



# Locating Mesolithic Hunter-Gatherer Camps in the Carpathian Basin

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## Abstract

The Mesolithic in Eastern Europe was the last time that hunter-gatherer economies thrived there before the spread of agriculture in the second half of the seventh millennium BC. But the period, and the interactions between foragers and the first farmers, are poorly understood in the Carpathian Basin and surrounding areas because few sites are known, and even fewer have been excavated and published. How did site location differ between Mesolithic and Early Neolithic settlers? And where should we look for rare Mesolithic sites? Proximity analysis is seldom used for predictive modeling for hunter-gatherer sites at large scales, but in this paper, we argue that it can serve as an important starting point for prospection for rare and poorly understood sites. This study uses proximity analysis to provide quantitative landscape associations of known Mesolithic and Early Neolithic sites in the Carpathian Basin to show how Mesolithic people chose attributes of the landscape for camps, and how they differed from the farmers who later settled. We use elevation and slope, rivers, wetlands prior to the twentieth century, and the distribution of lithic raw materials foragers and farmers used for toolmaking to identify key proxies for preferred locations. We then build predictive models for the Mesolithic and Early Neolithic in the Pannonian region to highlight parts of the landscape that have relatively higher probabilities of having Mesolithic sites still undiscovered and contrast them with the settlement patterns of the first farmers in the area. We find that large parts of Pannonia conform to landforms preferred by Mesolithic foragers, but these areas have not been subject to investigation.

**Keywords** Mesolithic · Early Neolithic · Hunter-gatherers · Archaeological predictive model · Carpathian Basin · GIS

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## Introduction

The settlement of Europe by the first farmers drastically and permanently altered the floral and faunal composition of the landscape (Barker, 1985; Shennan, 2018). The impact on the indigenous residents of Europe, the hunter-gatherer populations of the Mesolithic, was equally dramatic. Yet in the Carpathian Basin, the gateway to the European interior, both the Mesolithic and the transitional period of overlap with the Early Neolithic settlers are still poorly understood (notable exceptions include Bonsall, 2008; Borić, 2011; Borić et al., 2018; Mathieson et al., 2018). Whether the first farmers essentially rolled into virtually uninhabited lands or shared several generations of exchanges and interactions with Mesolithic foragers is unknown by comparison with other parts of Europe where indigenous hunter-gatherers and their first interactions with Neolithic peoples have been studied (*e.g.*, among Ertebølle groups in Southern Scandinavia, Craig et al., 2011 and elsewhere: *e.g.*; Fischer, 1982; Rowley-Conwy, 2004; Vanmontfort, 2008; see papers in Whittle & Cummings, 2007). We share the recently expressed view that “the nature of the Mesolithic-Neolithic transition in southeastern Europe cannot be understood until there is sufficient archaeological evidence on the distribution and size of the local Mesolithic population” (Mihailović, 2021).

There are two important reasons why this transition is so poorly understood in the Carpathian Basin. First, except for the rich data from the Danube Gorges, we have not identified evidence of interactions between foragers and farmers in the Carpathian Basin outside of ancient DNA (Gamba et al., 2014; Mathieson et al., 2018). Second, we have not known where to look for areas of overlap between Mesolithic sites and Early Neolithic sites, nor have we generally tried to target Mesolithic sites in systematic surveys. This reticence partly stems from a weak grasp on the differences in site choice and contrasting settlement logics between Mesolithic peoples and the first farmers.

Pannonia in particular, defined by the alluvial basins of the Danube and the Tisza rivers and including modern Hungary and small sections of Serbia, Romania, Ukraine, and Slovakia, was a major platform where these interactions should be visible. In this paper, we address this imbalance and focus on the Mesolithic and transitional data required to understand how the advances of first farmers unfolded in southeastern Europe. Initially, using proximity analysis, we seek to build a profile of Mesolithic site locations in the Carpathian Basin, and in the Pannonian Region in particular (Verhagen, 2007). We then aim to highlight how Mesolithic and Early Neolithic site locations differed from each other in Pannonia and interpret those differences from an explicitly socioeconomic perspective. Finally, we confront the problem of how to carry out prospective survey for Mesolithic sites by mobilizing existing site data into predictive models (Kvamme, 1988a, 1988b; Verhagen, 2007). The basic predictive modeling used in this paper could be implemented in any part of the world, even those with no previous systematic survey, and low site counts over large areas.

We choose the Carpathian Basin as the extent of our study because it 1) forms a coherent geological and ecological system, despite great variation within it; 2)

contains enough sites to identify coherent patterning and statistical exploration; 3) has both areas of many known sites, and areas with similar characteristics with no known sites; and 4) has background hydrological data predating canalization efforts starting in the eighteenth century. We use natural features of the landscape such as rivers and wetlands that were important economic resources for Mesolithic foragers, and incorporate the locations of lithic raw material quarries, important resources for tool making, that may have played a role in determining camp location.

### What Is the Mesolithic?

Broadly defined, the Mesolithic is the time frame between the end of the Last Glaciation and the onset of food production and its expansion across Eurasia, ca. 9.7–3.4 ky BC. This long period in Europe was characterized by variable effects of deglaciation, resource availability, and human population density. While Mesolithic-Early Holocene hunter-gatherers in southwestern Asia, at the onset of food production, were actively engaged in domesticating plants and animals in the beginning of this process, hunter-gatherers in the Baltic regions only interacted with the descendants of these populations several thousand years later (Price, 2000).

The Carpathian Basin lies squarely between these two worlds and served as a route for the dispersal of farmers from the Near East to the European interior. Surrounded by the arcs of the Alps to the west, the Carpathian Mountains in the north and east, and the Dinaric Alpine mountain range in the south, the Carpathian Basin was one of few routes by which farmers moved into the continent, and indigenous foragers became immersed and enveloped by new lifeways.

There are Mesolithic radiocarbon dates from several corners of the Pannonian region (Gutay & Kerékgyártó, 2019; Marton et al., 2021; Živaljević et al., 2021; Whittle et al., 2002, 2005). The Mesolithic began in the Carpathian Basin ca. 9.7 ky BC at the beginning of the Holocene and persisted up until, and for some time after, the arrival of the farming and pottery using Starčevo-Körös-Criș material culture, a total of 4000 years (Eichmann et al., 2010). Without radiocarbon dating, Mesolithic sites are recognizable based on characteristic geometric and microlithic tool-types often found as surface scatters or in stratified contexts (*e.g.*, Kertész, 1996a). The Mesolithic is a crucial period in prehistory as it is both the last time in which the hunter-gatherer lifestyle dominated in Europe in the ecological context of interglacial climatic conditions, and the frame during which farming communities gradually moved across the landscape and practices changed. Although the ultimate consequences of the farmers' incursions into Europe are clear, the timing, frequencies, varieties of interactions during this process, and the ways in which forager lifestyles changed over time are murky in the Carpathian Basin because few sites are known on the landscape.

Mesolithic sites are small and compared to the first farming settlements of Europe, far less intensively researched. In the Carpathian Basin, the gateway to the European interior, the sparsity of Mesolithic sites preceding the earliest Neolithic has been variously attributed to lack of habitation for much of the Mesolithic (Biagi

& Spataro, 2002), patchy occupation (Zvelebil & Lillie, 2000), preservation and recovery bias (Chapman, 1989), and biased research coverage (Borić, 2005; Eichmann et al., 2010; Kozłowski, 2001). In the southern third of this area, in the northern Balkans, some researchers also point out that dense temperate forests covered much of the landscape during the Mesolithic and may not have been attractive as they would have been to Early Neolithic farmers (Gurova & Bonsall, 2014; Willis, 1994).

Several authors have suggested where to look for Mesolithic sites. David Clarke (1976) and John Chapman (1989) argued that sites should be found along the major rivers, though they expected most were covered in alluvium. Róbert Kertész observed in the Jászság region in northeastern Hungary the close proximity of multiple sites to subsidence basins, generally ancient wetlands or inundated areas (Kertész, 1996a). He also suggested we target alluvial fans, although he too thought the identification of sites towards the south of the Great Hungarian Plain would be more likely to be covered in alluvial deposits. There has been no systematic attempt to identify clear patterning in the location of Mesolithic sites however, and preliminary investigation of Mesolithic site depths below the surface suggests that assuming sites are mostly buried may be unwarranted.<sup>1</sup>

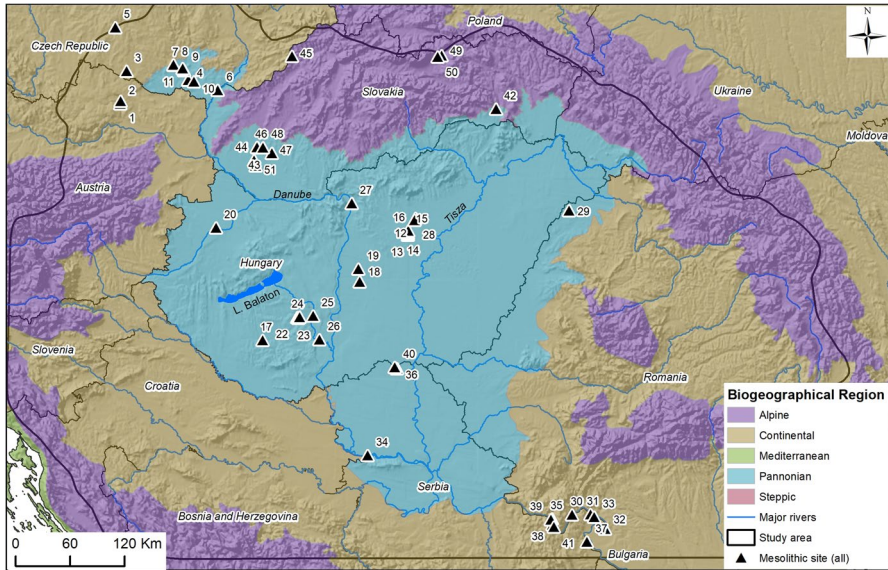
### The Environmental and Archaeological Context for the Mesolithic-Early Neolithic Transition

The known Mesolithic sites in the Carpathian Basin span across diverse biogeographies. The biogeography of the Carpathian Basin is dominated by Continental, Pannonian, and Alpine conditions and their modern extents and the distribution of sites in the study region are displayed within them in Fig. 1. For consistency across national boundaries, we used the European Environment Agency's definitions to outline the biogeography of the study region (EEA, 2009). Boundaries between major regions would have been similar relative to each other in the Early Holocene given the importance that elevation, major river locations, and proximity to the Mediterranean play in determining plant and animal communities.

