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Neolithic land-use, landscape development, and environmental dynamics in the Carpathian Basin

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ABSTRACT

Holocene environmental dynamics and the onset of early subsistence farming during the Neolithic period have led to major surface modification and landscape transformation in the Carpathian Basin. In this context, Neolithic settlements and agricultural activities were supposed to be located on Chernozem soil patches, which originated from loess-covered surfaces of the uneroded Pleistocene and early Holocene palaeolevees. Chernozem soil distribution is seen as an important precondition of agricultural expansion. However, Chernozem soil genesis and the anthropogenic modification of soil organic matter and Black Carbon (BC) content from clearing and vegetation burning are not yet fully understood and there is increasing evidence for the active role of human landscape interaction in the process of Chernozem development. Consequently, Neolithic land-use would not have been necessarily linked to Chernozem but rather triggered its development from alluvial and meadow soils through intensified surface transformation. This article applies a GIS-based multivariate surface analysis and a statistical evaluation to 49 Neolithic sites to track environmental location factors, soil preferences, and potential land-use strategies in Neolithic Hungary. The combination of remotely sensed surface data, environmental GIS-attributes, quantitative statistics, and archaeological datasets reveals site-location parameters during the Early to the Late Neolithic and critically discusses Chernozem soil development and utilization during agricultural transformations across Europe.

1. Introduction

Various interdisciplinary studies on Early to Late Neolithic mobility and migration, land-use, and settlement development have been carried out recently, which result in detailed knowledge about cultural and social processes in prehistoric Hungary (Domboróczki and Raczky, 2010; Giblin et al., 2013; Gronenborn, 1999; Haak et al., 2005; Salisbury, 2013; Whittle, 2007). The rapid spread of early farming techniques and the uniformity of the archaeological material culture (Bánffy, 2019; Bille and Sørensen, 2019; Bonsall et al., 2002) indicate intense mobility, communication, and exchange patterns on a considerable short-term temporal scale (Bánffy, 2019; Haak et al., 2015; Szécsényi-Nagy et al., 2015). In that period, an early domestic subsistence economy and a highly diverse mosaic of permanent settlements and transient camps on loess-covered areas and in close connection to running fresh water has been assumed (Hedges et al., 2013; Sielmann, 1972; Whittle, 2007).

This Neolithic landscape, however, developed from dynamic riverbed fluctuations and annual flooding, which created a mosaic landscape pattern characterized by backswamps and non-permanent oxbow lakes in reactivated Holocene palaeochannels (Gillings, 1995, 2007). So-called avulsion events (abandonment of the established river channel in favor of a new channel in the adjacent floodplain (Heyvaert and an and Walstra, 2016)), which occurred prior to the transformation of the anastomosing river system, frequently led to the establishment of new channel systems. Eventually, the palaeolevees remained uneroded after the stabilization of the run-off behavior and the development of a meandering streamflow character (Magyari, 2011). In this setting, the former palaeochannels were still periodically flooded during heavy rainfall events, which triggered the deposition of fine-grained clayey material and the subsequent formation of waterlogged soils that reinforced the flooding vulnerability and the development of oxbow-shaped wetlands and swamps. It is highly debatable, whether these soils were agriculturally exploited or if we lack traces because human activity is

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buried under the alluvial deposits (Sherratt, 1983). Alternatively, continuous occupation of the elevated loess-covered areas with thick and fertile Chernozem coverage has been assumed (Garnett, 1945; Hedges et al., 2013; Kreuz, 2007; Sielmann, 1972). Recently, however, Eckmeier et al. (2007) emphasized that buried Neolithic soils do not necessarily need to be connected to *in situ* developed fertile Chernozem soils but can carry a significant amount of charred material with up to 70% total organic carbon – a soil-charcoal mixture that gives the impression of a relict Chernozem soil (Acksel et al., 2017; Eckmeier et al., 2007; Schmidt et al., 1999; Schmidt and Noack, 2000). This raises the question to what extent thick and fertile Chernozems were already developed in the Neolithic or if their development was connected to local steppe vegetation, forest coverage, climate oscillation, and human surface modification, land-use, and deforestation activities (Barczi et al., 2006; Gerlach and Eckmeier, 2012; Lorz and Saile, 2011; Preston and Schmidt, 2006; Schmidt et al., 1999; Schmidt and Noack, 2000; Starling, 1983; Strouhalová et al., 2019; Vysloužilová et al., 2015).

This article addresses multi-layered environmental surface data to estimate Holocene landscape development and the impact of Neolithic surface modifications on soil development in Hungary (Fig. 1). A comprehensive understanding of ecological and palaeo-environmental feedbacks supports the hypothesis that fertile and extensive Chernozem coverage could be strongly connected to Neolithic agricultural exploitation, forest clearing, and vegetation change.

2. Material and methods

The sample, which is used in this article is based on the database of the research project *Population history of the Carpathian Basin in the Neolithic Age and its influence on settlement in Central Europe,* which was funded by the German Research Foundation (DFG, grant number Al 287/10–1) and led by Eszter Bánffy and Kurt Alt. Through the integration of various methods from archaeology, anthropology, molecular genetics, and biogeochemistry, it was possible to visualize the structure and dynamics of settlement processes and population development in the Carpathian Basin in their spatio-temporal depth (Bánffy, 2019; Haak et al., 2015; Lipson et al., 2017; Mathieson et al., 2015; Szécsényi-Nagy, 2015; Szécsényi-Nagy et al., 2015). One sub-study focused on strontium and oxygen isotope analyses led on Neolithic populations to track past human mobility patterns (Depaermentier et al., 2020a, 2020b). It covers the Hungarian part of the Carpathian Basin and is based on the same sample that has already been used for nitrogen and carbon stable isotope as well as aDNA analyses (Szécsényi-Nagy, 2015; Szécsényi-Nagy et al., 2015). In this context, a comprehensive Holocene landscape evaluation was carried out to address site location hypothesis and potential land-use strategies in relation to strontium and oxygen stable isotope analysis in the Carpathian Basin (Depaermentier et al. 2020). Consequently, this paper includes 49 Neolithic sites, which were also investigated for mobility patterns on the site-specific to the micro-regional scale (Depaermentier et al., 2020; Kempf et al., 2020) (see Fig. 1 and Table 1. for location and chronological periods).

2.1. Archaeological sites

The western part of the Carpathian Basin played a major role in Europe during the Neolithic period. Transdanubia and the southern lowlands were the most northerly distribution area of the so-called *Starčevo-Körös-Criş* cultural complex (see Table 1). In the central part

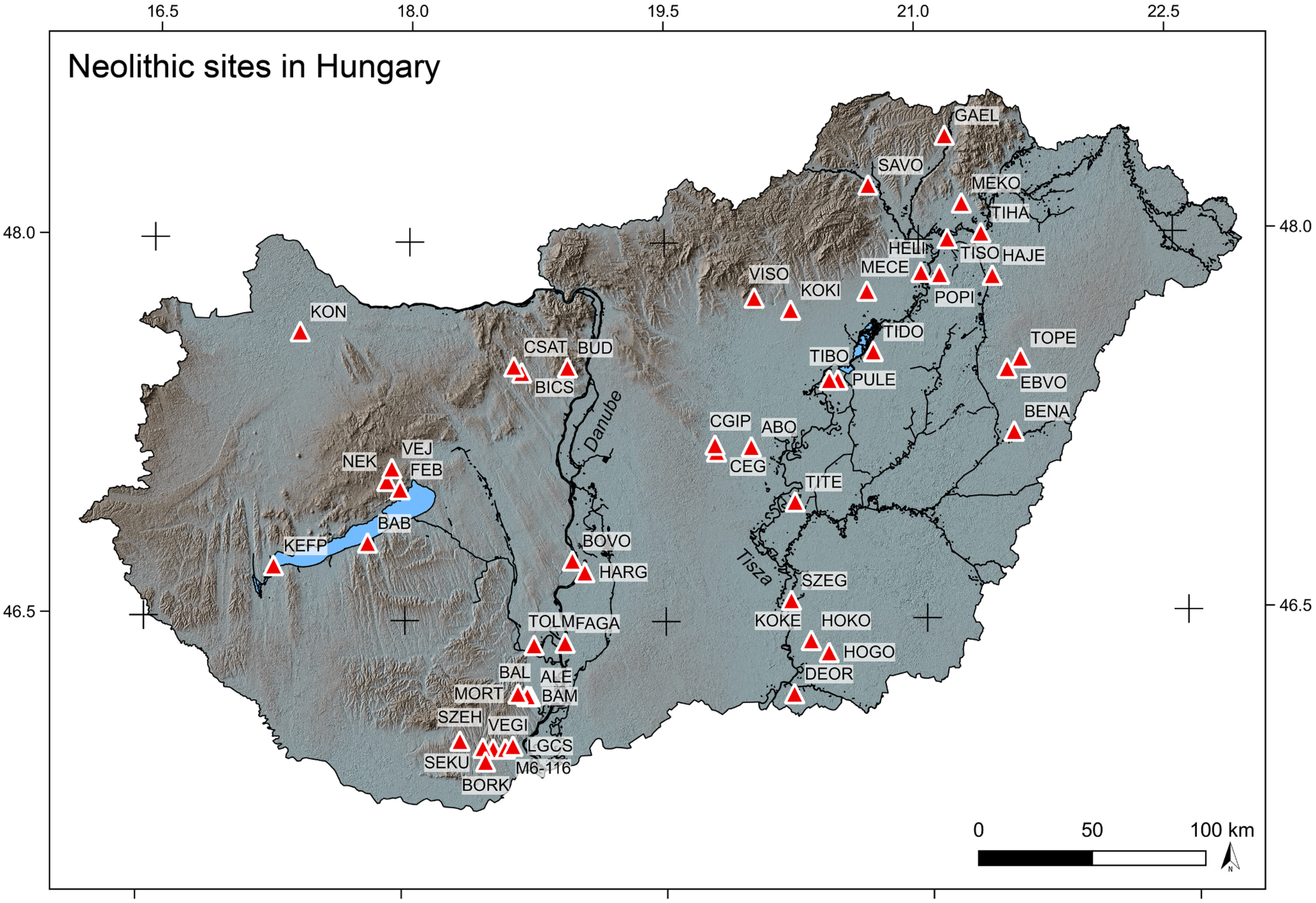

Fig. 1. Neolithic site distribution. 49 sites in Hungary were analyzed for site-catchment properties and potential land-use strategies.

Table 1

Site names, abbreviations, and chronological periods of the sites used in this article. The geological and pedological information of each site is given using the major soil type classification of Hungary (see Tab. 2 for the correlation with the WRB system) and the geological EGDI datasets (see Fig. 4). The classification of the sites is based on the database of the DFG-project. Some sites comprise multifold chronological periods and the database also includes Chalcolithic occupation, which was additionally modelled for the sake of completeness (EN = Early Neolithic, MN = Middle Neolithic, LN = Late Neolithic, CHAL = Chalcolithic).

Site name	id	Culture	Period	lat	lon	Soil units	Geological units
Abony 60. lh.	ABO	Tiszapolgár, Szakálhát	MN/CHAL	47.19	20	sand soil	diamicton
Alsónyék elkerülö 2. lh.	ALE	Sopot	MN	46.2	18.72	meadow soil	diamicton
Balatonszemes Bagódomb	BAB	TLBK	MN	46.81	17.78	meadow soil	silt
Bátaszák-Lajvér	BAL	Lengyel II	LN	46.2	18.7	meadow soil	diamicton
Bátaszék-Mérnöki telep	BAM	Starčevo	EN	46.21	18.71	meadow soil	diamicton
Berettyóújfalu-Nagy-Bócs dűlő	BENA	Esztár, Kőrös, Hungarian Conquest Period	EN/MN	47.23	21.53	meadow soil	diamicton
Bicske Galagonyás	BICS	Sopot	MN	47.49	18.66	salt affected soil	diamicton
Borjád Kenderföldek	BORK	Lengyel I-II (?)	LN	45.94	18.47	meadow soil	silt
Bölcske Gyürüsvölgy M3-TO 14. lh.	BÖVÖ	TLBK - Zseliz	MN	46.74	18.96	sand soil	diamicton
Budakeszi 8. lh. Szőlőskert-Tangazdaság	BUD	TLBK	MN	47.51	18.93	brown forest soil	impure limestone
Cegléd	CEG	Szakálhát	MN	47.17	19.8	meadow soil	silt
Cegléd Ipari park	CGIP	Szakálhát	MN	47.2	19.79	meadow soil	silt
Lanycsók Csata alja	CSAT	Lengyel	LN	47.51	18.62	brown forest soil	silt
Deszk Ordos	DEOR	Tisza	LN	46.21	20.23	peat soil	diamicton
Ebes-Zsong-völgy	EBVÖ	Esztár	MN	47.48	21.5	Chernozem	silt
Fajsz	FAGA	Sopot	MN	46.42	18.92	alluvial soil	diamicton
Felsőörs-Bárókert	FEB	Lengyel II	LN	47.02	17.96	brown forest soil	limestone
Garadna- Elkerülö 2.lh	GAEL	Bükk, ALBK	MN	48.41	21.17	brown forest soil	diamicton
Hajdunanas-Eszlari ut, M3-46	HAJE	ALBK	MN	47.85	21.43	Chernozem	diamicton
Harta-Gátőrház	HARG	TLBK	MN	46.7	19.03	Chernozem	diamicton
Hejökürt-Lidl logisztikai központ	HELI	Tiszadob	MN	47.87	21.01	meadow soil	diamicton
Hódmezővásárhely-Gorzsa V. lh Homokbànya	HOGO	Baden	CHAL	46.37	20.43	meadow soil	diamicton
Hódmezővásárhely Kotacpart	HOKO	Körös	EN	46.42	20.33	meadow soil	diamicton
Keszthely-Fenékpuszta Pusztaszentegyházi dűlő	KEFP	Balaton-Lasinja	CHAL	46.71	17.24	meadow soil	org. rich sediment
HMV Kökénydomb	KÖKE	Tisza	LN	46.42	20.33	meadow soil	diamicton
Kompolt-Kígyós-ér	KOKI	ALBK	MN	47.73	20.24	meadow soil	tuff-breccia
Kóny 85 Enese	KON	TLBK, Latest Lengyel/Balaton Lasinja, late TLBK_Zseliz, Lengyel III	MN	47.64	17.36	meadow soil	diamicton
Lánycsók Gata Csatola	LCGS	Starčevo	EN	46.01	18.62	meadow soil	silt
Lanycsók Csata alja	M6-116	Starčevo, Latest Baden/Vučedol, Balaton Lasinja	EN/CHAL	46	18.58	Chernozem	diamicton
Mezökeresztes-Cethalom	MECE	ALBK 2–3	MN	47.8	20.69	meadow soil	diamicton
Mezőzombor – Községi temető	MEKÖ	ALBK, Bükk, Tiszadob	MN	48.14	21.26	meadow soil	diamicton
Mórágy Tűzkődomb B1	MORT	Lengyel	LN	46.21	18.65	brown forest soil	silt
Nemesvámos-Kapsa	NEK	Sopot	MN	47.05	17.88	brown forest soil	silt
Polgár-Piócási-Dűlő	POPI	ALBK	MN	47.86	21.12	salt affected soil	diamicton
Pusztataksony Ledence	PULE	Tisza, Szakálhát, Tiszapolgár, ALBK	MN/LN	47.45	20.51	sand soil	diamicton
Sajoszentpeter-vasúti örhaz	SAVÖ	Bükk, ALBK	MN	48.22	20.71	skeletal soil	diamicton
Szederkèny-Kukorica-dülö 95. lh.	SEKU	Vinča	MN	46	18.45	meadow soil	silt
no data	SZEG	Tisza	LN	46.58	20.22	alluvial soil	diamicton
Szemely-Hegyes M60/83. lh.	SZEH	Sopot, TLBK	Mn	46.03	18.32	brown forest soil	silt
Tiszabura Bonishat	TIBO	ALBK	MN	47.45	20.46	sand soil	diamicton
Tiszaszőlős - Domaháza-puszta, Réti-dűlő	TIDO	Szakálhát, Kőrös, Szakálhát or early Tisza, ALBK	EN/MN	47.56	20.72	alluvial soil	diamicton
Tiszalök Hajnalos	TIHA	no data	MN	48.02	21.37	meadow soil	silt
Tiszadob-Okenéz	TISO	Tiszadob/Bükk	MN	48	21.17	alluvial soil	diamicton
Tiszaföldvár Téglagyár	TITE	Szakálhát	MN	46.97	20.25	meadow soil	diamicton
Tolna-Mözs TO 026	TOLM	Balaton-Lasinja, TLBK	MN/CHAL	46.41	18.74	Chernozem	silt
Debrecen Tócópart Erdöalja	TOPE	Esztár	MN	47.52	21.58	meadow soil	silt
Versend-Gilencsa	VEGI	Vinča	MN	46	18.51	Chernozem	mudstone
Veszprém-Jutasi-Munkacsy út	VEJ	Lengyel II, Balaton-Lasinja	LN/CHAL	47.1	17.91	brown forest soil	silt
Visonta	VISO	ALBK	MN	47.78	20.03	meadow soil	diamicton

of Transdanubia, the first Neolithic arable farming culture in Central Europe (*Linearbandkeramik*, LBK, 5500 to 4800 cal BC) developed around 5500 cal BC – probably in strong interconnection with hunter-gatherer groups (Bánffy, 2004, 2006; Bánffy and Bognár-Kutzián, 2007; Bánffy et al., 2008; Eichmann et al., 2010). Eventually, the *Transdanubian LBK* (TLBK) spread rapidly across Central Europe (Szécsényi-Nagy et al., 2014) and existed alongside the *Central European LBK* (Oross and Bánffy, 2009). Around 5300/5200 cal BC, the so-called *Vinča* culture influenced southwestern Hungary (Jakucs et al., 2016). After 5000 cal BC, the so-called *Sopot* culture alternated the LBK, which introduced new cultural characteristics at the onset of the Late Neolithic in Transdanubia. From 4900/4800 cal BC onwards, the Sopot impulses triggered the formation of the large Late Neolithic *Lengyel* cultural complex, which represented imprints from both, the LBK and the Sopot material culture. The Lengyel period was characteristic across Europe (Stadler and Ruttkay, 2007) and in its late phase reached into the Chalcolithic period around 4300 cal. BC. Finally, the so-called *Balaton-Lasinja* culture marked the end of the transition from the Late Neolithic and Early Chalcolithic to the Middle Copper Age.

