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Between Cereal Agriculture and Animal Husbandry: Millet in the Early Economy of the North Pontic Region

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Abstract

Broomcorn millet (*Panicum miliaceum* L.) was first domesticated in China and dispersed westward via Central Asia in the 3rd millennium BC, reaching Europe in the 2nd millennium BC. North of the Black Sea, the North Pontic steppe and forest-steppe areas are key regions for understanding the westward dispersal of millet, as evidenced by the earliest direct radiocarbon dates on European millet grains, which we present here. Examining various lines of evidence relevant to crop cultivation, animal husbandry, contacts and lifestyles, we explore the regional dynamics of the adoption of millet, broadening knowledge about past subsistence strategies related to the 'millet farmers/consumers' who inhabited the northern Black Sea region during the Bronze and Iron Ages. Our re-evaluation of crop evidence contributes to ongoing discussions on the mobility of prehistoric communities in the Eurasian steppe and forest-steppe—for instance, on whether millet was linked to full-time mobile pastoralists, who occasionally grew or only consumed it, or whether it was linked to sedentary farmers and cattle herders who regularly cultivated millet, among other crops. From the Bronze Age to the Late Antique, this crop is attested under different socio-cultural conditions that suggest it was adaptable to stockbreeding and the natural environment and consumed since the mid 2nd millennium BC in the northern Black Sea region.

Keywords Broomcorn millet · *Panicum miliaceum* · North Pontic · Bronze Age · Iron Age · Steppe

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Introduction

Why Broomcorn Millet?

In the North Pontic area stretching between the Danube and Don rivers, north of the Black Sea, broomcorn millet (*Panicum miliaceum* L.) is a long-established component of the traditional cuisine. Millet-based recipes include a nutrient-rich porridge eaten by the Cossacks on their military campaigns (Pashkevych, 2022) and known as *kulish* (куліш) in Ukraine, or *kulesh* (кулеш) in Belarus and south Russia (e.g. Klynovetska, 1991; Yakovenko, 2013; www.ukrainefood.info). Alongside its place in the regional gastronomic heritage, the valuable biological, nutritional and medical properties of millet are widely recognized by agronomists and farmers. There are programs developing local varieties, some particularly bred for the production of millet groats for porridge (https://grain.in.ua/ru/cilyushhi-vlastivosti-prosa-korist-pshonyano%D1%97-kashi.html).

The tradition of broomcorn millet cultivation and consumption in the region is deeply rooted and it is mentioned by the Roman author Pliny the Elder: 'there is no aliment held in higher esteem than panic by the peoples of Pontus' (Plin. NH 18.25.191; Rackham 1950, trans.). Broomcorn millet has recently been a major focus of scientific research in the context of early food globalization and trans-Eurasian movements of crops and food-ways (Filipović et al., 2020; Hunt et al., 2008; Jones et al., 2011; Liu et al., 2019; Miller et al., 2016; Motuzaite Matuzeviciute et al., 2013a, 2013b; Spengler, 2019; Stevens et al., 2016). Originating in East Asia, where it was domesticated by c. 6000 BC (e.g. Bao et al., 2018; Jones & Liu, 2009; Leipe et al., 2019; Liu et al., 2009, 2016; Lu, 2017; Ma et al., 2016), *Panicum miliaceum*—together with *Setaria italica* (foxtail millet)—represented one of the key innovations transferred along the east–west cross-continental trajectory. For some time, scholarly attention has been drawn to several early Western records of these eastern cereals, principally associated with China. It is now clear that they were once among the most widespread food crops, expanding from China to Central Asia and possibly South Asia during the 3rd millennium BC, and then to Europe and Africa in the 2nd millennium (for a review, see Liu et al., 2018). Their route to Europe differs from that taken by large-grained cereals such as hulled wheat and barley, which were the first domesticated crops to reach Europe from Southwest Asia (Körber-Grohne, 1994; Padulosi et al., 1996; Salavert, 2015; Zohary et al., 2012). The western spread of millet resonates instead with the eastern expansion of wheat and barley into East Asia (Jia and Chau, 2019; Liu et al., 2017; Long et al., 2018).

The North Pontic region was a possible key corridor for millet's journey westwards, and in this paper we return to the earliest history of millet cultivation and use there. We focus on *Panicum miliaceum*, for which directly dated records are available, whereas the status of *Setaria italica* in Europe requires future investigation (Miller et al., 2016; Reed & Drnić, 2016).

The oldest finds of broomcorn millet in the North Pontic region thus far are dated from the mid 2nd millennium BC and were recovered from archaeological sites in Ukraine, Romania and southwestern Russia. Their prehistoric age has been confirmed by radiocarbon dating, which showed that these are also the earliest millet finds in the areas of Europe investigated to date (Filipović et al., 2020; mostly central and Eastern Europe).

We present the North Pontic finds and analyze their broader cultural context, paying particular attention to the subsistence strategy and lifeway (e.g. settlement pattern) followed at the time both locally—at the sites that yielded the dated evidence—and in the wider region. Here we reassess the role of cereal cultivation in the economic models proposed for North Pontic prehistoric communities, which typically often contrast agricultural and pastoral activities (Fig. 1). These models also further relate subsistence changes to climate change (as a causative factor), and to different degrees of mobility (as an adaptive strategy), as evidenced by different kinds of archaeological sites. In this sense, crop cultivation is often seen as connected to phases of humid/warm climate and the archaeological trace of domestic dwellings and structures, that is, settlements with assumed permanent occupation. By contrast, an economic focus on animal husbandry is usually seen as an outcome of aridification (drier/colder climate), also resulting in a scarcity of settlements—ascribed to human mobility for pastoral nomadism—and an abundance of monumental graves in the archaeological record. Thus, these models extend beyond the economic aspect, as well as beyond our scope here. Nevertheless, re-evaluating the evidence of agriculture may help to better delineate the ways of living of people in the North Pontic regions and explain cultural developments. Finally, we aim to update the history of millet in the agricultural and culinary traditions north of the Black Sea.

Millet, a Cereal with Special Traits and Multiple Kinds of Archaeological Trace

From an agronomic perspective, broomcorn millet is a drought-resistant crop with a short growing period of c. 60–90 days; grains of small size; and nutritive values that are non-inferior to wheat (e.g. high vitamin B and minerals: Taylor & Duodu, 2020). Millet can grow in different environmental conditions, in moderate altitude regions as well as on floodplains (Chen et al., 2015; d'Alpoim Guedes, 2018; Miller et al., 2016; Moreno-Larrazabal et al., 2015). In terms of labor, in areas with summer rainfall millet does not require irrigation (Baltensperger, 1996; Cavers & Kane, 1990; Champion & Fuller, 2018; Miller et al., 2016), intensive soil labor or manure before seeding, but it benefits from weeding during seedling development (Anderson & Greb, 1987; Cappers & Neef, 2012; Taylor & Duodu, 2020).

According to botanical taxonomy, broomcorn millet belongs to the Panicoideae subfamily of the Poaceae, which includes a group of small-seeded grasses commonly used as crops for food and forage (Gemeinholzer, 2018; Weber & Fuller, 2008). Although defined in Europe as 'minor cereals', they include diverse genera and species that are staple crops in Africa and Asia (e.g. *Sorghum* and *Pennisetum*: Ge et al., 2020; Madella et al., 2016; Soreng et al., 2015; Taylor & Duodu, 2020; Winchell et al., 2017). So far, the oldest attestation of domesticated millets as crop

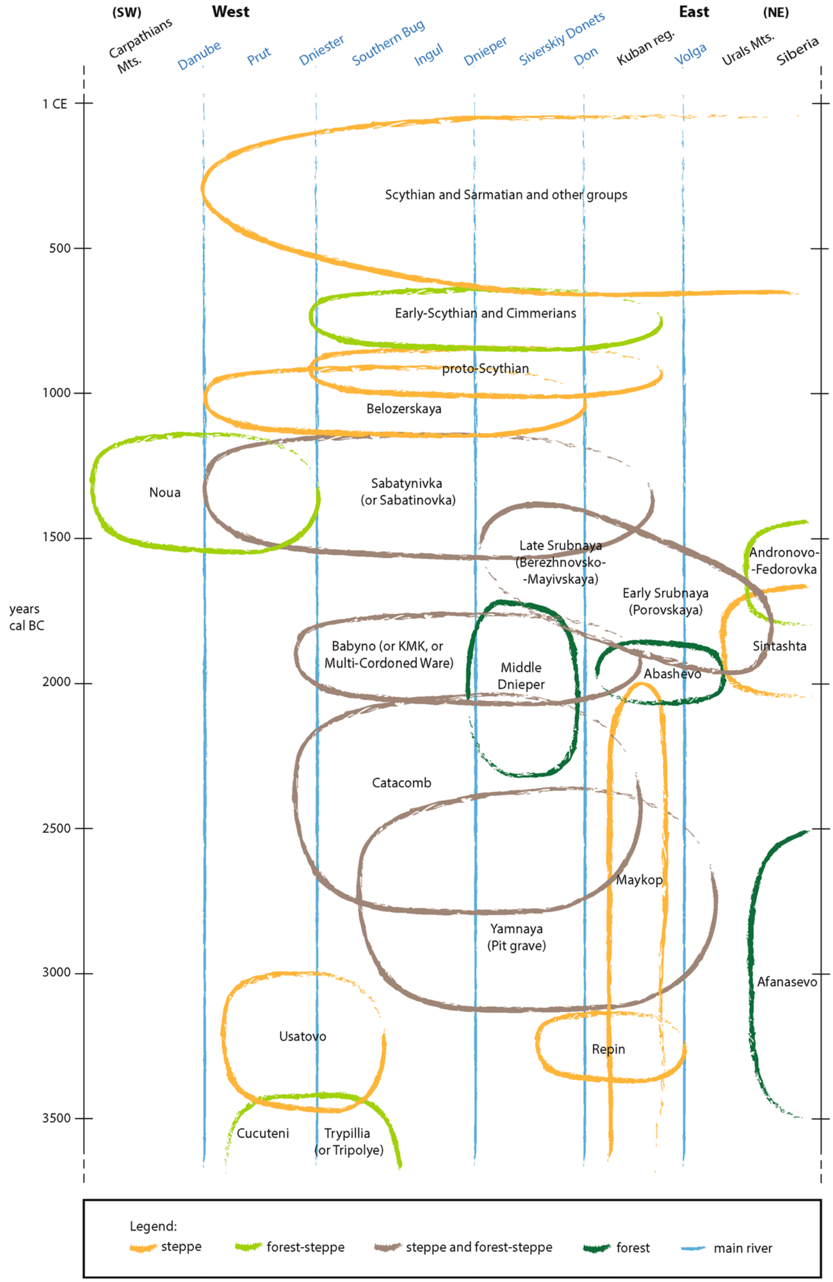

Fig. 1 Schematic overview of the main groups cited in the text that lived in the North Pontic region and close surroundings between the mid 4th and the 1st millennium BC. The archaeological groups are displayed according to chronology and geographical partition after main rivers (in west–east order) and main mountains (Anthony et al., 2016; Hanks et al., 2007; Müller et al., 2016; Parzinger, 2013; Kaiser, 2019 and references therein). (Graphic work M. Dal Corso)

in Europe concerns *Panicum miliaceum* (Liu et al., 2019), which is the focus of this study. *Setaria italica*—which requires a separate investigation—is also often found in early deposits with broomcorn millet, where it is regarded as either a weed of millet fields, or, in the case of mass finds, as a cultivated plant (Kroll, 1983; Miller et al., 2016; Reed & Drnić, 2016; Zohary et al., 2012). Some wild panicoid grasses that are now ubiquitous in Europe (Tutin et al., 2001) are also known in prehistoric deposits, namely *Echinocloa crus-galli*, *Digitaria sanguinalis* and *Setaria viridis* (e.g. Motuzaite Matuzeviciute et al., 2012; Pashkevych, 2001; Stobbe et al., 2019). Finally, other small-seeded panicoid crops of African origin, such as *Sorghum* sp., are only attested in Europe at a later stage (e. g. *Sorghum bicolor* in the 1st millennium AD in Italy: Castiglioni & Rottoli, 2010; Liu et al., 2019).

From a physiological perspective, broomcorn millet—like other millets and maize—uses the C_4 photosynthetic pathway, a typical plant adaptation to the arid regions where panicoid grasses are widespread. Other cereals like wheat and barley, and most plants in temperate regions, instead follow the common C_3 photosynthetic pathway (Dolukhanov, 2009; Pyankov et al., 2010). The C_4 mechanism causes much less isotopic fractionation of photosynthesized carbon than C_3, resulting in much higher $\delta^{13}C$ values in C_4 plant tissues. The regular consumption of C_4 plants like broomcorn millet leaves an isotopic signature in human and faunal remains (e.g. Ambrose, 1993; Gerling, 2014, 2015; Hermes et al., 2019; Herrscher et al., 2018; Lightfoot et al., 2013, 2015a, 2015b; Liu et al., 2012, 2014; Makarewicz, 2018; Murphy et al., 2013; Shishlina et al., 2012; 2018a, 2018b; Svyatko et al., 2013; Ventresca Miller et al., 2021).

A similar distinction of panicoid grasses from other grass subfamilies in the natural vegetation has climatic/ecological implications and it can also be traced through analyzing phytoliths from soil and sediment samples (e.g. Barboni & Bremond, 2009; Silantyeva et al., 2018; Strömberg et al., 2018; Twiss, 1992). The assemblage of phytoliths—siliceous microfossils produced within plant tissues and released in the soil after plant decay—reflects the main vegetation components. Moreover, phytoliths from grass inflorescences—for example cereal ears (Ball et al., 2016; Ge et al., 2020; Lu et al., 2009; Weisskopf, 2017) —or from leaves (Out & Madella, 2015), provide diagnostic traits to distinguish broomcorn millet from other cereals.

