn millet yielded calibrated ranges characteristic of the final Tei horizon. These values fall squarely within the 13th–12th century BC span attributed to the closing phases of

Table 2 Radiocarbon ages, calibrated 2σ intervals, and median calibrated dates for the directly dated millet grains

Lab ID	Species	Lab code	^{14}C	Calibrated date (2σ)	Median date $\pm \sigma$
P207	<i>P. miliaceum</i>	RoAMS-5520.2	2809 ± 60	1125–818 cal BC (95.4%)	968 ± 82 cal BC
P208	<i>S. italica</i>	RoAMS-5521.2	3017 ± 60	1418–1107 cal BC (93.1%) 1096–1080 cal BC (1.3%) 1068–1056 cal BC (1.1%)	1260 ± 92 cal BC
P209	<i>P. miliaceum</i>	RoAMS-5522.2	2912 ± 60	1272–926 cal BC (95.4%)	1107 ± 91 cal BC

Table 3 Stable isotope results for the millet grain GUM-122

Lab ID	Species	%N	$\delta^{15}\text{N}$ (‰)	%C	$\delta^{13}\text{C}$ (‰)	C:N
GUM-122	<i>P. miliaceum</i>	2.9	3.5	56.2	-10.3	22.9

Tei IV–V, providing independent support for the placement of the upper cultural horizons at Gumelnița–Valea Mare within the final centuries of the Tei cultural sequence as previously mentioned (Leahu, 2003; Morintz, 1978; Ștefan, 2021).

According to the cultural-historical archaeology, the Tei culture spans the Middle and Late Bronze Age and is generally understood to emerge from the Glina–Schneckenberg and Cernavodă–Foltești substrata. Its development extends across most of Muntenia, into regions east of the Danube, and briefly into south-eastern Transylvania before being superseded there by the Sighișoara–Wietenberg culture (Leahu, 2003). When aligned with absolute chronology, the Tei cultural sequence can be placed—based on the radiocarbon framework synthesised by Ștefan (2021) together with broader regional ^{14}C correlations—between roughly 2050 cal BC and 1200 cal BC, with Tei I/Cățelu Nou emerging shortly after 2050 cal BC, Tei II consolidating around 1900–1750 cal BC, Tei III/La Stejar flourishing between approximately 1750–1500 cal BC, and the later Tei IV–V horizons spanning ca. 1500–1300 cal BC and 1300–1200 cal BC, respectively.

Updating the Chronology of Millet in Romania

These new findings align with the timing of broomcorn millet's introduction to Eastern Europe described in Filipović *et al.* (2020) (Fig. 2a). Directly dated broomcorn millet remains from other Romanian contexts (*e.g.* Cornești, Măgura-Buduiasca, Teleac) likewise support its uptake during the later 2nd millennium BC (Filipović *et al.*, 2020; Motuzaitė-Matuzevičiūtė *et al.*, 2013) (Fig. S8), and recent synthesis for the wider region has expanded the comparative radiocarbon base (An *et al.*, 2025). Our single directly dated *Setaria italica* grain (P208) demonstrates that foxtail millet was present in Romania by the late 2nd millennium BC; this is, to our knowledge, the earliest securely dated occurrence of foxtail millet in Europe. An earlier dated occurrence has been reported at Pichori on the Black Sea coast of the western Caucasus (2011 cal BC – 1771 cal BC) (Martin *et al.*, 2021) but this locality lies south of the Greater Caucasus range and is conventionally situated within Transcaucasia (Asia). Taken together, the available evidence is compatible with a broadly contemporaneous westward dispersal of both millet taxa, but our dataset ($n = 1$ for *Setaria*) cannot by itself demonstrate a coupled 'package' dispersal pathway.

Radiocarbon results indicate a time frame that covers the Late Bronze Age (P208–209) and the Early Iron Age (P207) (Table 2). Our archaeobotanical finds are located in the vicinity of the Tei settlement (Late Bronze Age) (Figs. S1&S9), previously reported (Leahu, 2003; Morintz, 1978; Șerbănescu, 2009), and the first logical attribution would therefore be to this site (Text S1). A parsimonious interpretation is therefore that charred crop remains from disturbed Bronze Age features were reworked vertically and laterally into older Chalcolithic grave fills. We note, however, that alternative sources remain possible, including reworked agricultural topsoil, refuse disposal or activity areas not directly associated with standing habitation structures, and/or small, as-yet undetected Bronze Age features within the terrace landscape.