In the lowlands, the Hungarian Early Neolithic is characterized by the so-called *Körös* culture, which spread over the northern Balkans from the Maros region of the southern Alföld after 6000 cal BC along the rivers Tisza, Körös, and Berettyó (Domboróczki and Raczky, 2010; Raczky et al., 2005; Whittle et al., 2002). The Middle Neolithic of the Hungarian Plain is mostly dominated by the *Alföld Linear Pottery culture* (ALBK), which formed around 5600–5400 cal BC. The ALBK spread from its origin over the entire Hungarian lowlands (Oross and Bánffy, 2009). Around 5300 cal BC, a differentiation process began, in the course of which several regional groups emerged (Hertelendi et al., 1995).

Along the lower and middle parts of the river Tisza, the so-called *Szakálhát* culture (Kalicz and Makkay, 1977) was one of the most widespread group, which occupied a large part of the former distribution area of the Körös culture. The distribution area of the *Bükk* group partly overlapped with that of the *Zseliz, Esztár* and *Szakálhát* groups (Raczky and Anders, 2009). The Szakálhát culture also maintained contacts with the Middle Neolithic so-called 'note-head' and *Zseliz* groups in Transdanubia and with the Vinča culture in the northern Balkans (Kalicz and Makkay, 1977). The northern Alföld including the Bükk and Mátra mountains were the distribution area of the so-called *Tiszadob* group, which first appeared around 5300 cal BC, and the subsequent *Bükk* group (Csengeri, 2010; Kalicz and Makkay, 1977). Around 5100 cal BC the *Tisza* culture appeared in southern Alföld (Hertelendi and Horváth, 1992; Kalicz and Raczky, 1987) and spread to the central and northern Alföld (Kalicz, 1994; Kalicz and Raczky, 1987).

In the statistical analysis, which was carried out using the entire Neolithic and Chalcolithic data, both chronological periods were integrated for the sake of completeness. The Neolithic sites were further differentiated into Early Neolithic (EN), Middle Neolithic (MN), and Late Neolithic (LN) following the Hungarian chronological periods (see Table 1). A few sites show more than one cultural and chronological occupation.

2.2. *Climatic conditions*

Hungary is dominated by a moderate continental climate with marine and Maritime influences (Ács, Breuer and Skarbit, 2015; Demény et al., 2013). The topographical conditions and the large-scale of the Carpathian Basin cause an increase in continentality towards the lowlands with lowest precipitation rates in the center of the plain (Fig. 3) (Jakab et al., 2009). During the Holocene, the harsh climatic conditions were reinforced by desiccating winds that limited tree growth and favored the accumulation of sandy deposits (Gardner, 2002; Novothny et al., 2010). That led to an Early Holocene steppe/forest-steppe vegetation cover followed by a rapid forest decline and niche forest habitats surrounded by an extensive steppe plain (Gardner, 2002; Magyari et al., 2010; Uj et al., 2016; Willis et al., 1997, 2000). The Boreal in the Great Hungarian Plain was characterized by grassland surfaces and a regional climate that was drier and warmer than today (Hertelendi et al., 1992; Magyari et al., 2010; Magyari, 2011). Magyari (2011) and Magyari et al. (2010) see a tendency towards drier conditions after 8.4 ka BP that were accompanied by decreasing lake levels and increased fire outbreaks as reported from micro-charcoal dispersal (Magyari et al., 2010; Magyari, 2011). The subsequent Atlantic phase is assumed to have experienced a climatic optimum approximately 9 k to 5 k cal BP (Hedges et al., 2013; Hertelendi et al., 1992; Magyari et al., 2001).

2.3. *Sedimentological conditions*

Large parts of the Great Hungarian Plain (Alföld) are covered with Quaternary sediments, which are composed of gravel, sand, silt, and clay (Kercsmár et al., 2015). The Upper Pleistocene loess is characteristic for the hilly margins of the plain, the Mezőföld west of the Danube, and mainly the alluvial fans of the basins. The origin, thickness, and age of the loess deposits show local discontinuities (Varga, 2011). The deposits can alternate with sandy layers and are frequently disturbed by palaeosoil horizons, which developed during warmer and wetter interglacial periods (Kovács et al., 2013). Massive sand deposits occur mainly in the Danube-Tisza Interfluve and the Kiskunság east of the Danube (Kercsmár et al., 2015).

The Danube-Tisza Interfluve (hereinafter termed DTI) is the largest sand-covered area in Hungary (Fig. 2, Fig. 4). The wind-blown sediments derived mostly from the palaeo-alluvial fans of the rivers and are connected to Quaternary landscape formations under increased wind speed and activity (Ladányi et al., 2015; Novothny et al., 2010). Finally, the most significant aeolian deposition occurred in the Upper Pleniglacial and was again reworked during the cold and dry phases during the Older and Younger Dryas (Nyári et al., 2014). In the Early Holocene, the gradual increase of the mean temperature reached today's characteristics with a July value of 22 °C as reported from mollusc faunal analysis by Sümegi et al. (2015). The data samples were taken from carbonate rich lakes that formed at the DTI at the end of the Pleistocene and Early Holocene when the Danube accumulated a huge alluvial fan (Knipl and Sümegi, 2012). Aeolian redistribution and relocation of the sandy deposits formed small-scale basins where water was trapped after flooding events. The mineral mixture of the lake water and the carbon dioxide entrapment in combination with the saline and alkaline salt content led to the sedimentation of dolomite mud during the Neolithic (Sümegi et al., 2015).

The eastern part of the Carpathian Basin is dominated by hydrologic channel shifts and floodplain dynamics of the late Pleistocene/Holocene river Tisza (Kasse et al., 2010; Kiss et al., 2015; Moskal-del Hoyo et al., 2018; Timár et al., 2005), the river Körös (Petrovszki and Timár, 2010), and the river Maros (Kiss et al., 2014). The sand-covered DTI experienced alterations of fluvial deposits from the Danube, palaeosoil development after the west drift of the river, and depositional activity superimposed on palaeosoils (Nyári et al., 2014).

2.4. *Soil conditions and textures*

According to Laborczi et al. (2016), soil texture information is an essential data source for modelling climatic, hydrological, and agricultural conditions. Surface cover transformations and degradations caused by wind erosion or compaction strongly depend on local topsoil textures (Birkás et al., 2004; Laborczi et al., 2016; Várallay, 1989). For this reason, the research group among László Pásztor[1] converted large datasets of Hungarian soil survey information into digital formats that are organized in spatial soil information systems (SSIS) (Laborczi et al.,

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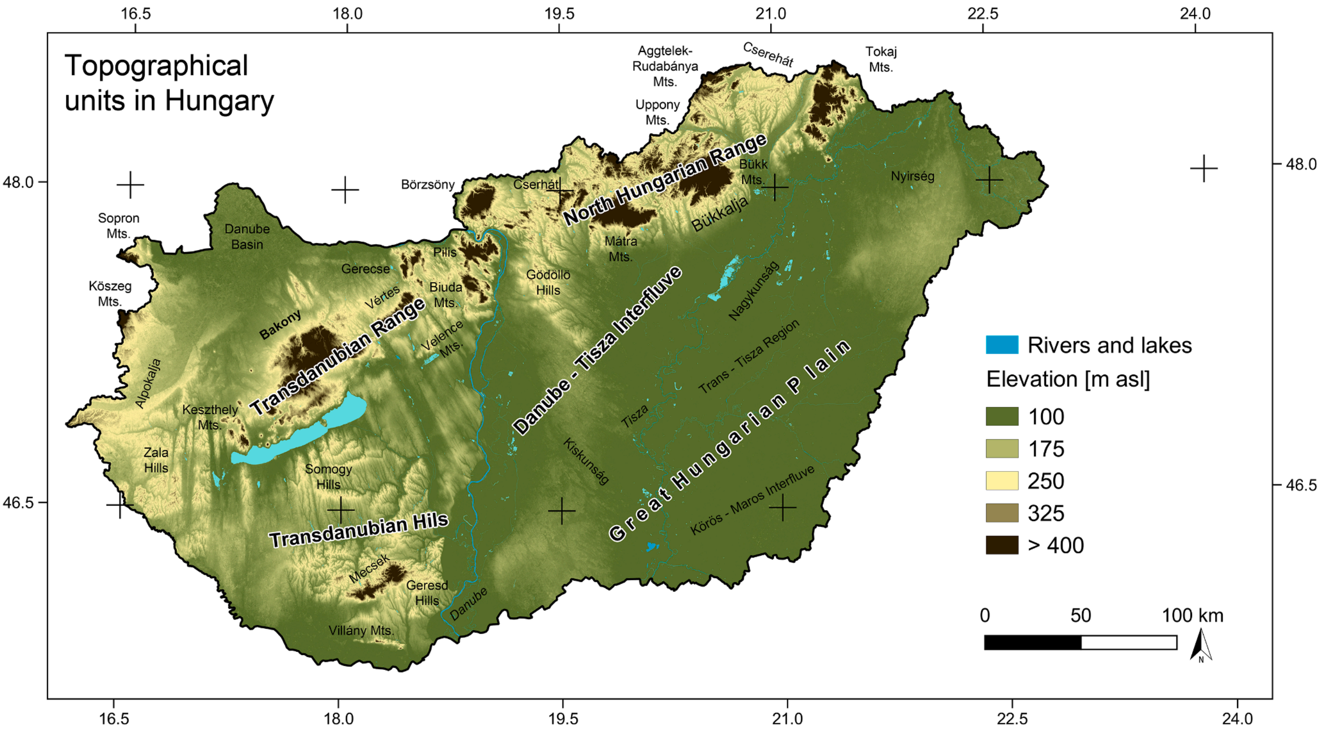


Fig. 2. Topographical units and environmental regions in Hungary.

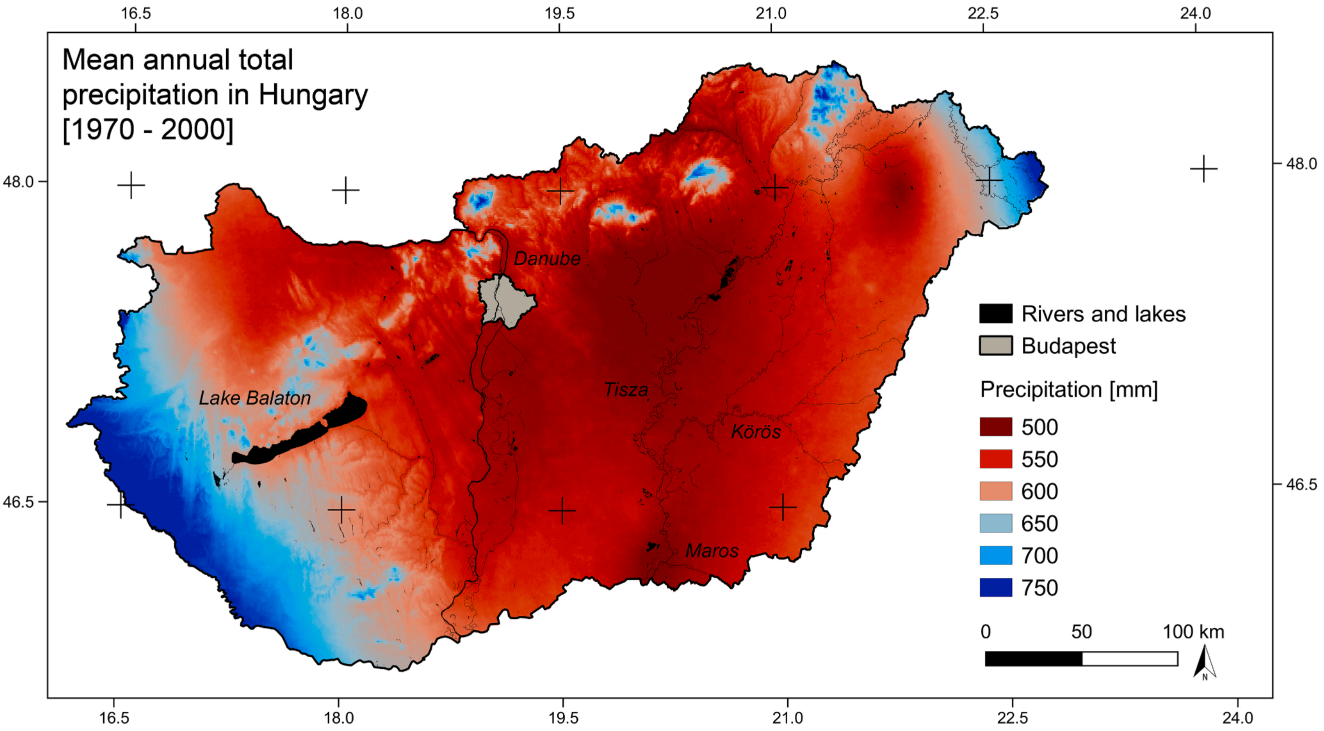


Fig. 3. Modelled mean annual total precipitation in Hungary for the reference period 1970 – 2000. The continental climate with dry conditions and annual total precipitation amounts around 500 mm generates steppe vegetation in large parts of the Great Hungarian Plain. The moisture regime varies from moderately moist (Ukrainian border) to moderately dry and dry (central part of the Tisza plain) (Ács, Breuer and Skarbit, 2015). Climate data based on worldclim.org (Hijmans et al., 2005).

2019; Pásztor et al., 2012, 2016, 2014a, 2014b, 2015a, 2015b, 2002; Waltner et al., 2018). Finally, soil maps of different spatial resolution were generated that allow for the evaluation of soil textures and types as well as degree of degradation, salinization, and erosion (Fig. 5 and Fig. 6) (Pásztor et al., 2012, 2016; Schofield et al., 2001). Additional information on wetland dynamics, floodplain development and flooding vulnerability can be obtained from the data (Bozán et al., 2018; Pásztor et al., 2015a, 2015b).