The climate of the Alpine region is temperate in the north and Mediterranean in the south, with the zones distinguishable where low temperatures limit tree growth, generally over 600 masl in central Europe. Scrub and dwarf shrubs predominate in

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<sup>1</sup> Early Neolithic Körös sites are often only just below the ploughzone, ca. 40 cm (Makkay, 2007). Where studied in depth, Early Neolithic sites seem to be on high points in the (otherwise very flat) landscape, and likely escaped most alluviation (Gillings, 2007; Sümegi & Molnár, 2007). An opportunistic sample of deposit depths of Mesolithic and Early Neolithic material suggests that fears of deeply buried Mesolithic sites may be exaggerated, with Mesolithic ( $n=8$ ) deposits on average of 73 cm below the surface, but with a standard deviation of 64 cm. Six of the eight sites with depth data are 50 cm or less, generally within the ploughzone, and outliers such as Páli-Dombok and Szekszárd-Palánk clearly abut foothills that would generate high sedimentation. Early Neolithic ( $n=11$ ) deposits are on average 45 cm below the surface, but with a standard deviation of 8 cm (Online Resource 1). Both depths would be disturbed by modern plough agriculture which bring material to the surface and make the sites discoverable during survey.



**Fig. 1** Major biogeographical zones and extent of the study region. Site names are found in Table 1

these areas, with lower biodiversity than lower altitudes. The Continental region is crossed by Europe's large rivers, which played a significant role in forming the landscape and its biodiversity. The Continental region connects to most other biogeographical regions of Europe. The landscape is generally flat in the north, but hillier in the south, with huge floodplains flanking the Danube. The climate is continental, characterized by warm summers and cold winters, with rainfall abundant during summer, though there is less rainfall and temperatures are lower as one moves east.

The Pannonian region is dominated by the alluvial basins of the Danube and the Tisza, two major rivers that transect it. Weather patterns are a complex product of wet air coming from the west, the warmer winds from the Mediterranean, and the cooler temperatures of the Alpine regions. The result is a mosaic vegetation structure unlike those seen in most other zonal arrangements. The basin was once covered with large tracts of oak-dominated thermophilous forests and forest steppes, and vast areas of standing water over flat terrain creating shallow ephemeral marshes and lakes (see [Model Parameters section](#)).

Despite many similarities, several characteristics differentiate the ecology of the Carpathian Basin during the Mesolithic from that of today. The Mesolithic took place in the Early Holocene and was punctuated by several impactful climatic events (Rasmussen et al., 2014). Around 8 ky BC, the environment may have been a few degrees warmer than it is today, and a 'cold event' is identifiable in cores from Greenland at 7.3 ky BC (Magyari et al., 2012). The 6.2 ky BC event, another abrupt decrease of temperature that occurred for more than 200 years in the Northern Hemisphere, is the sharpest known episode of climatic change during the Holocene, and corresponded to an increase in moisture during winter and spring (Pál et al., 2016). It occurred immediately before the spread of farming economies into Europe, and

we know that it impacted the longevity of settlements and changed the regional settlement pattern in some regions of Europe (de Pablo & Jochim, 2010). There does not seem to be any significant drop in population or change in settlement patterns corresponding to climatic deteriorations in the Carpathian Basin, however. Several changes can be observed in trade patterns and mortuary customs of Mesolithic people over this time in intensively studied areas such as the Danube Gorges, but there are also remarkable continuities (Borić, 2011; Borić & Cristiani, 2022).

The environment in the Carpathian Basin during the Mesolithic was much more heavily vegetated than it is today. At the start of the Early Holocene (c. 9.7 ky BC), between the Alps and the Carpathians, the region comprised forest, forest steppe, and taiga environments (Feurdean et al., 2014; Sümegi & Náfrádi, 2015). At lower elevations in the Carpathian Basin, an increase in open woodlands of cold deciduous temperature species began ca. 9.7 ky BC, followed by a rapid increase in temperate forests at 9.3 ky BC, with a more open character, preserved until 6 ky BC (Feurdean et al., 2014; Gumnior & Stobbe, 2021; Járαι-Komlódi, 1987; Sümegi, 1999; Sümegi & Kertész, 2001; Willis et al., 1995, 1997, 1998). In the Romanian Banat, *Corylus*, *Tilia*, and *Quercus*, prevailed (Gumnior & Stobbe, 2021). From 8 ky BC, the river systems became much more stable than they had been in the terminal Pleistocene (Gyucha et al., 2011; Kiss et al., 2015).

Parallel to the changes in the environment, animal populations also changed; new species appeared to replace the extinct animals and the species that had migrated to other regions (Vörös, 1987). The consequences of the Early Holocene environment for the animal populations of the Mesolithic period are that the lower altitudes of the Carpathian Basin, comprising floodplains and terrasses, would have been rich with wildlife (Bartosiewicz et al., 1995, 2001, 2008; Borić, 2001, 2003; Borić et al., 2014). We especially see red deer, wild boar, roe deer, aurochs, and less frequently wild horse and bison, in the faunal assemblages, with most assemblages coming from sites near water features (Kertész, 2002).

Data from modern-day hunter-gatherers indicate that dependence on large game hunting increases residential and logistical mobility while the focus on aquatic resources invariably leads to low residential mobility, even though long logistical boat trips could easily be envisaged in the latter context (Kelly, 2013: 90, 95–96). While seasonal rounds could potentially include long distance movements, for most foragers, the maximum distance of 20–30 km round trips in a day would be the norm (Kelly, 2013: 97). Changes in diet breadth with climatic oscillations would be narrow (Miracle & O'Brien, 1998).

The most intensively researched area of the Carpathian Basin during the Mesolithic is in the Jászág region of northeastern Hungary and can provide an example of what we might expect to encounter with new sites. Sites occur in the flat subsidence basin of the Jászberény-Jászkóhalma-Alattyán area, on floodplain levees of the Late Pleistocene-Early Holocene Ancient Zagyva River and at the edges of flat banks close to former channels (Kertész, 1996a: 13). They fall within 90–92 m above sea level, and there are no marked high areas.

The Jászág sites are artifact scatters about 50×40 m in size, and only 10–15 cm thick directly beneath the topsoil on eroded levees (Kertész, 2002: 288). Pollen diagrams from nearby oxbows are suggestive of Mesolithic environments, showing

dominance of oak, elm, willow, and lime (Kertész, 1994). Green corridors in the river valleys and in the tectonic subsidences seem to have provided excellent conditions for settlement for Mesolithic groups. Their campsites are found on sand dunes of the aeolian loess-covered, Pleistocene alluvial fans and island-like, Late Pleistocene sand dunes (Kertész, 1996a: 8–13). Mesolithic hunter-gatherers benefited from the cut-off channels and oxbows with marshland and lush vegetation even in the dry summer months. The waters here had fish, molluscs, and waterfowl, and the gallery woods and meadows were rich in herbivore mammals and fur animals. The smaller ridges above the marshland provided attractive camping sites (Kertész, 1996a: 13).

Other sites in the vicinity, such as those at Pásztó-Mária tanya, suggest Mesolithic foragers also flocked to areas near the open hydro- and limnoquartzite sources in the Northern Mountain Range and the river valleys connecting these two regions (Simán, 1993: 248, Fig. 1.7). The dominant raw material is 25–50 km away in the Mátra Mountains. Settlement locations in more intensively investigated areas, while not necessarily representative, provide a more detailed picture of what Mesolithic camps can look like in the Carpathian Basin.

A research initiative started in the early 2000s by Róbert Kertész, William J. Eichmann, and Tibor Marton focused on the reevaluation of existing finds and field surveys in Transdanubia. This research led to the discovery of an important concentration of sites in southeastern Transdanubia in the valleys of the Kapos and Koppány Rivers, near the villages of Kaposhomok and Regöly (Eichmann et al., 2010; Marton et al., 2021) (Fig. 1, Table 1). While most of the sites are determined as surface scatters of ca. 100 x 70 m, at the site of Regöly 2, systematic excavations brought to light an undisturbed Mesolithic layer with the remains of a slightly sunken dwelling feature with a circular ground plan that was 4 m in diameter, circled by regularly spaced postholes (Marton et al., 2021: 9), that in shape and size resembles the remains of a similar dwelling structure excavated at Jásztelek I in northeastern Hungary (Kertész, 1996a: 19–22; Kertész, 2002).

Excavations were also recently conducted in northwestern Hungary in the Rába River alluvial plain at the site of Páli-Dombok. Here, within an active gravel quarry, a very likely Mesolithic lithic industry almost exclusively made from radiolarite raw material originating in the Bakony Mountains was discovered in blackish-gray palaeosol (Mester et al., 2014, 2015). Recent excavations were also conducted at the site of Erk-1 in the Tarna River Valley, at a distance of 400 m from the current river course. The site of ca. 50 x 50 m, and the 2015 excavations yielded flint artefacts within several pedological horizons. A canid tooth provisionally dates this assemblage to the Early Mesolithic, 8545–8285 cal BC at 95 percent confidence (DeA-7424: 9171 ± 46 BP) (Gutay et al., 2016).

Traces of Mesolithic material culture in the form of unilateral barbed points, as an important *fossile directeur* of some confirmed Mesolithic localities in southeastern Europe (e.g., Borić and Cristiani, 2016), are chance finds from the localities of Csór–Merítőpuszta and Nádasdladány in Sárrét. These two specimens are very similar on typo-morphological grounds (Marton et al., 2021: Fig. 2). The barbed point from Nádasdladány has been directly AMS-dated to 9155–8640 cal BC at 95 percent confidence (Poz-25427: 9520 ± 60 BP), falling into the Early Mesolithic time span (Kaczanowska and Kozłowski, 2014).

The locations settled by the first farmers arriving in the Carpathian Basin have been much better studied (Chapman, 2010; de Vareilles et al., 2022; Gillings, 2007; Sherratt, 1980; van Andel & Runnels, 1995). The earliest radiocarbon dated settlements are found along the major arteries of movement, the Tisza and Danube rivers, and this surely reflects the initial path of migration into the area (Whittle et al., 2002; Fig. 2). Micro-regional studies indicate that early farmers preferred natural ridges in wetland areas, high and dry points in otherwise very wet environments (Gillings, 2007). The catchments of these sites were certainly dynamic but were probably not as susceptible to overbank river flooding as traditionally believed (Frolking, 2021; Gyucha et al., 2011). In addition to the economic resources afforded by the oxbows and temporary lakes nearby, there is also recent evidence that it was not chernozem soils in particular that early farmers were targeting when initially settling in the Carpathian Basin, but instead soils broadly comprised of hydromorphic soil compositions (Kempf, 2021). While we have general expectations regarding how Mesolithic and Early Neolithic site location choice differed, no proximity investigation has ever taken place.

## Methods

We carry out proximity analysis of Mesolithic site location at two scales: the Carpathian Basin and the Pannonian region. Within the Pannonian region, we analyze spatial associations of Early Neolithic sites as well, and contrast precisely where and why these sites are placed on the landscape. For both datasets at this scale, we also produce predictive models of site location to guide future work.