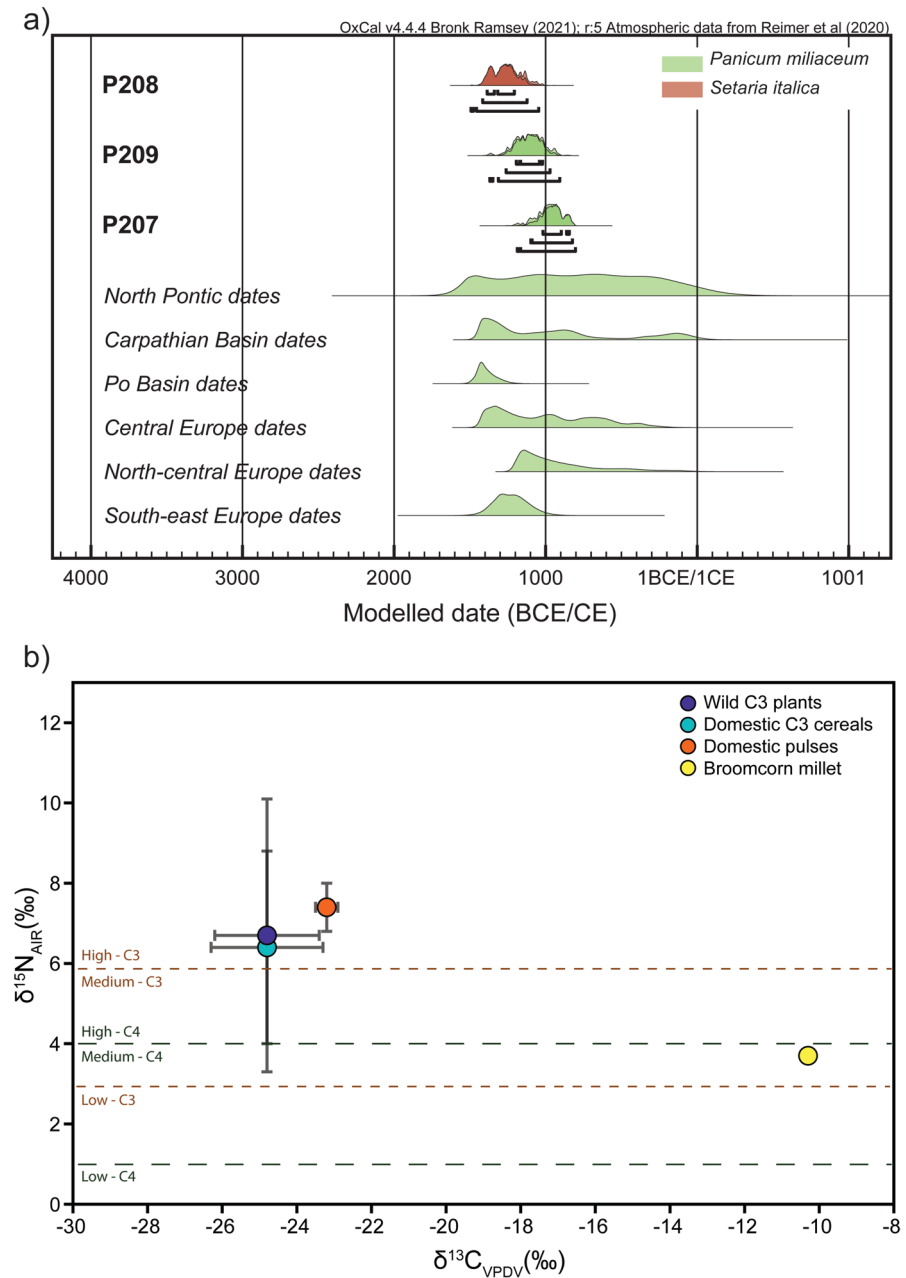


Fig. 2 **a** Broomcorn and foxtail millet grains from Gumelnița (samples P207–P209), alongside the model for the arrival of broomcorn millet in Europe adapted from Filipović *et al.* (2020). **b** Isotopic results from the Gumelnița site C3 plants (Chalcolithic chronology) from García-Vázquez *et al.* (2023) compared with the broomcorn millet grain analysed in the present study. The dashed lines indicate the threshold of the different levels of manuring for millet following Yang *et al.* (2024) (black) and for C3 plants following Fraser *et al.* (2011) (brown)

From Intrusive Finds to Archaeological Proxies

Having placed the directly dated millet grains in the right chronological context, we note their compatibility with later Bronze Age and Early Iron Age horizons. The next step is to assess their interpretive value within the disturbed archaeological landscape of the Gumelnița site. Instead of treating these charred grains simply as contaminants, we ask if they can still provide meaningful, though limited, proxies for later activity. This applies in areas where the matching archaeological record is fragmentary, reworked, or lost, if we have shown the grains are intrusive. Doing this means shifting focus away from the cultural attribution of the grave fills to the taphonomic pathways, spatial patterns, and evidential limits. Through these, displaced macroremains might document less-visible periods of site use.