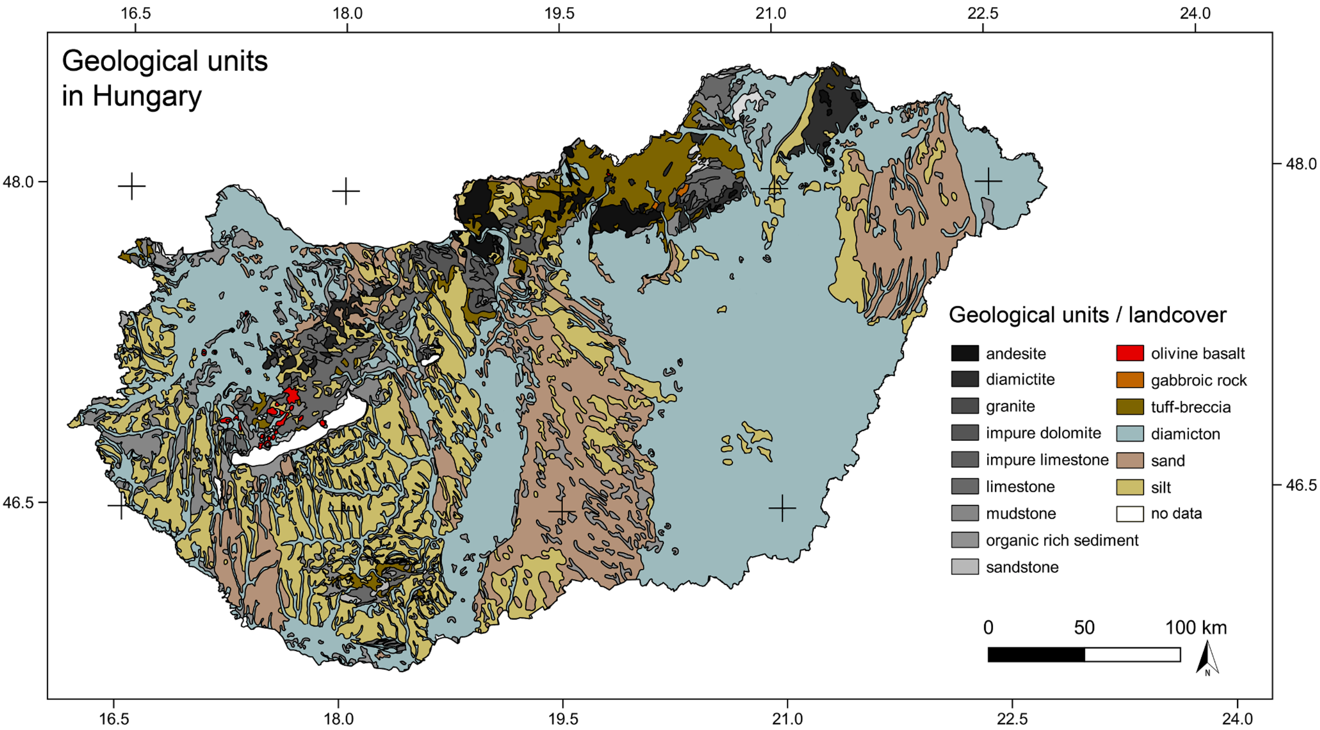
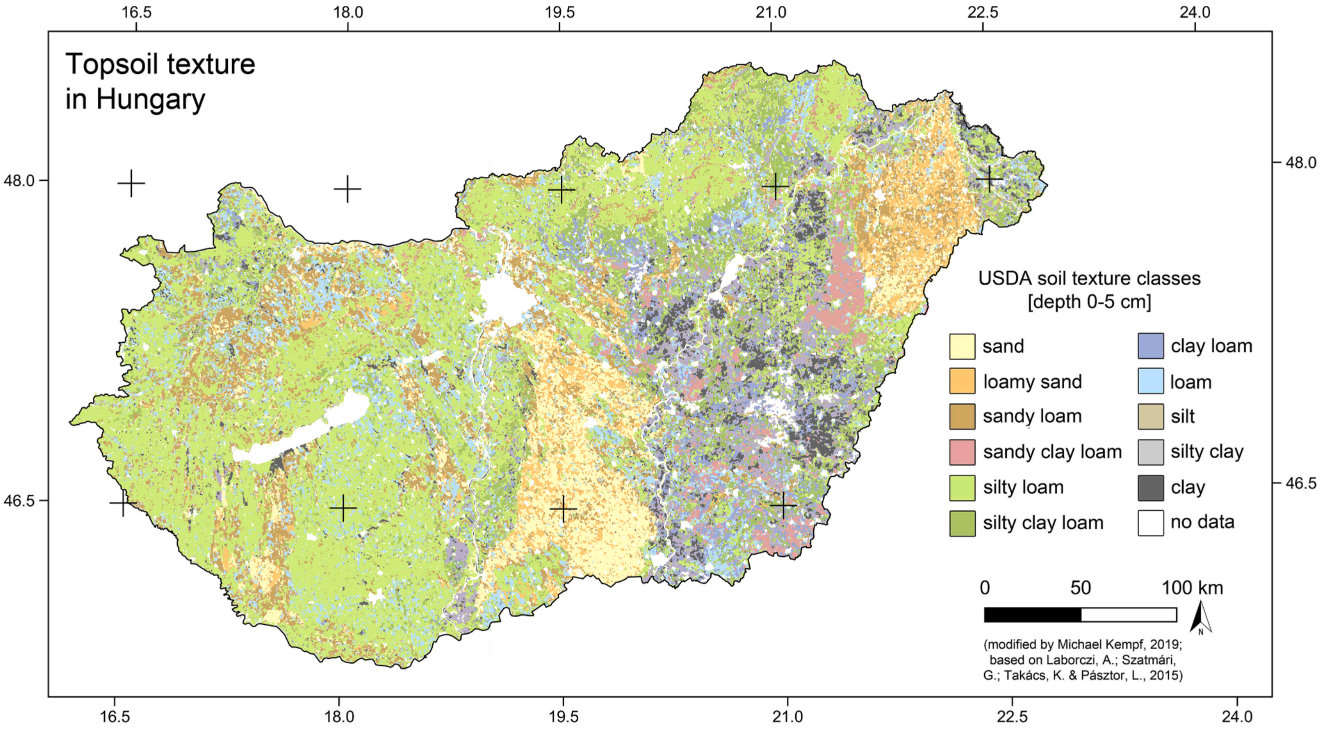


Fig. 4. Geological units in Hungary. The floodplains of the river Danube and the Tisza river-system are characterized by Holocene unsorted or poorly sorted, clastic sediments with a wide range of particle sizes. The DTI is mainly composed of sandy deposits. Large parts of the Carpathian basin and the hilly margins are covered with silty deposits and silty mud. The EGDI dataset refers to the units as follows: Diamicton = unsorted/poorly sorted clastic sediments, Holocene; silt = mud that consists of greater than 50% silt-sized grains, Pleistocene; sand = clastic sediments (<30% gravel), Holocene; organic rich sediment = greater than 50% organic material, Holocene; limestone = Triassic carbonates; impure limestone = Eocene impure carbonate sediments; tuff breccia = Miocene pyroclastic rock.



(modified by Michael Kempf, 2019; based on Laborczi, A.; Szatmári, G.; Takács, K. & Pásztor, L., 2015)

Fig. 5. Topsoil texture in Hungary based on the supplementary data of A. Laborczi, G. Szatmári, K. Takács and L. Pásztor (2015) in (Laborczi et al., 2016).

The most used soil classification system is the World Reference Base for Soil Resources (WRB). In this context, the Hungarian soil classification system was first correlated to the WRB classification by Michéli et al (2006) and Krasilnikov et al. (2009) (Balla, Novák and Zichar, 2016; Krasilnikov et al., 2009; Michéli et al., 2006). According to Krasilnikov et al. (2009), the system originally is based on four types (main type, soil

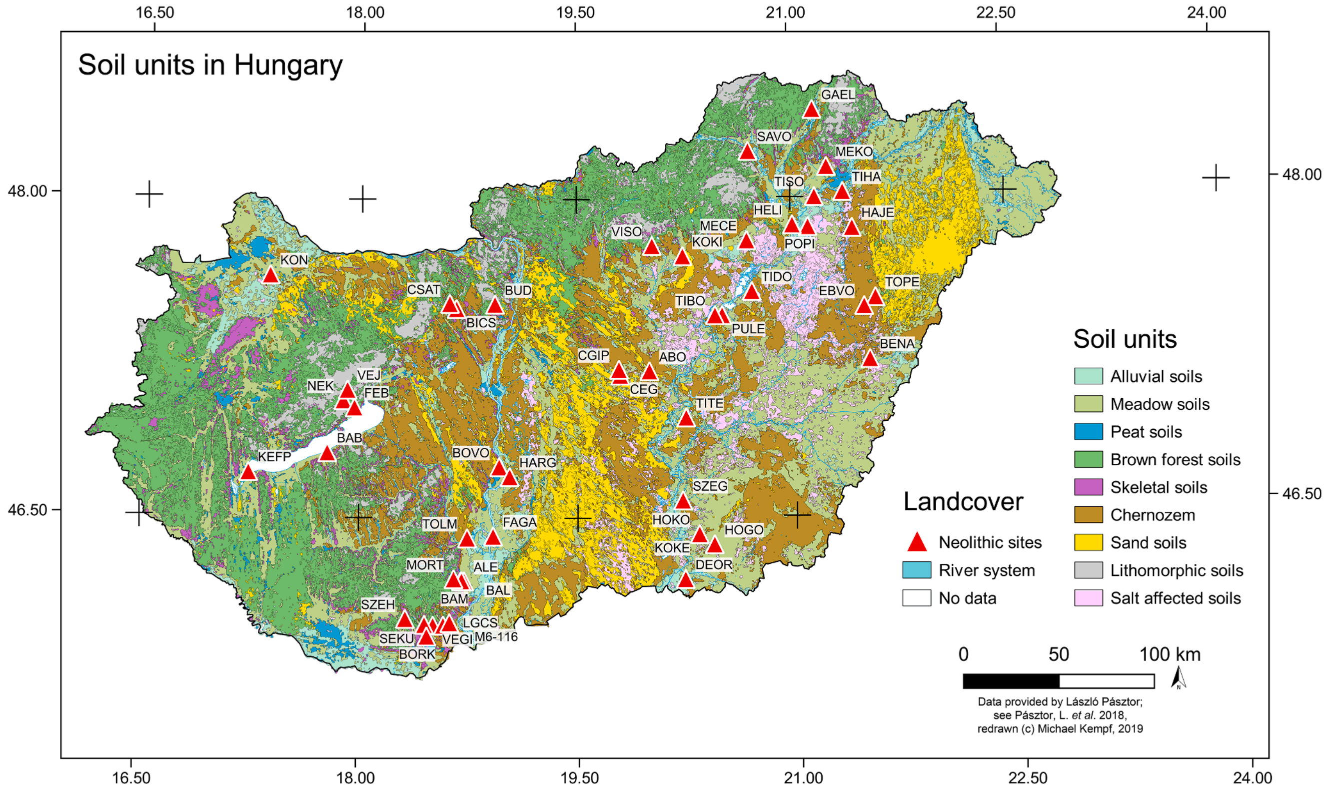


Fig 6. Neolithic study sites modelled on soil units in Hungary. The sites follow a spatial pattern with preferred occupation of meadow soils and Chernozems that are frequently distributed in the central part of the Carpathian Basin and along the broad floodplain patches of the major river (soil data kindly provided by László Pásztor).

type, subtype, and varieties), which can be correlated to the WRB as shown in Table 2.

Hungarian soils cover an area of approximately 9.3 Mha of which 6.4 Mha are agriculturally used and 4.5 Mha are arable land. Over 40% show degradation processes and over 20% are compacted due to human activity (Birkás et al., 2004; Schofield, Thomas and Kirkby, 2001; Szilassi et al., 2006). Hungary shows very heterogenous soil compositions according to the manifold geological basements and sedimental fluvial infills. In the northern mountainous areas and on eroded slopes with mainly consolidated limestone, dolomite, basalt, and andesite, lithomorphic soils are present. Although these soils can show very particular physical and chemical aspects, they share similar vegetation (forest-) coverage and are grouped together (Dobos et al., 2000). Further south and in the western, more humid part of Hungary, Brown Forest soils (*Haplustalfs*) developed that show significant clay illuviation. Descending from the mountains, the clay content decreases and the transition zone to the lowlands is characterized by Chernozem-Brown soils (*Haplustolls* and *Hapludolls*). The loess-covered plains are mainly dominated by Chernozems (*Pachic* and *Typic Claciustolls*) with distinct hydromorphic conditions in depressions (*Aquic Calciustolls* and *Haplustolls*) (Dobos et al., 2000).

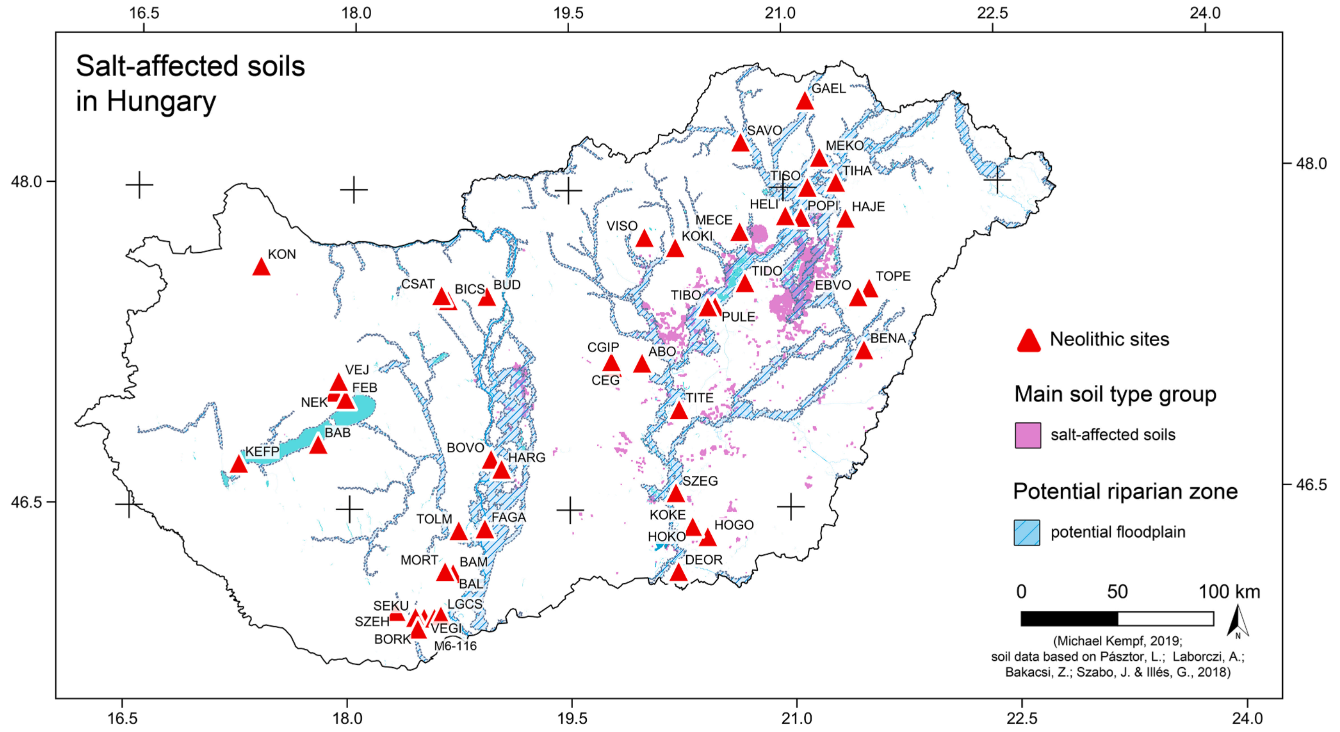
Table 2
Correlation of the Hungarian soil classification and the World Reference Base for Soil Resources (WRB) based on Michéli et al (2006) and Krasilnikov et al. (2009).

Hungarian soil classification	WRB classification
Skeletal soil	Leptosols/Arenosols/Regosols/Calcisols
Lithomorphic soils	Leptosols/Regosols/Phaeozems/Cambisols
Brown forest soils	Cambisols/Luvisols/Umbrisols
Chernozems	Chernozems/Phaeozems/Kastenozems/Vertisols
Salt-affected soils	Solonchaks/Solonetz/Vertisols/Chernozems
Meadow soils	Humic Gleysols/Mollic Gleysols/Gleyic Phaeosems/ Gleyic Chernozems
Sand soils	Arenosols/Cambisols/Lamelli-Arenic Luvisols
Peat soils	Histosols
Alluvial soils	Fluvisols

Over the last full glacial period, the central plain suffered from very dry climatic conditions with low precipitation rates and saline soils already started to develop accordingly – triggering a saline-tolerant vegetation that persisted throughout the Holocene (Magyari, 2011). Saline groundwater reached the soil surface and the annual evaporation was higher than the annual precipitation rate. Consequently, salt-affected soils developed (Schofield et al., 2001; Tóth et al., 2001). In the DTI, blown sand (*Typic Ustipsamments* and *Quartzipsamments*) is frequently abundant (Dobos et al., 2000). However, a significant salt impact from the closed off Para Tethys Sea sedimentation regime with saline marine and lacustrian infills can also be detected in the DTI and especially in the Tisza plain (Mádl-Szőnyi et al., 2008; Tóth et al., 2001). Quaternary loess originating from the Russian Puszta further strengthened the saline signal in the groundwater and the fine-grained soils (*Solonchak soils*) (Fig. 7) (Schofield et al., 2001).

2.5. *Hydrologic systems and hazards*

Modern Hungary is located at the western border of the Eurasian Steppe Belt (Molnár et al., 2012; Pinke and Lövei, 2017). The country experienced not only a highly dynamic environmental and cultural history but also a turbulent recent transformation with political and economic developments and upheavals (Bánffy, 2019; Bentley et al., 2012; Bickle et al., 2017; Schulze, 2000). Crop production became increasingly important in Hungarian 19th and 20th century modernization what led to massive impacts on the environmental settings of the country through canalization and drainage activity of the broad wetlands, wind driven soil erosion, and local agricultural overstraining (Pinke and Lövei, 2017; Uj et al., 2016; Ujházy and Biró, 2018; van der



(Michael Kempf, 2019; soil data based on Pásztor, L.; Laborczi, A.; Bakacsi, Z.; Szabo, J. & Illés, G., 2018)

Fig. 7. Salt-affected soils (purple) and the potential floodplains of the main river systems in Hungary (blue). Saline soils are mostly located in the Tisza floodplain and the DTI. Neolithic sites (red triangles) are situated in more than 250 m distance to the saline soils that show only a poor agricultural potential (one site (CEG) is situated on a saline soil patch of 800 m diameter). Soil data is based on (Pásztor et al., 2018); the potential floodplain is projected from Corine Riparian data.

Zee et al., 2017). Consequently, Pleistocene and Early Holocene river channels and systems in Hungary vary greatly from the modern modified hydrologic streamflows. The hydrological development of the river Danube is strongly connected to the sedimentation regime during the late Pleistocene and the Early Holocene. The eastern part of the broad alluvial plain is bordered by a slightly elevated plateau-like palaeo-alluvial fan that was first deposited by the river and then cut several times during flooding events and avulsion activity, which caused relocation of the alluvial deposits (Knipl and Sümegi, 2012; Ujházy et al., 2003). Finally, the DTI was created that mainly consist of relocated alluvial sands with local loess cover.