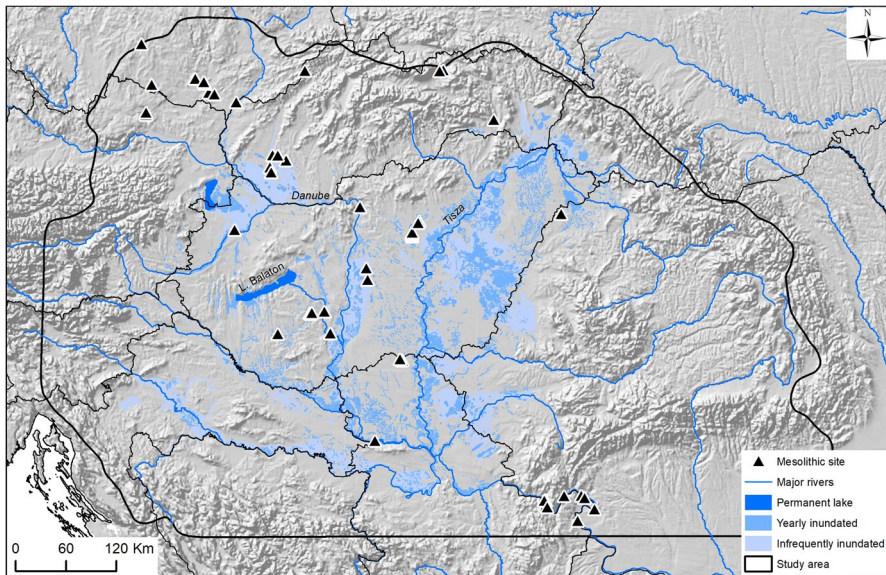


Fig. 2 Hydrology in the study region



## Predictive Modeling in Archaeology

Predictive modeling in archaeology predicts where archaeological sites will be found in a region based either on a site sample of that region (“inductive” or “correlative” modeling) or on fundamental assumptions concerning human behaviour (“deductive” modeling) (Kohler & Parker, 1986; Kvamme, 2006). Despite the pitfalls of archaeological predictive models (henceforth APMs)—such as incomplete archaeological datasets, biased selection of environmental parameters, and the underuse of cultural data in favor of readily available geographic data (Ebert, 2000)—many archaeologists still support this method (Wheatley & Gillings, 2002; Yaworsky et al., 2020). Archaeologists’ ability to model site location grew astronomically once geographic information systems (GIS) became widespread, especially within the cultural resource management industry (Brandt et al., 1992; Lock & Harris, 2006; Stančić & Veljanovski, 2000; Verhagen, 2007; Wescott & Brandon, 2000). Modeling increasingly enjoys greater methodological sophistication due to our ability to test the reliability of our models (Kvamme, 2006; Yaworsky et al., 2020).

For this study, we adopt a combination of inductive and deductive modelling. We (deductively) choose parameters for analysis (*e.g.*, proximity to raw materials and hydrological features) suspected on theoretical grounds of being important in the decision-making process of Mesolithic foragers. The extent to which these parameters are important is unknown however, so we (inductively) rely on the distribution of parameter values in site data, and our understanding of these data, to create decision rules for predictive model construction. Specifically, we employ an unweighted additive map using decision-rules to produce site probability landscapes for the Pannonian region of the Carpathian Basin, a large area of southeastern Europe (Dalla Bona, 2000; Deeben et al., 1997; Kohler & Parker, 1986: 424; Wescott & Kuiper, 2000). It is admittedly a very large area, but modeling is always limited by the data sets available (Verhagen & Whitley, 2012: 89–90).

Associations between patterns in the natural environment and the distribution of hunter-gatherer archaeological features are well established (*e.g.*, Jochim, 1981). Despite between-site variability, we would expect all foraging systems to include camps with special use areas, field camps, logistical stations, and caches as different parts of an annual mobility circuit that responds to the particulars of that cultural landscape (Binford, 1982). We include analysis of five environmental parameters and one technologically specific parameter to build our models: biogeographical zone, elevation, slope, distance to rivers and lakes, distance to inundated areas, and distance to lithic raw material sources used in the Mesolithic. We break the distribution of values in these parameters into groups and assign them values using decision rules. We then assess the utility of the outcome based on the precision and efficacy of the predictions (Kvamme, 1988a).

While we would like to measure the predictive error of the maps using logistic or linear regression techniques, no training samples are available in this region. That is, archaeologists have not carried out systematic surveys for Mesolithic sites in the Carpathian Basin, and we have no true negative data where areas have been surveyed and identified to be “non-sites,” a prerequisite for statistical analysis like regression techniques (Kvamme, 1988b; Warren & Asch, 2000). Instead, we have

large areas with no known sites (but where no one has looked). Even without measuring error, new sites do get discovered using APMs, and for this reason the inherent problems still make the approach worthwhile (Verhagen, 2007). In this paper, we build a multi-criteria model in Model Builder in ArcGIS 10.5, with additional analysis performed in R. The resulting products are generalized site probability maps useful as a starting point for more detailed modeling and survey.

## Site Database

There are compilations of Mesolithic sites in the Carpathian Basin at the general (Krauß, 2016), national (Dobosi, 1975; Kaminská, 2014; Oliva, 2016; Vértes, 1965), and regional levels (Biró, 2002a, 2002b; Eichmann et al., 2010; Kertész, 1996a, 2002). We have made use of these sources, the primary sources, and unpublished data from the Hungarian National archives to confirm locations and authenticity of Mesolithic assemblages (HNMAD, 2021). There are more known Mesolithic sites in the Carpathian Basin than we include here, but the locational data and publication quality are variable, sometimes only locatable within 2 to 3 km. For our model, we use sites with spatial coordinates we could verify as accurate to at least 500 m (Table 1). We only use open-air sites, as the locations of caves and rockshelters cannot be modeled on the landscape like elevation or proximity to water because of the idiosyncratic processes regulating their development (Kvamme, 1983: 68).

The Early Neolithic site database we use here ( $n=658$ ) is restricted to the Pannonian region, and we list them in the Online Resource 3 along with the results from the analysis. The database includes most known sites from Vojvodina in Serbia and the Romanian Banat (including sites from Luca et al., 2011; Porčić et al., 2021; Vander Linden & Silva, 2021) and includes all sites in Hungary found in the National Hungarian Museum database. Precise location coordinates for Hungarian sites are not listed in keeping with Hungarian law (HNMAD, 2021).

## Model Parameters

We determined the extent of the Carpathian Basin using the World Resources Institute's Major Watersheds of the World Delineation, produced by the Food and Agriculture Organization (FAO) of the United Nations (WRI, 2006). Within this zone, we included only the area for which we have pre-regulation hydrological data specifying the extent of inundated areas.

## Elevation and Slope

Elevation and slope are frequently used in predictive models as they in part determine the biotic environment available for early hunter-gatherers. Site elevation is available from the Shuttle Radar Topography Mission (SRTM), and slope can be derived from these data in ArcGIS. Published site elevations are rare, so SRTM data are often used when not available (Hauck et al., 2018). The resolution of the data is ca. 30 m per pixel in central and eastern Europe in Version 3 SRTM (2013).

## Rivers

Excavation data indicate that major rivers, small rivers, and tributaries were important areas for Mesolithic camps. River valleys were extremely important corridors of movement and migration. Rivers were sources of protein (including fish, turtles, waterfowl, mussels, and snails) and drinking water for land mammals, and provided foraging areas of dense river plants, seeds, and fruit (e.g., Clarke, 1976). We use European river data generated from the MARS geodatabase (Globevnik et al., 2017; Lyche Solheim et al., 2019). The classification consists of two “top-down” generalized hydrological classifications of all Europe’s rivers based on altitude, size, and basin geology which correct the artificial modifications of the hydrology carried starting in the eighteenth century. Forager camps likely benefited from access to rivers of different size classes, and the confluences they create, so these were separated for analysis. We use the 12-class typology and simplify it further by catchment size into three classes (Table 2). River Class 1, for example, would be a major source of large fish (like sturgeon, cf. Bartosiewicz et al., 2008). Close proximity to Class 1 rivers would suggest reliance on aquatic resources for over 25 percent of their diet, and would require investment in specialized fishing gear, hence costly with possibly smaller territories. River Class 3 would include much smaller freshwater fish but greater quantities of birds, freshwater mussel shells, plant foods and terrestrial game, hence the expectation would be of significantly less than 25 percent of aquatic resources in diet and less costly investment in the fishing technology with possibly larger hunter-gatherer territories (cf. Kelly, 2013:45–46).

## Inundated Areas

Access to wetlands was certainly important for Early Neolithic farmers, who disproportionately settled in the marshes of what is now the Körös region of the eastern Carpathian Basin (Kempf, 2021; Kosse, 1979). For wetlands and seasonally inundated areas, we use a model for the entire basin produced by the Hungarian Ministry of Agriculture in the earlier part of the twentieth century (HIRHMA, 1938). It shows the inundated areas of the Carpathian Basin before Habsburg engineers drained swamps and built levees and canals starting in the eighteenth century and is an important hydrological record relevant to pre-modern Holocene hydrology. We use two classes of data from the map in the analysis—yearly inundated, and infrequently inundated (Fig. 2, Online Resources 7). Only two shapes on the map are classified as permanent lakes in this dataset, Lake Balaton and Lake Fertő in Hungary—they were not included in the analysis, nor were a few other possible permanent lakes described in the literature for the earliest Holocene (Sümegei et al., 2008). A georeferenced color raster map was converted to polygons using band analysis in ArcGIS, and manually corrected. Comparison with other data sources indicates that the spatial error for this dataset is usually less than 1 km, and few areas with sites had this much error. This background map also defines the extent of our study within the Carpathian Basin.

**Table 1** Mesolithic sites included in the study. Latitude, longitude, the precision of coordinates, and results of the analysis are provided in the Online Resource 2

Country	Map ID	Site	Context	C14	Fauna
Austria	1	Kamegg (Berg and Gulder 1956; Nutz 2006)	Stratigraphic		
Austria	2	Mühlfeld bei Horn (Gulder 1953; Weiser 1980)	Surface		
Czech Republic	3	Bítov (Kaputška, pers. comm.)	Surface		
Czech Republic	4	Dolní Věstonice IV – Na pískách (Klíma, 1953; Oliva, 2016; Verpoorte, 2000)	Surface		
Czech Republic	5	Mikulčice (Klíma, 1953; Oliva, 2016)	Surface		
Czech Republic	6	Kostelec u Jihlavy (Kaputška, pers. comm.)	Surface		
Czech Republic	7	Moravský krumlov XI – Krumlovský les (Kaputška, pers. comm.)	Stratigraphic	X	
Czech Republic	8	Moravský krumlov XII – Krumlovský les (Kaputška, pers. comm.)	Stratigraphic	X	
Czech Republic	9	Přibice III (Oliva, 2016; Valoch, 1975)	Surface		
Czech Republic	10	Šakvice Na Toufance, Břlé břehy (Klíma, 1953; Oliva, 2016)	Surface		
Czech Republic	11	Smolín (Valoch, 1963, 1978, 1989)	Stratigraphic	X	X
Hungary	12	Erk-1 (Gutay & Kerékgyártó, 2019; Gutay et al., 2016)	Stratigraphic	X	X
Hungary	13	Jászberény I (Kertész, 1996a)	Stratigraphic	X	X
Hungary	14	Jászberény II (HN MAD, 2021; Kertész, 1996a)	Surface		
Hungary	15	Jászberény IV (HN MAD, 2021; Kertész, 1996a, 1996b)	Surface		
Hungary	16	Jásztelek I (HN MAD, 2021; Kertész, 1996a)	Stratigraphic		
Hungary	17	Kaposhomok (Marton, 2003; Pusztai, 1957)	Surface		
Hungary	18	Kunadacs-Köztemető (Horváth, 1983a, 1985a)	Stratigraphic		
Hungary	19	Kunpeszér-Felsőszéri út-Homokbánya (Horváth, 1983b, 1985b, 1985c)	Stratigraphic		
Hungary	20	Páli-Dombok (HN MAD, 2021; Mester et al., 2013)	Stratigraphic		
Hungary	21	Regöly 1 (Marton, et al., 2021)	Surface		
Hungary	22	Regöly 2 (Eichmann et al., 2010; HN MAD, 2021)	Stratigraphic		
Hungary	23	Regöly 5 (Marton et al., 2021)	Surface		
Hungary	24	Regöly 9 (Marton et al., 2021)	Surface		
Hungary	25	Sárszentlőrinc 1 (Marton et al., 2021)	Surface		
Hungary	26	Szekszárd-Palánk (Gábori, 1968; HN MAD, 2021; Kertész & Demeter, 2011; Vértes, 1962)	Stratigraphic	X	