Finally, the biomarker miliacin—a resistant molecule found in *Panicum miliaceum*—also attests to the presence of the plant in sediment (e.g. Bossard et al., 2013; Jacob et al., 2008; Motuzaite Matuzeviciute et al., 2016) and pottery (e.g. Heron et al., 2016). In addition to the study of botanical macro-remains, these characteristics of millet provide other ways to trace this crop in archaeological contexts, broadening our knowledge of ancient diet and land use; such analyses are accordingly mentioned when they have been carried out.

The North Pontic Environmental and Cultural Setting

Biogeographically, the North Pontic region can be divided into three main ecozones (Fig. 2). Broad-leaved forests—among the most extensive in Europe—dominate in the north. The central part is a forest-steppe, mosaic-like, ecotonal region,

Fig. 2 Location of the sites with dated grains of broomcorn millet and potential natural vegetation. (Graphic K. Winter, Kiel University)

with patchy forest cover and grasslands, now largely arable. The southern region is characterized by steppe vegetation, representing the western fringe of the Eurasian steppe. The Eurasian steppe belt extends for thousands of kilometers west to east, from central Europe into Central Asia. The part of it considered in this study lies immediately north of the Black Sea. This region is dissected by several large rivers, from the Danube in the west to the Don in the east. It has a warm/hot humid continental climate (Dfb/Dfa in the Köppen scheme: see Köppen, 1936; www.climate-data.org), with fewer cold months, less snow cover and milder conditions than the more continental and much drier eastern and northern parts of the steppe in southern Russia and Central Asia (Bendrey, 2011; Stobbe et al., 2015). The dominant soil type is chernozem, fertile dark earth typical of areas under grass vegetation, mainly developed on a loess substrate (e. g. Dreibrodt et al., 2020; Kremenetski, 2003).

Due to its ecological and climatic characteristics, the steppe is usually associated with mobile human groups whose subsistence economy mostly relies on animal husbandry (Salzman, 2004). With no claim to completeness—and referring the reader to the specialized literature for an overarching view of the complexity of pastoralism, nomadism and transhumance—these concepts are briefly introduced here. Pastoralism has been defined as the 'raising of livestock on natural pastures unimproved by human intervention' (Salzman, 2004, p. 2), and is the main productive activity/economic baseline for some communities. Pastoralists employ a variety of strategies—nomadic, semi-nomadic, semi-sedentary as well as sedentary—to manage their animals, and these result in different lifestyles. The choice of strategies is influenced by the environment, the effects of seasonality on pastures—the 'extensive resource' that pastoralists rely on (Salzman, 2004, p. 3) —and other aspects, such as their relations with non-pastoral communities. While the latter is a vast topic, here we simply underline the character of (inter)dependence in such a relation; for instance, in the supply of non-animal-derived products for pastoralists (e.g. Khazanov, 1984; Taylor, 1994). Moreover, if pastoral groups move in areas controlled by large political organizations, limits could be imposed on pastoralists according to other economic and socio-political interests (e.g. Balatti, 2017; Salzman, 2004). Nomadism is a mobile lifestyle that applies when the whole community regularly shifts dwelling location and it is often—but not exclusively—associated with pastoralism as a form of specialized production (e.g. Barfield, 1993; Cribb, 1991; Khazanov, 1984; Kradin, 2006; Salzman, 2004). Transhumance is a herding practice based on seasonal movements of the domestic herds led by specialized actors (i.e., a part of the community) to ensure adequate grazing and water (Arnold & Greenfield, 2017; Greenfield, 1999; Jones, 2005); it can be found in mixed farming economies in settled communities (Jones, 2005; Salzman, 2004). These concepts are multifaceted and intertwined in various ways in different parts of the world (Cribb, 1991; Khazanov, 1984; Kradin, 2006). In the North Pontic region, the extensive grasslands offer rich pastures, between mixed herbaceous-gramineous steppe and gramineous-wormwood steppe (e.g. Pashkevych & Shovkoplyas, 2013; Shishlina, 2001), while the northeastern zone, with its more strongly continental climate, was not seen as favorable for cereal agriculture (at least in pre-industrial times: Werger & van Staalduinen, 2012). Therefore, people who occupied the steppe in prehistory are often grouped under the label of 'Eurasian stockbreeding cultures' (Chernykh, 2008) or associated with pastoral nomadism (e.g. Hanks, 2002; Videiko & Burdo, 2004). Apart from material culture, archaeological research has mainly focused on human and faunal remains for reconstructing the lifestyle of the steppe people in the North Pontic region. Specifically, some recent zooarchaeological (e.g. Hermes et al., 2019; Morales Muñiz & Antipina, 2003), isotopic (e.g. Gerling, 2015; Motuzaite Matuzeviciute, 2016; Motuzaite Matuzeviciute et al., 2015a, 2015b; Murphy et al., 2013; Privat, 2004; Shishlina et al., 2018a, 2018b; Ventresca Miller et al., 2020; Ventresca Miller & Makarewicz, 2019) and genetic (e.g. Allentoft et al., 2015; de Barros Damgaard et al., 2018; Haak et al., 2015; Immel et al., 2020; Juras et al., 2018; Mathieson et al., 2018; Nikitin et al., 2017; Rascovan et al., 2019) studies have reconstructed certain aspects of mobility and dietary patterns of the prehistoric steppe communities in great detail, showing wide variation beyond the generic label of 'pastoral nomads' (see discussion in Honeychurch & Makarewicz, 2016). The picture of crop agriculture is less clear. Because of their ephemeral nature, plant remains have received comparatively less attention, although archaeobotanical analyses and flotation have been carried out at some sites (e.g. Lebedeva, 2005; Motuzaite Matuzeviciute, 2012, 2013; Motuzaite Matuzeviciute et al., 2009, 2012, 2015a, 2015b; Motuzaite Matuzeviciute & Telizhenko, 2013; Pashkevych, 1999, 2001, 2003, 2004, 2005a, 2005b, 2012; Rühl et al., 2015; Sava & Kaiser, 2011; Spengler et al., 2014; Spengler, 2015; Stobbe et al., 2015).

The steppe is commonly seen as a natural communication 'corridor' where long-distance contacts and mobility in prehistory have been attested archaeologically (Anthony, 2007; Chernykh, 2008; Cunliffe, 2015); linguistically (Anthony, 2007);

and genetically (Allentoft et al., 2015; Haak et al., 2015; Immel et al., 2020; Mathieson, 2015, 2018). Some 'mobility waves' in prehistory seem to have brought people (identified genetically as having some degree of 'steppe component') towards Europe: for instance, Yamnaya (c. 3300–2700 BC) and Corded Ware (c. 2800–2600 BC) people in the Early Bronze Age (Allentoft et al., 2015; Haak et al., 2015; Rascovan et al., 2019), and Scythians in the Iron Age (Eighth–third centuries BC) (de Barros Damgaard et al., 2018; Gerling, 2015; Haak et al., 2015). There were also earlier, smaller-scale movements in the Copper Age (Immel et al., 2020; Nikitin et al., 2017).

In the North Pontic region, archaeological traces from both the Bronze and Iron Ages are dominated by burials (kurgans) rather than settlements. This funerary practice and other elements of the material culture (e.g. decorative Scythian animal style) are consistently found over a vast region stretching from Central Asia to the Urals and the eastern borders of east-central (Hungary, Poland) and southern Europe (Romania, Bulgaria) (Cunliffe, 2019; Taylor, 1994). The transcontinental cultural contacts contributed to the dispersal of several technological innovations (Frachetti, 2008; Kohl, 2007), most prominently the domestication of the horse and the use of wheeled wagons around 3500 BC (Anthony, 2007, 2016; Cunliffe, 2015; Fages et al., 2019; Klimscha, 2017; Rascovan et al., 2019), and horse-riding dating from at least the early 2nd millennium BC according to some authors (Boroffka, 2004; Chechushkov et al., 2018; Dietz, 2003; Hüttel, 1994) or from the late 2nd millennium BC according to others (Taylor et al., 2020). Other archaeological materials—mainly metal objects—reveal that in the 3rd–2nd millennia BC this prehistoric communication network extended as far east as modern China (Chernykh, 2008; Kohl, 2007; Sherratt, 2006). Around 2200–1900 BC, weapons and casting technology attributed to Seima-Turbino groups—mostly concentrated in the northern forests of the Upper Volga—have been attested as far west as Moldova and as far east as China (Chernykh, 2008; Hanks et al., 2007; Parzinger, 2013). Similarly, materials attributed to the Abashevo culture (late 3rd–2nd millennium BC), located in the forest and forest-steppe regions of the Don and Volga in the west, spread further east (Chernykh, 2008; Marchenko et al., 2017; Parzinger, 2013), while materials of the Sintashta and Petrovka cultures in the forest-steppe and steppe of the Trans-Urals (Koryakova & Epimakhov, 2007; Krause & Koryakova, 2013) reached Kazakhstan and Siberia.

Economy and lifestyle are key factors for evaluating mobility and cultural transfer patterns. Most Eurasian steppe cultures are considered highly mobile, although Srubnaya and Andronovo settlements have been documented where metalworking played an important role (Anthony, 2007; Chernykh, 2008; Koryakova & Epimankov, 2007; Parzinger, 2013) and the Sintashta culture (2100–1700 BC) is even defined by fortified settlements. The economy of the Middle and Late Bronze Age steppe cultures was mainly based on stockbreeding and fishing, whereas traces of cultivated plants are scarce and doubtful in the 2nd millennium BC in the Trans-Urals (Chernykh, 2008; Lebedeva, 2005; Morales Muñiz & Antipina, 2003; Privat, 2004; Rühl et al., 2015; Stobbe et al., 2015, 2016). Farming was not practiced in the permanent Sintashta settlements (Rühl et al., 2015; Stobbe et al., 2015, 2016).

How does the North Pontic region in the southwestern Eurasian steppe fit into this complex socio-economic picture? To further reconstruct subsistence strategies and advance hypotheses about cultural developments in this region, we should consider the record of cultivated plants. In this reconstruction, millet testifies to inter-regional communication and the spread of influences, materials, and skills. By following directly dated millet deposits and re-evaluating published botanical records, this study aims to contribute to the analysis of the complex economy of North Pontic communities during the metal ages.

Evidence of Broomcorn Millet in and Around the North Pontic Region

Archaeobotanical studies based on flotation with fine-meshed sieve, big data approaches and direct radiocarbon dating of individual seeds or fruit have led to important advances in our understanding of the global spread of crops (Filipović et al., 2020; Hunt et al., 2008; Liu et al., 2019; Miller et al., 2015; 2016; Motuzaite Matuzeviciute et al., 2013a, 2013b; Stevens et al., 2016). This applies particularly to broomcorn millet, whose history can be traced with other lines of evidence in addition to botanical macro-remains, as mentioned above.

Broomcorn and foxtail millet were first cultivated during the Neolithic (c. 6000 BC) at a series of foothill locations in North China, in a topographic region known as the 'millet hilly flanks' (Liu et al., 2009, 2012). There, along the Yellow River, wild panicoid grasses occur in the natural vegetation and rain-fed agriculture was practiced (e.g. Liu et al., 2019; Wang et al., 2019; Weisskopf, 2017). From a European perspective, in respect to the other cereals coming from the Near East and cultivated since the Neolithic, this different origin of broomcorn millet implies different modes and times of introduction westwards, the trajectories and cultural conditions/implications of which remain unclear (Liu et al., 2019; Miller et al., 2016; Wang et al., 2019).

The earliest archaeobotanical attestation of *Panicum miliaceum* outside China occurred in the western Himalayas (Kashmir Valley) in the mid 3rd millennium BC (2580–2340 cal BC, 2σ—oldest of three dates on multiple millet grains in Yatoo et al., 2020). Other evidence from the inner Asian mountain corridors suggests the spread of East Asian and Southwest Asian cereals in the 3rd millennium BC. At the pastoralist campsite of Begash in Kazakhstan (2460–2150 cal BC, 2σ, date on millet and wheat: Frachetti et al., 2010; Spengler et al., 2014), herders who were considered to rely solely on a pastoral economy were revealed to possess cereals and be likely responsible for their further transmission (Frachetti et al., 2010). Millet dated some centuries later has been found at Ojakly in eastern Turkmenistan (direct date 1740–1610, 2σ cal BC) (Spengler et al., 2014), while millet found dating much later (direct date 1124–421, 2σ cal. BC) (Trifonov et al., 2017) has been found at Guamsky Grott in the Southern Caucasus, a region where the isotopic signal of C_4 plants is already attested in human remains of the seventeenth century BC (Herrscher et al., 2018).

In Europe, where rare broomcorn millet grains have been found in Neolithic sites, direct radiocarbon dating of single charred millet grains has shown that they were intrusions from later periods. This evidence led to a revision of the previous interpretation (e.g. Kreuz & Schäfer, 2011) of this plant as a weed. A pioneering ^{14}C-study by Motuzaite Matuzeviciute et al., (2013a, 2013b) on seven sites, and a recent further in-depth investigation by Filipović et al. (2020) on charred grains from 75 European Neolithic to Bronze Age sites, contested all Neolithic evidence and established the presence of broomcorn millet in Europe as a Bronze Age phenomenon starting in the second half of the 2nd millennium BC (Filipović et al., 2020). Indeed, in the European archaeobotanical records of Late Bronze Age contexts, a widespread change in the crop spectrum is registered, characterized—for instance—by a more heterogeneous spectrum of cultivated plants (e.g. Effenberger, 2018; Gumnior et al., 2020; Kneisel et al., 2015; Liu et al., 2018, 2019; Stika & Heiss, 2013; Stevens et al., 2016; Valamoti, 2016; Wang et al., 2019). The spread of millet had also been observed based on plant impressions on Bronze Age ceramic fragments in the North Pontic region (Yanushevych, 1989). In fact, in Ukraine and Moldova, the rare preservation of carbonized plant remains—likely a taphonomic bias due to pedogenesis (Dreibrodt, pers. comm.)—directed early archaeobotanical research to focus on plant impressions in ceramic and daub fragments (e.g. Pashkevych & Videiko, 2006, and references therein). For contexts of the Ukrainian Neolithic and Copper Age, the attestations of broomcorn millet based on plant imprints were recently re-evaluated (An et al., 2019a, 2019b) and proved incorrect for evidence pre-dating the Late Bronze Age (Endo pers. comm.). The radiocarbon dating model for charred grains developed by Filipović et al. (2020) indicates that the earliest European dates on *Panicum miliaceum* grains are from Ukraine, and we present this data in detail here for the first time.

