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► **To cite this version:**

Robin Brigand, Jérôme Dubouloz, Olivier Weller. Colonization Dynamics of LBK Farmers in Europe under Geostatistics Test. *Documenta Praehistorica*, 2022, 49, pp.2-45. 10.4312/dp.49.12 . hal-03792124

**HAL Id: hal-03792124**

**<https://hal.science/hal-03792124>**

Submitted on 29 Sep 2022

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# Colonization dynamics of LBK farmers in Europe under geostatistics test

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**ABSTRACT** – Exploiting a database developed during a previous research project, this study uses factor analyses, GIS techniques and basic geostatistics to evaluate in detail the agro-ecological determinants of the first Neolithic diffusion in continental temperate Europe (the Linearbandkeramik or LBK), as well as its underlying settlement dynamics around half a millennium (5550–4925 BCE). More than 6600 LBK site locations, spread from Moldavia to Normandy, are initially assessed for their informative coherence and ability to offer a unified perspective on the evidence established at more local and regional levels. Most of these data can be used to define the broad geo-pedological options involved in the location of sites across Europe; loess substrate was far from being an exclusive settlement choice and a variety of soils, typically of medium moisture, were exploited. LBK farmers thus had a great capacity to adapt to the different geographical contexts they encountered. With regard to settlement dynamics in Central and Western Europe, the data reveal a systemic interplay between creation, stability and abandonment of sites, supporting the diffusion of the LBK subsistence system. The progressive decline in the number of new sites was compensated by an increase in their stability until the last stage of the expansion process. At this point, abandonments became widespread without significant renewal, except in the westernmost regions. The easternmost parts of Europe could not be integrated in the large-scale temporal modelling, since the chronological data available in the database are insufficiently precise. Shedding new light on the systemic variability of the geo-environmental options followed by these early farmers and highlighting some modalities and spatial-temporal limits of the resilience of their agro-sylvo-pastoral system, our overall analysis confirms and somewhat clarifies current interpretations of the LBK phenomenon.

**KEY WORDS** – Neolithic; LBK; Europe; colonization; geo-environment; settlement dynamics

## Geostatistični test kolonizacijske dinamike LTK kmetov v Evropi

**IZVLEČEK** – S pomočjo podatkovne baze, vzpostavljene v prejšnjem raziskovalnem projektu, v tej študiji predstavljamo rezultate faktorskih analiz, tehnik GIS in osnovne geostatistike, s katerimi natančneje vrednotimo agro-ekološke dejavnike med prvo neolitsko difuzijo v Evropo z zmernim celinskim podnebjem (področje kulture linearno trakaste keramike ali LTK) in poselitveno dinamiko v pol tisočletnem obdobju med 5550–4925 pr. n. št. Več kot 6000 LTK lokacij, ki se raztezajo od Moldavije do Normandije, smo najprej ocenili glede na njihovo informativno koherentnost in sposobnost ponuditi poenoten pogled na podatke, razvidne na lokalni in regionalni ravni. Večina teh podatkov je mogoče uporabiti za določanje širokega nabora geo-pedoloških danosti na lokacijah po vsej Evropi; puhlica še zdaleč ni bila izključna poselitvena izbira, raznolika, srednje vlažna tla so bila pogosta izbira. LTK kmetje so se bili sposobni prilagoditi različnemu okolju, s katerim so se srečevali. Glede

na poselitveno dinamiko v srednji in zahodni Evropi podatki kažejo sistemsko povezanost postavitve, stabilnosti in opustitve naselij, skladno z difuzijo LTK preživetvenega sistema. Postopno zmanjševanje števila novih naselij je nadomestila njihova stabilnost, ki se je ohranila do zadnje stopnje procesa širjenja. V njej so opustitve naselij brez obnove postale, razen v najbolj zahodnih področjih, zelo pogoste. V časovno modeliranje nismo vključili najvzhodnejših delov Evrope, saj so kronološki podatki, ki so na voljo, premalo natančni. Z analizo smo osvetlili sistemsko geo-okoljsko variabilnost in modalitete ter prostorsko-časovne omejitve odpornosti agro-gozdno-pašnega sistema prvih kmetovalcev ter potrdili oz. pojasnili veljavne interpretacije LTK fenomena.