Table 1 (continued)

Country	Map ID	Site	Context	C14	Fauna
Hungary	27	Sződliget 1954/1967 (Gábori, 1968) <sup>9</sup>	Stratigraphic		
Hungary	28	Tarnaörs Fodor-tanya (HN MAD, 2021; Kertész, 2005)	Stratigraphic		
Romania	29	Ciumești II (Pămescu, 1964, 1970, 2001)	Stratigraphic		
Romania	30	Icoana (Bonsall et al., 2015)	Stratigraphic	X	X
Romania	31	Ostrovl Banului (Dinu et al., 2007)	Stratigraphic	X	
Romania	32	Ostrovl Corbului (Dinu et al., 2007)	Stratigraphic	X	X
Romania	33	Schela Ciadovei (Bartosiewicz et al., 1995, 2001; Bonsall, 2015)	Stratigraphic	X	X
Serbia	34	Bačka Palanka (Brukner, 1966)	Surface		
Serbia	35	Hajdučka Vodenica (Borić 2011; Borić & Miracle, 2004; Jovanović, 2008)	Stratigraphic	X	X
Serbia	36	Hajdukovo, Nosa-Peres (Berta, 2017; Brukner, 1966)	Surface		
Serbia	37	Kula (Borić, 2011)	Stratigraphic	X	X
Serbia	38	Lepenski Vir (Bonsall, 2015; Borić, 2011, 2019a)	Stratigraphic	X	X
Serbia	39	Padina-Gospodin Vir (Borić, 2011; Jovanović, 2008)	Stratigraphic	X	X
Serbia	40	Talánterem (Berta, 2017)	Surface		
Serbia	41	Vlasac (Borić, 2011; Borić et al., 2014)	Stratigraphic	X	X
Slovakia	42	Barca I (Bárta, 1972, 1980; Némegut, pers. comm.; Prošek, 1959)	Stratigraphic		
Slovakia	43	Dolná Streda (Bárta, 1965)	Stratigraphic		
Slovakia	44	Mostová (Bárta, 1960)	?		
Slovakia	45	Sedmerovec-Podjamie (Cheben et al., 2017)	Stratigraphic		
Slovakia	46	Sereď (Bárta, 1957, 1972; Némegut, pers. comm.)	Stratigraphic	X	
Slovakia	47	Sládeckovoce (Némegut, pers. comm.)	?		
Slovakia	48	Šoporča-Štrkovec (Némegut, pers. comm.)	?		
Slovakia	49	Spíská Belá-Hoher Rand (Valde-Nowak & Soják, 2010)	Stratigraphic		
Slovakia	50	Spíská Belá-Vyšná zákruť II (Valde-Nowak & Soják, 2010)	Stratigraphic		
Slovakia	51	Tomášikovo (Bárta, 1955, 1957; Némegut, pers. comm.)	?		

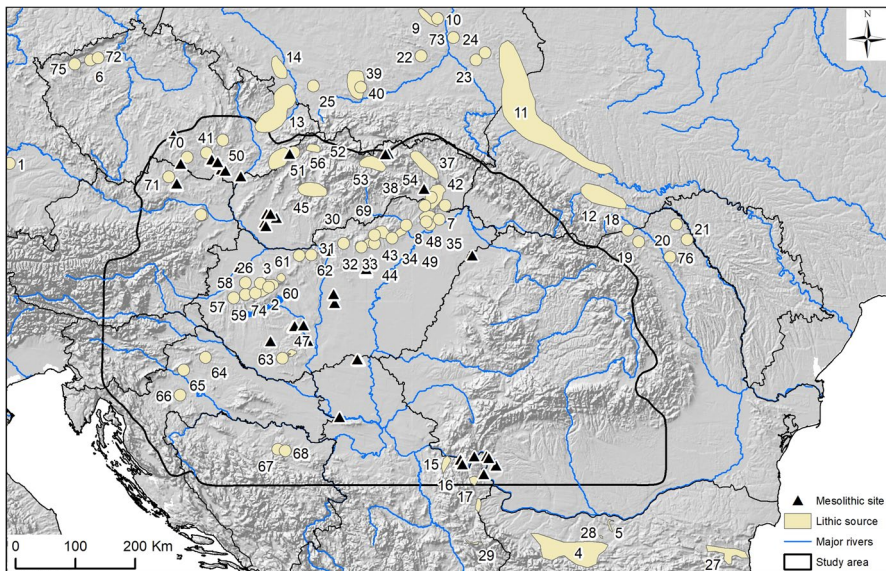
**Table 2** River classifications used in the study

Type	Full description	Size only	Catchment	River class
RT1	Very large rivers	Very large	> 10,000 km <sup>2</sup>	1
RT2	Lowland, calcareous or mixed, medium-large	Medium-large	100–10,000 km <sup>2</sup>	2
RT3	Lowland, calcareous or mixed, very small–small	Very small–small	< 100 km <sup>2</sup>	3
RT4	Lowland, siliceous incl organic, medium-large	Medium-large	100–10,000 km <sup>2</sup>	2
RT5	Lowland, siliceous incl organic, very small–small	Very small–small	< 100 km <sup>2</sup>	3
RT6	Mid-altitude, calcareous, incl. organic, medium-large	Medium-large	100–10,000 km <sup>2</sup>	2
RT7	Mid-altitude, calcareous or mixed, very small–small	Very small–small	< 100 km <sup>2</sup>	3
RT8	Mid-altitude, siliceous incl organic, medium-large	Medium-large	100–10,000 km <sup>2</sup>	2
RT9	Mid-altitude, siliceous incl organic, very small–small	Very small–small	< 100 km <sup>2</sup>	3
RT10	Highland and glacial	Other		4
RT11	Mediterranean perennial	Other		4
RT12	Mediterranean temporary and very small	Temporary and very small		5

## Lithic Raw Material

The locations of lithic raw material sources used by Mesolithic peoples have been identified at various levels of precision (Bárta, 1972, 1989; Biagi, 2015; Biró, 2011; Biró et al., 2009; Cheben et al., 2017; Dinan, 1996a, 1996b; Eichmann et al., 2010; Gutay & Kerékgyártó, 2019; Kaminská, 2013, 2014; Kertész, 1993, 1994, 1996a, 2005; Kertész & Demeter, 2011; Kozłowski, 2013; Kozłowski & Kozłowski, 1982, 1983; Kraus, 2011; Leitner, 1984; Marton, 2003; Mateiciucová, 2008; Mester & Faragó, 2016; Mester et al., 2013; Mihailović, 2004; Nutz, 2006; Prošek, 1959; Rácz, 2012; Radovanović, 1981; Šarić, 2008; Szekszárdi et al., 2010; Szilágzi et al., 2020; Valde-Nowak, 2010; Valde-Nowak & Soják, 2010). The raw materials included here derive from publications specifying raw material present in Mesolithic site assemblages in our study area (Online Resource 4). Map depictions of sources are described as specific outcrops following the contours of geological members in precise cases and are described as single point sources (with a pin marker) in others. We used specific geological outcrops when possible, generalized polygons when not available, and circles of 20 km in diameter when only point markers have been published (Online Resource 5, 7). Raw material identifications such as calcedony, jasper, and spongolite are too ambiguous to assign to specific categories of raw material and are excluded.

Though not exhaustive, Fig. 3 displays the principal sources of lithic raw material in the Carpathian Basin found in Mesolithic archeological assemblages in this area. We provide a distance analysis of sites to sources, but for simplicity do not discriminate between sources. We use this same sample for the Early Neolithic, as



**Fig. 3** Principal locations of lithic raw material used for Mesolithic stone tool manufacture in the Carpathian Basin. For numerical key, see Online Resource 5

people used similar sources (Starnini, 2001) even though distances involved in raw material transfers in different periods might have differed significantly (*e.g.*, Gurova et al., 2016).

## Results

### Distribution of Sites in the Carpathian Basin

The majority (69%) of the sites in the sample are found in the Pannonian region, with Continental (25%) and Alpine (6%) regions in far lower numbers. Alpine sites are found in Slovakia, the Pannonian sites are in Hungary and southern Moravia, and Continental sites fall in Serbia, Romania, and Czech Republic (Table 3).

The landscape data associated with Mesolithic at the Carpathian Basin and Pannonian scales are presented Table 4, as are the Early Neolithic data for the Pannonian region. We provide summary statistics and the data partitioned into three quantiles with a density histogram (grey) (Fig. 4), overlaid with the background distribution of the same area for comparison generated by a million random points (clear). The distribution of elevation data deviates from the background in having a higher proportion of settlement at lower elevations, though Slovakian sites, and the Czech and Austrian sites, are noticeable deviations in the right tail. Slope of sites on the

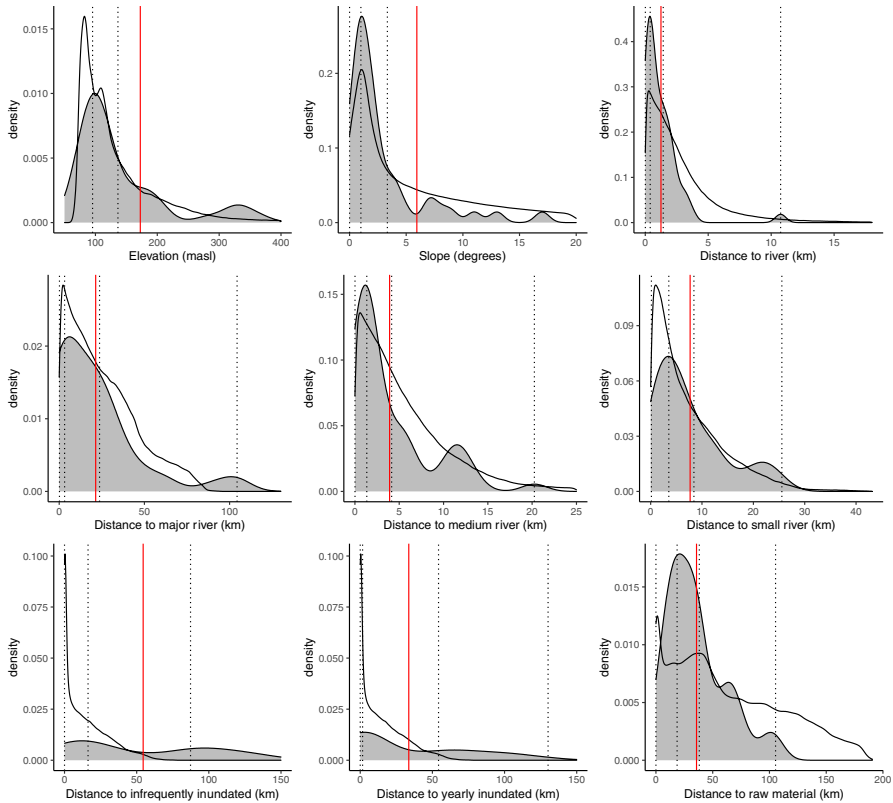
**Table 3** Mesolithic site distribution by environmental region