Materials and Methods

Study Sites in the North Pontic Area

The radiocarbon dates on millet presented in this study come from eight archaeological sites in modern Ukraine spanning from the Neolithic (1. Ratniv-2); the Copper Age (3. Maidanetske); the Late Bronze Age (5. Vinogradnyi Sad, 6. Dykyi Sad); and the Iron Age (7. Zalissia, 8. Ivane -Puste, 9. Zanovskoe, 10. Olbia) (Fig. 2, Table 1). Additional dates come from a Copper Age site in Romania (2. Baia) (Fig. 2, Table 1) and a Middle Bronze Age site in southwest Russia (4. Rykan-3).

1. Ratniv-2 (*Ратнив-2*; Volyn region, western Ukraine) is a settlement of the Linear Pottery culture (Linearbandkeramik: LBK) situated in the Volyn plateau in the forest-steppe. A round pit house with two fireplaces and four pits has been excavated (Motuzaite Matuzevičiūtė & Telizhenko, 2016). Materials include ceramic, flint sickle-blades, and the faunal record is dominated by cattle followed by pigs, sheep and goats. The archaeobotanical record revealed grains and chaff of einkorn (*Triticum monococcum*); emmer (*Triticum dicoccum*); probably the 'new type glume wheat' (*Triticum timopheevi*); hulled barley (*Hordeum vulgare vulgare*); lentil (*Lens culinaris*); pea (*Pisum sativum*); and flax (*Linum usitatissimum*). Two dates on emmer grains from a fireplace provide the oldest attestation of agriculture in

Table 1 Summary of the archaeological context of the samples considered in this study

Site number and name	Location	Archaeological culture	Time period and site chronology	Sample context	Quantity of millet in the original archaeobotanical sample(s)	Lab sample number of the radiocarbon dated millet	References for the archaeobotanical record
(1) Ratniv-2	Volyn region (Ukraine) forest-steppe	Linear Pottery culture (LBK)	Neolithic (5500–5200 cal BC)	Fireplace 1 within pit house n. 17	< 50	(1) UBA-30430 (2) UBA-30431	Motuzaite Matuzeviciute and Telizhenko (2016)
(2) Baia (Baia-În Muchie)	Suceava region (Romania)	Pre-Cucuteni and Horodiștea cultures	Copper AgeCopper Age (4800–4500 cal BC) and 200–400 cal AD	(1) Fill of pit 3 (2) Fireplace 1 (3) Fireplace 1	(1) 20 (2) > 15 (3) > 15	(1) OxA-31350 (2) OxA-31351 (3) OxA-31352	An (2018)
(3) Maidanetske	Cherkasy region (Ukraine) forest-steppe	Trypillia culture	Copper Age (3950–3650 cal BC)	Cultural layer, unit 51,001, square I3, level 3	2	Poz-97652	Dal Corso et al. (2019)
(4) Rykan-3	Voronež region (Russia) Middle Don; forest-steppe	Catacomb culture	Middle Bronze Age (2600–2400 cal BC)	(1) Central hearth in a dwelling (2) Post-hole	(1) 1 (2) 1	(1) Poz-61887* (2) Poz-61889*	*Gak et al., (2019)
(5) Vinogradnyi Sad	Mykolaiv region (Ukraine) Southern Bug; steppe	Sabatynivka culture	Late Bronze Age (15th–13th century BC)	(1) Cultural layer, square 276 (2) Cultural layer, square 275	(1) 2 (2) 3	(1) Poz-103215, KIA-53658 (2) Poz-105275	Pashkevych & Kostil'ov (1992), Pashkevych (2012), Sharafutdinova (1987)
(6) Dykyi Sad	Mykolaiv region (Ukraine) Southern Bug; steppe	Belozerska culture	Late Bronze Age (12th–10th century BC)	(1) Pit n. 3, profile II-14 (2) Pit n. 3, profile II-15	(1) 233 (2) 69	(1) Poz-103214 (2) Poz-105274	Gorbenko (2007), Gorbenko & Pashkevych (2010) Pashkevych (2012)

Table 1 (continued)

Site number and name	Location	Archaeological culture	Time period and site chronology	Sample context	Quantity of millet in the original archaeobotanical sample(s)	Lab sample number of the radiocarbon dated millet	References for the archaeobotanical record
(7) Zalissia	Ternopil region (Ukraine) Podolian upland; forest-steppe/mixed oak forest	Early Scythian	Iron Age (5th–4th century BC)	Cultural layer from an area with furnaces and hearths, profile 2, square 14, sample 9, depth 40 cm	25	Poz-103216	Ganina (1984), Pashkevych (1999)
(8) Ivane-Puste	Ternopil region (Ukraine) Podolian upland; forest-steppe/mixed oak forest	Early Scythian	Iron Age (6th–5th century BC)	(1) Cultural layer from a burnt building, square 23, depth 80 cm (2) Cultural layer from a burnt building, square 30, depth 80 cm	(1) Lumps of fused grains (2) 10	(1) Poz-103286 (2) Poz-105276	Ganina, (1965), Pashkevych (1999)
(9) Zanovskoe	Luhansk region (Ukraine) Donets floodplain	Sarmatian–Scythian culture	Iron Age (5th–1st century BC)	(1) Pit 18, sample 31 (2) Pit 18, sample 32	(1) 15 (2) 10	(1) OxA-18316** (2) OxA–18317**	**Motuzaite Matuzeviciute et al., (2012)

Table 1 (continued)

Site number and name	Location	Archaeological culture	Time period and site chronology	Sample context	Quantity of millet in the original archaeobotanical sample(s)	Lab sample number of the radiocarbon dated millet	References for the archaeobotanical record
(10) Olbia	Mykolaiv region (Ukraine) Southern Bug; Black Sea lowland	Greek harbor active until Roman times	Iron Age (7th cent. BC–5th cent. AD)	(1) Burnt storage from upper town, sector 25 (1st–4th cent. AD), sample 58 (2) Cultural layer from lower town, sector NGS (3rd–2nd cent. BC), sample 73	(1) Lumps of fused grains (2) Lumps of fused grains	(1) Poz-105277 (2) Poz-105012	Pashkevych (2001)

Dates already published are associated with their reference in the table by asterisks the area, between 5470 and 5220 cal BC (Motuzaite Matuzeviciute & Telizhenko, 2016).

2. Baia-În Muchie (hereafter *Baia*; Suceava county, Romania) is a late pre-Cucuteni (first half of the 5th millennium BC) and Horodiștea cultural settlement. However, the stratigraphic sequence of the site includes finds from the Bronze Age as well as the first centuries AD, indicating occupations in the post-Copper Age eras. The site is situated on the edge of a flood terrace, between two tributaries of the Moldova River, the Şomuzul Mocirlos and Şomuzul Mare in the sub-Carpathian region. Between 2012 and 2014, a total area of 524 m^2 was excavated at the site, which was first discovered in 1998. Flotation work was carried out in the summer of 2013 and archaeobotanical analysis was carried out at the McDonald Institute, Cambridge (An, 2018). The assemblage includes more than 80 charred caryopses identified as *Panicum miliaceum* and a few *Setaria italica.* These millet remains are from a variety of contexts, such as pit fills and fireplaces, including those identified as pre-Cucuteni features based on associated artifact typology.

3. Maidanetske (*Майданецьке*; Cherkasy region, central Ukraine) is a giant settlement of the Trypillia (or Tripolye) culture, active in the period 3990–3640 BC (Müller et al., 2016; Ohlrau, 2020). The site is located over a loess plateau close to the Talyanka River in the forest-steppe region on the Southern Bug–Dnieper interfluve. It comprises c. 2900 burnt houses in semi-concentric layout (Hofmann et al., 2019; Ohlrau, 2020). Agriculture at the site is attested by emmer, einkorn, free-threshing barley, and pea (Kirleis & Dal Corso, 2016; Dal Corso et al., 2019; Pashkevych & Videiko, 2006, p. 78). After a recent systematic flotation program, two charred caryopses of *Panicum miliaceum* were also retrieved from the uppermost cultural layers.

4. Rykan-3 (*Рыкань-3*; Voronež region, southwestern Russia) is a settlement of the Catacomb Culture of the Middle Bronze Age, radiocarbon dated to the 26th–24th centuries BC. The site is located in the Don forest-steppe on the banks of the Usman River. The stratigraphy and materials showed a single-layered occupation with fireplaces and postholes derived from repeated seasonal (winter) activities focused on cattle breeding and bone and wood working (Gak et al., 2019). Plant remains were few, mostly related to wild plants apart from three millet grains, and they all dated later than the site (Gak et al., 2019).

5. Vinogradnyi Sad (*Виноградний Сад*; Mykolaiv region, central Ukraine) is a settlement of the Sabatynivka (or Sabatinovka) culture of the Late Bronze Age. The settlement itself dates to the 15th–13th centuries BC. It measures approximately 600 × 100 m and is located in a narrow floodplain on the right bank of the Southern Bug (Sharafutdinova, 1987). The remains of stone foundations of residential buildings and craft workshops—including some for processing bones and animal skins—and a large number of tools were found at the site (Balushkin, 1990; Sharafutdinova, 1968, 1987; Sharafutdinova & Balushkin, 1997). Particularly noteworthy is the discovery of kilns that the excavators consider were used to dry cereal grains; the excavators further suggested that the site may have specialized in cereal trade. Abundant grains of hulled barley (a mass find of 3464 charred grains: Pashkevych & Kostilov, 1992) were found, along with emmer, broomcorn millet, free-threshing wheat, and a few pulses (green pea and vetch) (Pashkevych, 1991, 2012; Pashkevych & Kostilov, 1992). An isotope study on osteological remains of numerous wild and domesticated animals and three human individuals attested to the consumption mainly of C_3 terrestrial products, and thus not millet (Privat, 2004).

6. Dykyi Sad (*Дикий Сад*; also transliterated as *Dikii Sad*) in the center of the modern city of Mykolaiv (southern Ukraine) is a stone-built hillfort of approximately 3–4 ha that dates to the 13th–10th centuries BC (Gorbenko & Grebennikov, 2009; Gorbenko, 2014) and belongs to the Belozerska culture of the Final Bronze Age. Dykyi Sad is located on a high terrace on the left bank of the Ingul River, at its confluence with the Southern Bug. Excavated in the 1990s (Gorbenko, 2007; Gorbenko & Grebennikov, 2009), the site is a fortified settlement with two ditches, crossed by stone bridges. One ditch encloses the so-called 'citadel', where the buildings were very close to each other, and separates it from the 'suburb', which includes a district inhabited by craftsmen and merchants (Gorbenko, 2013; Gorbenko & Grebennikov, 2009). The macro-remains record from post holes and structures attested various cereals (barley, millets, hulled and naked wheats) and weeds (Gorbenko & Pashkevych, 2010; Pashkevych, 2012).

7. Ivane-Puste (*Іване-Пусте*; Ternopil region, western Ukraine) is a settlement of the Early Iron Age dated to the 7th–5th centuries BC by the presence of a typical grey ceramic, Greek amphorae, metal object of Hallstatt type and Scythian materials (Daragan, 2009; Vakhtina & Kashuba, 2013). The excavation at the site in the late 1950s and 1960s focused on two buildings that were burnt in a fire where many charred seeds of cultivated plants (millet, barley, hulled and free-threshing wheat, pea, lentil and flax) and weeds were preserved (Ganina, 1965, 1968; Pashkevych, 1999, 2012).

8. Zalissia (*Залісся*; Ternopil region, western Ukraine) is a settlement of the Early Iron Age located near to Ivane-Puste, on the right bank of the Zbruch River, the left tributary of the Dniester. In the 1970s, several rectangular buildings with remains of furnaces and open hearths were excavated (Ganina, 1984). The record of charred macro-remains showed the presence of food crops (millet, hulled barley, naked wheat, emmer and lentil); flax—most probably used for oil production; and a concentration of the weed *Chenopodium album* (Pashkevych, 1999, 2012).

The two sites of Ivane-Puste and Zalissia are characterized by the confluence of materials of different cultural traditions, attesting an active network (Daragan, 2009; Vakthina & Kashuba, 2013).

9. Zanovskoe (*Зановское*; Luhansk region, eastern Ukraine) is a site on the left bank of the Siverskiy Donets River, where two pits, radiocarbon dated to the Scytho-Sarmatian period, were cut into older archaeological stratigraphy. The archaeobotanical record from the pits revealed mostly millet and panicoid grasses, interpreted as potential arable weeds and/or part of the millet harvest (Motuzaite Matuzeviciute et al., 2013a, 2013b). From the analysis of biomarkers from sediment in stratigraphic correlation (i.e. contemporaneous) with the excavation of the pits, miliacin biomarker derived from broomcorn millet was identified, attesting to its local cultivation on the floodplain soils by the Scytho-Sarmatian people (Motuzaite Matuzeviciute et al., 2016).

10. Olbia Pontica (*Ольвії*; Mykolaiv region, southern Ukraine) was a Greek colony on the estuary of the Bug River. Olbia was founded in the late 7th/early 6th century BC, during the Greek colonization of the northern Black Sea. Between the 5th and the 3rd century BC, the city flourished and maintained contacts with the local Scythian populations in the hinterland. Afterwards, up to the 5th century AD, the site was occupied by various groups, including Celtic tribes, the Getae, Romans, and Goths, and Olbia maintained its heterogeneous character as a cultural crossroads (Fornasier, 2016; Fornasier et al., 2018; Kryzhitsky et al., 1999; Rusyaeva & Rusyaeva, 2004; Vinogradov & Kryzickij, 1995). Discovered in the late 18th century, the site has a long history of archaeological research since 1921 and is currently managed by the Institute of Archaeology of the National Academy of Sciences of Ukraine, which has also conducted archaeobotanical analyses (Pashkevych, 1995, 2001; Stobbe et al., 2019; 2021). In sector NGS in the lower town, deposits of the third and second centuries BC gave a cereal record dominated by *Triticum aestivum* and *Hordeum vulgare*, with some broomcorn millet and *Secale*. In sector 25, dating to the 1st–4th centuries AD, *Panicum miliaceum* prevails, followed by, among others, *Hordeum vulgare* and *Triticum aestivum*, while weeds of summer crops are also attested (Pashkevych, 2001). An amphora from the middle of the 3rd century AD was recently found in the southeastern part of the Roman citadel. Ninety-five percent of the macro-remains comprised broomcorn millet, testifying to the storage of untreated millet with glumes of local production in Roman times (Stobbe et al., 2019). The diet of five human individuals has been studied through stable isotopes, which positively indicate the consumption of millet (Privat, 2004). The human remains are attributed to Greek members of the town's population, although information is missing about the dating and archaeological context of origin of the individuals. This should be clarified, since Olbia was an emporium in Greek times, a cultural crossroads, and was later occupied by different groups.