KLJUČNE BESEDE – neolitik; LTK; Evropa; kolonizacija; geo-okolje; poselitvene dinamike

## Introduction

This paper discusses the settlement dynamics of the LBK (Linearbandkeramik), from Hungarian Transdanubia to the shores of the English Channel and the Black Sea, between 5550–5500 and 4950–4900 BCE (Figs. 1.a and 2). The origin of this large cultural complex is to be sought in the peripheral areas of the Painted Pottery cultures of the Carpathian-Balkan regions, most notably the Starčevo/Körös-Criş which extended during the first half of the 6<sup>th</sup> millennium from Serbia to the lower Danube basin. In its early phase of development, the LBK is characterized by the low variability of its ceramics, house types and more generally settlement and food production systems (Bánffy, Oross 2010; Czekaj-Zastawny 2009; Kreuz et al. 2005; Kulczycka-Lecieje-wiczowa 2000; Lenneis 2001; 2003; 2010; Lenneis, Pieler 2016; Lichardus et al. 1985; Lüning 2005; Oross, Bánffy 2009; Quitta 1960; Pavlů 2000; Salavert 2017). Recent bioarchaeological and palaeogenetic research supports the migration hypothesis developed as early as the 1920s (Childe 1929) and describes a process of direct population movement (Brandt et al. 2013; 2015; Lipson et al. 2017; Mathieson et al. 2015), in addition to the internal mobility of individuals, particularly women (Price et al. 2001; 2002; Bentley et al. 2012). Current palaeogenomic analyses point to an incipient genetic admixture from local hunter-gatherers during the LBK period, further developing through the succeeding centuries (Brunel et al. 2020; Rivollat et al. 2020). Prior to these new insights, a pure migration hypothesis formed the basis of a multi-agent modelling approach (ANR-09-CEP-004-01/OBRESOC project), exploring multiple socio-environmental interactions (Bocquet-Appel et al. 2015; *in prep.*; Dubouloz et al. 2017). Following this experimental approach and based on the archaeological data collected on this occasion (Dubouloz, Gawvry, *in prep.*), our objective here is to carry out a detailed evaluation of the site database and its capacity to account for settlement dynamics. In order to address this issue and

refine our understanding of its geography, a planimetric dataset was built around this archaeological database, inspired by the GIS approaches developed in the ‘ArcheoMedes’ and ‘ArchaeDyn’ programmes (van der Leeuw et al. 2003; Gandini et al. 2012; Gauthier et al. 2022).

After a general analysis of the archaeological and environmental data, we will address the question of the dynamics of archaeological settlements based on measures of geographical distribution.

An in-depth exploration of the agro-ecological relationships involved in this archaeological distribution will be the subject of another paper developing a space-time model of the LBK expansion process. Finally, to bring this research to a close, a third contribution will focus on the role of salt resources in the overall LBK process, in relation to this ecological modelling.

## The archaeological data

The analysis includes 6639 sites, spread over 14 countries and eight major river basins (Danube, Dniestr, Elbe, Oder, Rhine-Meuse, Seine, Vistula, Weser). The database (BD\_LBK) is informed by various descriptors presented in sections 1.1 and 2.1 and Appendix 6. The initial ‘OBRESOC’ database, with 6566 units, was corrected and reorganized to enable SQL queries, and then amended by including data from Romanian Moldavia (Robin Brigand, Oliver Weller) and the Republic of Moldova (Madalin-Cornel Văleanu, Brigand, Weller). The study window was extended by a buffer zone of 70km around outlying LBK sites. This measurement corresponds to half the observed maximum inter-site distance, which is theoretically possible to cover in two days’ walk. This brings the total study area to 1 211 807km<sup>2</sup>. For some regions, the BD\_LBK contains fewer sites than those recorded in the literature. This is principally the case

in the Kraichgau and Middle/Upper Neckar (Baden-Württemberg), where the number of known sites is much higher than in the database (Bogaard et al. 2016). As the latter was designed as an inventory of fully identified sites, many locations on published maps without precise bibliographic and geographical references have been ignored. Additional work to identify all the available sites will be necessary here in order to address these gaps. The question will arise later of the impact of these deficits (~5%) on our overall results (see section Brief synthesis and perspectives).