Region	Area (km <sup>2</sup> )	Area %	No. of sites
Alpine	113,956.968	25	3
Continental	194,900.586	43	13
Pannonian	148,821.9894	32	35
	457,929.2753	100	51

**Table 4** Parameter values for the samples in the Carpathian Basin and Pannonian region

Parameter	Carpathian Basin Mesolithic		Pannonian Mesolithic		Pannonian Early Neolithic	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
Elevation (masl)	172.45	161.57	108.46	26.3	85.40	14.20
Slope (slope)	5.94	21.32	1.71	1.5	0.99	1.01
Distance to River (km)	1.25	1.66	1.56	2.02	3.17	2.98
Distance to River Class 1 (km)	21.4	25.27	19	14.4	12.96	14.00
Distance to River Class 2 (km)	3.92	4.59	3.35	4.7	6.00	4.71
Distance to River Class 3 (km)	7.79	6.99	11.02	7.71	10.11	6.71
Distance to inundated area (km)	32.78	44.44	0.6	1.1	0.55	1.70
Distance to inundated infrequently (km)	54.49	49.68	13.78	13.67	3.28	6.42
Distance to inundated yearly (km)	33.61	40.83	2.12	2.98	0.90	1.83
Distance to lithic raw material (km)	35.72	25.97	48.36	27.2	106.48	30.79





**Fig. 4** Variable data associated with Mesolithic sites in Carpathian Basin. The grey curve represents the site distribution and the clear curve represents the random point distribution. Mean values are in red and 33.3% quantiles are dotted

landscape follows a similar pattern, with slopes distributed across all three biogeographical regions. Naturally, the Pannonian sites have the lowest slopes, given the overall grade of this large region. The highest slope of occupation is in the Danube Gorges area of Serbia and Romania, where sites are positioned on steep banks adjacent to the river.

We calculated distance to rivers for individual river size classes as well as the aggregated river dataset. Although cost-distance (including for example, slope) would be more effective than Euclidean distance, we do not pursue cost-distance analysis because we do not model at the scale of the Carpathian Basin. Euclidean distances are measured from site centroids to river polyline, and since both site extent and river channel vary in size, the true distance is always somewhat less than calculated (typically ca. 50 m less). The general river data has the narrowest range with virtually all sites under 4 km to water, with a mean value of 1.25 km. There seems to be a preference for proximity to medium sized rivers, but the differences are not substantial.

We calculate distance to different river types separately as they offer different resources and advantages and we present the distance to inundated areas with yearly and infrequently inundated areas separated as they represent different conditions.

At this scale, distance to yearly and infrequently inundated areas is broadly distributed across the background range, with disproportionately low proximity to these areas. Given that wetland areas are concentrated at lower elevations, and the mean elevation for sites in the Carpathian Basin is relatively high (172 masl), the pattern above all illustrates the broad distribution of sites outside the lowest parts of the basin. At higher resolution however, close proximity to ancient rivers and infrequently inundated wetlands seems to be especially important in some areas, such as on the left bank of the Danube near Sered in Slovakia (Fig. 5).

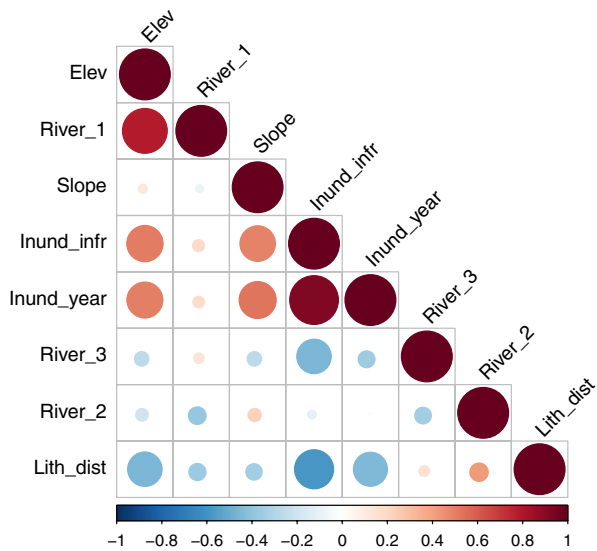
Distance to lithic raw material has a mean of 35.72 km. With some exceptions (such as the upper Tisza in Hungary and the micro-region around Zagreb), inundated areas and lithic raw material sources generally do not co-occur in close proximity.

Two sets of parameter values in the Mesolithic sites database are correlated: elevation and major rivers (River 1), and areas inundated yearly and infrequently (Inund\_infr and Inund\_year) (Fig. 6). The correlation of site distances to both yearly and infrequently inundated areas is not particularly surprising, as these two areas are spatially autocorrelated—infrequently inundated areas are often just extensions of the yearly flooded areas during particularly wet years. The positive correlation between elevation and larger rivers is less intuitive, as it comes despite the cluster of sites at lower elevations in the Danube Gorges. This likely indicates that the Danube Gorges cluster is an anomaly and an unusual feature of the Mesolithic landscape.



**Fig. 5** Site cluster with proximity to rivers and infrequently inundated areas near Sered, Slovakia. Background imagery from the Hungarian Ministry of Agriculture (HIRHMA, 1938)

**Fig. 6** Correlation matrix of variable values for sites



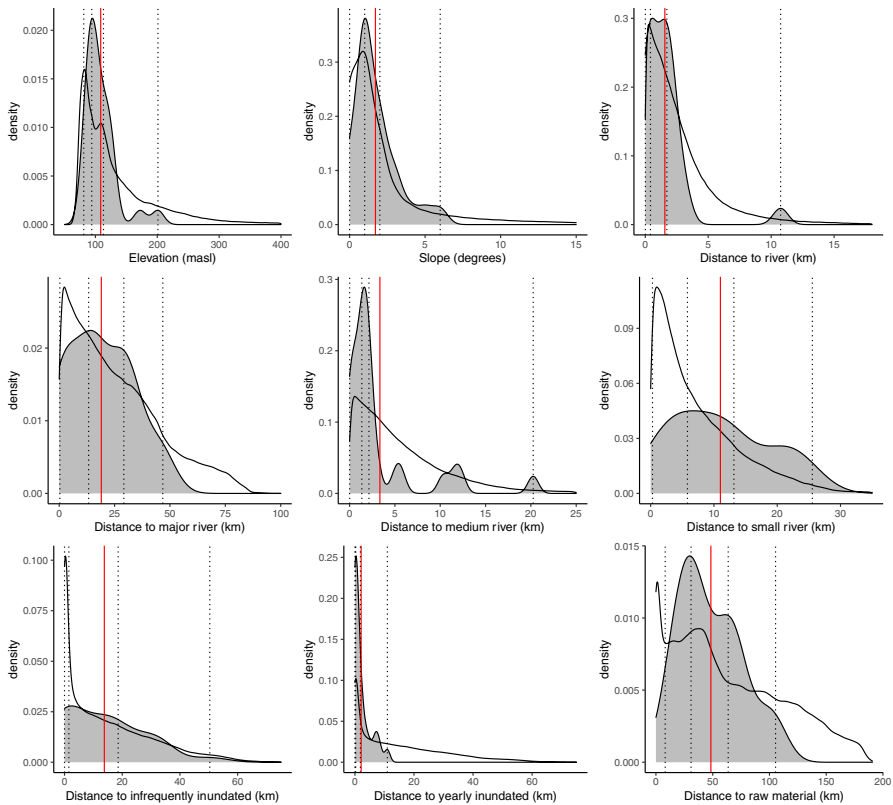
From a methodological perspective, auto-correlation is not so important to the deductive model outcomes here as it would be in a fully inductive model.

In sum, the visual analysis of site locations in the Carpathian Basin suggests preference for lower elevations and slopes, proximity to any class of river, and proximity to raw material zones. The broad distribution of sites across multiple biogeographical zones however, most clearly visible in the distance to wetlands, is surely lumping together very different forager adaptations and site types (Kohler & Parker, 1986: 406).

### Distribution of Mesolithic Sites in the Pannonian Region

We chose a sub-section of the Carpathian Basin, the Pannonian region, to reduce the environmental variability used in generating a predictive model and reduce the number of adaptations and site types lumped in the sample. We excluded the Czech constellation of sites in Moravia, which exhibit different spatial patterning from those at lower elevations. The parameter data for the Pannonian region alone are displayed in Fig. 7.

Several patterns emerge that are quite at odds with the aggregated data at the scale of the Carpathian Basin. Firstly, site elevation is higher than a random distribution, now that the Carpathian Mountains, and most of the foothills, are excluded. Site slope has a more restricted range with the Danube Gorges and mountainous sites pulled out but is not otherwise appreciably different from the Carpathian Basin scale. Distance to any kind of river is also similar at both scales. The details of river sizes do vary more at this scale, however. Distance to medium-sized river is much higher than the expectations from the random sample, illustrating clear preference to be closer. The patterning with greater distances to major rivers and smaller rivers may be a product of this choice, although the possibility of other modes in the tail



**Fig. 7** Pannonian region parameter distributions. The grey curve represents the site distribution and the clear curve represents the random point distribution

of the medium river distance distribution problematizes this interpretation. Distance to wetlands also differ appreciably from both the random sample and the scale of the Carpathian Basin. Where the Carpathian Basin scale conflates many site niches at varying distance to wetlands, distance to predictable yearly inundated areas in Pannonia is very tightly bound to site location, just over 2 km on average. Finally, the shape of the distance to raw material distributions are not very different between the two scales, but the mean is, with 36 km average rather than 48 km in Pannonia alone. This is a consequence of situating oneself in Pannonia, a sedimentary basin with raw material outcrops only near the fringes of the region (Table 5).