Sample Selection and AMS-Radiocarbon Dating

Information about the sample and context of origin of the dated material is provided in Table 1. From the site of Maidanetske (3), the dated millet grain was retrieved in 2016 from a bulk sample of 10 l of sediment from cultural layers during a standard flotation procedure using a sieve with a 300 µm-mesh (Dal Corso et al., 2019). Similarly, for the site of Rykan-3 (4), three grains of millet were dated, retrieved after flotation on multiple 10-l bulk samples (only two dates are considered here, a third one being modern: Gak et al., 2019). From Baia (2), macro-remains have been retrieved using a locally-built flotation machine with a water pump, modified from the SMAP type initially designed by Patty Jo Watson in the 1960s. From the site of Zanovskoe (9), the dated millet grains came from two samples of 12 l of archaeosediment, obtained through flotation using a sieve with a 300 µm-mesh during excavation in 2006 (Motuzaite Matuzeviciute et al., 2012). The broomcorn millet dated from the sites of Vinogradnyi Sad (5), Dykyi Sad (6), Zalissia (7), Ivane-Puste (8), and Olbia (10) were subsampled in 2018 from macro-remain records stored in dry, labeled carton boxes at the archive of the 'D. Dobrochayev Botanical Museum' of the National Museum of Natural History in Kiev. This material originates from studies by Galyna Pashkevych, who carried out flotation at Vinogradnyi Sad (1986), Ivane-Puste (1959) and Olbia (1988 and 1992) from targeted contexts with a visibly high concentration of charred remains. Some samples (Fig. 3) come from deposits with a very small number of millet grains (1–3 grains per sample in Ratniv-2, Rykan-3, Baia, Maidanetske and Vinogradnyi Sad), while other samples come from deposits with a larger number of millet grains (Dykyi Sad: 233 and 69 grains per sample, respectively; Ivane-Puste: 10; Zalissia: 25; Zanovskoe: 10–15 per sample; Olbia: numerous), and in some cases (Ivane-Puste, Olbia) lumps of fused-together broomcorn millet grains were found.

According to the laboratory procedure, a minimum of 300 µg of pure carbon is required to achieve maximum possible precision in measurement. For the samples from Maidanetske (3), Vinogradnyi Sad (5), Dykyi Sad (6), Zalissia (7) and Ivane-Puste (8), after double checking with a binocular microscope, one large, well-preserved, individual seed per sample was selected and newly dated (Poznan Radiocarbon Laboratory; Leibniz Laboratory in Kiel). A single charred grain per sample has also been dated from Baia (1) (Oxford Radiocarbon Accelerator Unit; An, 2018); Ratniv-2 (2) (Belfast Radiocarbon Laboratory); Rykan-3 (4) (Poznan Radiocarbon Laboratory; Gak et al., 2019); and Zanovskoe (9) (Oxford Radiocarbon Accelerator Unit; Motuzaite Matuzeviciute et al., 2012). From Olbia (10), two small lumps of multiple charred millet grains fused together were dated (Fig. 3).

The results have been calibrated using OxCal 4.4 (Bronk Ramsey, 2009; https://c14.arch.ox.ac.uk/oxcal.html 12 Aug 2020) and the atmospheric curve IntCal20 (Reimer et al., 2020), rounded outwards to decadal endpoints (Table 2).

The multiplot in Fig. 4 shows the results according to a model that combined dates from the same site before calibration with the OxCal function 'R_combine'. When calibration showed a very close age for two or more samples from the same archaeological context (e.g. Ratniv-2: Table 2), we can assume that they come from a single depositional event. In this case, combining them prior to calibration (i.e. calibrating their weighted mean radiocarbon age) provides a more precise date for this deposition.

Results

AMS-Radiocarbon Dating

The results of the radiocarbon dating are shown in Table 2 and Fig. 4. Certain sites have several date estimates, so as to increase accuracy and reliability. Dates from the sites Ratniv-2 (1), Baia (2), Vinogradnyi Sad (5), Dykyi Sad (6), Ivane-Puste (8) and Zanovskoe (9) are statistically consistent with a single date and therefore the R-combine function has been applied to them (Fig. 4). The same does not apply to a sample from the sites of Vinogradnyi Sad (5) and the samples from Olbia (10), and thus they have been kept separate (Table 2, Fig. 4).

The oldest millet grain in this study comes from a cultural layer of the Late Bronze Age site of Vinogradnyi Sad (5), which dates to between the end of the 17th and the mid 15th century BC (1630–1450 cal BC, 94.5% or 2σ probability, as for the other dates mentioned in brackets hereafter). Another two grains from another

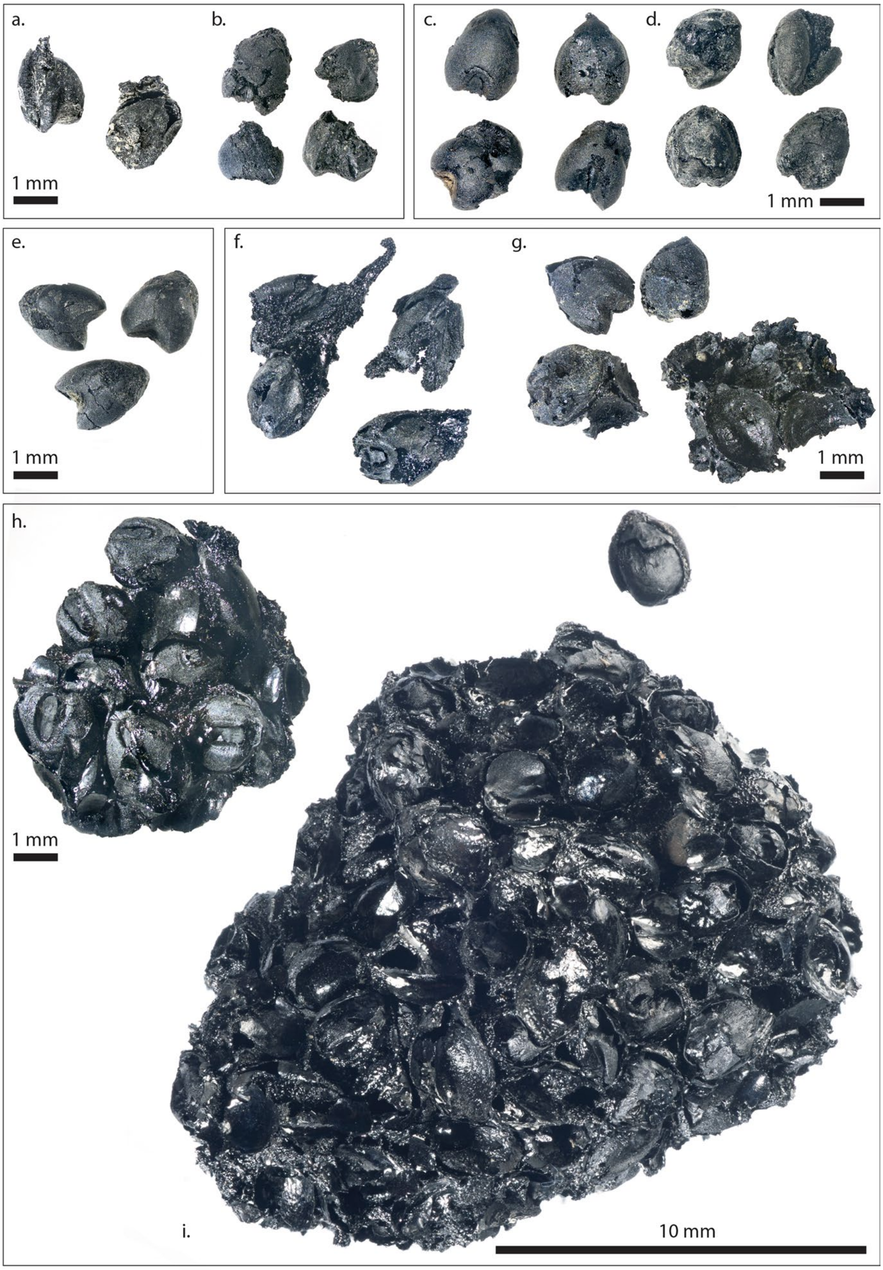

Fig. 3 Microphotographs of the material subsampled for dating in Kyiv from the sites of Vinogradnyi Sad (a., b.), Dykyi Sad (c., d.), Zalissia (e.), Ivane-Puste (f., g.) and Olbia (h., i.). Photographs by A. Heitmann and W. Kirleis, Kiel University

Table 2 Results of the radiocarbon dating of millet grains from the sites in Table 1. Dates from Zanovskoe (9) were already published in Motuzaite Matuzeviciute et al. (2012), dates from Rykan-3 (4) in Gak et al. (2019). All dates are calibrated using the software OxCal 4.4 (Bronk Ramsey, 2009) and the atmospheric curve IntCal 20 (Reimer et al., 2020)

Site number and name	Radiocarbon sample	Material	Date BP	Date cal. BC/AD (1σ, 68.2%)	Date cal. BC/AD (2σ, 95.4%)	$\delta^{13}C$ (‰)
(1) Ratniv-2	UBA-30430	1 charred grain of *P. miliaceum*	1739 ± 37	250–380 cal AD	240–410 cal AD	n. m
	UBA-30431	1 charred grain of *P. miliaceum*	1742 ± 36	250–370 cal AD	240–410 cal AD	n. m
(2) Baia	OxA-31350	1 charred grain of *P. miliaceum*	1734 ± 26	250–380 cal AD	240–410 cal AD	− 8.6
	OxA-31351	1 charred grain of *P. miliaceum*	1808 ± 25	210–320 cal AD	160–340 cal AD	− 10.8
	OxA-31352	1 charred grain of *P. miliaceum*	1780 ± 29	240–330 cal AD	210–360 cal AD	− 7.9
(3) Maidanetske	Poz-97625	1 charred grain of *P. miliaceum*	1110 ± 30	890–990 cal AD	880–1020 cal AD	n. m
(4) Rykan-3	Poz-61887 (Gak et al., 2019)	1 charred grain of *P. miliaceum*	1630 ± 30	400–540 cal AD	380–550 cal AD	n. m
	Poz-61889 (Gak et al., 2019)	1 charred grain of *P. miliaceum*	2165 ± 35	360–150 cal BC	370–50 cal BC	n. m
(5) Vinogradnyi Sad	Poz-105275 (square 275)	1 charred grain of *P. miliaceum*	3275 ± 35	1610–1500 cal BC	1630–1450 cal BC	− 15.0
	Poz-103215 (square 276)	1 charred grain of *P. miliaceum*	3160 ± 30	1500–1410 cal BC	1510–1320 cal BC	− 11.0
	KIA-53658 (square 276)	1 charred grain of *P. miliaceum*	3090 ± 35	1420–1290 cal BC	1440–1260 cal BC	− 8.5
(6) Dykyi Sad	Poz-103214	1 charred grain of *P. miliaceum*	2905 ± 35	1190–1010 cal BC	1220–990 cal BC	− 19.7
	Poz-105274	1 charred grain of *P. miliaceum*	2895 ± 35	1130–1010 cal BC	1220–980 cal BC	− 8.4

Table 2 (continued)

Site number and name	Radiocarbon sample	Material	Date BP	Date cal. BC/AD (1σ, 68.2%)	Date cal. BC/AD (2σ, 95.4%)	$\delta^{13}C$ (‰)
(7) Zalissia	Poz-103216	1 charred grain of *P. miliaceum*	2475 ± 35	760–540 cal BC	770–420 cal BC	− 12.8
(8) Ivane-Puste	Poz-103286	2 fused grains of *P. miliaceum*	2490 ± 30	760–540 cal BC	780–480 cal BC	− 9.7
	Poz-105276	1 charred grain of *P. miliaceum*	2495 ± 30	770–540 cal BC	780–510 cal BC	− 12.1
(9) Zanovskoe	OxA-18316 (Motuzaite Matuzeviciute et al., 2012)	1 charred grain of *P. miliaceum*	2275 ± 45	400–230 cal BC	410–200 cal BC	− 11
	OxA-18317 (Motuzaite Matuzeviciute et al., 2012)	1 charred grain of *P. miliaceum*	2227 ± 32	370–200 cal BC	390–190 cal BC	− 11.1
(10) Olbia	Poz-105012	Lump of c. 12 charred grains of *P. miliaceum*	2020 ± 30	50 cal BC–30 cal AD	100 cal BC–110 cal AD	− 10.0
	Poz-105277	Lump of c. 15 charred grains of *P. miliaceum*	1765 ± 30	240–340 cal BC	230–380 cal AD	−17.9

The results have been rounded outwards to decadal endpoints. For some samples, the $\delta^{13}C$ has not been measured (n. m.)