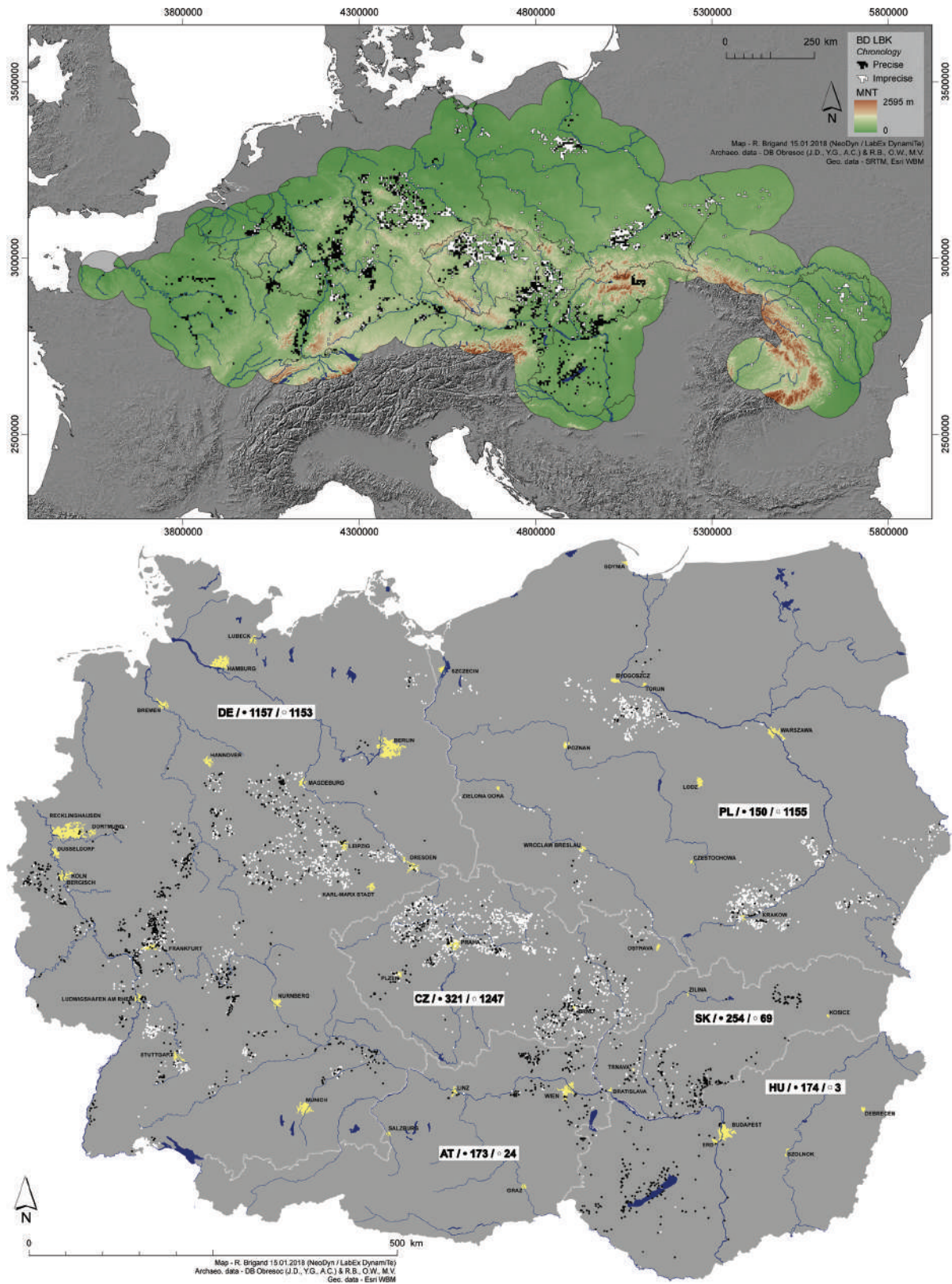
### **Archaeological descriptors**

Each site is recorded by several descriptors of a strictly archaeological nature or linked to a brief geographical description (countries, rivers watershed). They are presented below in increasing order of relevance.