### Distribution of Early Neolithic Sites in the Pannonian Region and Contrast with the Mesolithic

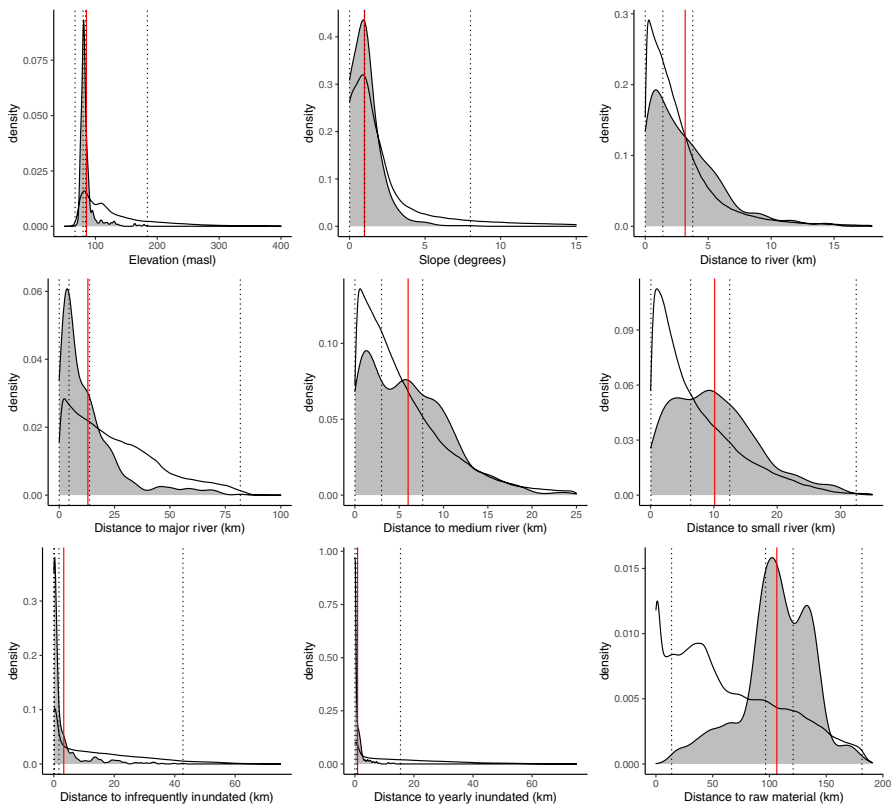
The locational data of the Earlier Neolithic site sample (with cultural taxonomic units identified as Starčevo, Körös, and Criş) differ in several respects from the Mesolithic sample—the distributions for the former are displayed in Fig. 8. The

**Table 5** Data and decision-rules for Mesolithic sites in the Pannonian region

Parameter	High probability	Low probability	Mean	Std dev
Elevation (masl)	85–129	< 86 and > 128	108.46	26.3
Slope (degree)	0–3	> 3	1.71	1.5
Distance to River Class 2 (km)	< 2.5	> 2.5	3.35	4.7
Distance to inundated yearly (km)	< 1.9	> 1.9	2.12	2.98
Distance to lithic raw material (km)	< 106	> 106	48.36	27.2

significance of these differences listed in Table 6 is even more informative. Nine of ten variables show significance below  $p < 0.05$ .

The elevation and slope ranges are much more restricted in the Early Neolithic, and overall lower, than those of the Mesolithic. Distance to river is not so constrained in the Early Neolithic. Rather than preference for medium sized rivers found



**Fig. 8** Pannonian region parameter distributions for Early Neolithic sites. The grey curve represents the site distribution and the clear curve represents the random point distribution

**Table 6** Results of significance for the two sample Mann–Whitney *U*-test (Early Neolithic,  $n = 658$ , Mesolithic,  $n = 28$ )

Variable	<i>statistic</i>	<i>p</i>
Elevation (masl)	1983	1.71E-12
Slope (degree)	6302.5	0.00215
Distance to river	12,887	0.000372
Distance to River Class 1 (km)	6892	0.0233
Distance to River Class 2 (km)	12,868.5	0.000399
Distance to River Class 3 (km)	8713.5	0.619
Distance to inundated area (km)	7408	0.0462
Distance to inundated infrequently (km)	5452.5	0.00022
Distance to inundated yearly (km)	6824	0.0169
Distance to lithic raw material (km)	16,759	2.42E-13

in the Mesolithic, there is a greater tendency to be closer to major rivers in the Early Neolithic (average 13 vs 19 km in the Mesolithic). Aggregated distance to yearly and infrequently inundated areas falls just under the  $p < 0.05$  threshold, and the differences are even greater when separated, with Mesolithic sites averaging 2.12 km from yearly inundated areas, and Early Neolithic sites averaging 0.9 km. There is also a significant difference between the two periods with respect to distance to raw material sources, with the Mesolithic averaging 48 km and the Early Neolithic averaging 106 km.

### Discussion of Location Choice in the Mesolithic and Early Neolithic

Mesolithic people often lived at higher altitudes in Pannonia, choosing foothills of the Carpathian Basin that bordered on the plains. These areas (such as Sered and Jászág regions) represented transitional zones from more mountainous ecozones to flatter landscapes rich in wetland areas, and Mesolithic sites often seem to have avoided the interior of the Great Hungarian Plain. This may indicate that it is rather catchments of locations, rather than individual attribute values, that were selected for. In other words, elevation may only have been a stand-in for sets of attributes (Kohler & Parker, 1986: 407–8).

In contrast with foragers, Early Neolithic farmers came from the south and south-east, stayed in low elevations, and did not extend outside of the flattest and wettest parts of the Carpathian Basin. The lower elevations characteristic of these sites are more likely to be a byproduct of other choices than elevation standing as a proxy for length of growing season. These major rivers were central arteries of migration and other scales of mobility and would have been the launching points for daughter communities (Whittle et al., 2002). Once having left the arteries of the Tisza and Danube, proximity to rivers may not have been as important to early farmers as it was for foragers as they sought primarily farming in rich wetlands such as the Körös region. The standing water typical of vast marshlands such as the “Nagy Sárrét” (“Big Mud Meadow”) in Békés county would not have drinking water year-round,

so well digging could have been part of the farming lifestyle that was not found among Mesolithic foragers.

The preference of Mesolithic foragers to be near active river channels of moderate size surely stems from a wide range of foraging opportunities from waterfront mollusk gathering to large game hunting (Kertész, 2002: 284), as illustrated in the faunal assemblages at the Jászberény sites, though this attribute is partly a function of elevation and may also just be a proxy for desirable forager catchments.

The way in which farmers could be so close to wetlands without suffering from inundation of their settlements is often in choosing relic paleochannels (many dating to the Pleistocene) that are higher than the wetlands around them, yet only occasionally connected to active stream channels (Gillings, 2007; Gyucha et al., 2011). Relative elevation in wet areas was demonstrably important for settlement not only in the Neolithic, but also in later periods (Duffy, 2014: 234–258; Gillings, 2007). Proximity to predictable yearly wetlands was twice the distance for Mesolithic foragers (2.1 km rather than 0.9 km), and questions remain as to how differently these areas might have been exploited by these different groups. When the first farmers settled on the high natural levees of marshy areas, they would have certainly cleared some of the existing vegetation before house building (Magyari et al., 2012: 29–291). Reed harvesting would be an important activity every few years to maintain houses, and marshes provided a rich source of thatching. Trees for building material would still be common, only succumbing to felling pressure and environmental change towards the Middle Neolithic.

Differences in distance to raw materials are also significant. Although not the case at the very beginning, one can imagine down-the-line trade in raw materials being more efficient for early farmers than for Mesolithic hunter-gatherers. Even if Mesolithic populations were large, the density and connectivity between Early Neolithic settlements as they expanded from the Balkans would be substantial, possibly making movement of raw materials more predictable and reliable. This idea is consistent with abundant evidence of long distance transfers of certain raw materials across the central Balkans and the Carpathian Basin, such as the proliferation of the so-called Balkan yellow white-spotted flint with sources in northern Bulgarian around Nikopol (Gurova & Bonsall, 2014; Biagi and Starnini, 2010).

The core result of these differences is that despite overlap, Early Neolithic sites and Mesolithic sites are not likely to be found in survey using the same predictive model. Even when Mesolithic and Early Neolithic sites are found in the same micro-region (*e.g.*, Ludaš Lake, Berta, 2017), the location of Early Neolithic sites is not a good predictor of Mesolithic site location, and vice versa. This necessitates creating different decision-rules to generate different predictive models, which we pursue in the next section.

## Predictive Modeling of Sites in the Pannonian Region

We generated several models, varying the inclusion and thresholds of different parameters to minimize the percentage of the map predicted to have high relative density scores and maximize the percent of sites in our sample that occurred in this

high relative density area. We assessed the performance of each model by calculating Kvamme's Gain, a commonly used measure to quantify the improvement of a model in predicting site location compared to a random selection of points from the same map (Kvamme, 1988a). The equation is broadly:

$$G = 1 - (Pa/Ps)$$

where  $G$  is the gain statistic,  $Pa$  is the area of high relative density in the study area divided by the total study area, and  $Ps$  is the number of sites in the high relative density area divided by the total number of sites.

Gibson (2005) suggests that a "good working model" should have at least 70% of all sites in no more than 10% of the area, resulting in a Kvamme's Gain statistic of 0.86 or more, which is a "very high standard of performance" by expert accounts (Verhagen, 2007: 135). But gains of 0.5–0.7 are common for archaeological models in the archaeological literature, and by reducing the area a higher gain can be achieved, as larger proportions of the site sample become excluded. By expanding the area included, the proportion of sites included will also grow, but the gain will fall. We therefore discuss two different gain statistics for each model, and the advantages and disadvantages of them.

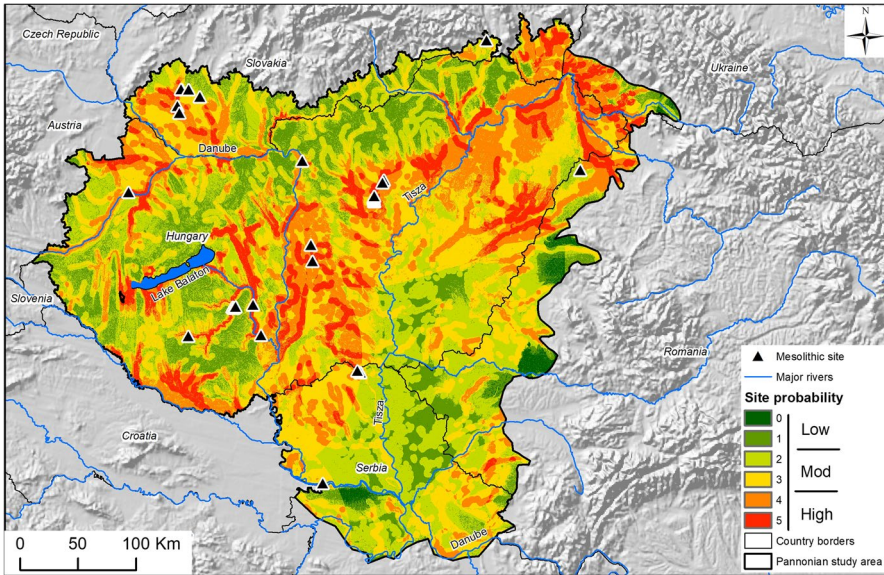
We mark the thresholds of each parameter into a binary high/low judgement based on observation of the data in each class. Of the variables, we include distributions that have some predictive power and allow us to exclude area from the model to achieve a high gain but also must be justifiable based on our understanding of hunter-gatherer behaviour. For rivers, we include medium-sized rivers because there appears to be active proximity selection. Moreover, when variables have broad distributions, such as "distance to small river" (Fig. 7), little is gained by adding them to the model because any distance within 25 km is as good as any other, and these distributions may indicate that several different selective behaviours are included in the range. It would be possible to include the full range (25 km), but to do so does not eliminate any areas in the model not already excluded by other parameter decision rules.