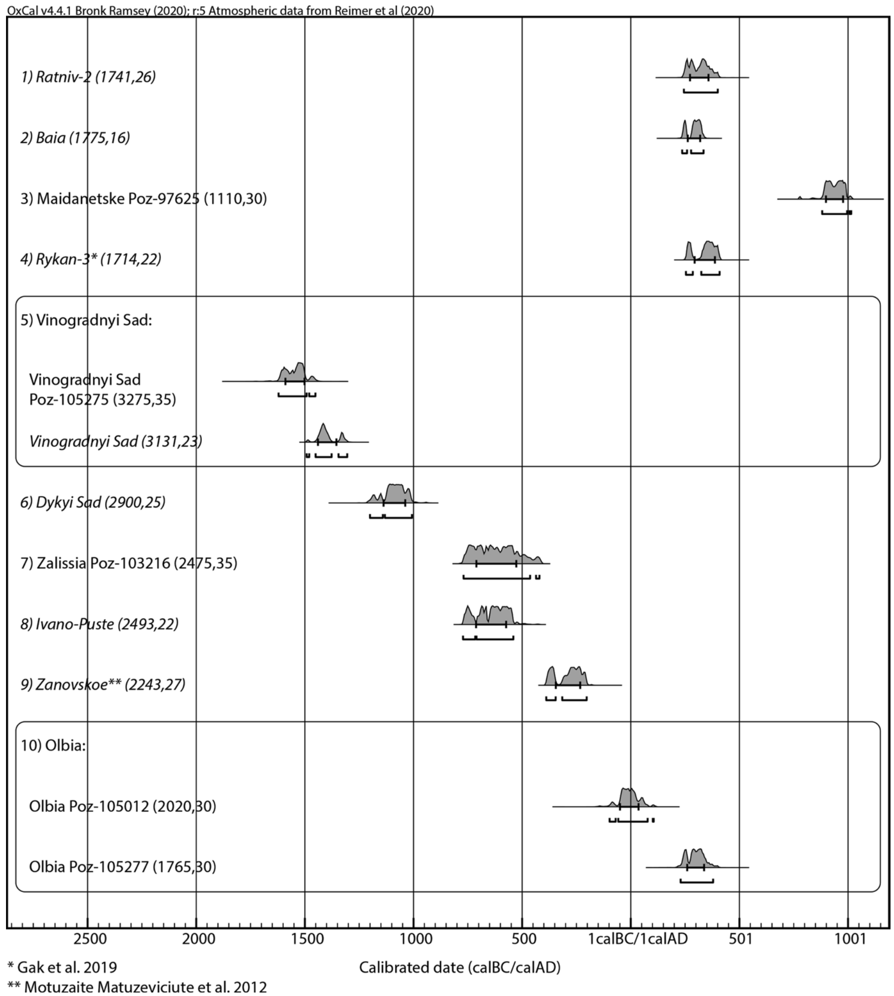

Fig. 4 Multiplot with the calibrated radiocarbon dates on broomcorn millet considered in this study, including those previously published from Zanovskoe in Motuzaite Matuzeviciute et al. (2012) and from Rykan-3 in Gak et al. (2019). The dates of sites in italics have been statistically combined by the Oxcal function 'R_combine'. The sites with a single date such as Maidanetske and Zalissia, and those with dates non-statistically consistent among each other—i.e. one date from Vinogradnyi Sad and the two dates from Olbia—were kept separate

archaeobotanical sample in the same context date a century younger, to the end of the 16th–13th century BC (1510–1320 cal. BC and 1440–1260 cal. BC).

The Final Bronze Age site of Dykyi Sad (6) follows, with grains from a pit fill rich in millet dating to the end of the 13th to the beginning of the 10th century BC (1220–980 cal BC).

From the Iron Age sites, there is earlier evidence of millet in western Ukraine close to the River Dniester at Zalissia (7), between the 8th and the 5th century BC

(770–420 cal BC), and at the nearby site of Ivane-Puste (8), between the 8th and the 6th century BC (780–480 cal BC). The samples from these sites come from cultural layers related to burnt buildings at Ivane-Puste and an area with furnaces and hearths at Zalissia. To the east, at Zanovskoe (9), on the floodplain of the river Donets, the grains from two pits date slightly younger to the 5th–2nd centuries BC (410–190 cal BC). The site of Olbia Pontica (10) —on the estuary of the Bug River—presented very large deposits of millet in the lower town, which date between the 1st century BC and 1st century AD (100 cal BC–110 cal AD), when the site underwent a period of instability and conquest by the Getae. The millet sample from the upper town dates later, to the Roman occupation in the 3rd–4th centuries AD (230–380 cal AD), consistent with the mass find of millet in the amphora from the middle of the 3rd century AD.

All of the samples from the aforementioned sites were consistent with the chronology of the archaeological context, unlike other broomcorn millet grains in this study. The two broomcorn millet grains from the Neolithic site of Ratniv-2 (1) and the three dates from the early Copper Age features at Baia (2) result from the intrusion of millet from younger deposits into the older contexts. They date to the first centuries AD: at Ratniv-2 240–410 cal AD; and at Baia 160–410 cal AD. Moreover, the Copper Age site of Maidanetske (3) dates much later, to early medieval times (880–1020 cal AD), when different nomadic groups—from Magyars to Pechenegs—occupied this area. Finally, two grains from the Middle Bronze Age site Rykan-3 (4) date respectively to the late Iron Age/Roman time (370–50 cal. BC) and the period of Germanic and Hunnic incursions (380–550 cal. AD).

Discussion

Absence of Broomcorn Millet Evidence in the North Pontic Region Before the 2nd Millennium BC

In this study, in the archaeological sites of the Neolithic and Copper Age active prior to the 2nd millennium BC, the results of dating proved that broomcorn millet was an intrusion from later periods in the prehistoric stratigraphy. For the Neolithic site of Ratniv-2 (LBK, 6th millennium BC) and the Copper Age site of Baia (Pre-Cucuteni culture, 5th millennium BC), the dates on charred millet revealed that people who were consuming this crop inhabited the forest-steppe area east of the Don River and the eastern Carpathian foothills in the early1st millennium AD. Similarly, in the forest-steppe of central Ukraine at Maidanetske (Trypillia culture, 4th millennium BC), millet dates not to the Copper Age period but to the Early Medieval Period.

In accordance with extensive recent studies that have re-evaluated imprints previously attributed to millet in clayey artifacts (An et al., 2019a, 2019b; Endo pers. comm.), the idea that broomcorn millet was present during the Neolithic and Copper Age in the North Pontic region is now proven to be incorrect. In those periods, cereal production was focused on large-grained cereals, especially hulled wheat like emmer and einkorn, barley, and pulses (Dal Corso et al., 2019; Gaydarska, 2020; Kirleis & Dal Corso, 2016; Motuzaite Matuzeviciute & Telizhenko, 2016; Motuzaite

Matuzeviciute, 2014; Pashkevych, 2003, 2005a, 2005b, 2012; Pashkevych & Videiko, 2006; Salavert et al., 2020; Shukurov et al., 2015).

Isotopic studies carried out on human and animal remains from Ukrainian sites dating to the Neolithic and Copper Age (e.g. Budd et al., 2020; Ledogar et al., 2019; Lillie et al., 2009, 2011) did not indicate any consumption of C_4 plants such as millet. Phytolith analysis from Copper Age settlements in Romania (Danu et al., 2019) and Ukraine (Dal Corso et al., 2018) also showed no evidence of millet.

In the Early Bronze Age, Yamnaya settlement sites are under-investigated archaeologically as well as archaeobotanically, (with the exception of Michajlovka in south-central Ukraine: Kaiser, 2019 and references therein). Flotation has also not been systematically applied to grave contexts. This aspect of research history may have masked the visibility of cereal agriculture, which is commonly considered not economically relevant for the period (e.g. Kaiser, 2019), including in areas where cultivation and cereal use are known in previous periods, for instance the forest-steppe of central Ukraine. This discrepancy between the archaeological evidence from, on the one hand, funerary and, on the other hand, domestic-productive contexts may have biased discussion on subsistence economy in diachronic perspective.

The Middle Bronze Age settlement of Rykan-3 (Middle Don Catacomb Culture, c. 2500–2350 cal. BC, Kaiser, 2019) also provided no evidence of millet, nor of any other cultivated or wild plant, since the plant remains post-date the site occupation (Gak et al., 2019). In general, direct traces of agriculture from sites of the Catacomb Culture are rare and doubtful (Lebedeva, 2005), and possibly linked to cereal imports from further southwest (e.g. for barley, Shishlina et al., 2018a). In fact, in Crimea, at Bolotnoe—a funerary site of the Catacomb culture—an exceptional find of a sack made of plant fibers with emmer and einkorn grains was found deposited as a grave good (Yanushevych, 1986). Access to cereals and their deposition in a ritual context suggest the probable relevance of cereals for people of the Catacomb culture in the Kuban region, although they do not necessarily indicate local farming.

The study of C and N stable isotopes from human and animal remains of sites of the Early and Middle Bronze Age Yamnaya and Catacomb cultures in the North Pontic region did not suggest the consumption of millet, but a diet based on C_3 plants and products derived from herbivores eating C_3 plants (Gerling, 2015; Privat, 2004). In grazing animals, indication of C_4 plant consumption has not been associated with millet in the more arid eastern steppe zones, where the natural C_4 vegetation component in dry grasslands and salt marshes is higher (e.g. in the Caucasus: Iacumin et al., 2004; in the Caspian steppe: Shishlina et al., 2012), nor in Romania, where it has been attributed to grazing of ruderal C_4 plants near settlements (Balasse et al., 2017). However, this signal in herbivores from C_4 natural plants was not observed in the North Pontic region (Gerling, 2015).

Enriched values of both C and N stable isotopes also attest to the consumption of fish during the Copper Age and Early Bronze Age in the North Pontic region and southern Russia, albeit with a less pronounced role than in the Urals and other northern regions (Gerling, 2015; Privat, 2004).

During the 3rd millennium BC, signs of C_4 plant consumption assumed to indicate millet are first attested at the western fringe of the study area, in Bulgaria, at the kurgan of Boyanovo with Early–Late Bronze Age burials (one individual dating to 2890–2660 2σ cal BC: Gerling, 2015; Privat et al., 2018).

The Onset of Millet Cultivation in the North Pontic Region in the 2nd Millennium BC

In the North Pontic region, the earliest direct date available on millet goes back to the mid 2nd millennium BC (1630–1450 cal BC; Poz-105275, 3275 ± 35 BP), at the Late Bronze Age site of Vinogradnyi Sad. This date slightly anticipates the time of first site occupation, previously considered to fall in the 15th century BC, but it is in line with other recent dates from the eponymous site Sabatynivka 1 of the Sabatynivka (or Sabatinovka) culture, which dates prior to the 16th century BC (Kiosak & Siekerska, 2021). Settlements of the Sabatynivka culture—like Vinogradnyi Sad—are associated with the Noua and Coslogeni cultures in Moldova and Romania due to similarity in material culture (Boroffka, 2013; Gershkovych, 2003; Parzinger, 2013; Sava, 2005, 2014). Several hundred settlements of the so-called Sabatynivka–Noua–Coslogeni cultural block are currently known, distributed south of the forest-steppe and into the steppe zones between the Carpathian basin, the lower Danube River, the lower Dnieper River, as far as the Sea of Azov (Gershkovych, 2003; Parzinger, 2013; Sava & Kaiser, 2011; Sava, 2014). This abundance of settlement sites in the Late Bronze Age contrasts with previous (and subsequent) cultures that occupied the regions north of the Black Sea, whose groups are indeed mostly known for their widespread burial mounds or *kurgans*, usually associated with a mobile society, for example, the Yamnaya people in the Early Bronze Age and the Scythians in the Iron Age (Anthony, 2007; Kaiser, 2019; Kohl, 2007; Parzinger, 2013; Taylor, 1994). In the easternmost part of the region, numerous permanent settlements attributed to the Sabatynivka culture are attested by buildings with stone foundations and workshops, as in Vinogradnyi Sad. By contrast, the westernmost Noua culture is characterized archaeologically by multi-phase sites with sun-dried wattle-and-daub architecture, resulting in thick grey deposits identified in the history of research as 'ash mounds' (see discussion in Sava & Kaiser, 2011). These deposits have usually been interpreted as farmsteads for cattle herders and their herds (e.g. Odaia-Miciurin, Moldova: Sava & Kaiser, 2011). The level of mobility of Noua groups is uncertain. It is possible that year-round occupation of dwellings occurred, as suggested by the large quantity of animal bones and the presence of domesticated pigs (Sava & Kaiser, 2011, p. 346), or that regular long-distance movements were involved and for several consecutive years the dwellings were only seasonally occupied when pastures were available nearby (Gershkovych, 2003; Sava, 2005; Sava & Kaiser, 2011). In both cases, according to the authors, after some time the residential location was moved a few kilometers to allow pasture regeneration and prevent overgrazing. In this way, a link to the territory would have been maintained, suggesting a particular bond to the local resources that is also seen ethnographically (e.g. within nomadic groups in Iran: Salzman, 2002). Accordingly, the large number of residential sites is not a reflection of huge demographic growth but of a certain kind of subsistence strategy based on the use of pastureland (Sava, 2014; Sava & Kaiser, 2011) and the necessity to rebuild earthen architecture, perishable in temperate environments (Amicone et al., 2020). In some cases, the ash mounds have been interpreted as deriving from collective activities including feasting and leatherworking (e.g. Rotbav, Romania: Dietrich, 2011; Dietrich et al., 2017). In the economy of these Late Bronze Age groups, the huge number of bones and bone tools hints that stockbreeding played a very important role, with a focus on cattle followed by sheep/goats, horses, and, in westernmost sites, also pigs (Morales Muñiz & Antipina, 2003; Morgenstern, 2011; Sava & Kaiser, 2011). At such sites, agriculture is also attested by charred cereals, including millet, and metal sickles and their stone moulds (Kohl, 2007; Gershkovych, 2003). At Vinogradnyi Sad, a large concentration of barley was found, along with other cereals (Pashkevych & Kostilov, 1992; Pashkevych, 1991, 1997, 2012) and it was associated with kilns that could have been used for parching and drying the crops. Thus, it has been suggested that the site was a center specialized in cereal processing and trade (Sharafutdinova & Balushkin, 1997). Arable weeds and ruderal plants suggest open areas for local cereal cultivation on wet, sandy-loam soils on the river banks (Pashkevych, 2012) where most Sabatynivka sites are located (Gerškovič, 1999). Several grains of charred *Panicum miliaceum*—currently undated—have also been found at Noua sites in Moldova such as Odaia-Miciurin, where it was the most represented crop in the albeit small archaeobotanical dataset (ashmound n. 17, radiocarbon dated to the 14th–12th century BC: Sava & Kaiser, 2011), and in Romania at Coslogeni, where it was also the most represented cereal for the layers attributed to the Late Bronze Age, followed by hulled barley, emmer and a small amount of free-threshing wheat (Lebedeva, 1995, 2005).