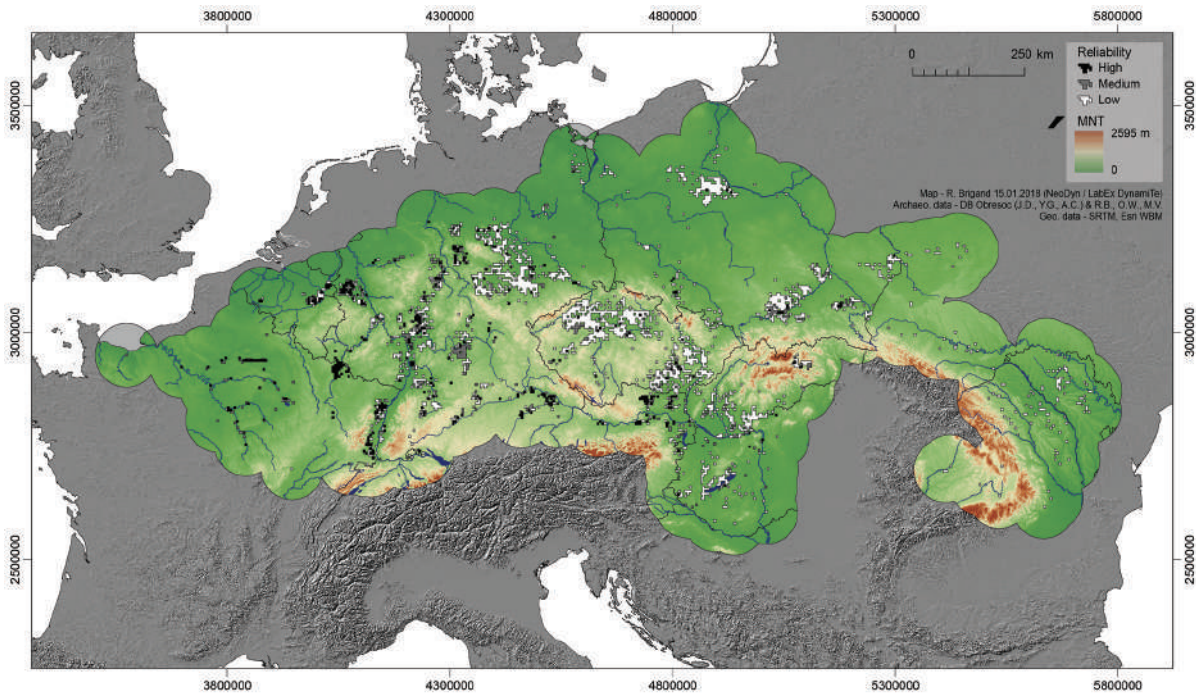
- ❶ The 'Country' variable is coded by two letters (ISO 3166-1 alpha-2). It reflects the general effects of history and research policies in major political regions.
- ❷ The 'Basin' variable is derived from a simplified map of rivers drawn up by the European Commission Environment Agency (Catchments and Rivers Network System, 2012). It shows the apparent structuring role of river basins in the geography of LBK diffusion. After verification of its operational value, it will not be used in the multivariate analyses.
- ❸ The 'Nature of the intervention' variable is a means of assessing the primary quality of the archaeological data, mostly derived from random collection (Collect., 50.7%), organized survey (Survey, 23.9%) and partial excavation (F.Part., 22%); extensive excavations are very much in the minority (F.Ext., <4%). This variable makes it possible to modulate the results according to the uncertainties of the database.
- ❹ The variable 'Category' of sites (settlement, enclosure, shelter/cave, cemetery, etc.) is mostly not filled in (67.5%). Therefore, on a European scale, all the entries in the database are integrated under the neutral term 'site'.
- ❺ 'Spatial accuracy' is of uneven quality: 39.6% of the coordinates of the sites are very well to fairly well positioned (Loc ++ ≤100m and Loc +- ≤500m), while 60.4% are more poorly located (Loc -- ≥1000m). But this range of uncertainty usually coincides with the resolution of the geo-environmental data.
- ❻ The 'Area' of a settlement should be a relevant criterion for describing its importance, but the low occurrence of documented instances (18.4%) rules out statistical analysis.
- ❼ The 'Dating' variable (see section Chronology of settlements and Appendix 13 for more details) describes the dating evidence in Boolean coding. Sites dated by major chrono-cultural stage are characterized by a 'first settlement' variable (St. x) and a 'duration of occupation' variable in years of continuous occupation (D. x00); the absence of information is coded 'nr' in both cases. The mapping of dating precision (Precise = St. x Loose = St. nr) reveals a very strong dichotomy (Fig. 1.a) between Western Europe (France, Belgium), where sites are more often well dated, and Eastern Europe (Ukraine, Romania, Republic of Moldova). Central Europe (Fig. 1.b) is intermediate in this respect, with some well-documented sectors (Hungary, Austria, Slovakia and Germany to a lesser extent) and others that are often more limited (Poland, Czech Republic).
- ❽ 'Reliability' is a synthetic variable which describes the overall quality of the archaeological map. It combines the values of three variables: geography (accuracy of location), chronology (accuracy of dating) and contextual expertise (type of fieldwork). The mapping of this index is carried out through a transformation of the point entity into a raster information with 5km sides, from the most reliable to the least reliable. This mode of representation offers a general view of the state of research on the data (Fiab.A = 3 positive variables; Fiab.B = 2 positive variables including chronology; Fiab.C ≥ 2/3 negative variables = 80.2% of sites). There is a strong heterogeneity in the database (Fig. 2), very similar to that produced by the 'Dating' variable. The western and southern 'half' (Seine, Meuse and Moselle basins, Rhine and Weser basins, Hesse and Württemberg, Danube valley, Austria) is generally well documented. The other 'half', in the centre and the east of the map (Thuringia/Saxony-Anhalt/Saxony, Bohemia, Moravia, Slovakia, Hungary, Poland, Romania, Moldova and the Ukraine) often shows a more limited documentary quality.