We include the full range for distance to raw material however, because this does allow exclusion of certain areas, which may be deemed "too far away from raw materials," even though the range within it likely also combines different landscape selection behaviors (such as lithic procurement and reduction sites, and sites "far down-the-line." Proximity to yearly inundated area is included because it strongly differs from the random sample and is clearly selected in Pannonia.

The decision rules involved in each chosen parameter threshold received a score of 1 or 0. For example, if a site is found within the lowest third of distance to inundated yearly (within 1.9 km) the parameter received a score of 1 for this parameter. If the site is also within the cut-off for slope (0–3 degrees), it receives another 1 point. The resulting predictive model has map scores out of 5 and is found in Fig. 9.

For this map, the highest relative density score (5) is only 8% of the total area, and 39% of the sites are classified as being in a high probability area. This makes for a Kvamme's gain of 0.78, which is a good working model for an area this size (145,891 km<sup>2</sup>). If we include relative density scores 4–5, our model includes 29% of the total area, but 71% of the sites in the sample, and achieves a gain of 0.59. This is





**Fig. 9** Predictive model for Mesolithic sites in the Pannonian region

a less precise map but may do a better job at highlighting areas profitable for survey, as it includes information from a larger proportion of the input sites.

To build a predictive model for the Early Neolithic, we again used parameters that deviated substantially from the random control sample and created decision-rules using thresholds that would achieve as high a gain as possible. Elevation, slope, proximity to major river, proximity to yearly inundated, and distance to raw material all met the criteria. Creating decision-rules nonetheless proved difficult for the Early Neolithic sample because the values for these parameters are more continuous. The decision rules of the predictive model for the Early Neolithic are presented in Table 7, and illustrated in Fig. 10, a notable contrast with the Mesolithic map.

For the resulting predictive model, the highest relative density score (5) is 6% of the total area, but only 36% of the sites are classified as being in the highest probability area. This makes for a Kvamme's gain of 0.82, which is a high gain and a precise map, but excludes two thirds of the Early Neolithic sites. If we include values 4–5, we end up with a model encapsulating 18% of the landscape, but now includes

**Table 7** Data and decision-rules for Early Neolithic sites in the Pannonian region

Parameter	High probability	Low probability	Mean	Std Dev
Elevation (masl)	70–90	< 70 and > 90	85.40	14.20
Slope (degree)	0–2	> 2	0.99	1.01
Distance to River Class 1 (km)	< 10	> 10	12.96	14.00
Distance to inundated yearly (km)	< 0.93	> 0.93	0.90	1.83
Distance to lithic raw material (km)	< 140	> 140	106.48	30.79

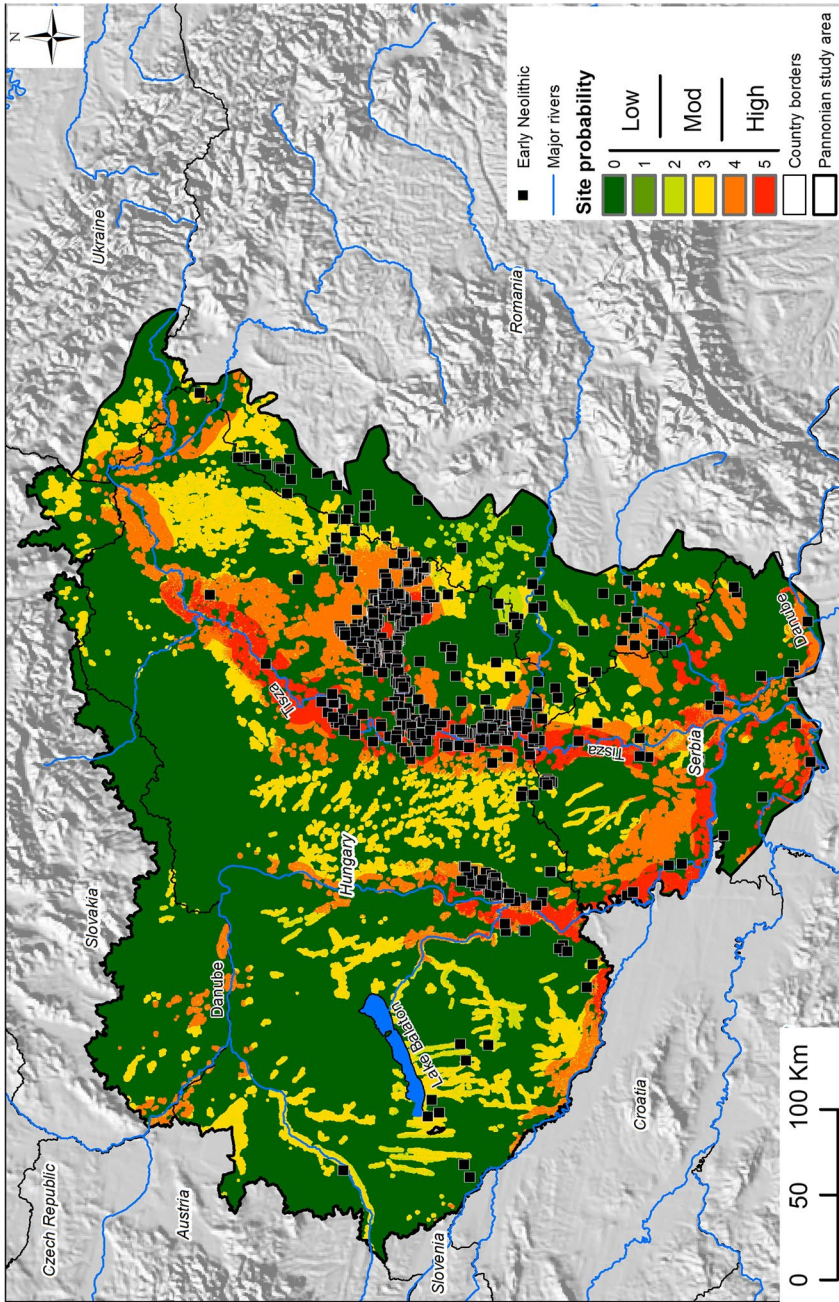


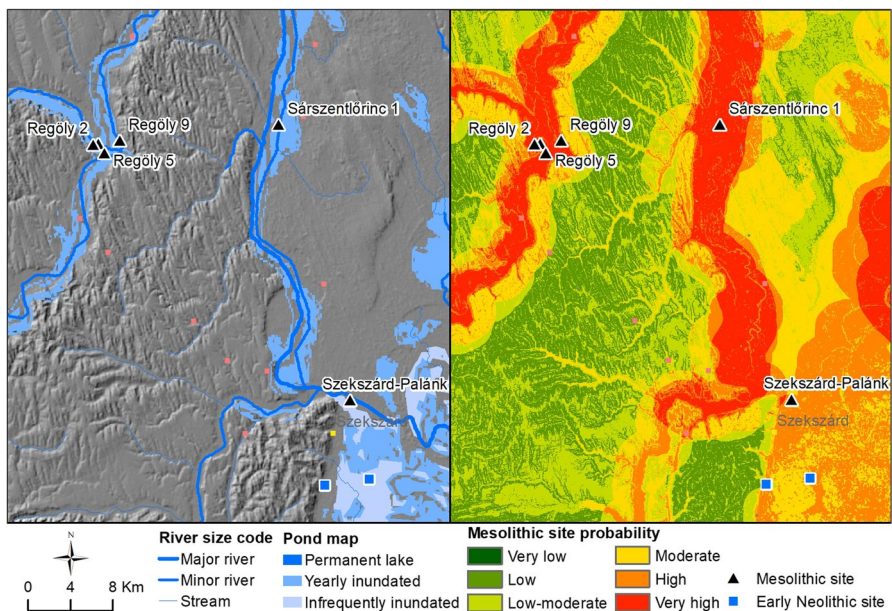
Fig. 10 Predictive model for Early Neolithic sites in Pannonic region

65% of the sites, and a gain of 0.72. This second model, while producing a lower gain, better reflects the broad characteristics of the site sample.

There are several reasons why we may not be able to achieve a high gain with a larger percentage of the site samples. One possibility is that the parameters are not independent enough from each other. Another is that there are not enough variables included to discriminate against more of the landscape. Finally, and certainly contributing noise in both models, is the conflation of sites that are different from one another in important ways. We know little about most of the Mesolithic sites in this sample as most of them are surface finds, and it is likely that they date across thousands of years during which conditions and adaptations would have changed. It is also likely that we are lumping together base camps, logistical stations, and raw material procurement sites, which would naturally be found on different parts of the landscape. The Early Neolithic sample includes Körös, Starčevo, and Criş culture sites, which, being broadly contemporaneous, do have some chronological and regional differences in adaptation and lifestyle (Luca et al., 2011; Oross & Siklósi, 2012; Whittle et al., 2002).

Several areas of greater interest regarding Mesolithic sites emerge, and the actual resolution of the model becomes clearer with the presentation of close-ups. We present one such area of Transdanubia in Fig. 11.