The modern river Tisza is the second largest river in Hungary and one of the main tributaries to the river Danube (Kasse et al., 2010; Nagy et al., 2010). Subsidence of the Great Hungarian Plain controlled the drainage and hydrologic systems through basin development. Consequently, large-scale alluvial fans with fragmented palaeochannels were created by the river. Quaternary fluvial deposits mainly consist of fine-grained clay, silt, and sand with a seismic thickness of up to 700 m (Kasse et al., 2010; Kiss et al., 2015; Moskal-del Hoyo et al., 2018; Nádor et al., 2011; Timár et al., 2005). Prior to massive channeling and regulations in the 19th century, large parts of the floodplain were periodically inundated (Bezdán, 2010; Guida et al., 2015) and the riverbed changed frequently (Kasse et al., 2010; Sipos et al., 2016). Holocene floodplain dynamics, as reported by Kasse et al. (2010), show a continuous trend of riverbed relocation and avulsion of more than 4 km in distance. The discharge of the fluvial system fluctuated due to climate variability: during humid and rather warm conditions, riverbed dynamics are considered to follow a meandering pattern, while the subsequent, short-term dry and cold phase triggered a braided river system of the Tisza-tributaries due to sparse vegetation coverage (Kiss et al., 2015). The Tisza discharge levels increased in the Atlantic Phase due to humid conditions what supported the development of large meanders in the Upper Tisza region and a general discharge volume of 5520 m^3/s – 20 times greater than the Boreal value and 10 times greater than the modern ratio (Kiss et al., 2015). The high flooding vulnerability of the river Tisza is coupled with the main tributaries (the rivers Bodrog, Sajó, Bódva, Hernád, Szamos, Kraszna, Körös and Maros) and their high slope gradients that can cause rapid increase of the water level in the course of intense rainfall in the upper parts of the headwaters and the catchment areas (Fig. 8) (Nagy et al., 2010; Schweitzer, 2009).Fig. 9.

2.6. *Multivariate environmental model and quantitative statistics*

In landscape archaeology, multivariate modelling is performed by integrating different GIS-based environmental and surface data sets (Groenhuijzen, 2019; Howey, 2011; Howey and Brouwer Burg, 2017; Kempf, 2019b, 2020; van Dinter, 2013). In most cases, the method is used to investigate movement corridors or to model accumulative and multi-layered environmental data surfaces that represent a classified permeability of spatial information (Kempf, 2019a; van Lanen et al., 2015a, 2015b). The multivariate landscape model identifies the areas that best fulfill the empirically addressed environmental parameters. In contrast to the validation of a deductively developed theory of human activity patterns in the landscape, an inductive approach is based on the conclusions of the case studies underlying site-specific research (Güimil-Fariña and Parcero-Oubiña, 2015; Verhagen, 2019; Weaverdyck, 2019). For this purpose, large-scale surface models are tested against each other on different local scales to identify changes in the immediate landscape elements at continuous distances from the sites. This results in a pattern for different *radii* around each site, which allows determining the range at which significant changes in the composition of the landscape elements can be observed. This is the threshold value that indicates the transition between the environmental dependence of the site-catchment and the randomness of the periphery.

2.6.1. *Site location analysis*

Site preference analysis and the analysis of surface conditions within a given catchment of a site are sound methods in archaeological research for some time now (Roper, 1979; Ullah, 2011; Vita-Finzi et al., 1970). The most strongly discussed issue, however, remains the determination

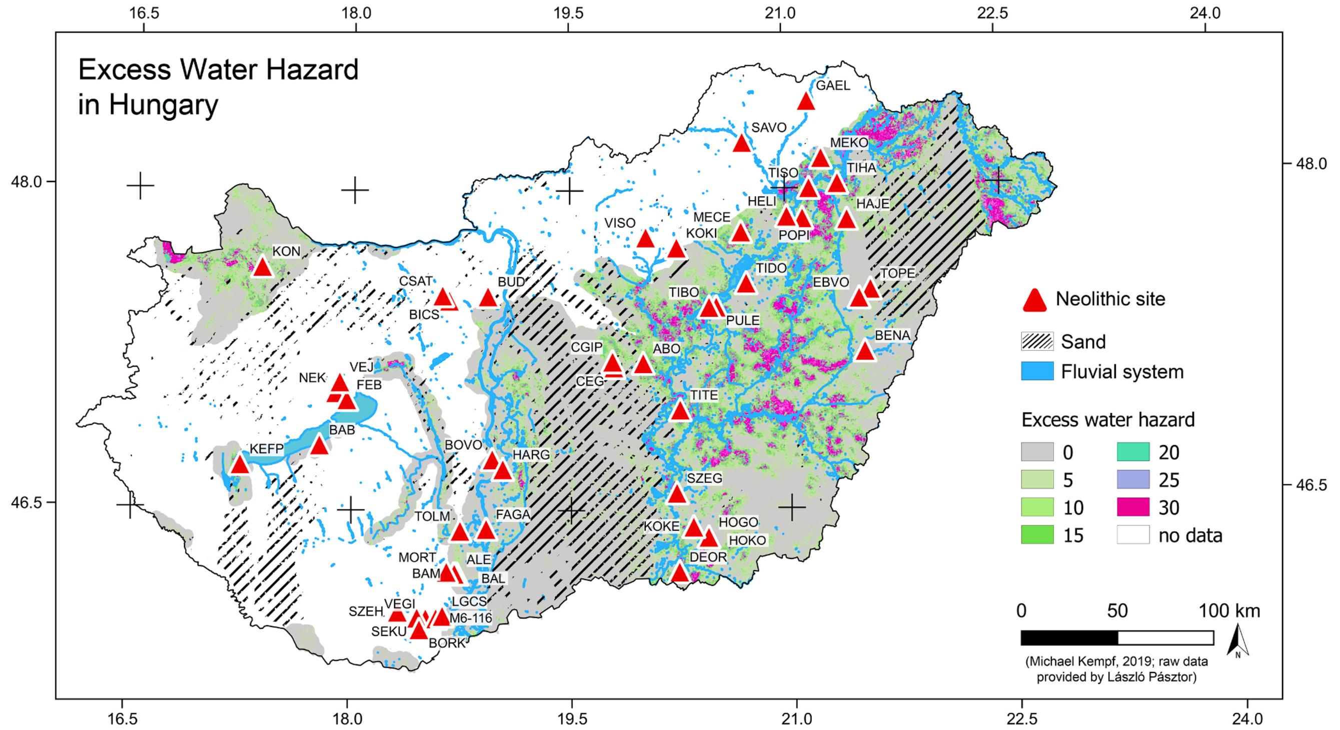


Fig. 8. Inland excess water hazard map (IEW) from Hungary. The map shows frequently inundated areas with high flooding potential (>15), medium flooding potential (10 – 15) and low flooding potential (<10). The sand-covered regions in Hungary are characterized by low flooding vulnerability and dry conditions. The IEW data was kindly provided by László Pásztor (Bozán et al., 2018; Pásztor et al., 2015a, 2015b) and sand-covered areas were processed from (Pásztor et al., 2018).

of the (fixed) distance (buffer) around a site, which can be spatial (distance) or spatio-temporal (walking distance). In this case, a different set of fixed distance buffers from 1 to 5 km were applied to estimate spatial components of the geological, pedological, and hydrologic components. Finally, a spatio-temporal consideration based on slope gradient, accessibility, and permeability has been applied within a fixed 3 km buffer around the sites, which represents the threshold, at which the surface conditions approximate random conditions.

Consequently, a surface model to identify suitable site-ranges was created around the sites. The spatial analyses were performed using QGIS 3.6.0 (*Open Source Geospatial Foundation Project*, http://qgis.osgeo.org) and GRASS 7.6.0 software (*Geographic Resources Analysis Support System*, http://grass.osgeo.org). All statistical calculations were performed using R software (*The R Project for Statistical Computing*, www.r-project.org). All 49 sites were first analyzed for their spatial relationship to the soil units in Hungary (Pásztor et al., 2018). The chi-square goodness-of-fit test was applied to examine the frequencies of site distribution and soil dispersal (Kvamme, 2020). The null hypothesis is formulated as follows: Neolithic sites in Hungary were randomly distributed. The statistical evaluation can be achieved using this equation:

$$X^2_{Obs} = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

Where O_i are observed and E_i expected sites within the respective soil unit. The soil units are dispersed as follows: Chernozem (18,5%), brown forest soil (22,14%), meadow soil (26,5%), sand soil (11,25%), alluvial soil (5,2%), skeletal soil (3,2%), salt affected soil (6,34%), lithomorphic soil (4,56%), and peat soil (1,59%). The results show no significant deviation of the observed from the expected site distribution (*X-squared* = 13.884, *df* = 8, *p-value* = 0.08485). This evaluation, however, is point-based and does not allow to draw conclusions about the individual soil composition at variable distances around the site locations.

To understand the preferences and particularly the soil components around the sites, which were modelled from GIS-surface calculations, a statistical analysis was carried out using a combination of GRASS and R software. First, the soil data was spatially analyzed using the *r.neighbors* function in GRASS. This function looks at each soil-cell of the raster input layer and considers the adjacent values assigned to that cell in a custom neighborhood. In this case, the assigned cells were located in a circular pattern around each cell. The function outputs a new raster layer where every cell is assigned a value, which is a function of the values of the surrounding cells. To calculate fixed radii with a cell size of 100 m, neighborhoods of 21, 41, 61, and 101 cells were chosen, which equals circular buffers of 1, 2, 3, and 5 km around each cell (the center cell is included in the calculation). In a second step, all Neolithic sites were assigned the soil value of their location using the *point sampling tool* plugin in QGIS. This outputs a csv-file with multiple point locations from a set of raster layers. Finally, a comparison dataset with 1000 randomly distributed points was generated, and every point was assigned the value of the respective soil raster layer based on the function described above. This comparison dataset was used to evaluate the expected and observed distribution of soil composition in different *radii* around the 49 Neolithic sites. For this reason, the two-sample *Kolmogorov-Smirnov test* (KS-test) was applied to compare the samples (Nakoinz and Knitter, 2016). This test works under the 0-hypothesis, that both samples are drawn from the same distribution. The test allows to check whether two samples derive from the same distribution (or population) or if they are different. However, it does not allow to draw conclusions about how or what these differences are. P-values range from 0 to 1 with strong significant differences in the distribution at 0.01 and no differences at 1. To enhance the statistical information of the two-sample KS-test, the *Vargha-Delaney A* test (VD A) was applied (Vargha and Delaney, 2000). Just like in the KS-test, the Neolithic sites were compared to the comparison data in a two-sample test. The R-package *effsize* (Efficient Effect Size Computation) created by Marco Torchiano includes the algorithm for the VD A test. Eventually, KS-test and VD A test were performed for both site datasets on the nine soil classes and over the chronological periods Early, Middle, and Late Neolithic as well as the Chalcolithic period,

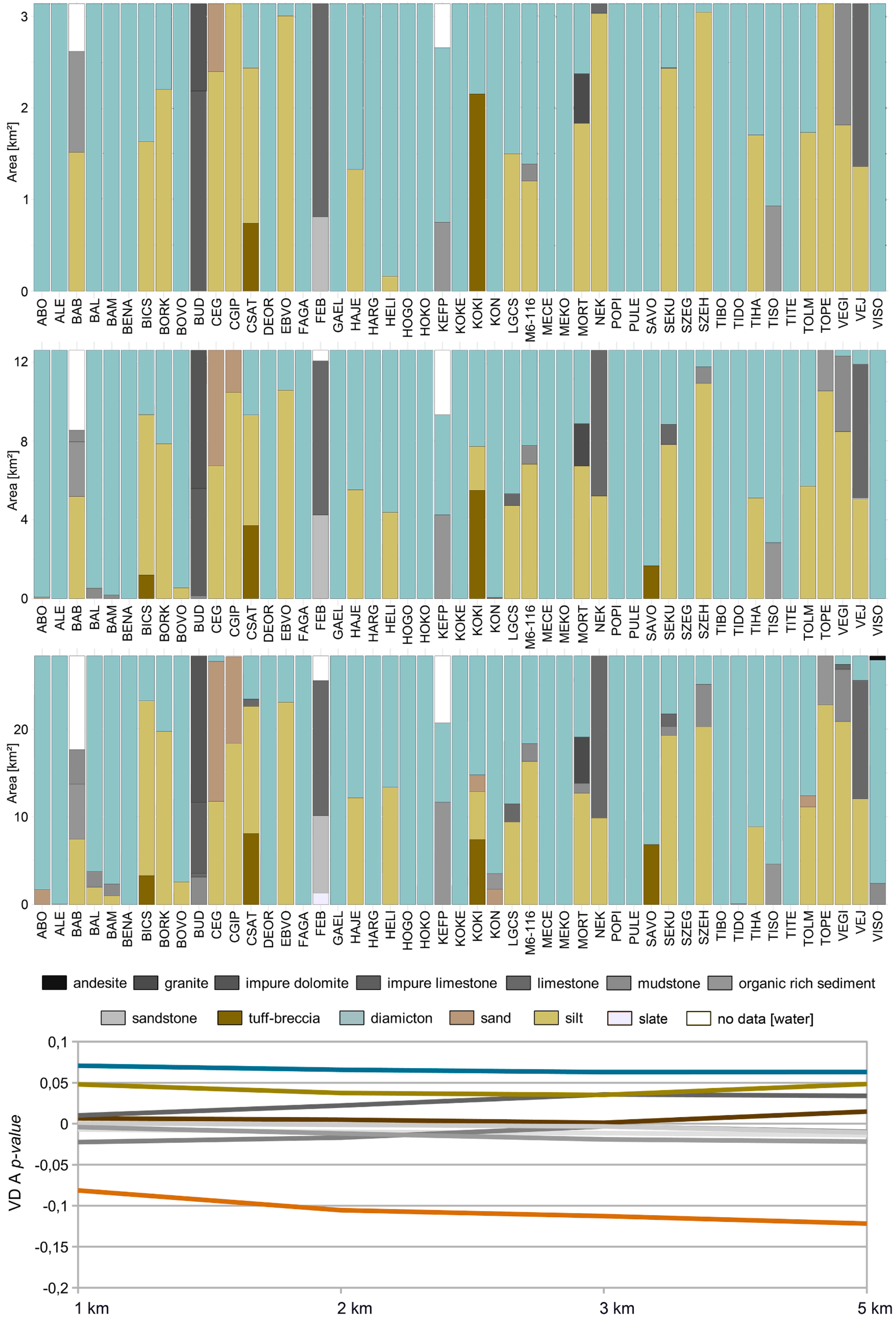


Fig. 9. Geological conditions in the site catchments of the 49 Neolithic sites in Hungary. Three buffer distances (r = 1 km, r = 2 km, r = 3 km) were selected and the respective areas covered by each geological unit were plotted for each site. The buffer of 1 km shows spatial significance of fluvial deposits (diamicton) and silty material (loess). With increasing buffer, the geological diversity increases. The VD A p-values confirm the preference for diamicton and silt, while sand is completely avoided, and the other geological units were not considered in the site location decision-making during the Neolithic period.

which allowed to track site location preferences as a function of soil distribution in variable distances around the sites (Table 4). The p-values range from 0 to 1. The plotted p-values of the VD A calculations were subtracted by 0.5 to generate significant values in the positive and negative value range (Fig. 12). Positive values indicate significant site preferences, values around 0 point toward no particular preference, and negative values indicate significant avoidance of the given soil distribution within the spatial range. The geological dataset from the EGDI database was processed using the same parameters.

2.6.2. Accumulative surface model

Floodplain dynamics were simulated from buffered large rivers (river Danube and Tisza and the major tributaries) and the small scale hydrological system in Hungary with a fixed distance buffer of 20 m. Accordingly, the observed floodplain extent of the Corine riparian delineations was modelled for the major river courses (https://land.copernicus.eu/local/riparian-zones; last accessed 09.12.2019). The results were merged to simulate a potential flooding vulnerability in Hungary based on soil composition, hydrological ecosystem, and streamflow dynamics (CLC, CRD 2019). Palaeochannels along the river Danube and the river Tisza were identified from satellite imagery, historical maps, and partly from the geological and pedological signatures. For this reason, Sentinel-2 multispectral images with a medium-resolution of 10 m in the visible range have been spectrally modified to obtain information about modern crop diversity and land-use patterns in the floodplains. Through the evaluation of vegetation indices (NDVI = Near Infrared – Red/Near Infrared + Red) (Lasaponara and Masini, 2006; Montandon and Small, 2008; Verhulst et al., 2009) that mirror the physical plant condition, patterns of modern cropland, sealed areas, forest cover, and wetlands were identified. In the satellite imagery, former palaeochannels and oxbow lakes are visible in the land-use patterns and the type and physical conditions of the vegetation cover, which mostly consists of forest or grassland coverage.

Terrain roughness in Hungary was processed from a digital elevation model (DEM) with a 25 m spatial resolution that was downloaded free of charge from the United States Geological Survey (USGS). All slopes greater than 10° were considered unfavorable for agriculture due to their increased erosion vulnerability during heavy rainfall and weakly developed soil coverage. Furthermore, potential accessibility and permeability as well as crop irrigation possibility decrease with growing distance and slope gradient. That is a generalized limitation as the heterogeneous soil mosaic in Hungary shows very different erosion susceptibility. Soils that developed over loess deposits with a higher water storage capacity show different erosion behavior than shallow soils on lithic debris with little vegetation coverage. However, as has been pointed out by Sümegi et al. (2012), the various micro-regional and local floral refuges have produced a highly diverse soil development in the Holocene and a slope generalization to 10° allows for standardized digital analyses.

From these components, an accumulative permeability and usability surface was calculated using the r.cost-function in GRASS. The surface represents the potential accessibility of the site catchments of each site. Permanent waterbodies, palaeochannels, the observed and the potential floodplain as well as high terrain roughness were accumulated to represent areas of high and low accessibility.