Northeast of the core of the Sabatynivka Culture, from the left bank of the Dnieper to the slopes west and east of the Ural Mountains, partly contemporaneous sites of the Srubnaya Culture (1950–1500 cal BC: Hanks et al., 2007) are attested, focused on metalworking and stockbreeding. It has been suggested that these people adopted a sedentary lifestyle in order to practice mining and metalworking, rather than agriculture (Chernykh, 2008); this was likely related to the availability and exploitation of wood in the forests of the northern Don and Donets valleys (Kremenetski, 1991, 2003). Large metal sickles have been found there that have been attributed to the collection of hay for winter, rather than cereal harvesting, likely related to a permanent year-round settlement (Boroffka & Mantu-Lazarovici, 2011; Cunliffe, 2019; Gershkovych, 2003). Indeed, after a preliminary flotation program at 49 Bronze Age sites, finds of cereals were extremely rare (Lebedeva, 2005). The oldest cereal record includes broomcorn millet, emmer, barley, and free-threshing wheat, and comes from Russkaya Selitba in the Samara region, a site of the late Srubnaya culture (other sites with some cereal remains are Bezymennoe I and II and Shirokaya Balka: Lebedeva, 2005). At present, these finds are undated and may have doubtful chronology (Lebedeva, 2005 and pers. comm.).

The analysis of C and N stable isotopes from human and animal remains in Ukraine has been carried out on several Middle–Late Bronze Age sites (KMK [*Kul'tura mnogovalikovoi keramiki* or 'multi-cordoned' ware], Srubnaya, post-Srubnaya, Sabatynivka). The results mostly indicate a diet based on C_3 plants, plus animal products and fish for humans (Privat, 2004). Millet consumption is only suggested for two human individuals dating to a post-Srubnaya time (here meaning after the 13th century BC) at the multi-phase site of Glubokoe Ozero II in the forest-steppe west of the Donets river. Since animals indicated a C_3 plant-based diet instead, direct use of millet as food is suggested (Privat, 2004). The only site of the Sabatynivka culture where stable C and N isotopes were studied is Vinogradnyi Sad, where the three human and the numerous wild and domesticated animal specimens studied did not show any isotopic evidence of millet consumption (Privat, 2004). Despite the small sample size of human individuals, at present the comparison of archaeobotanical and isotopic data from Vinogradnyi Sad suggests that millet at the site was not the most common cereal and that it was probably not used for fodder.

The evidence of millet in the macrobotanical record is more substantial during the Final Bronze Age at Dykyi Sad, a fortified site of the Belozerska culture that is represented not only by settlements but also by kurgans and burials across the North Pontic zone and Crimea. These sites are characterized by long-distance contacts with the surrounding regions (Gershkovych, 2003), and possibly favored by rivers (Gorbenko, 2007; Otroshchenko, 2009). The region where Vinogradnyi Sad and Dykyi Sad are located centres on the valley of the Southern Bug river and is the far western fringe of the steppe zone, the 'Bug steppe' (Gorbenko, 2007; Matvinko, 2012). Cultures in this border region had extensive contacts across the Southern Bug westward, with Carpatho-Transylvanian centers and Central Europe, as well as southward to the Danube and Balkans (Gorbenko, 2007; Klushwencev, 1981; Sharafutdinova, 1968), and further north-east through the Dnieper with the Baltic regions (Gorbenko, 2007; Gorbenko & Grebennikov, 2009). Such contacts are testified by many artifacts of varied origins and technology (e.g. ceramic, amber and house-urns: Gershkovych, 2003). It is possible that this well-established network facilitated the rapid spread of millet in Europe, where it was established in the Carpathian basin by the 15th century BC (Filipović et al., 2020; Motuzaite Matuzeviciute et al., 2013a, 2013b). Furthermore, in this advanced phase of the Final Bronze Age, settlements like Dykyi Sad are considered as emerging 'regional cultural, trading and political centers' housing the local élite, in a rupture with the previous Late Bronze Age phase (Gershkovych, 2003). During this time, the number of settlements decreased and scholars suggest that the preconditions were formed for the transition from a sedentary form of agro-pastoralism to pastoral nomadism, based on regular mobility for animal herding (Chernykh, 2008; Makhortykh, 2012; Matvienko, 2012). Climate impact is usually considered to be behind this change in settlement and economic strategies (Fig. 5). According to some authors, a climatic oscillation towards humidity in the mid 2nd millennium BC (1500–900 cal. BC in the Mid Dnieper: Kremenetski, 2003; 1400–1200 BC in south-central Ukraine: Gerasimenko, 2019) might have favored cereal farming at that time in the areas of the Noua-Sabatynivka Culture, in contrast to previous and subsequent periods when aridity triggered an economy based on stockbreeding (Gerasimenko, 2019; Gershkovych, 2003; Pashkevych & Shovkoplyas, 2013). Climatic proxies to sustain this interpretation of a humid period in the second half of the 2nd millennium BC and later aridification at the end of the Bronze Age are mainly based on on-site palynological studies (e.g. the Sabatynivka site of Novokyivka: Gerasimenko, 2019), due to the rarity of suitable natural archives, which—when available—are rarely continuous in sedimentation

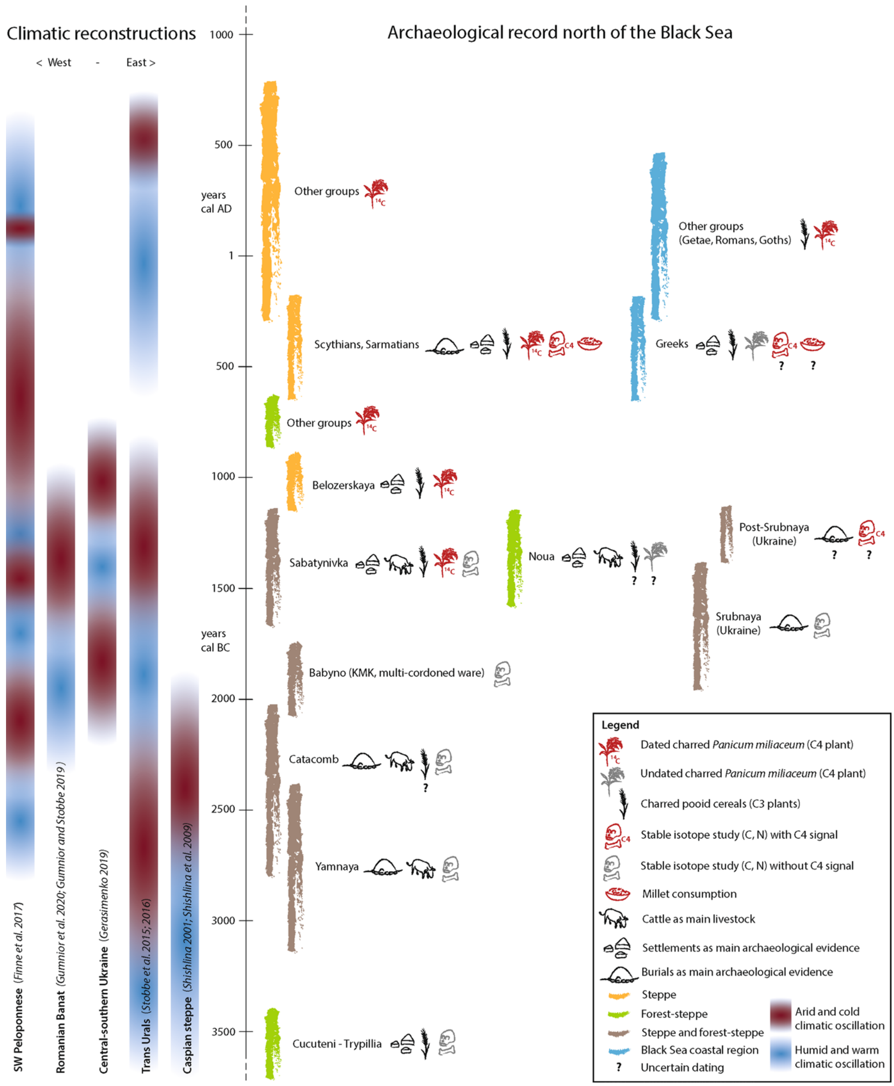

Fig. 5 Schematic illustration of the main traits of the archaeological record used for economic reconstructions in the central portion of the North Pontic region (right) and climatic reconstructions in the North Pontic region and surrounding areas (left) based on studies mentioned in the text. The diachronic spread of millet in the central North Pontic region is shown by different kinds of evidence (red symbols). (Graphic work M. Dal Corso)

(e.g. the mire Kardashinskoye in the lower Dnieper: Kremenetski, 2003). In research areas in the first half of the 2nd millennium BC (2000–1600 BC) a Bronze Age humid period has been recognized in the Trans-Urals, where it favored sedentism and the emergence of many permanent settlements, although without crop cultivation and in relation to an increased plant biomass enhancing animal herding (Stobbe et al., 2015, 2016). Aridification is detected in the mid 2nd millennium BC—after 1600/1500 BC—in the Trans-Urals (Stobbe et al. 2021) and the Romanian Banat (Gumnior & Stobbe, 2019, 2021; Gumnior et al., 2020) and after 1200/1100 BC in Ukraine (Pashkevych & Shovkopylas, 2013 and references therein).

Despite aridification, at Dykyi Sad charred cereals (barley, millet, hulled and naked wheats) and weeds were recovered from post holes and burnt structures (Gorbenko & Grebennikov, 2009; Pashkevych, 2012), which also indicates continuity in the consumption (and, we can postulate, the production) of agricultural products in the Final Bronze Age in the North Pontic region. This challenges the view that mobile stockbreeding was an exclusive activity at the end of the Bronze Age in the North Pontic region. Despite the likely impact of changes in precipitation and temperatures on ecological threshold zones such as the south-western Eurasian forest-steppe (Pashkevych & Shovkoplyas, 2013; Shishlina, 2001), cereal finds at the end of the Bronze Age indicate a degree of resilience in the economic system, with millet possibly also playing an increasingly important role in response to climate changes. Contrasting climatic reconstructions require further study and suggest the possibility of different (micro-) regional responses to the relatively short oscillations at the end of the 3rd and during the 2nd millennium BC (e.g. Finné et al., 2017), rarely registered with solid dating in sedimentary archives.

The Final Bronze Age—at the transition to the Early Iron Age—in southeastern Europe is generally seen as characterized by a new communication network and changes in technology due to the crisis of bronze raw materials (Chernykh, 2008; Makhortykh, 2012; Matvienko, 2012; Parzinger, 2013). Imports of metal objects and production after western models show a renewed orientation towards the Balkans, Carpathians and Danube (Chernykh, 2008). As previously anticipated, changes in settlement system and economy from a sedentary agro-pastoralism to a more mobile form of pastoralism have also been postulated (e.g. 'transhumant pastoralism': Cunliffe, 2019; Gershkovych, 2003; Makhortykh, 2012; Matvienko, 2012), usually linked to climatic deterioration (cooler temperatures and aridification). For now, the 'rupture' identified in comparison with the previous Late Bronze Age period is not reflected in substantial changes in the choice of staples, apart from the continuity in the use of millet, which suggests that people became accustomed to this new crop over time. Other factors inducing a change in settlement system could still be found in socio-political or economic developments, such as a specialization of production with clearer economic division between stock-breeders and agriculturalists, oriented to trade and beyond local subsistence, although for now such a subdivision is not clearly visible. An increased relevance of horseback riding in stock tending is most likely (Cunliffe, 2019), although horseback riding in itself was an earlier innovation (Anthony, 2007).

The 2nd millennium BC in the North Pontic region can be characterized as a period with high stability in staple crops, despite climatic oscillations and socio-cultural changes, with the increasing relevance of millet (growing and consumption).

Established Millet Cultivation in the North Pontic Region in the 1st Millennium BC

In the Iron Age, from the 9th to the 3rd century BC, the North Pontic steppe and forest-steppe were populated by a number of groups, including the Scythians, and the Greek colonists on the northern Black Sea coast. The Scythians are primarily seen as nomadic tribes of mounted warriors and herders that moved across the steppe looking for new territories for pastures (Cunliffe, 2019). They are known for their monumental kurgans, the animal style in their ornaments and weapons, and for a stratified society with contacts with many different cultures, including the Greeks, as well as more distant people such as the Persians and Chinese (Alexeyev, 2017; Cunliffe, 2019; Simpson & Pankova, 2017; Taylor, 1994). Although a mobile lifestyle is attributed to Iron Age groups, there are hillforts that attest the presence of sedentary people closely related to the Scythians and likely engaged in agriculture, as suggested by the evidence of granaries and charred cereals (Pashkevych, 1999, 2001, 2005a, 2005b). In fact, during the Iron Age, cereals (and notably broomcorn millet) continue to be present in the North Pontic region.

The earliest Iron Age dates of broomcorn millet come from the settlements of Ivane-Puste and Zalissia, located very close to each other in the forest-steppe region of the Middle Dniester, western Podolsk, in western Ukraine, which was densely populated in the 7th–5th centuries BC. Like the sites of the Final Bronze Age, these sites present diverse materials testifying to many contacts and influences: Scythian weapons, horse harness and kurgan burial mounds accompany monochrome grey wheel-made ceramic after a technology acquired from the Balkans and eastern Carpathian regions (Daragan, 2009; Vakthina & Kashuba, 2013). Further links existed between the population of these sites and their western (Hallstatt), southwestern (Dacian and Thracian), and southern (the Greek colonies in the northern Black Sea region) neighbors. At these sites, agriculture is indicated by charred grains and weeds in addition to imprints of grains and cereal by-products in clay artifacts (Pashkevych, 1999; Yanushevych, 1976, 1986). Broomcorn millet dominated the cereal grains, which also include hulled barley, emmer, einkorn, spelt, free-threshing barley and rare free-threshing wheat (Pashkevych, 1999). Moreover, green pea, lentil and flax were attested. At Zalissia, flax seeds were particularly abundant (Pashkevych, 1999).