For grave M10, the spatial patterning (Fig. S9) and proximity to the reported Tei occupation area suggest a local source for the intrusive Bronze Age grains (P208–P209), although, until now, this remains unproven. Modern mechanical truncation associated with the borrow pit likely removed or disturbed the overlying Late Bronze Age features, creating pathways for lightweight charred seeds to enter earlier deposits. By recognising the intrusive grains as possible indicators of broader site activity, we interpret them more cautiously as chronologically compatible with Late Bronze Age millet presence in or near the terrace sector. They do not constitute direct evidence for specific grave-related activities, and the exact source context of the grains remains unresolved.

In contrast, Grave M8 lies well beyond the presumed Bronze Age settlement core (Fig. S10), and the ^{14}C determination obtained for sample P207 likewise indicates a later horizon than the intrusive ecofacts from M10 (P208–P209), placing it at the beginning of the Iron Age (Table 2). However, this part of the site yielded no Late Bronze Age or Early Iron Age materials during our systematic excavations between 2017 and 2023. Only small Late Iron Age (La Tène) features were documented in this area during the 1960s (Marinescu-Bilcu, 1962), and no earlier deposits were identified. The Romanian Cartographic Server and the National Archaeological Record, however, indicate the presence of Early Iron Age (Basarabi-period) material approximately 2.5 km north-west of the Gumelnița necropolis at the multi-layered site of Oltenița–Coadă Lupului (Fig. S10 and Supplementary Text S2). This site provides one nearby comparative context that may be relevant to the date obtained for such intrusive grains. In a broader Early Iron Age radiocarbon horizon of south-eastern Europe, the intrusive millet grain from context M8 at Gumelnița (Table 1) (2809 ± 60 BP; calibrated to 1125–818 cal BC, 2σ) fits comfortably into the chronological bandwidth defined for the transition between the 12th and 9th centuries BC, paralleling the Noua-Coslogeni group, generally placed in the 13th–11th centuries BC (Bolohan, 2016), and aligning with the calibrated ranges characteristic of the Basarabi culture (multi-sites summative: 1300 cal BC to 830 cal BC) (Conrad & Krauss, 2020), as well as with data of the pair group Babadag (most clustering between 1250–900 cal BC) (Ailincăi *et al.*, 2017, 2022, (Ailincăi *et al.*, 2024)), and the contemporaneous ^{14}C determinations from the Early Iron Age in the Republic of Moldova (series from Saharna Mare), which cover interval of 1114–807 cal BC (Băț & Zancă, 2022). So, the calibrated interval of sample P207 shows that this

intrusive find is within the established Early Iron Age chronological horizon of the Balkans, aligning it with the wider regional transition from the late second to the early 1st millennium BC. However, this regional comparison supports an Early Iron Age attribution for the grain, but it does not identify a specific source deposit.

Nevertheless, the considerable distance between this settlement and the locus of discovery also suggests alternative possibilities: small-scale storage or agricultural activity by Basarabi communities along the terrace; the presence of as-yet undetected Early Iron Age features now obscured by recent afforestation; or the destruction of relevant deposits beneath the extensive footprint of the former agricultural combinate at Ulmeni (Figs. S1 and S10). Within this interpretative landscape, the intrusive grain recovered from M8 (P207) may be cautiously regarded as a limited chronological indicator of an Early Iron Age horizon in the vicinity of Gumelnița, while the precise source context remains unknown.

Overall, the Gumelnița site case study shows that intrusive macroremains may, in carefully controlled circumstances, provide limited archaeological indications when their context is explicitly tested and interpreted. In landscapes heavily disturbed by modern and historic activities, directly dating individual grains helps distinguish primary from intrusive deposits. Under such conditions, displaced grains may contribute constrained evidence for otherwise underrepresented phases of site use.