3. Results

Variable distances around 49 Neolithic sites were tested for their surface conditions, soil texture and compositions as well as geological units, permeability, and accessibility. In this context, particularly geological conditions and soil composition play a major role in site location parameters in the immediate surrounding of the sites. Water availability further increases the potential land-use and settlement site opportunities.

3.1. Geological and pedological site locations

Geological conditions were measured in 1, 2, 3, and 5 km distance to the sites following the parameters described above. Table 3 shows the VD A statistics for the entire Neolithic. There is a clear differentiation between Holocene sand soils, which were significantly avoided by Neolithic groups and floodplain-related soil units. Most geological units did not play a significantly important role in the choice of potential settlement locations. Only Pleistocene loess-covered area, partly calcareous patches characterized by limestone or dolomite, and diamicton showed significant preferences in the database. However, due to the rather coarse resolution and harmonization of the geological data, the preferences for alluvial sediments and loess-covered areas can only indicate an overall trend in potential land-use patterns.

Consequently, the major soil type classification of Hungary based on the data provided by Pásztor et al. 2018 was spatially analyzed for site catchment compositions (Fig. 10, Fig. 11). Nine major soil types – according to climatic, geographical, and genetic basis – can be distinguished that show local subdivisions as reported from Michéli et al. (2006). The soil types consist of skeletal soils, shallow lithomorphic soils, sand soils, brown forest soils, Chernozem, peat soils, meadow soils, alluvial soils, and salt affected soils (Michéli et al., 2006; Pásztor et al., 2018). Hungary is mostly covered by brown forest soils, meadow soils and the various derivatives of Chernozem (Fig. 10). The Neolithic site distribution correlates spatially with the soil proportions, however there is a significant increase in site density on meadow soils (n = 23) and a rather unproportional distribution on Chernozems and brown forest soils. Skeletal, salt affected, sandy, peaty, and lithomorphic soils show the expected low site concentrations. The results were further evaluated for site-distance analysis of the nearest soil patches around the sites. Sandy soils, peat soils, lithomorphic soils as well as skeletal, and salt affected soils are dispersed in greater distance to the sites. Chernozem, meadow soils, and alluvial soils are whether direct location parameters of the sites or available in very close distance.

There is significant support of distance relationships between sites and soil distribution within a radius of 3 km around the Neolithic sites in Hungary. The catchment analysis of the major soil types was processed for 1 km, 2 km, and 3 km (Fig. 11) distances for spatial visualizations and for 1, 2, 3, and 5 km for statistical analysis compared to a random point distribution (Fig. 12). There is considerable difference of soil composition between the ranges. The 1 km radius shows the dominance of meadow soils, Chernozems, and forest brown soils in the immediate surroundings of the sites. The soil mosaic increases in variability at a 2 km radius with continuous dominance of meadow soil patches. Unfavorable soil units like sand soils decrease in the ratio while a slight increase of salt affected soils can be detected in the assemblages. The 3 km radius intensifies the number of salt-covered soil variations with increasing variety of Chernozems and meadow soils in the near distance to each site. From these results, a site-catchment radius of maximum 3 km distance around each site was considered to best fulfill the potential activity ranges of Neolithic groups in the study area.

3.2. Soil composition at variable distances

To evaluate the results from the surface model, statistical analyses using the KS test and the VD A statistics have been carried out. Despite the natural distribution proportions of the nine major soil types in Hungary and the predominance of meadow, forest and Chernozem soils, a preference for meadow, alluvial, and Chernozem soils in the Neolithic is significant. (Fig. 14). The p-values of both the K-S test and the VD A statistics show very significant results for the three soil units in a 1 km circular buffer around all Neolithic sites. Sand soils and surprisingly Forest Brown soils were clearly avoided at this distance, which strengthens the argument for statistical analysis and comparison datasets. Skeletal, lithomorphic, peaty, and salt affected soils have no influence on the decision of a settlement site at 1 km distance

Table 3
VD A p-values and KS test results for the geological units within 1, 2, 3, and 5 km distance around the Neolithic sites.

Geological unit	Total 1 km D	Total 1 km KS p-value	Total 1 km VDA p-value	Total 2 km D	Total 2 km KS p-value	Total 2 km VDA p-value	Total 3 km D	Total 3 km KS p-value	Total 3 km VDA p-value	Total 5 km D	Total 5 km KS p-value	Total 5 km VDA p-value
Volcanic	0.035247	1.0	0.5065612	0.039275	1.0	0.5047755	0.049345	0.9999	0.5012143	0.056785	0.9982	0.5148571
Clastic	0.0070493	1.0	0.4930	0.013092	1.0	0.49	0.016113	1.0	0.4885	0.021148	1.0	0.4860
Diamicton	0.17229	125	0.5707347	0.15215	0.2299	0.5657143	0.14095	0.3116	0.5628367	0.18149	0.09224	0.5630408
Calcareous	0.029266	1.0	0.5101939	0.059005	0.9969	0.5222143	0.087737	0.8649	0.5356735	0.092032	0.8239	0.5339796
Mudstone	0.055121	0.9989	0.4774694	0.087346	0.8684	0.4830306	0.075529	0.9527	0.4967245	0.084325	0.8941	0.4902041
Metamorphic sediments	0.01638	1.0	0.5006735	0.015373	1.0	0.4986939	0.015373	1.0	0.4967347	0.017387	1.0	0.4894286
Organic rich sediments	0.032226	1.0	0.4958163	0.028197	1.0	0.4880918	0.034918	1.0	0.4808776	0.052038	0.9996	0.4781327
Holocene sand	0.18402	0.08462	0.4185714	0.21169	0.03045	0.3944082	0.20994	0.03261	0.3872959	0.22317	0.01909	0.3782347
Pleistocene silt	0.1803	0.09603	0.5479184	0.16446	0.1599	0.5374796	0.11034	0.6204	0.5350918	0.11678	0.5474	0.5484694

measurement. This trend can be observed for all distances, although there is a significant increase in salt affected soils with greater distance from the site. Skeletal soils also increase, which is probably linked to increased distance from fresh water. The strong preference for meadow and alluvial soils further indicates that settlement and land-use strategies are strongly connected to the lower parts of the floodplains and the fertile and more humid soil compositions. Despite an increased flooding vulnerability, intensive agricultural exploitation and pasture can be assumed in close distance to the settlements. The chronological differentiation reveals a somewhat heterogeneous result. In the Early Neolithic period, meadow soils played a significantly major role in close distance to the settlement. At small-scale, Chernozem soils are important location factors as well while sand soils, lithomorphic soils and Brown Forest soils were avoided. Surprisingly, salt-affected soils were significantly located in a one to five kilometer distance around the sites, which could point towards salt exploitation or environmental change and extensively flooded and shallow lake areas with salt accumulation from weathering processes during the Early Neolithic. The Middle Neolithic provided the most homogeneous results, probably linked to the largest sample size. During this period, floodplain-related soils like alluvial and meadow soils are significantly distributed within all distances. Salt affected soils gain in importance with larger distances from the sites. All other soils were avoided or did not play a major role in the decision-making process of a settlement location during the Middle Neolithic. In the subsequent Late Neolithic, alluvial soils were again the predominant soil type in the catchments of the sites. Surprisingly, Chernozem soils cannot be considered significant location parameters according to the p-values. Sand soils were clearly avoided while lithomorphic and more stony soils can be found in variable significance around the sites.

3.3. Multivariate surface analysis

The very close distance between the sites and the next available meadow and alluvial soil patches underlines the importance of rather wet or hydromorphic soils close to fresh water outside the periodically flooded areas. The local agricultural interaction radius was set to a 3 km buffer what supports the theory and the results of local cereal growing supported by pollen data (Bogaard et al., 2007).

However, some sites are not situated on suitable soils. The sites at ABO, FAGA, DEOR, SAVO, SZEG, TIDO and TISO are located in modern urban agglomerations, which does not allow for the determination of a clear soil signal due to the modern bias. Only the site at PULE neither shows a modern urban bias nor *in situ* high quality soil conditions. However, extensive meadow soils and Chernozem are available in very close distance to PULE. The availability of running fresh water and the protection from flooding becomes visible in the spatial behavior of the sites. No Neolithic sites are located in the observed floodplain and the accumulated potential water surface.

The intense agricultural utilization of the modern Hungarian landscape can be estimated from modern satellite imagery analyses. Most of the low-lying parts of the Great Hungarian Plain are used for (irrigated) crop cultivation, which caused dramatic shifts in the surface composition due to drainage or irrigation channel construction. Furthermore, the modern river system has experienced massive regulations and channeling activity during the 20th century what makes it difficult to draw conclusions about premodern environmental dynamics from modern datasets. However, the strong modern overprint that is visible in the 3 km buffer around the archaeological sites would suggest a hypothetical site-continuity in agriculturally favorable areas with high quality soil properties and low environmental vulnerability. On the other hand, the archaeological record used in this paper could also be significantly biased by the modern built-up change, which created an Neolithic distribution in areas that are spatially congruent with recent earth movements, extensive surface re-modelling, and an active archaeological survey activity. Both results can be considered a realistic contribution to potential Neolithic site dispersal in Hungary. It is however noteworthy, that the modern urban agglomerations are often spatially identical with the archaeological record.

Terrain roughness and landscape permeability were assessed via a digital elevation model and the calculated slope gradients >10°. Most of the sites are located in flat areas with no steep slopes. Some sites do show considerable terrain roughness in the catchment areas. This is mostly due to their location outside the floodplain and on palaeolevees along the valleys.

A landscape accessibility surface was processed from the hydrological and topographical landscape analyses. Fig. 13 shows an example of the accumulative surface with a fuzzy gradient from high to low. A high value is equal to high landscape accessibility and enables an individual to travel from one point to another without expending a high amount of energy. Due to the fact, that these surfaces include hydrological information and the spatial extent of the observed/accumulated flooding zone, the limitations of the movement corridor within the catchments varies greatly depending on the location close to a river or the shoreline of Lake Balaton. Most sites are located within a reasonable movement corridor that allows for high mobility at low-energy expenditure. Several sites show strict limitations due to the accumulation of the hydrological situation in the vicinity (e.g. TISO and BOVO) or the adjacent topographical conditions (e.g. BUD and the BAM, BAL, ALE and MORT complex). It becomes clear that the terrain roughness creates movement corridors along the valleys which fit the pedological conditions and the accumulated alluvial deposits that produce rather fertile soils in comparison to the lithic or sandy soils of the adjacent hills (e.g. SEKU, BORK). The site location parameters of rapid fresh-water access and fertile soils in a highly permeable landscape determine the most suitable natural prerequisites.

Finally, a potential model for land-use opportunities around the 49 Neolithic sites in Hungary was processed from the accumulative site-catchment analyses, the accumulative potential water surfaces,

Table 4

Table showing the results of the Kolmogorov-Smirnov test (D, p-value) and the Vargha-Delaney A test (p-value) for nine soil classes in Hungary. The soil values were created using the r.neighbors function in GRASS, which makes each cell category value a function of the category values assigned to the cells around it. Neighborhoods of 1,2,3, and 5 km from each soil raster cell were chosen and the values for the chronological periods from Early, Middle, and Late Neolithic as well as the Chalcolithic were calculated.

Soil class	Total 1 km D	Total 1 km KS p-value	Total 1 km VDA p-value	Total 2 km D	Total 2 km KS p-value	Total 2 km VDA p-value	Total 3 km D	Total 3 km KS p-value	Total 3 km VDA p-value	Total 5 km D	Total 5 km KS p-value	Total 5 km VDA p-value
Chernozem	0.19643	0.05439	0.5655204	0.2191	0.02256	0.5843673	0.24729	0.006607	0.5818367	0.21988	0.02185	0.5805408
Forest Brown soil	0.14337	0.2923	0.4483469	0.14337	0.2923	0.4575714	0.13237	0.3863	0.4641735	0.14159	0.3062	0.4670306
Meadow soil	0.27261	0.001931	0.6319184	0.23884	0.009697	0.6173367	0.23865	0.009777	0.6068469	0.21592	0.02567	0.6045102
Sand soil	0.10114	0.7257	0.4513061	0.15051	0.2405	0.4196122	0.17792	0.1039	0.4178776	0.17651	0.1089	0.4218367
Peat soil	0.014633	1.0	0.5037347	0.07349	0.9625	0.5344694	0.063714	0.9914	0.5297755	0.065449	0.9882	0.5199592
Alluvial soil	0.25416	0.004787	0.6119898	0.2498	0.00588	0.6107041	0.23543	0.01128	0.6147041	0.22861	0.01515	0.6249388
Lithomorphic soil	0.071	0.9726	0.5036633	0.046	1.0	0.5011122	0.043898	1.0	0.5094796	0.086347	0.8771	0.5288571
Skeletal soil	0.090898	0.835	0.518602	0.11808	0.5327	0.5268163	0.12512	0.4575	0.5502959	0.19553	0.05621	0.5686122
Salt-affected soil	0.055	0.9989	0.5043673	0.098571	0.7545	0.5267653	0.16261	0.1690	0.5602347	0.21888	0.02277	0.5861327
Soil class	**Early Neolithic 1 km D**	**Early Neolithic 1 km KS p-value**	**Early Neolithic 1 km VDA p-value**	**Early Neolithic 2 km D**	**Early Neolithic 2 km KS p-value**	**Early Neolithic 2 km VDA p-value**	**Early Neolithic 3 km D**	**Early Neolithic 3 km KS p-value**	**Early Neolithic 3 km VDA p-value**	**Early Neolithic 5 km D**	**Early Neolithic 5 km KS p-value**	**Early Neolithic 5 km VDA p-value**
Chernozem	0.40733	0.2757	0.6486667	0.39233	0.3176	0.62675	0.39533	0.3089	0.6231667	0.37267	0.3789	0.64275
Forest Brown soil	0.3910	0.3215	0.35275	0.3820	0.3489	0.3848333	0.3820	0.3489	0.4181667	0.3450	0.4767	0.4165
Meadow soil	0.55633	0.04985	0.77575	0.5420	0.06014	0.7916667	596	0.0289	0.7856667	0.5430	0.05937	0.7428333
Sand soil	0.2540	0.8363	0.3730	0.3750	0.3713	0.3125	0.3980	0.3013	0.3206667	0.4140	0.2583	0.3356667
Peat soil	0.7400	1.0	0.4630	0.21133	0.9527	0.5785	0.15833	0.9983	0.4639167	0.2620	0.8076	0.5154167
Alluvial soil	0.19433	0.9779	0.5715	0.11033	1.0	0.5310	0.1690	0.9957	0.56075	0.35433	0.4423	0.61225
Lithomorphic soil	0.1260	1.0	0.4370	0.17890	0.9910	0.4105	0.1990	0.9722	0.4589167	0.2510	0.8466	0.5604167
Skeletal soil	0.2180	0.9394	0.3910	0.2810	0.7340	0.5775833	0.3330	0.5228	0.5870	0.4130	0.2609	0.56675
Salt-affected soil	0.19933	0.9718	0.5623333	0.3260	0.5504	0.6033333	0.42933	0.2216	0.7040	0.5250	0.07467	0.7438333
Soil class	**Middle Neolithic 1 km D**	**Middle Neolithic 1 km KS p-value**	**Middle Neolithic 1 km VDA p-value**	**Middle Neolithic 2 km D**	**Middle Neolithic 2 km KS p-value**	**Middle Neolithic 2 km VDA p-value**	**Middle Neolithic 3 km D**	**Middle Neolithic 3 km KS p-value**	**Middle Neolithic 3 km VDA p-value**	**Middle Neolithic 5 km D**	**Middle Neolithic 5 km KS p-value**	**Middle Neolithic 5 km VDA p-value**
Chernozem	0.25047	0.0323	0.5906324	0.30188	0.004991	0.6238382	0.33794	0.001095	0.63125	0.28053	0.01131	0.6238676
Forest Brown soil	0.14435	0.4997	0.4520294	0.14459	0.4976	0.4430	0.16118	0.3602	0.4465294	0.15218	0.4316	0.4518824
Meadow soil	0.27141	0.01574	0.6306176	0.23165	0.05867	0.6079853	0.20365	0.1307	0.5926471	0.21412	0.09808	0.5838529
Sand soil	0.079176	0.9861	0.4861765	0.11859	0.7442	0.4661324	0.11459	0.7810	0.4675735	0.12	0.7309	0.4713676
Peat soil	0.040588,	1.0	0.5055882	0.058471	0.9999	0.5129559	0.060647	0.9997	0.5068824	0.091882	0.9441	0.4731471
Alluvial soil	0.21935	0.08448	0.5964853	0.23059	0.06059	0.6013529	0.25224	0.03047	0.6211176	0.27271	0.01503	0.6535294
Lithomorphic soil	0.0740	0.9938	0.4797794	0.069765	0.9972	0.4812059	0.084176	0.9739	0.4767647	0.069176	0.9975	0.4929118
Skeletal soil	0.061471	0.9997	0.4973971	0.066882	0.9985	0.4764412	0.078471	0.9874	0.5020	0.11329	0.7925	0.5218824
Salt-affected soil	0.082118	0.9796	0.5271912	0.19941	0.1463	0.5710882	0.22024	0.08236	0.5839559	0.23629	0.05085	0.6050
	Late Neolithic 1 km	**Late Neolithic 1 km**	**Late Neolithic 1 km**	**Late Neolithic 2 km**	**Late Neolithic 2 km**	**Late Neolithic 2 km**	**Late Neolithic 3 km**	**Late Neolithic 3 km**	**Late Neolithic 3 km**	**Late Neolithic 5 km**	**Late Neolithic 5 km**	**Late Neolithic 5 km**