Other Late Iron Age sites (5th–3rd centuries BC) in the steppe region of the lower Dnieper presented hulled barley and broomcorn millet as the most common cereals (e.g. in storage pits in Lysa Gora: Pashkevych, 1999, 2000). At the hillfort of Knischivske, a storage pit with a mass find of almost pure hulled barley was found (Pashkevych, 1999), while millet, wheat and barley are attested at the fortified site of Bel'sk (Pashkevych, 2005a, 2005b).

Later cultivation of broomcorn millet, during the 5th–1st centuries BC, has been attested by the dates on grains at Zanovskoe (Motuzaite Matuzeviciute et al., 2012), along the Donets river. Scythian and Sarmatian mobile groups were known in the region at that time, and cultivated small plots with broomcorn millet in the Donets floodplain, as attested at Zanovskoe by charred grains and weeds (including *Echinocloa crus-galli*, *Setaria viridis*, *Digitaria sanguinalis*) and direct evidence in the sediments of the molecule miliacin, derived from *Panicum miliaceum* (Motuzaite Matuzeviciute et al., 2016). Floodplain cultivation would have suited people who moved seasonally, as the naturally nutrient-rich sediment of the plain allowed them to sow a fast-growing grain like millet—this practice is known from ethnographic sources for some nomadic groups in Central Asia (Di Cosmo, 1994). The presence of grains in pits is something attested ethnographically, where we see that the harvest was partially stored in straw-lined pits for the following year (Di Cosmo, 1994). Archaeobotanical evidence of threshing remains among cereal grains from pits at the Iron Age site of Kozyrka 9 from the 6th century BC further suggests the practice of covering clay-lined pit walls with cereal straw and by-products, firing them to increase their insulating properties (Pashkevych, 2001).

Recent isotopic study on human and animal remains from the Scythian period in the Eurasian steppe has sharpened the picture of their mobility and diet. Diverse subsistence economies coexisted, all in general based on animal-derived products along with freshwater fish and cereals, often including intensive millet consumption (Gerling, 2015; Privat, 2004; Ventresca Miller et al., 2019, 2021). A case study in Kazakhstan showed that local Scythian groups derived one-third of their dietary intake of protein from millet, and local river bank cultivation was also suggested in this case (Murphy et al., 2013). As for mobility, a recent study based on Sr isotopes at the fortified Scythian site of Bel'sk, in the forest-steppe of eastern Ukraine, stressed the coexistence of a main sedentary component of the population—compatible with agriculture—and a minor, more mobile component (Ventresca Miller et al., 2019). These results are further supported by a more extensive isotopic study of Iron Age communities in Ukraine (Ventresca Miller et al., 2021).

The contemporaneous Greek colonies on the northern coast of the Black Sea had a different set of cereals, mainly composed of bread wheat (*Triticum aestivum*) and hulled barley (Pashkevych, 1996, 2001). This difference between their crops and those of other local groups indicates that bread wheat was imported, or that the custom of cultivating it was maintained by the Greek people from their homeland, despite increased requirements in terms of soil fertility and long growing season. However, millet was also found: Olbia was an emporium with local contacts and a multi-phase occupation. For the time of Greek occupation, the analysis of C and N isotopes from five human individuals from Olbia attested millet consumption (Privat, 2004). The individuals are identified as Greek colonists, although dating and contextual evidence supporting this attribution is not published. The most recent archaeobotanical investigations in Olbia (German–Ukrainian DFG research project) originate from pit houses in the suburbs from the 6th/5th centuries BC. They revealed a rich spectrum of cultivated plants including emmer, einkorn, bread wheat, hulled barley, lentil and pea. *Panicum miliaceum* has also been identified, but direct dating has not yet been carried out (Stobbe et al., 2021).

The dated broomcorn millet from Olbia Pontica—founded by the Greeks—does not correspond to the period of Greek foundation but rather those of Roman occupation and later invasion by the Goths. During Roman times, broomcorn millet was cultivated in the region, as also attested by the millet dates from Neolithic and Copper Age archaeological deposits presented above, among others (e.g. botanical macro-remains from the hillfort of Zolotoy Mys: Pashkevych, 2000, 2001). Probably after a process of acculturation, millet was also eaten by Roman soldiers in Olbia, as shown by the exceptional find of an amphora full of untreated millet grains in deposits dated to the latest Roman occupation phase (Stobbe et al., 2019). In Moldova, millet was found in Roman-period sites of the steppe, forest-steppe and forest zones (Yanushevych, 1976), for example, at the settlement of Chalyk II, where together with emmer it predominates in the record of charred cereals (Yanushevych, 1987).

The Integration of Millet in the Farming Economy

The North Pontic region north of the Black Sea has a north–south ecological gradient from widespread woodland cover to patchy, mosaic ecosystems and natural open grasslands, with a warm/hot humid continental climate and year-round precipitation. The borders of these vegetation zones shifted with changing climate during the Holocene. Beginning in the Neolithic in the 6th millennium BC (e.g. Motuzaite Matuzeviciute & Telizhenko, 2016), with increased habitation in the Copper Age (e.g. Müller et al., 2016; Harper et al., 2019; Gaydarska, 2020), the forest-steppe represented a convenient setting for agriculture based on the cultivation of large-seeded cereals and pulses, alongside animal herding (Fig. 5).

A change in subsistence economy towards greater reliance on animal products is shown by the focus on cattle that emerged with Yamnaya groups in the 3rd millennium BC (Kaiser, 2019), if not some centuries earlier (Harper et al., 2019). Long phases of mainly (semi-) nomadic lifestyles related to pastoral practices—such as the pursuit of seasonal pastures along river courses (Kohl, 2007)—have been postulated in the North Pontic region; for instance, during the Early and Middle Bronze Age and the Iron Age. Two main factors support this picture (Fig. 5): the uneven visibility in the archaeological record of domestic contexts in comparison with burials, and the scarcity of cereal finds. Nonetheless, it is possible that the former has been enhanced by an archaeological focus on funerary contexts, and the latter by the difficulty of retrieving perishable organic remains such as cereals in sites with very active pedogenesis and likely perishable structures, as can be postulated for seasonally occupied settlements. Thus, these factors may have led to an underestimation of the role of plant cultivation in human nutrition. The application of stable isotope analysis of C, N, Sr and O on bones and teeth and the attention devoted to dental health (e.g. Ledogar et al., 2019; Murphy et al., 2013) provide further insights into people's diet and mobility (Gerling, 2015; Ventresca Miller et al., 2021), highlighting the need to reconsider the role of cereals and the association of archaeological records, mobility models and subsistence economies. After the analysis of dental pathologies in Ukrainian prehistoric sites, the increase of caries in the Late Neolithic–Copper Age as compared to the Mesolithic—for instance—indicates the consumption of carbohydrates likely derived from cereals (Karsten et al., 2015).

In this frame, the study of millet in the North Pontic region allows us to follow the process related to the integration of a new staple in the diet and economy of (agro-)pastoralist people. Based on the available data, this process seems to have occurred gradually in the 2nd millennium BC and to have been successfully maintained (Fig. 5). Although an improvement in sample size may possibly change the picture, based on the current state of research the first appearance of this crop in the region is in Sabatynivka settlements attributed to agro-pastoralist groups, where other large-grained cereals are abundant and millet is present only sporadically. At this time, settlements were widespread in the region and western contacts were frequent (e.g. Gershkovych, 2003; Matvienko, 2012; Sava, 2014; Sava & Kaiser, 2011). Contemporaneous isotopic signal of millet is absent from the human and animal specimens analyzed to date in the area of the steppe and forest-steppe (Privat, 2004). Isotopic signal in animal diet of C_4 plants typical of dry grasslands and salt marshes—identified isotopically in studies on the steppe further east (e.g. Iacumin et al., 2004; Shishlina et al., 2012)—is also absent (Gerling, 2015; Privat, 2004). In western Noua sites with (seasonal) occupation linked to animal herding, millet was also found to dominate the scarce botanical record (undated multiple grains; Sava & Kaiser, 2011; Lebedeva, 2005). By the end of the 2nd millennium BC, when a rearrangement of the settlement system is visible in a decreased number of sites and the emergence of Belozerska hillforts with many external contacts (e.g. Gorbenko, 2007; Matvienko, 2012), millet is found in abundance (Pashkevych, 2012). With the Iron Age, millet is attested in the charred cereal record of sites in the Ukrainian steppe and forest-steppe associated with Scythian and Sarmatian groups (e.g. Motuzaite Matuzeviciute et al., 2012; Pashkevych, 1999, 2001, 2005a, 2005b), and isotope analyses on human remains indicate that it was an important component of the diet (Privat, 2004; Ventresca Miller et al., 2019, 2021). Contemporaneous groups of Greek colonists had a different set of crops, including free-threshing wheat, previously uncommon in the region (Pashkevych, 2001). However, millet consumption in Greek individuals has also been detected (even though Greek attribution is unclear) and millet was found in the pit houses of the suburb (6th/5th BC), which would show (when confirmed) acculturation with the custom of local groups. During Roman times, millet was abundantly consumed in the North Pontic steppe and forest-steppe by Roman and local groups (Pashkevych, 2001; Stobbe et al., 2019). Especially in the late Roman Imperial period in the first centuries of the 1st millennium AD, when different mobile groups populated the region, millet was found in stable fortified settlement sites (Pashkevych, 2001) as well as areas without traces of settlement, as attested by some dates on intrusive millet in this study. In the latter case, mobile groups might have been responsible for its cultivation.

Not only Pastoral Nomads?

As mentioned above, the people of the steppe are usually associated with a pastoralist economy relying on animal herding and a mobile lifestyle, usually referred to as nomadic, although data on cereal consumption and cultivation suggest that alternatives to nomadism—for example, transhumance, rather than regular movements of the whole community—should be considered. Depending on area, resources and economic foci, the level and type of mobility may have been quite varied; one possibility is seasonal displacements possibly involving only a part of the society, while most of it occupied permanent settlements (di Cosmo, 1994; Frachetti, 2008; Honeychurch & Makarewicz, 2016; Morales Muñiz & Antipina, 2003; Rühl et al., 2015; Salzman, 2004; Stobbe et al., 2015, 2016; Taylor, 1994; Ventresca Miller et al., 2020). When the existence of settled communities is evident, only mobile herders could have been involved in transhumance. The presence of crops—especially broomcorn millet—needs to be better integrated into the ongoing discourse about the socio-economic organization and lifestyle of people living in the Eurasian steppe. The successful adoption of millet into the North Pontic dietary routine in prehistory and its continued use in the present day indicate some advantages to the cultivation of this crop in this region. Two main physiological aspects of the crop itself should be considered, the first being its adaptability to arid conditions. In an area with sufficient summer rainfall for rain-fed agriculture, such as the regions north of the Black Sea (Miller et al., 2016), millet cultivation requires low labor investment and thus could be combined with other activities.

The second aspect is the fast growth of millet compared with other crops, which allows cultivation after a first harvest in a rotation system (millet as 'summer crop'). With its short vegetative cycle, millet ripens within a couple of months, offering the opportunity for two harvests in a year. In an isotopic study on cereal grains from Late Bronze Age sites in northern Greece, comparable nitrogen values in barley and millet suggested that cultivation occurred in the same arable plots, where millet could be sown after barley was harvested, thus providing an additional harvest (Nitsch et al., 2017). Pliny the Elder also reports the use of millet in rotation systems with barley: 'If the soil is of that nature which we have already spoken of as "tender", after a crop of barley has been grown upon it, millet may be sown, and after the millet has been got in, rape' (Plin. NH 18.25.101). It is possible that this also happened in the North Pontic region, where millet has often been found with abundant barley at Late Bronze Age and Iron Age sites. It has also been suggested that both millet and barley could be used as winter fodder, especially in permanent settlements, since millet provides good green fodder for cattle (Moreno-Larrazabal et al., 2015; Pashkevych, 2001) and hulled barley can be given to horses (Pashkevych, 2001). However, for now in the North Pontic region the isotopic signal from animals does not indicate millet fodder in the Bronze Age and Iron Age (Gerling, 2015; Privat, 2004), although further studies may be needed, especially for the Late and Final Bronze Age.

Another consequence of a short life cycle is that millet could be planted in environmental niches that were otherwise neglected—for example, due to remoteness from the residential site or temporary accessibility, for example flooded areas in river valleys. The North Pontic steppe environment is traversed by large rivers, with extensive floodplains where agriculture has been attested through the presence of miliacin in the Iron Age (Motuzaite Matuzeviciute et al., 2016). It has been suggested that, in the Northwest Caspian steppe zone, annual movements of people and their animals from autumn–winter pastures along rivers to watersheds in spring occurred since the Early Bronze Age Yamnaya culture (Kohl, 2007; Shishlina, 2004). For Catacomb sites in the North Caucasus, pastoral mobility is connected with the seasonal use of river zones and open steppe (Shishlina, 2003). By contrast, for the western Eurasian steppe in the North Pontic region, short-distance movements are identified in the Early and Middle Bronze Age (Gerling, 2015) and the Iron Age, when some movements of people within a 90 km arc were identified that may relate to herders moving for pastures (Ventresca Miller et al., 2019). In the Late Bronze Age Sabatynivka-Noua sites, the seasonal re-use of the same residential place is attested by multiple dwelling phases (resulting in a 'tell-like' stratigraphy; Sava & Kaiser, 2011), and by the existence of numerous such residential places a few kilometers distant from each other, likely in relation to fixed pasture locations (Sava, 2014).