In Transdanubia, the Regöly sites are known from more recent investigations (Eichmann et al., 2010; Marton et al., 2021), and are far from Early Neolithic sites. In the adjacent river system however, at Sárszentlőrinc 1, potsherds certainly dating from the Early Neolithic Starčevo culture were found in the vicinity of typical



**Fig. 11** A Transdanubian closeup. Municipalities of different sizes are illustrated by orange and yellow dots to guide the reader, and larger urban centers are labelled

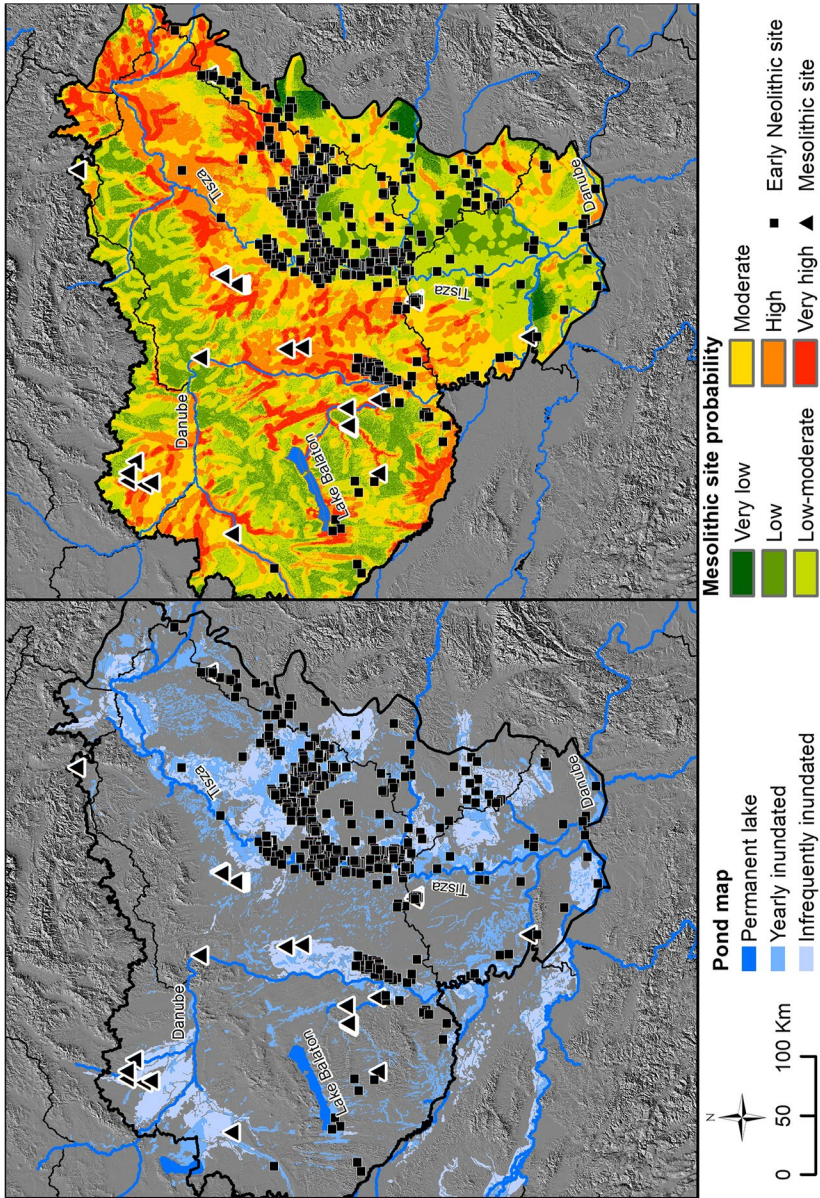


Fig. 12 Side-by-side comparison of Mesolithic and Early Neolithic site locations in the Pannonian study region, hydrology on the left, and Mesolithic predictive map on the right. Early Neolithic sites are found in low lying marshy areas not preferred by Mesolithic foragers

Mesolithic chipped stone artefact types (Eichmann et al., 2010; Marton et al., 2021). Szekszárd-Palánk has been published for sixty years (Vértes, 1962), and has several sites within a ten-km radius—the area is potentially rich in further Mesolithic finds according to the predictive map. Further work in the Szekszárd area could be of value from the perspective of studying hunter-gatherer-first farmer interactions. They are areas of rapidly changing ecozones as one moves across the landscape, going from flat, swampy areas near to major rivers, to slightly higher areas prioritizing access to medium sized rivers closer to raw material sources. In Online Resource 6, we highlight additional areas of potential interest, including the Jászág and Sered regions, known areas of Mesolithic activity, but also the Kaposhomok and Hajdu-kovo regions, which each have Mesolithic sites known from surface collection, but seem to be good regional candidates for systematic survey.

## Discussion

The landscape associations of Mesolithic and Early Neolithic sites paint two different pictures of the kinds of lands sought by ancient people between 8 and 6 ka BC. These result from different routes of incursion and different uses of the landscape. Mesolithic sites are the harder of the two site types to find, so we plot locations of Mesolithic and Early Neolithic sites over the Mesolithic predictive map in Fig. 12 to illustrate these differences. Although there are broad similarities between the two—for example, in being close to marshland and settling in flat areas—it is clear that Early Neolithic farmers settled in areas least preferred by Mesolithic foragers, though dates obtained on human remains at the Early Neolithic site of Maroslele-Pana and others indicate occasional presence of Mesolithic-age material on Early Neolithic sites in the region (Borić, 2005; Whittle et al., 2002, 2005; Živaljević et al., 2021).

Searching for evidence of temporal overlap between the last foragers and first farmers, and identifying interactions between them, would nonetheless take us to parts of the Carpathian Basin where there is clearer spatial overlap in settlement patterns, even though so far it seems as though almost exclusively Early Mesolithic dates have been obtained in the Carpathian Basin with little evidence of temporal overlap with the first Neolithic farmer occupations. At least at lower elevations, this could result from more severe erosional events during the later part of the Mesolithic. Such a scenario has been suggested based on the results of a systematic archaeological survey combined with geomorphological observations and radiocarbon dating of soil organic matter samples on exposed riverbank sections in the area downstream from the Danube Gorges along the Danube River between Radujevac and Prahovo. The results of these investigations suggested that while lower parts of the soil deposits dating to the period between  $12,710 \pm 70$  cal BC and  $9670 \pm 70$  cal BC at 68 percent confidence, *i.e.*, covering the duration of the Early Mesolithic, were preserved, the bulk of the deposits dated to the Late Mesolithic/Early Neolithic periods was lacking from these riverbank sections (Radovanović et al., 2014).

There has been some discussion suggesting that Mesolithic populations were so rare in certain areas of the Balkans in the late Pleistocene and early Holocene,

that we should not expect to encounter many sites (Gurova & Bonsall, 2014). We argue that any perceived rarity of Mesolithic sites could easily result from differing landscape usage between Mesolithic foragers and Early Neolithic farmers, and that researchers have not sufficiently targeted areas most sought by hunter-gatherers. In this paper, we have identified key differences in how Mesolithic and Early Neolithic (Starčevo, Körös, and Criş) peoples used the landscape, and generated predictive models as a starting point for the recursive process of field survey and model refinement.

As with ecologists answering similar questions about the plausible distribution of modern plant and animal species in unknown areas (Guisan & Zimmermann, 2000), archaeologists can use APMs for prospection. Yet since the 1980s, despite its demonstrated effectiveness in helping archaeologists discover new sites, continued methodological refinement, and the consistent loss of sites to development and destruction, predictive modeling has become unfashionable outside of cultural resource management in government agencies (Harris et al., 2015). Nonetheless, because of the apparent rarity of Mesolithic sites on the landscape, and their importance in understanding Early Holocene forager adaptations as well as the subsequent transition to agriculture in Europe, there is a substantial need to refine and reduce the search area in which they might be found, especially before we conclude that there are unlikely many out there to find (Mihailović, 2021: 8).

Although there is room for further refinement of these models, and even the addition of more parameters, what seems equally important is to begin targeting areas in the model for field survey (Banning, 2002; Kvamme, 1988a; Verhagen, 2007). This is a more costly and time intensive task than computer modeling but is ultimately required to advance our knowledge about Mesolithic site distribution in the Carpathian Basin and fine-tune the predictive models to be more effective. Even where known Mesolithic site numbers start out with very small numbers, as they did in southwestern Germany in the latter part of the twentieth century, targeted, and sustained, systematic survey dramatically changed this picture several decades later (Jochim, 2006). We anticipate this will also be the case in the Carpathian Basin. Besides Lake Balaton and Lake Fertő, there are no large lakes like those of southwestern Germany that attracted foragers, but the Carpathian Basin was rich in mid-sized rivers and wetlands before river regulations, which may have served a similar purpose.

In Pannonia, in areas of known Mesolithic sites, systematic gridded surface collection is extremely useful for targeting of areas for excavation (Gutay & Kerékgyártó, 2019). But site discovery based on knowledge from a small initial sample requires a birds-eye approach rather than intensive collection, moving from the known to the unknown. Fortunately, the process of predictive modeling is recursive, and involves modeling, field survey, updating of model assumptions, and further modeling. When applied to a micro-region such as those presented here, the process can become very fine tuned and effective at discovering new sites, especially when combined with Bayesian modeling. In survey carried out in Jordan, for example, model assumptions were updated every evening based on results from that day and generated new models and directives for where to survey next. Coupled with field walking calibration runs tailored to individual surveyors, the recovery of Mesolithic

finds in the absence of ceramics is much more likely (Banning & Hitchings, 2015; Banning et al., 2011).

While in this article we focused on the Carpathian Basin as a regional unit of analysis, the identified problems related to the visibility of Mesolithic open-air sites are endemic throughout southeastern Europe as a whole. Only some limited areas, such as certain parts of Albania (Runnels et al., 2004, 2009), Greece (Runnels & van Andel, 2003; Runnels et al., 2005), and Istria (Balbo et al., 2004), have seen targeted surveys in search of open-air forager sites, with variable success. Similarly, only recent targeted surveys enabled the location of first Epipalaeolithic and Mesolithic forager settlements, for instance, in the Karaburun Peninsula (Çilingiroğlu et al., 2020) and Bozburun Peninsula (Atakuman et al., 2020) of coastal western Turkey. Even in karstic areas of southeastern Europe where only caves and rockshelter sediments have so far yielded data on human occupation during the early Holocene (Borić et al., 2019, 2021; Forenbaheer et al., 2020; Galanidou, 2011; Hauck et al., 2017; Komšo, 2006; Mlekuž et al., 2008), it remains a priority to discover open-air sites in order to properly understand forager settlement patterns and the importance of ecological, climatic, and other changes that over the long term affected these forager groups. Hence, future predictive modelling and better understanding of potentially eroded and buried landscape surfaces of southeastern Europe with a methodology advocated in this paper can be applied further afield.

## Conclusion

The spatial analyses and predictive models provided here accomplish two broad tasks. First, they demonstrate the range of variability in key environmental variables that would have been important for Mesolithic foragers. The variables explored, while primarily environmental rather than cultural, indicate that parameters like distance to fresh water and slope of landscape were important enough for all Mesolithic camps that working predictive models can be built at scales as large as the Pannonian region for these mobile human populations. For Early Neolithic populations, the legacy of migration and perhaps higher degrees of overall mobility (c.f. Borić & Price, 2013) along major rivers, and their preference for vast swaths of wetlands and hydromorphic soils distinguish their site locations from any Mesolithic people who were present when they arrived and began expanding across the landscape. When combined with more detailed understandings of their ecological associations, we might eventually provide site typologies for comparison with forager toolkits, diet, and the mobility seen in strontium isotope data and aDNA, but more intensive work needs to be done on Mesolithic sites before this is a possibility. These areas of high probability are crucial to investigate before archaeologists accept the suggestion that foragers were rare prior to the first farmers, whether due to forest density, depopulation, or even the lack of raw material in loess plains (Krauß, 2016: 196). When the digitized hydrology of the inundated areas is overlaid with the Mesolithic site distribution, it becomes clear that there were more wetland areas in the northern and even central Balkans than some authors have considered. The predictive maps make clear that many of the conditions favoured by foragers in Hungary and Slovakia, for

example, are also found in Serbia and Romania, just across the border. This work can therefore serve as a call to action to those focused on the study of Early Holocene adaptations of last foragers and first farmers in southeastern Europe and provide a blueprint that might be productive for further research.

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## Declarations

**Conflict of Interest** The authors declare no competing interests.

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