(*continued on next page*)

Table 4 (*continued*)

Soil class	Total 1 km D	Total 1 km KS p-value	Total 1 km VDA p-value	Total 2 km D	Total 2 km KS p-value	Total 2 km VDA p-value	Total 3 km D	Total 3 km KS p-value	Total 3 km VDA p-value	Total 5 km D	Total 5 km KS p-value	Total 5 km VDA p-value
Soil class	**D**	**KS p-value**	**VDA p-value**	**D**	**KS p-value**	**VDA p-value**	**D**	**KS p-value**	**VDA p-value**	**D**	**KS p-value**	**VDA p-value**
Chernozem	0.24	0.6185	0.48655	0.2120	0.7651	0.4888	0.2	0.8233	0.50045	0.2440	0.5974	0.5051
Forest Brown soil	0.15	0.9791	0.51755	0.1270	0.9972	0.51805	0.1410	0.9893	0.5142	0.1770	0.9157	0.4861
Meadow soil	0.1770	0.9157	0.5438	0.3370	0.2108	0.5596	0.2690	0.4708	0.55385	0.2520	0.5557	0.5710
Sand soil	0.1540	0.9730	0.4206	0.2750	0.4424	0.3620	0.3230	0.2529	0.34585	0.31	0.2973	0.3406
Peat soil	0.0930	1.0	0.5160	0.09	1.0	0.52765	0.0820	1.0	0.49135	0.2260	0.6926	0.56995
Alluvial soil	0.3780	0.1181	0.66285	0.3930	0.09392	0.66465	0.32	0.2627	0.63745	0.3180	0.2693	0.60525
Lithomorphic soil	0.2930	0.3632	0.62595	0.3010	0.3310	0.61485	0.3160	0.2762	0.6402	0.3010	0.3310	0.6172
Skeletal soil	0.2940	0.3590	0.6052	0.2820	0.4105	0.5739	0.29	0.3757	0.59285	0.3680	0.1369	0.61625
Salt-affected soil	0.13	0.9962	0.4796	0.1810	0.9019	0.42385	0.17	0.9371	0.4718	0.1820	0.8983	0.52075
Soil class	**Chalcolithic 1 km D**	**Chalcolithic 1 km KS p-value**	**Chalcolithic 1 km VDA p-value**	**Chalcolithic 2 km D**	**Chalcolithic 2 km KS p-value**	**Chalcolithic 2 km VDA p-value**	**Chalcolithic 3 km D**	**Chalcolithic 3 km KS p-value**	**Chalcolithic 3 km VDA p-value**	**Chalcolithic 5 km D**	**Chalcolithic 5 km KS p-value**	**Chalcolithic 5 km VDA p-value**
Chernozem	0.23333	0.9015	0.4979167	0.17933	0.9908	0.5105	0.2280	0.9158	0.4836667	0.2830	0.7259	0.5021667
Forest Brown soil	0.22433	0.9249	0.4483333	0.21533	0.9449	0.4244167	0.21533	0.9449	0.4579167	0.17833	0.9914	0.4811667
Meadow soil	0.26033	0.8137	0.5183333	0.25533	0.8316	0.5424167	0.25133	0.8455	0.5499167	0.23933	0.8841	0.5461667
Sand soil	0.13467	0.9999	0.4721667	0.20833	0.9580	0.4204167	0.18933	0.9831	0.4390	0.23133	0.9070	0.4604167
Peat soil	0.096667	1.0	0.5408333	0.3640	0.4082	0.6533333	0.3250	0.5544	0.6281667	0.2170	0.9415	0.58125
Alluvial soil	0.21333	0.9489	0.57125	0.2720	0.7696	0.6059167	0.1790	0.9910	0.5714167	0.1510	0.9992	0.49175
Lithomorphic soil	0.088667	1.0	0.5179167	0.11567	1.0	0.50025	0.10667	1.0	0.4820833	0.13767	0.9999	0.5250
Skeletal soil	0.1320	0.9999	0.4703333	0.15933	0.9981	0.4926667	0.14267	0.9997	0.4575833	0.1530	0.9999	0.51975
Salt-affected soil	0.2190	0.9372	0.3905	0.2030	0.9666	0.46625	0.1290	1.0	0.5123333	0.1510	0.9992	0.49175

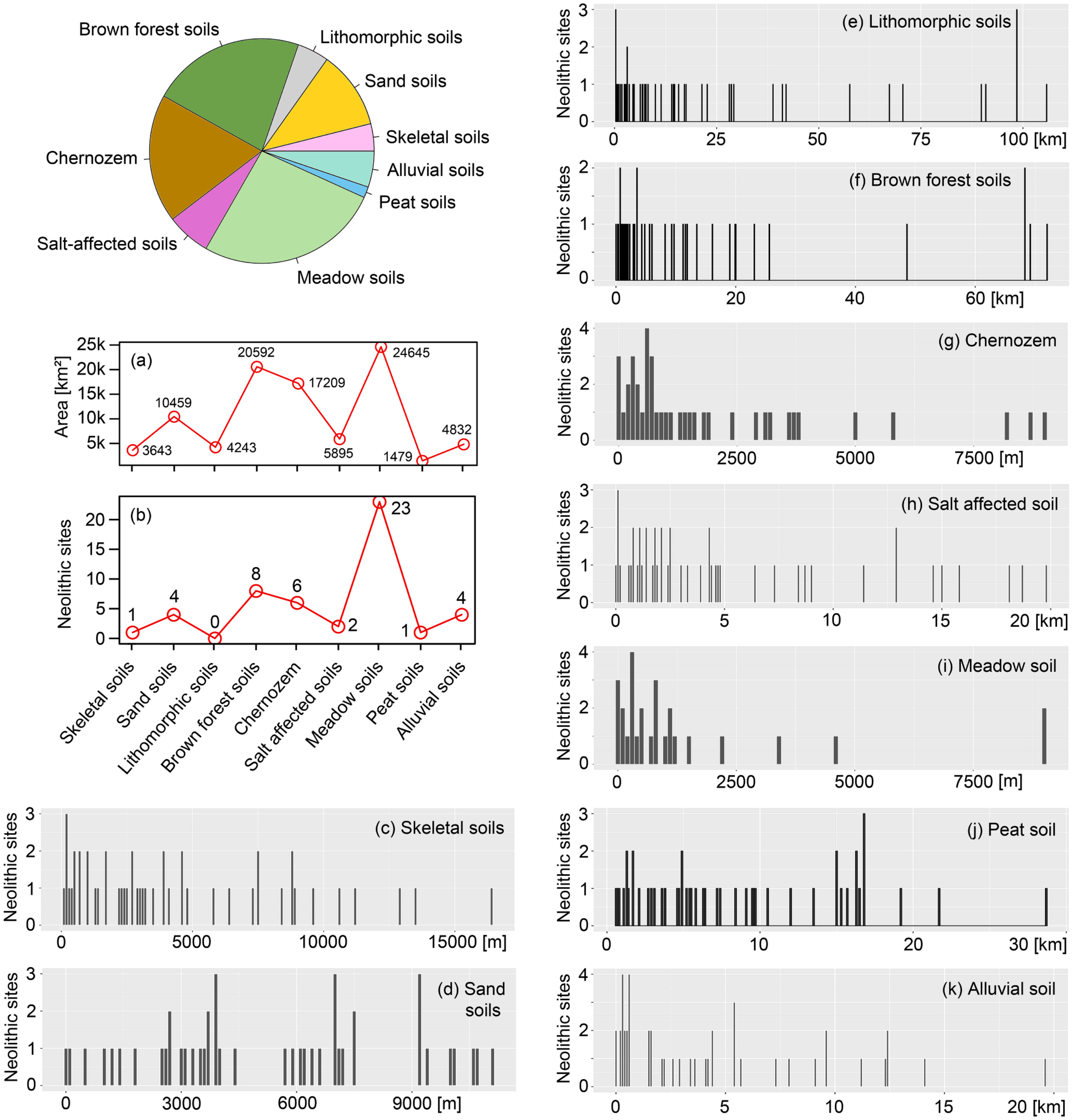


Fig. 10. Spatial analyses of the soil location parameters in Hungary. Hungary is mostly covered with brown forest soils, Chernozems and meadow soils. A significant portion is further covered by sand (a). Neolithic sites generally correlate spatially with the soil proportions, however there is a significant increase in site density on meadow soils (n = 23) and a rather unproportional distribution on Chernozems and brown forest soils. Skeletal, salt affected, sandy, peaty and lithomorphic soils show expected low site concentrations (b). The distance analyses (c-k) of the soil units and the sites that lie outside of the respective units reveal a strong spatial interrelation between site distribution and meadow soils, alluvial soils, and Chernozems. Most of the sites that are not already situated on meadow soils or Chernozem lie in short distance to the next respective soil patches. Only salt affected and alluvial soils show a slightly similar spatial behavior. The other soil units play a minor role as site-location factors.

landscape permeability, and the soil units in a three kilometer distance around each site (Fig. 14). The strong link between local environmental interaction and utilization ranges points towards a localized subsistence economy with local cereal growing and livestock breeding. Potential agriculture therefore would take place in the immediate surroundings of the sites that show fertile high-quality soils, a direct access to running fresh water and a high flooding security. Sites that are not directly located on high quality soil assemblages or do not feature potentially suitable landscape patches, are closely connected to utilizable areas within a short distance (e.g. ABO, BOVO, DEOR, FAGA, SAVO, SZEG, PULE, TISO and TIDO). Only the site GAEL at the river Hernád does not show any potential location parameters due to weak landscape permeability. The digital elevation model shows high slope gradients in the catchment that permit an overall accessibility of the site. The site MORT is located west of the river Danube in topographically elevated situation. The slope gradient and the soil compositions in the immediate

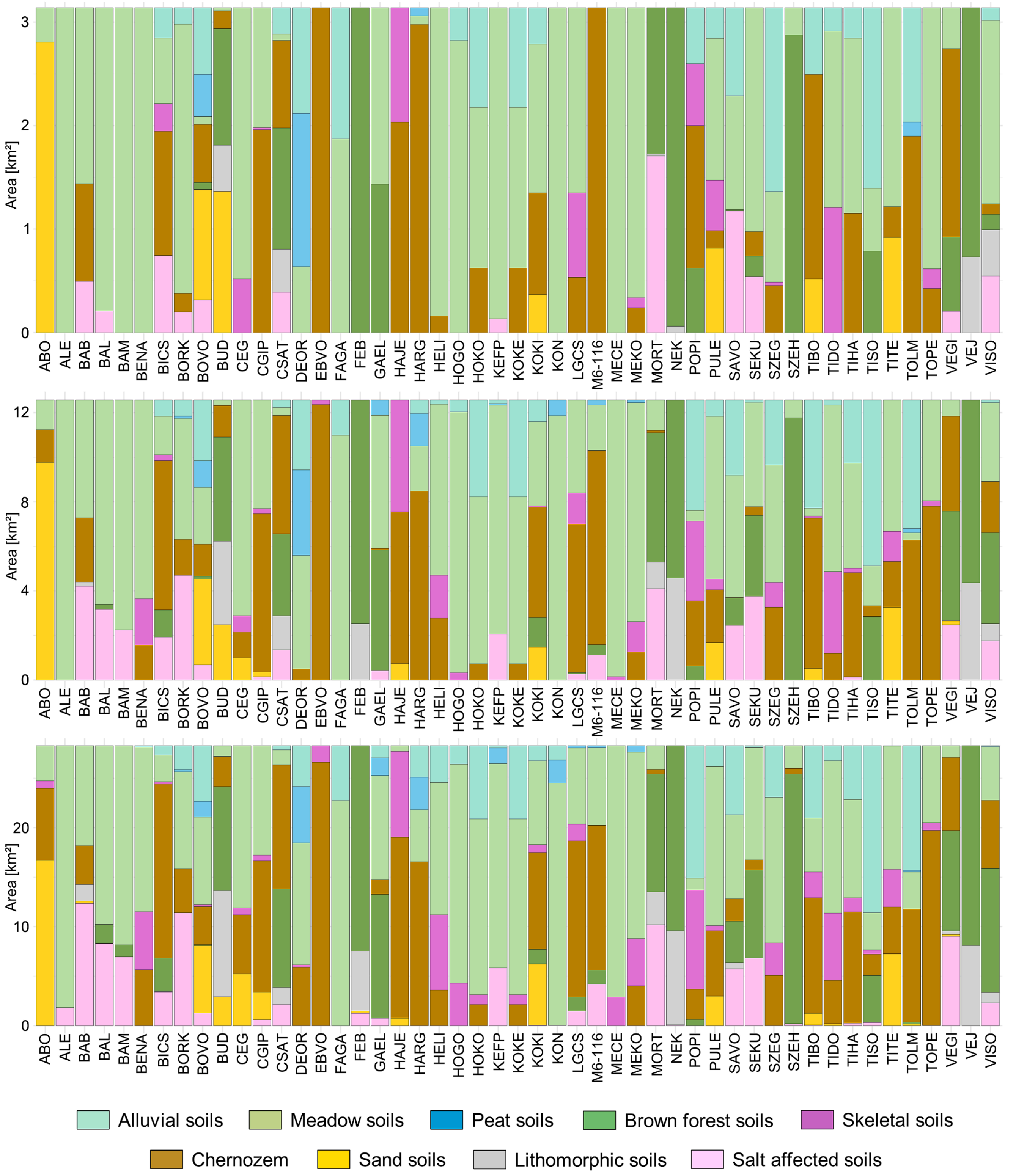


Fig 11. Soil distribution in the catchment areas of the study sites. Three buffer distances (r = 1 km, r = 2 km, r = 3 km) were selected and the respective areas covered by each soil unit was plotted for each site. The 1 km radius (upper bar plot) shows the dominance of meadow soils, Chernozems and forest brown soils in the immediate surroundings of the sites. The soil mosaic increases in variety at a 2 km radius (middle bar plot) with continuous dominance of meadow soil patches. Unfavorable soil units like sand soils decrease in the ratio with a slight increase of salt affected soils in the assemblages. The 3 km radius intensifies the number of salt-covered soil variations with increasing variety of Chernozems and meadow soils in the near distance to each site.

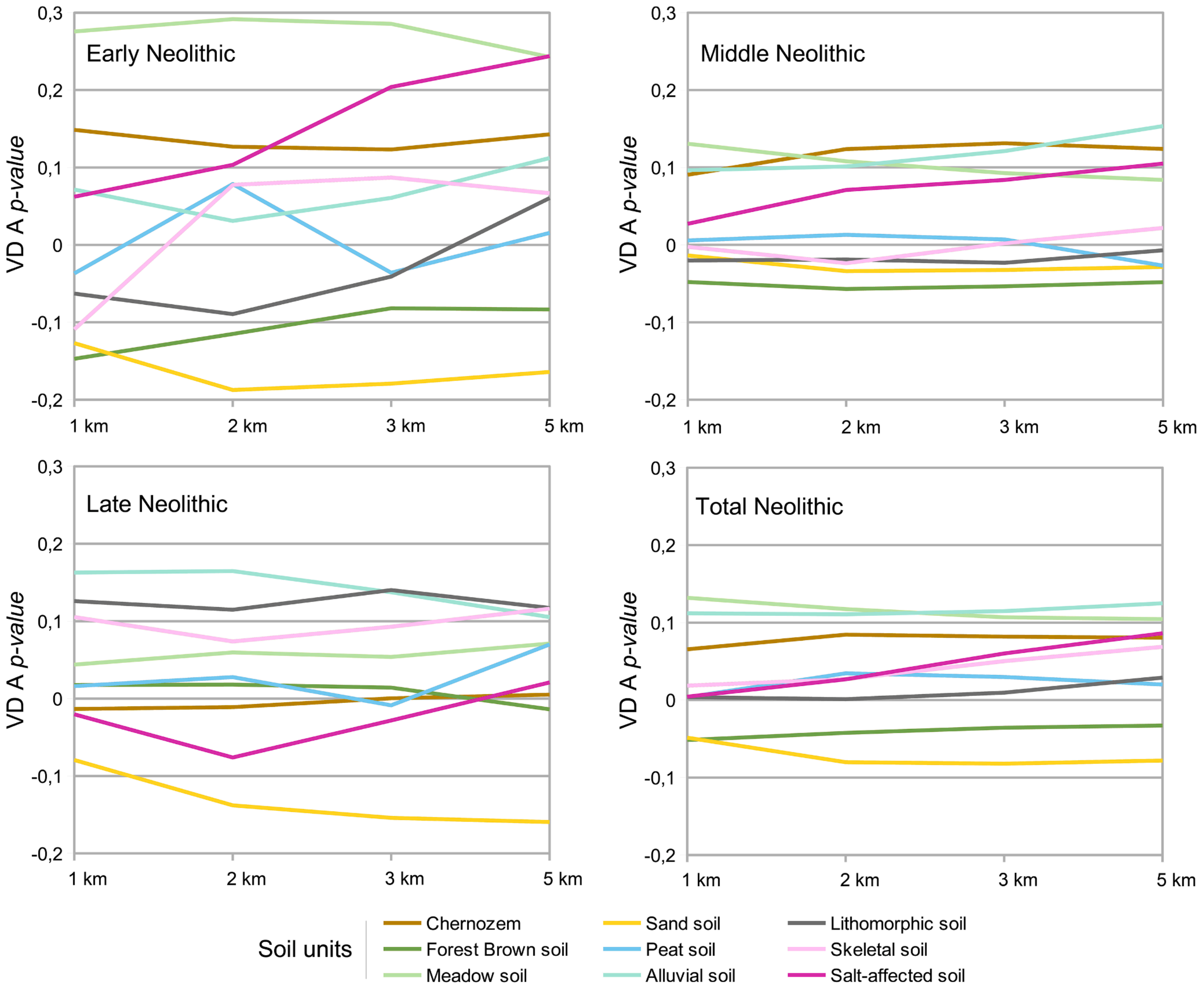


Fig. 12. *P-values* of the Vargha-Delaney A statistics from the soil composition of 49 Neolithic sites in Hungary compared to a set of 1000 random comparison points over variable distances around the sites. During the Early Neolithic, sand soils, Forest Brown soils, lithomorphic, and skeletal soils were avoided by early farmers and meadow soils, alluvial, and Chernozem soils were significantly favored. During the Middle Neolithic, the distinction becomes more significant and in the Late Neolithic, particularly soils close to the floodplain were favored while Chernozem soils decrease in preference. Through all periods, salt-affected soils could have played a considerable role in location choice. The signal of all Neolithic sites shows significant preferences for alluvial and meadow soils and partly Chernozem soils. Sand soils, Brown Forest soils, lithomorphic soils and peat soils were avoided by Neolithic communities. P-values were reclassified to increase readability. Positive values indicate significant preference, negative values indicate avoidance.

surroundings are not ultimately favorable for high quality crop cultivation. Furthermore, as reported from Zalai-Gaál (1990), severe surface erosion took place in the area what recently decreased the soil quality and probably biased the modern soil-datasets of the major soil types in Hungary (Zalai-Gaál, 1990).