Millet Cultivation at Gumelnița Site

Recent experiments on the effects of manuring on millet isotopic values by Christensen *et al.* (2022) demonstrated that broomcorn millet grown on manured soils exhibits markedly higher $\delta^{15}\text{N}$ values (mean 5.8‰) compared with plants cultivated on unmanured soils (mean 0.3‰). Yang *et al.* (2024) proposed interpretative thresholds of approximately 1‰ for low organic input and 4‰ for high input. Against these reference datasets, and in comparison with the thresholds established for C_3 plants by Fraser *et al.* (2011), the $\delta^{15}\text{N}$ value obtained for GUM-122 from the Gumelnița site (Fig. 2b) is compatible with moderate manuring. However, because this interpretation is based on a single grain, it should be regarded as provisional. Compared with the C_3 plant data from Gumelnița, the result may indicate different cultivation conditions, but it cannot independently demonstrate a specific manuring regime or cultivation location.

A further consideration is that, if millet was cultivated locally, it may have been grown on the adjacent river terrace rather than in the floodplain, as millet is a summer crop and the adjacent low-lying area is inundated during that season (see Fig. 1b from García-Vázquez *et al.* (2024)). However, this should remain a working hypothesis only. Based on a single grain, the isotopic evidence cannot demonstrate local cultivation, terrace cultivation, or the intended role of millet in human *versus* animal consumption. Independent validation will require larger directly dated datasets and contemporaneous faunal and human isotopic baselines.

Isotopic studies on the diet of Bronze Age inhabitants from Romania are scarce. The only study focuses on two sites from the Monteoru culture (Middle Bronze Age), dated to 2280–1500 cal BC (Agurauja *et al.*, 2018). Notably, millet remains

were absent from these sites, and isotopic data from both humans and animals indicate no evidence of C4 plant protein consumption. The absence of millet in both archaeobotanical records and stable isotope studies associated with the Monteoru culture supports the hypothesis of a large-scale introduction of millet into Europe—and specifically into Romania—after 1500 cal BC. Both our new data from Gumelnița and other radiocarbon dates from Romania (Fig. 2a and Fig. S8) postdate this threshold.

From ca. 1500 BC, a clear C4 isotopic signal becomes visible in human remains from sites in Poland and north-western Ukraine (Pospieszny *et al.*, 2021). During this period, millet was also incorporated into human diets in Italy (Varalli *et al.*, 2022). Taken together, these data indicate that millet expanded rapidly westwards from the North Pontic steppes across Europe, reaching the Iberian Peninsula by at least the 13th century BC (Alonso & Pérez-Jordà, 2023; González-Rabanal *et al.*, 2022).

Conclusions

The results presented here show that intrusive archaeobotanical macroremains can become analytically useful only when their intrusive status is demonstrated directly, and their pathways of displacement are discussed explicitly. At the Gumelnița site, AMS dating shows that the three millet grains recovered from Chalcolithic grave fills do not belong to the 5th millennium BC funerary contexts in which they were found, but to later horizons spanning the Late Bronze Age and the beginning of the Early Iron Age.

These grains should therefore not be interpreted as evidence for Chalcolithic crop use, nor as direct evidence for activities associated with the graves themselves. Rather, once their intrusive status and depositional history have been established, they may be cautiously interpreted as limited chronometric indicators of later prehistoric presence and millet occurrence in the investigated site.

Our main contribution is methodological. The Gumelnița case shows that directly dating individual grains, along with systematic sampling and explicit taphonomic reasoning, provides a practical framework for evaluating whether plant remains are primary or displaced at disturbed multi-period sites. Under such conditions, intrusive macroremains may contribute constrained chronological information, but only within carefully defined contextual limits.

In sum, the stable isotope result presented here should be regarded as exploratory because it derives from a single grain. It offers a basis for future testing rather than a standalone reconstruction of agronomic practice. Additional directly dated grains, contextual Bronze Age and Early Iron Age archaeobotanical assemblages, weed ecological evidence, geoarchaeological data, and faunal or human isotopic baselines will be required to evaluate hypotheses concerning cultivation location, cultivation inputs, and the wider role of millet in later prehistoric land use.

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Author Contributions A.G.V. and C.L. conceived and designed the study. M.G. conducted the archaeobotanical analysis. G.S. and T.S. performed the sample pretreatment and AMS radiocarbon dating. A.G.V. carried out the isotopic analyses. The draft of the manuscript and the first review were prepared by A.G.V. and C.L., and all authors contributed to subsequent revisions. All authors read and approved the final revised manuscript.

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Data Availability The datasets generated and/or analysed during the current study are available within this article and its supplementary information file.

Declarations

Competing interests The authors declare no competing interests.

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