Economically, in the North Pontic region, millet is usually integrated in agricultural systems with hulled cereals and pulses, thus suggesting a crop diversification that can be seen as a risk-management strategy. Similarly, a diverse livestock composition could also help to manage risk. These strategies would be particularly relevant in a production system mostly oriented to the subsistence of small agro-pastoralist communities (Bendrey, 2011; Ivanova et al., 2018; Miller et al., 2016; Murphy et al., 2013; Privat, 2004). For the Central Asian foothills, it has been suggested that when millet could be cultivated with rain-fed agriculture, it made a fallback crop particularly appealing to small-scale farmers and mobile pastoralists (Miller et al., 2016). In more specialized production systems, crop diversification may instead hint at the intensification of cereal production for redistribution/trade (Miller et al., 2016). For now, the latter does not seem to be the case for the North Pontic region and the heterogeneous range of resources used by Bronze and Iron Age communities is attributed to the use of different biomes rather than differences in social groups and production (e.g. Hanks et al., 2018; Miller et al., 2019; Privat, 2004). Trade in cereals—produced at sites favoring rain-fed agriculture rather than those where it is difficult (e.g. outside the study area, to the north-east)—has been postulated, although the general view is that millet was not produced for trade and people grew it for their own consumption (Murphy et al., 2013; Privat, 2004; Shishlina et al., 2018a, 2018b). A recent isotopic study on Iron Age communities in Ukraine shows a difference in diet between a few highly mobile individuals—not giving signal of millet consumption—and the sedentary groups, which were millet-consuming in most cases (Ventresca Miller et al., 2021).

Overall, traces of intensive hay-making for fodder are missing from the periods studied, which implies the availability of—and a preference for—pastureland where animals could graze, with periodic movements in the landscape in accordance with seasonal availability and to avoid overgrazing. Millet could provide a good fallback crop in the crop rotation of stable farming communities, and could also be cultivated in previously neglected environmental niches by groups of herders moving seasonally after pasturelands. In both scenarios, the distinction between herders and farmers became weaker, with a herder having the opportunity to cultivate a fast-ripening cereal, or herders and farmers coexisting in the community, with tasks possibly being further subdivided between different social groups and/or age classes. Millet might create a bridge in the traditional distinction of societies where either herding or crop farming is dominant, with the former being seen as composed by mobile pastoralists and the latter by settled agriculturalists. In agreement with recent zooarchaeological and isotopic research in

Central Asia (e.g. Ananyevskaya et al., 2018; Gerling, 2015; Hermes et al., 2019; Lightfoot et al., 2015a; Motuzaite Matuzeviciute et al., 2015a, 2015b; Spengler, 2015; Ventresca Miller & Makarewicz, 2019; Ventresca Miller et al., 2014, 2020), we suggest revising the simplistic and stereotyped idea of a dichotomy between animal herding and cereal growing in the Bronze and Iron Age North Pontic region—and the linking of stockbreeding with mobility and of cultivation with sedentarism—and acknowledging the much wider range of possibilities that is attested archaeologically (e.g. Chase et al., 2020; Frachetti, 2008; Honeychurch & Makarewicz, 2016; Mileto et al., 2017; Morales Muñiz & Antipina, 2003; Sava & Kaiser, 2011; Ventresca Miller et al., 2019, 2021).

Ethnographic Comparisons

Ethnographic studies of nomadic Kazakhs attest 'infinite variations that demonstrate a high degree of flexibility and adaptability' in the production and subsistence strategies of Eurasian nomadic societies (Di Cosmo, 1994). In their case, the consumption of cultivated plants (barley and broomcorn millet) in winter is mentioned as supplementing a diet based on meat and milk products in an economic system that was more autarchic when less specialized (Di Cosmo, 1994 and references therein). The ethnographer Rona-Tas (1959) reports cultivation along the valley of the Selenga River (northern Mongolia–South Siberia), where cereals were sown on the river bank in spring—before the animals were brought to the summer pastures—and harvested in autumn. The grains were then stored in pits, lined internally with straw.

Furthermore, the use of mostly perishable wooden tools during crop processing (e.g. plows and shovels) was observed, with grinding stones being the only durable tools. Thus, the archaeological trace of farming by these nomadic people was also limited (Di Cosmo, 1994; Hurcombe, 2014). According to the Russian agronomist Nikolaj Vavilov (1926), in the early twentieth century broomcorn millet was still the favorite crop cultivated by the Asian nomadic groups in desert regions—including the North Pontic steppe—who appreciated properties like the high yield with small sowing bulk, short life cycle and drought resistance.

Thus, there are several appealing qualities of broomcorn millet for semi-nomadic people. Millet is also easy to transport, there is a positive relationship between the weight of seeds and field surface (Pashkevych, 2001), and millet porridge can also be transported as a cooked meal to be warmed up with hot water (e.g. *kulish*; Pashkevych pers. comm.). All of these characteristics would seem relevant to the form of socio-political organization of the people living in the western Eurasian steppe and forest-steppe regions from the Late Bronze Age onwards, into the Iron Age and throughout the 1st millennium AD. External factors such as centralized political territorial occupation or centralized production can also force lifestyle and economic changes (e.g. in 20th century AD Iran: Salzman, 2002), and this has also been identified archaeologically (e.g. 1st millennium BC in Central Asia: Miller et al., 2016), although not in our study region.

Unknown Ways of Millet Dispersal and Further Research Directions

Millet may have spread from East Asia to central Europe along multiple pathways in the centuries between its attestation in Kazakhstan at the end of the 3rd millennium BC (Spengler et al., 2014) and its appearance in Europe in the mid 2nd millennium BC (Filipović et al., 2020). The North Pontic region is a possible key passage region, where the presence of broomcorn millet since the Late Bronze Age has been confirmed by the dates given here. Although the 2nd millennium BC—roughly corresponding with the Bronze Age—was characterized by long-distance movements of people and goods (e.g. Allentoft et al., 2015; Andrades Valtueña et al., 2017; Kristiansen, 2014), there is no clear chronological connection between the *terminus ante quem* millet that can be found in North Pontic domestic sites (seventeenth century BC) and major 'genetic turnovers' reflecting migrations within Eurasia, such as the westward movements of Yamnaya people or Scythians (Allentoft et al., 2015; Rascovan et al., 2019). However, the materials usually investigated for genetics do not mainly come from groups where millet has been attested, and the transfer of goods and know-how does not necessarily imply the migration of people. In addition, minor movements of people are attested since the Copper Age (Immel et al., 2020).

Archaeologically, metalworking and the need for metal resources is seen as a determining aspect shaping prehistoric networks (Artioli et al., 2020; Chernykh, 2008; Cunliffe, 2015; Pearce, 2015), and it might also have favored later millet circulation. A network of contacts since the 4th millennium BC between the North Pontic area and the West, based on metal ores and metalworking, has been recognized (Chernykh, 2008), and since the 3rd millennium BC contacts with the East are suggested by arsenical copper from the Caucasus (Chernykh, 2008; Kohl, 2007; Parzinger, 2013). Besides metals, material culture and settlement patterns indicate cultural phenomena crossing from Romania to Ukraine in the Copper Age Trypillia-Cucuteni sites (e.g. Müller et al., 2016; Gaydarska, 2020), and in the Late Bronze Age Noua-Sabatynivka sites (Gershkovych, 2003; Sava, 2005; Sava & Kaiser, 2011). Thus, long before the first appearance of broomcorn millet in Europe, contacts occurred between the western Eurasian steppe and forest-steppe areas and the Carpathians and Balkans. Such a long-established tradition of contacts may explain the fast movements and exchanges during the Late Bronze Age between the North Pontic region and continental Europe, where—for instance—millet has been attested in the Carpathian basin by the fifteenth century BC and in central Europe by the fourteenth century BC (modeled dates *ante quem* per region, see Filipović et al., 2020). However, the trajectory for the arrival of millet in the North Pontic region still has to be found. There is very little to support a northern route where cereal finds are rare and their direct dating has yet to be undertaken (Lebedeva, 2005; Kaiser, 2019). A cross-Caucasus route is more likely (Andrades Valtueña et al., 2017; Herrscher et al., 2018), although evidence remains unclear (Filipović et al., 2020). A southern route through Iran and then Anatolia to Greece or across the Black Sea requires further study and the support of direct radiocarbon dates on the few millet grains attested from deposits of the

3rd, and the more abundant evidence of the 2nd, millennium BC (for a summary of millet evidence, see Nesbitt & Summers, 1988 and Miller et al., 2016). For example, at Kastanas in northern Greece, millet mass finds—for now undated—are attested in units of the mid 2nd millennium BC (layer 18; Kroll, 1983), with rare finds also present in previous phases. Further data from northern Greece show the use of millet since the end of the 2nd millennium BC, as attested by macrobotanical remains and stable isotopes, and the fourteenth century BC AMS date on a millet grain from a mass find of millet at Assiros (Nitsch et al., 2017; Valamoti, 2016; Wardle et al., 2014). From Bulgaria, C_4 plant consumption is attested at the funerary site of Boyanovo through isotope analysis of individuals of the Early–Late Bronze Age at the end of the 3rd millennium BC (Gerling, 2015; Privat et al., 2018). This is very early evidence, for which a contemporaneous archaeobotanical millet record is currently missing (Marinova & Valamoti, 2014). Thus, a southeastern route up the Balkans or through the Black Sea, and the way(s) in which this transmission may have occurred, should be further investigated.

At the same time, much insightful discussion has been devoted to considering routes and chronologies of the eastern expansion of wheat and barley cultivation, which finds parallels with the western dispersals of millet (e.g. An et al., 2019a, 2019b; Liu et al., 2019; Long et al., 2018; Spengler et al., 2014). Recent studies of wheat and barley in eastern Asia raise awareness of the response of indigenous habits and customs to novel grains that are often geographically decoupled from their associated culinary systems and/or cultivation habits (Liu & Reid, 2020; Liu et al., 2017). One example is the arrival of barley in central China, which brought with it a degree of genetic diversity in terms of flowering time responses, allowing farmers to exploit both local and previously untenable farming seasons (Liu et al., 2017). Much more research is needed on millet in Europe in this respect (Hunt et al., 2011). Another example concerns the incompatibility of western grains with eastern food preparation habits. The introduction of wheat and barley—mainly used with roasting/grinding technologies (Fuller & Rowlands, 2011)—into central China may have involved a selection of phenotypic traits adapted to the eastern boiling-and-steaming tradition (Liu et al., 2016). Furthermore, there is recent isotopic evidence for a very gradual pace of adoption of wheat and barley as a staple food in this part of China, and it has been suggested that such initial rejection may relate to the distinctive local food preparation practice (Liu & Reid, 2020; Liu et al., 2014). This resonates with the gradual adoption of millet as a new staple in the North Pontic region. So far, we know little of the set of artifacts and know-how that accompanied millet in the North Pontic region (e.g. for Greece, Valamoti, 2016). Biomolecular analyses of ceramic, stone and bone tools in combination with their typology (e.g. for Poland, Heron et al., 2016) may shed new light on millet adoption and its significance for prehistoric European societies, particularly when combined with the isotopic study of millet consumption from human groups. With the advantages of boiling and steaming over roasting, grinding and baking, would millet dishes have filled a gap in terms of culinary practice, for example enhancing children's weaning? Alternatively, was millet cooked differently in the West and the East? The role of millet in the diet of prehistoric societies in Europe could be refined, as could its role in foddering practices to increase animal products. In this regard, especially for the Late Bronze Age, a larger dataset of isotopic signals from domesticated animals and wild plants—as well as a multiproxy geoarchaeological and archaeobotanical study of animal dung, when available—would help our understanding of feeding habits. Finally, fuller comprehension of lifestyle and mobility would be aided by a systematic comparison of the information on seasonality obtained from faunal assemblages with that obtained from archaeobotanical assemblages.

Conclusions

The oldest known millet grains in the North Pontic region have been dated to the 17th–16th centuries BC and come from the site of Vinogradnyi Sad, belonging to the Sabatynivka Culture in southern Ukraine. In Sabatynivka and Noua sites, where living conditions indicate recurrent occupation of farmsteads alongside permanent villages, and both animal herding and agriculture are attested, millet appears sporadically for the first time, without playing an important role in the average human diet. Only later did millet become a staple cereal in the North Pontic region. In the Final Bronze Age, within the hillforts of the Belozerska culture, in the Iron Age with the Scythians, and further in the Hellenistic, Roman and Late Antique periods, until the Middle Ages, this crop has been attested in the steppe and forest-steppe regions of the North Pontic region. Especially in the mid 1st millennium AD, the several dates that we had coincide with the period of instability and incursions by the Getae, the Germanic and Slavic groups, and the Huns. Its adoption by different groups and under different socio-economic circumstances shows the flexibility and adaptability of millet in the North Pontic mosaic environment. Furthermore, millet was mostly in use within sites where other crops were also cultivated, implying a multifaceted and diverse cereal production, which was probably a good risk management strategy. Since the Bronze Age sites investigated are on riverbanks, where, in many cases, weeds, other cereals and crop-processing by-products were also present, local cultivation seems plausible. This challenges the association between the 'pastoral nomad' label usually applied to North Pontic people and a subsistence production focused solely on livestock. Overall, broomcorn millet—a highly versatile cereal, with low demands and high nutritional values—was an established element of the 'culinary identities' of the many communities that occupied this vast region in ancient and more recent times.

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Editor's Note For the sake of consistency, in-text citations have been standardized as follows: the romanization from Cyrillic of names of Ukrainian people and archaeological sites follows the Ukrainian official system for romanizing Ukrainian (National 2010) available at https://en.wikipedia.org/wiki/Romanization_of_Ukrainian; the romanization from Cyrillic of Russian names follows the common system for romanizing Russian (Passport (2013) ICAO), available at https://en.wikipedia.org/wiki/Romanization_of_Russian. However, because many authors have published in a range of Roman-alphabet languages, where transliteration rules differ from familiar English transliterations (as, notably, between Ukrainian or Russian transliterations into German or French), the bibliography, while consolidating authors' works into standard chronological sequence, also supplies the actual transliteration of the source publication. Finally, archaeological sites are given in their current transliteration for Ukraine and Russia (as above), but with alternative versions given in brackets where these may be historically more familiar to readers.

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