The potential land-use model illustrates the strong link between site distribution and the soil properties. Probably the Chernozem soil patches did not play an overall major role in Neolithic land-use strategies but rather (hydromorphic) meadow soils and alluvial soil. A strong local restriction to Chernozem cannot be observed in the model. Apparently, the soil mosaic properties offered the greatest variety of potential surface utilization with crop cultivation on both loess influenced Chernozem soils and rather humid meadow and alluvial soils in lower parts of the catchments. Livestock breeding could have therefore been connected to the lower parts of the floodplains and the immediate access to fresh water.

4. Discussion

Scale-based site catchment analyses are subject to several filters, which contain a variety of variables. Among others, these are demographics, number and distribution of actual settlements, demand for land, land-use patterns, economic sustainability, and population-internal resilience. The determination of a potential land-use radius is therefore not subject to the individual perspective of the archaeologist or geographer, but rather to a statistical procedure for the spatial documentation of landscape elements and their behavior at different scales. The discussion of different scales in archaeological research is problematic – not only in terms of demographic predictions, but also for the analysis of the catchment area and the determination of a local, micro- and macro-regional scale (Knitter et al., 2018; Müller and Diachenko, 2019; Roper, 1979; Volkmann, 2018). Sites are perceived as 0-dimensional points from which economic, social and cultural activities were carried out (Roper, 1979). This enables quantitative statistics but denies that these activities depend not only on central-place-theory, but

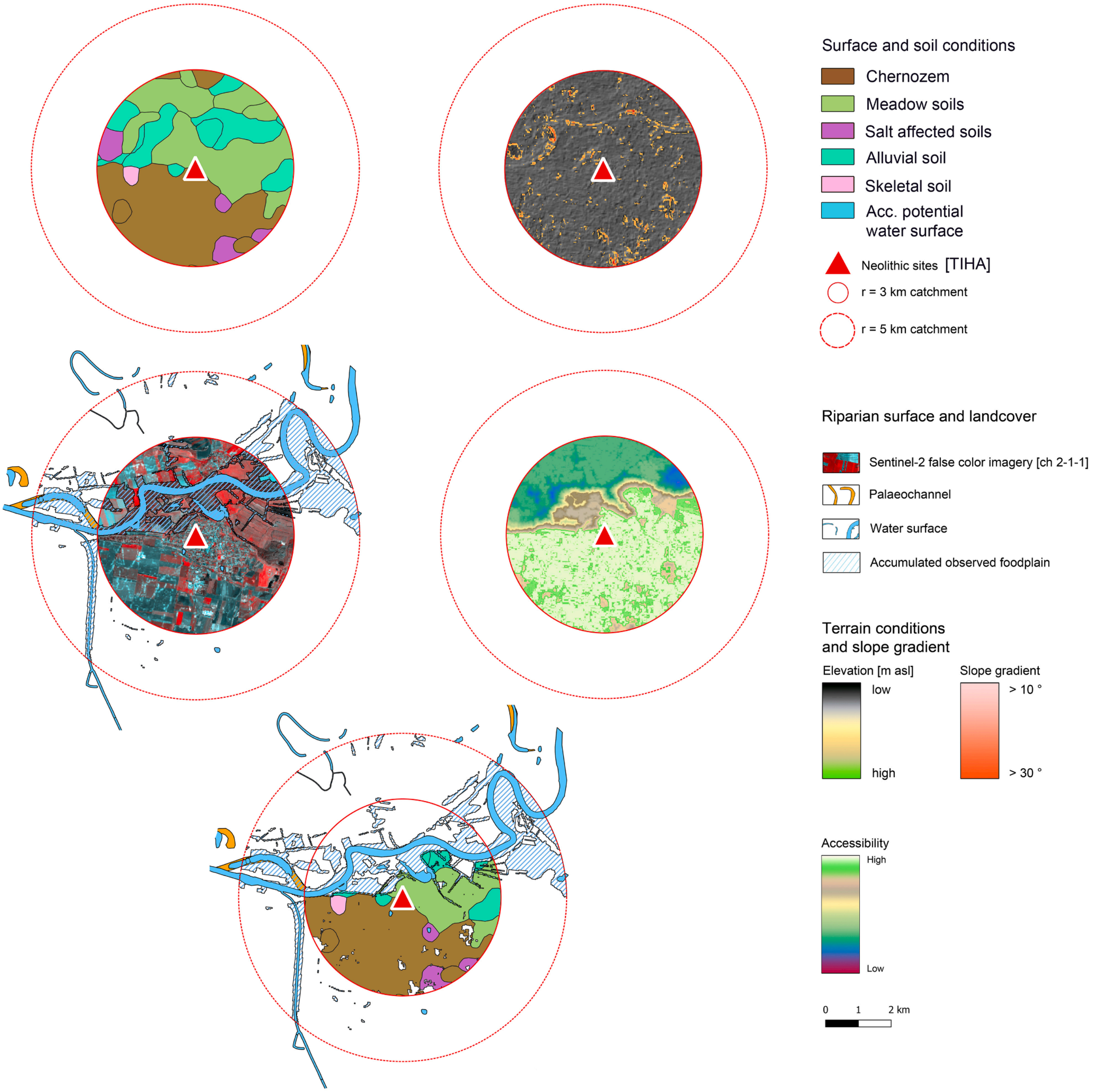


Fig 13. Exemplary visualization of the landscape analyses and finally land-use opportunities at Tiszalök-Hajnalos (TIHA), located at the river Tisza. Displayed are soil patches within a 3 km buffer around the site, accumulated floodplain dynamics and palaeochannels, elevation and slope gradients, and multivariate accumulative surface based on an accumulative flooding area, the hydrological system, and terrain roughness (slopes > 10°).

also on the immediate topography and thus the ultimate landscape permeability around the site. Although the supra-regional understanding of ecological feedback and interrelationships is inevitable for the interpretation of large natural environmental networks, an additional site analysis on the small-scale creates knowledge of the complex relationships between geological strata, soil coverage, surface development, and the hydrological system that control local human behavior within a local community. Depending on the extent of the research area, inaccurate terminology of scale and the unprecise implementation of site catchments can rapidly lead to misinterpretations of human-environment and human–human interactions (Harris, 2017). No-data corridors were created that either do not contain archaeological records or are considered lacking the potential of pre-modern development. Both considerations are misleading. With reference to spatial modelling, the scale-dependent critical analysis of topographic data is a way to getting closer to understanding potential pre-modern environmental conditions.

4.1. Holocene landscape dynamics

Holocene landscape and surface dynamics are ultimately linked to the hydrological system, soil development, climate oscillations, and vegetation shifts (Magyari et al., 2010). It has frequently been argued that the Hungarian hydrological system experienced major relocation processes in the Late Pleistocene and the Early Holocene. The river Tisza and the river Danube both changed their river-course several kilometers

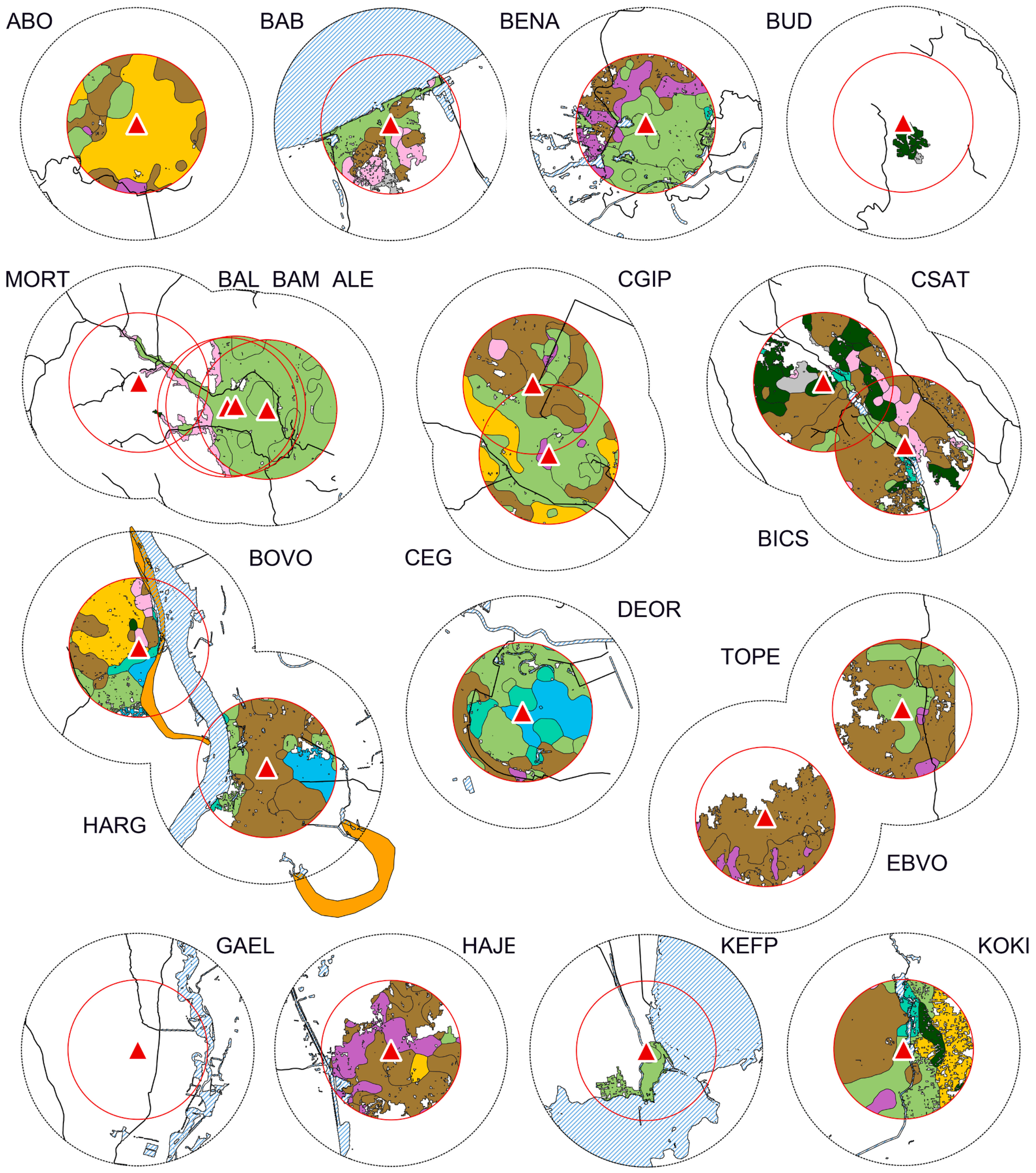


Fig. 14. Potential land-use around Neolithic sites in Hungary based on accumulative potential water surface, landscape permeability, and soil units.

to the west – what created sandy alluvial patches (e.g. in the DTI) that were locally covered with Late Pleistocene/Early Holocene loess on uneroded levees and fine-grained clayey material with high organic carbon content in the low-lying parts of the former palaeochannels. The Early Neolithic Körös culture and the Criş culture that occupied broad areas along the middle and the upper part of the river Tisza, however, can be traced on both sites of the river-course (Domboróczki and Raczky, 2010; Molnár and Sümegi, 2007), which points towards a stable riverbed system after the Early Neolithic.

The river Tisza is bordered to the west by the subsequent alluvial deposits of the elevated DTI. The Interfluve does not show significant archaeological records underlying this study. However, it has been argued by Bánffy (2012) that this is not necessarily connected to the limited land-use potential and the increasing aridity of the DTI but could also be due to limited archaeological research in the area (Bánffy, 2012). Consequently, the poor archaeological record of the DTI is not mandatorily attached to erosion and accumulation processes of the west-moving river Tisza floodplain.

Magyari et al. (2010) argued that persistent steppe vegetation with temperate deciduous wooded steppe grasslands and saline tall-grass

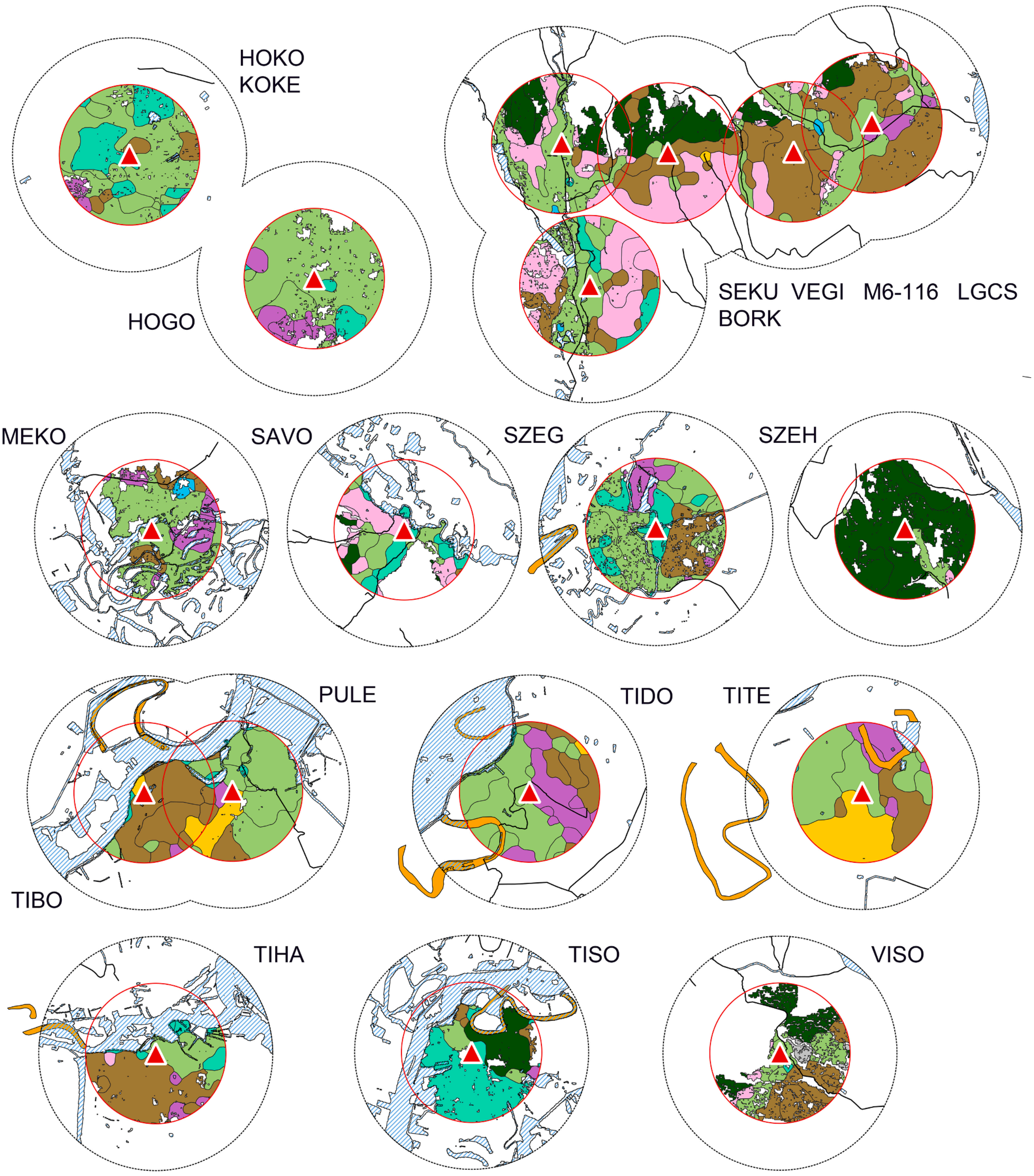


Fig. 14. (*continued*).

meadows developed in the Great Hungarian Plain throughout the Holocene. The *steppe-vegetation paradigm*, as labelled by Sümegi et al. 2019, however, can probably not be confirmed for entire Hungary and pollen analyses alone may not yield all the required information for a comprehensive palaeovegetation reconstruction (Sümegi et al., 2013b). Because Hungary was not glaciated during the last glacial period, cold-resistant species survived in micro-refuges in the southern part of the Carpathian Basin where continuous soil development took place (Sümegi et al., 2019, 2013b; Sümegi, Persaits and Gulyás, 2012). At the transition to the Holocene, a mosaic of boreal-type forest-steppe vegetation spread to the north, which was highly vulnerable to natural fires further accelerating the development of a forest-steppe coverage (Sümegi et al., 2012). In the Mid-Holocene, climate reconstructions propose increased warming and pollen analyses revealed a dramatic shift from coniferous to deciduous forest in the Early Holocene (Kasse et al., 2010). However, as Feurdean (2005) pointed out for the north-western part of Romania (Gutaj Mountains), *Corylus* became dominant in the forest while all other deciduous tree species declined between 7300 and 3750 BCE, probably due to cooler and drier conditions and a reversal to cooler and moister conditions from about 4800 BCE (Feurdean, 2005). Pollen analyses from the southern Carpathians further demonstrated Early Holocene warming and forestation followed by rapid summer cooling and increased moisture availability in the Mid-Holocene (Magyari et al., 2009). Vegetation response may thus be

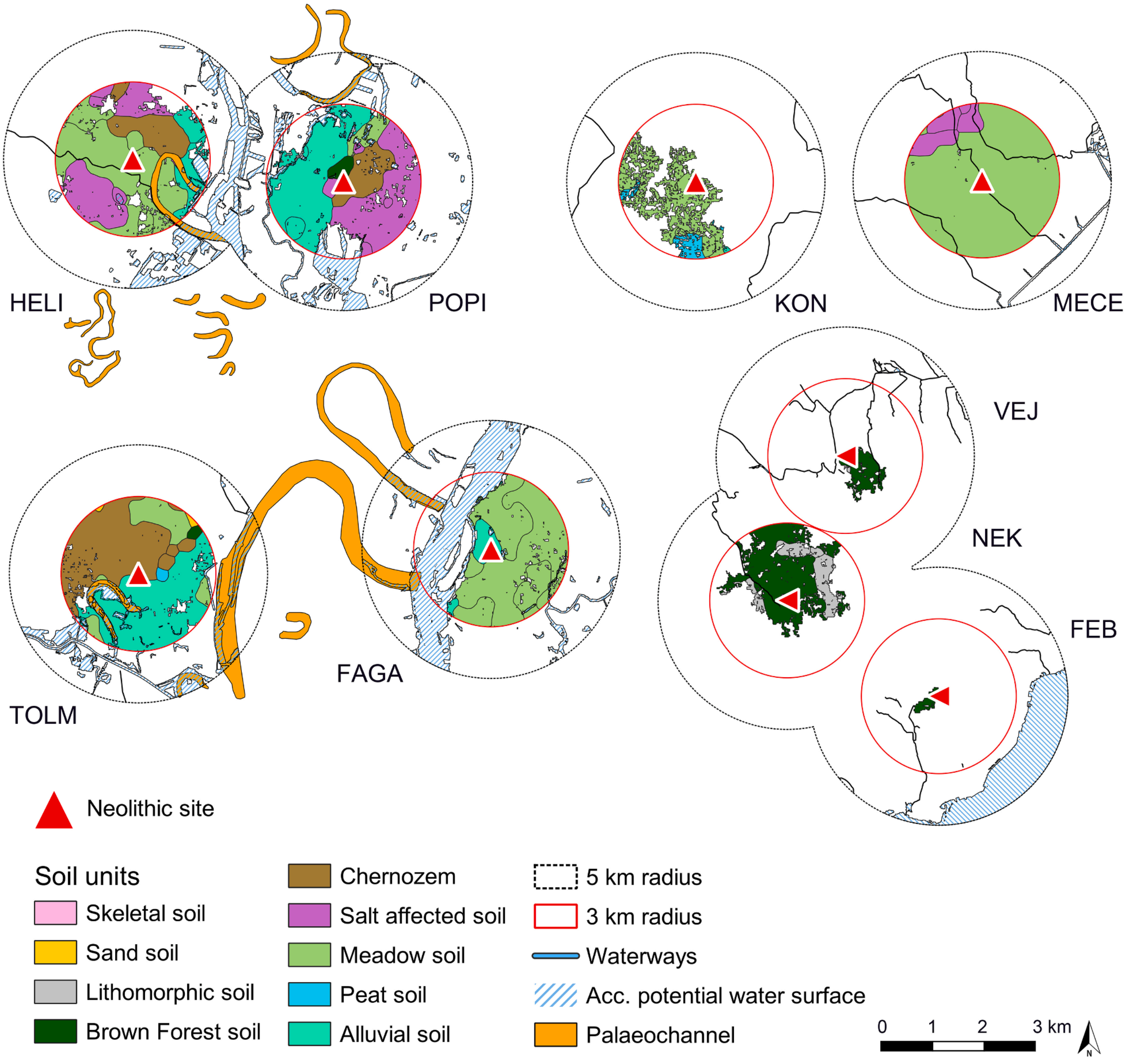


Fig. 14. (*continued*).

controlled by the topographical situation and cooler and drier conditions may have prevailed in the Great Hungarian Plain throughout the Early and Mid-Holocene while the Carpathian Mountains experienced increased moisture availability.

According to Kiss et al. (2015), groundwater dropping in the DTI led to forest decline and replacement by steppe vegetation during the Boreal Phase (Kiss et al., 2015; Sümegi et al., 2012). The subsequent Atlantic Phase was characterized by reforestation under warmer and moister conditions. However, the second half of the Atlantic Phase shows evidence for drier conditions and reactivation of aeolian activities. River dynamics during that time show strong avulsion events that most likely were triggered by tectonic subsidence processes and not by environmental shifts (Kiss et al., 2015). The increased vegetation coverage in the early Atlantic Phase thus would have prevented soil erosion and superficial runoff in the catchment areas of the tributaries of the river Tisza, which would result in decreased sediment input and fewer flooding events. Intra-floodplain channel erosion would rather stabilize the smaller Holocene channels of the meandering river (Kasse et al., 2010). However, Neolithic and the subsequent anthropogenic landcover change could have had a significant impact on the sediment transport and the fluvial regimes of the Hungarian river system. Deforestation activity and slash and burn agriculture may have not only had a strong effect on the soil assemblages and the transformation of Chernozems on loess-covered ridges but could have also led to the reactivation of palaeochannels during cooler and drier conditions (Heyvaert et al., 2012; Heyvaert and Walstra, 2016; Kabała et al., 2019; Lorz and Saile, 2011; Stouthamer and Berendsen, 2000).

4.2. Neolithic soil development and land-use strategies in the Carpathian Basin

Over the past decades, the importance of loess in the spread of Neolithic agriculture has been intensely discussed (Bakels, 2014; Gronenborn, 1999; Hedges et al., 2013; Kreuz, 2007; Saqalli et al., 2014; Sielmann, 1972). The spatial congruence of the loess belt and the development of early farming techniques is often used to explain different subsistence strategies, the theory of shifting cultivation, or the establishment of permanent and manured fields and settlement patterns from the Carpathian Basin to the northern margins of the river Rhine (Bogaard et al., 2013; Brounen et al., 2010; Gronenborn, 1999; Rivollat et al., 2016; Saqalli et al., 2014; Vanmontfort et al., 2010). However, the soil formation on loess varies locally due to variations in climate, the nature of the soil parent material, wildfire, and the impact of human land-use (Catt, 2001; Feurdean et al., 2020; Schmidt et al., 1999). Chernozems in Hungary are supposed to develop under steppe or deciduous forest vegetation and in combination with the subsequent human deforestation and utilization activity. The extensive development of the different types of Chernozems in Hungary is more complicated and locally dates back to the Holocene (Michéli et al., 2006; Smalley et al., 2011; Sümegi et al., 2013b; Vysloužilová et al., 2015). The Hungarian major soil type classification system distinguishes nine different soil characteristics (Michéli et al., 2006; Pásztor et al., 2018). According to Michéli et al. (2006), the various Chernozem types are frequently intermixing with each other, depending on groundwater level, vegetation type, and soluble salts, which generates a broad variety of subgroups such as meadow Chernozems or Chernozem brown forest soils.

Neolithic people, therefore, were not forced to prefer meadow soils in the close vicinity to Chernozem but rather focused on what was locally available in close distance to freshwater (Hedges et al., 2013). Even though the levees could have been broadly covered with loess, the generally sandy texture of the levee would rather not support agriculture due to the high surface water permeability, low water storage capacity, and the low-lying groundwater level (Sümegi et al., 2012). Crop cultivation on free-draining soils in considerable distance to a Neolithic settlement and under dry climatic conditions does not seem reasonable – as reported from other Neolithic sites (Araus et al., 1999; Roberts and Rosen, 2009; Wallace et al., 2015). Indications for crop planting in naturally wet soils that experienced periodical flooding and deposition of fine-grained marshy silt and relocated loess exists from the Near East (Araus et al., 1999). Yields on these fertile soils would have been higher than on the dry locations of the levees. Sümegi et al. (2013a), however, argue that in the alluvial Polgár island, a loess-covered lag surface in the upper Tisza region, Neolithic land-use took place on the Chernozem-covered palaeo-levees of the river (Sümegi et al., 2013c). The question remains, if this is due to the high flood vulnerability of the lower floodplain or the fertility of the Chernozem on top of the levees. According to the authors, the lower parts were still covered with Chernozem, hydromorphic Chernozem, and hydromorphic forest soils that developed under gallery forest vegetation (Sümegi et al., 2013c). Even though the mosaic soil patterns remain visible, the Neolithic land-use and deforestation had a considerable impact on the landscape, which is mirrored in the expansion of hydromorphic Chernozem soils and the disappearance of the forest soils (Sümegi et al., 2013c).

In addition, salt affected soils played a certain role in site location preferences of Neolithic farmers in Hungary (Bánffy, 2013, 2015, 2019). Saline soils are naturally tied to poor water drainage capacity and periodical waterlogging conditions. Generally, that does not enable intensive agricultural utilization. The amount of soluble salts in the soil and an evapotranspiration that exceeds the average precipitation determine the development of the strongly saline *Solonchaks* or the ameliorated steppe-meadow *Solonetz Soils* (Michéli et al., 2006). In the rather dry climatic conditions of the DTI, and especially in the river Tisza floodplain, large-scale salt affected areas are visible in the soil distribution maps (Fig. 13 b). Most of the sites are located in considerable distance to the next non-cultivable salt affected plains. However, salt-exploitation in the Neolithic Carpathian Basin is an important feature in the Neolithisation process due to the shift from a salt- and protein-rich meat-based diet towards a mixture of cereals with a low salt-content (Bánffy, 2013). Furthermore, salt is a substantial component of livestock breeding (Harding, 2015). A potential use of the extensive saline soils in parts of the Carpathian Basin is thus reasonable.

Despite the local Late Pleistocene/Early Holocene loess-coverage of the uneroded plateaus, the lower meadows would have been more suitable for agriculture. Soils that were dominated by a locally high aquifer or prone to periodical flooding would be classified as meadow soils in the typology – probably caused by the constant deposition of fine-grained clayey material and organic matter in topographical depressions (Michéli et al., 2006). Slightly elevated meadow soils with lower flooding vulnerability would consequently experience strong agricultural utilization, which would have strengthened the human-induced transformation of the parent-soil into a mature Chernozem (Barczi, Golyeva and Petö, 2009; Kleber et al., 2003; Strouhalová et al., 2019). In this context, strongly fragmented charred organic carbon (COC) and black carbon (BC) deriving from burning vegetation or by wind-blown transportation can be incorporated into the soil texture, which alters the composition, color, humic acid content, and soil organic matter (Schmidt et al., 1999; Schmidt and Noack, 2000). The carbon content from natural wildfires can be significantly increased through grassland or forest burning management. Although the environmental contexts cannot entirely be compared to the Neolithic soil development in the Carpathian Basin, Skejmstad et al. (1997) report from up to 30% increase of COC from artificially and continuously burnt Australian soil surfaces (Skejmstad et al., 1997) and Schmidt et al. (1999) confirm up to 45% of bulk organic carbon in chernozemic soils from Germany. Particularly the results by Schmidt et al. (1999) point towards Chernozem development in relation to increased COC content and burning activity from about 8.000 BP onwards, which aligns with the early Neolithic landscape transformation – independently from large-scale climatic conditions and vegetation patterns (Schmidt et al., 1999). Furthermore, the anthropogenic overprint of the ecosystem and the Neolithic landscape development was additionally reinforced by the increased presence of BC in the A-horizon of the cleared areas, which decreased regional surface reflectance and the albedo through enhanced ‘blackness’ of the surface (Hammes et al., 2007). Because of its pyrogenic origin and carbonaceous substance, BC is highly resistant to chemical and thermal degradation and has a long and stable residence time after accumulation and sedimentation, which highlights the importance of BC, fire, and anthropogenic land-use in the development of Chernozem across Europe (Hammes et al., 2007; Kleber et al., 2003; Preston and Schmidt, 2006; Schmidt et al., 2002; Thiele-Bruhn et al., 2014) and in particular in the Carpathian Basin during the Atlantic stage. This is in accordance with recent discussion about potential vegetation transition and recovery and the impact of herbivores on the natural vegetation as well as the maintenance of broad open landscape patches through fire and human impact (Doppler et al., 2017; Feurdean et al., 2020; Gerling et al., 2017; Kirby, 2004; Kreuz, 2007; Ochs et al., 2020).

Chernozem is the result of a long maturation of the soil organic matter. The black carbon can be a part of the soil organic matter, but this is not unconditional. Chernozem is in large parts of the world a zonal soil, where its formation is connected to the steppe vegetation, intensive bioturbation, carbonate parent material, and many other factors, which are not fully understood. Generally, the black color is due to the high organic matter content and the black carbon originating from vegetation burning can contribute to the soil organic matter. Across Europe, however, there is lack of direct evidence and analyses are still missing.

In addition to locally and regionally unclear soil development, the modern lowering of the groundwater level would further intensify soil degradation and erosion in most parts of the Great Hungarian Plain. Modern soil erosion during the past 100 years has locally removed the top-soil and the loess layers, which triggered the outcrop of the underlying geological basement (Kerényi, 1994) – making it particularly difficult to evaluate the original loess cover and the thickness of the prehistoric soil layers. Furthermore, a continuous Holocene soil development in the Carpathian Basin would implicate continuous climatic conditions and hence create homogeneous soil thickness with no interspersed palaeosoil layers or dust accumulations. Kiss et al. (2015) report from reactivated dust accumulation during drier periods in the Early Holocene and throughout the Atlantic Phase (Kiss et al., 2015). That fits the results from the Loess Plateau in China where Holocene dust deposits alternate frequently with weakly developed palaeosoil layers (Maher et al., 2003). With regard to Mid-Holocene climate variability in the Carpathian Basin and the trend towards cooler, drier, and windier conditions during the late Atlantic Phase, forest-cover decline, and the reactivation of sandy and silty deposits would also have reworked aeolian dust transportation. Weakly developed Chernozems would have then been covered by repeated loess sedimentation.

All Neolithic sites in this paper are situated outside the potential accumulated floodplain, which indicates protection from extensive flooding and loss of harvest and livestock. However, one can easily argue that our modern perception of the archaeological record is strongly biased by the findability of archaeological traces in modern land-use corridors (e.g. the massive built-up change) and in areas that did not experience strong surface cover modifications through erosion or accumulation processes. Hence, the fact that Neolithic records can be found outside the (modern and pre-industrial) erosion zone of the river Tisza and the river Danube seems logical. Moreover, as visible in modern satellite imagery, the whole landscape is ultimately restructured by recent anthropogenic overprints and interventions in the natural ecological balance. Drawing large-scale conclusions from modern datasets needs to consider the methodical limitations of the data.

5. Conclusions

Assessing Neolithic agricultural strategies through multivariate environmental analyses has proven to be a useful tool to understanding the scale of past human behavior. The integration of comprehensive ecological and geographical links and feedbacks in landscape archaeological research enables not only an interpretation of the spatio-temporal extent of human activity ranges but also the evaluation of palaeosurface changes and landcover modifications triggered by human-environment interaction. This approach represents an important link in interdisciplinary research and provides new insights in soil development, vegetation history, and palaeohydrological system transformation. In this article, 49 Neolithic sites have been investigated in terms of site location parameters and particularly soil preferences. Site-catchment analyses revealed a strong spatial relationship between site selection and soil properties with a significant preference for rather humid meadow and alluvial soils in close distance to running fresh water. The theory of a strong interrelationship between early agricultural strategies and Chernozem soil on loess-covered areas, alluvial fans, and palaeolevees cannot be completely traced throughout the Neolithic Period. This article furthermore suggests that the Neolithic impact on the surface cover could have triggered or enhanced soil development and thus would have contributed to the modern extensive Chernozem coverage in the Carpathian Basin through intensified land-use, clearing, and carbon input. The Neolithic preferences for meadow and alluvial soils would have therefore been much stronger and the modern soil data would be biased by the strong agricultural overprint of the past 7000 years. Future pedological analyses and the continuous incorporation of modern scientific data sampling in Neolithic excavations will clarify the picture of soil development during human-environmental interaction in the Carpathian Basin.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Datasets

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Corine Riparian delineations: https://land.copernicus.eu/local/riparian-zones; last accessed 09th December 2019.

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