### **Multiple Correspondence Analysis (MCA)**

A multiple correspondence analysis (MCA) was applied to the complete disjunctive table of most of the BD\_LBK's discrete data (Benzecri 1973; Escofier, Pagès 1990). This analysis will characterize the documentation in its suitability for addressing the issues of the determinants and rhythms of the LBK



**Fig. 1. Upper: LBK settlement map (6639 features) and chronological accuracy (each site – or group of sites – is represented by a pixel of 25km<sup>2</sup>). Bottom: map of LBK sites in Central Europe (Poland, Slovakia, Hungary, Czech Republic, Austria, Germany) precisely dated (black dots) and simply dated LBK (white dots).**



**Fig. 2. LBK settlement map (6639 features) and overall reliability of the archaeological information (each site, or group of sites = 25km<sup>2</sup>/pixel). Hydronyms are abbreviated: Bu. Bug, Da. Danube, Dn. Dniestr, Dr. Drava, El. Elbe, Is. Isar, Ma. Main, Ma. Marne (Fr.), Me. Meuse, Mo. Moravia, Mo. Moselle, Od. Oder, Pr. Prut, Rh. Rhine, Sa. San, Se. Seine, Va. Vah, Vi. Vistula, Vl. Vltava, Wa. Warta, We. Weser, Yo. Yonne.**

agro-sylvo-pastoral system in its continental development. Six variables are mobilised for 38 active modalities: the variables 'Category', 'Area' and 'Basin' were excluded from the analysis because of the insufficient quality of the available information or because they were too general.

A preliminary reading of the relative contributions of the six variables themselves provides a framework for the following detailed analysis of their modalities involved in the MCA (Fig. 3).

This first approach shows that five variables out of six contribute, through some of their modalities analysed below, to explaining the intrinsic variability of the data recorded in the inventory. The 'Country' variable does not seem to play a particular explanatory role in the overall construction, which is reassuring. The 'Reliability' variable, despite its polythetic dimension (*cf.* 1.1-8), does not sum up the patterning of the data alone: its statistical weight is only significant on the first factor. We shall see below that different modalities of its own descriptors are particularly discriminating throughout the analysis. The other four variables do not show very strong correlations: for example, 'Duration' is not strictly related to the age of the installation ('Chronology') nor to the research intensity ('Fieldwork');

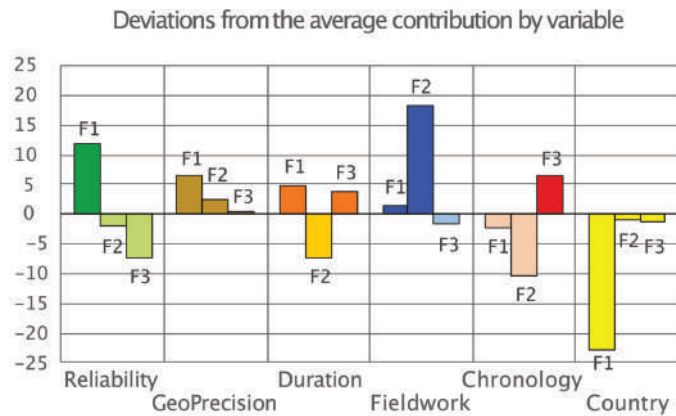
in the same way, geographical precision seems only partially related to 'Fieldwork'. These general observations suggest that a rather complex dispersion characterizes the variability of the data, which are therefore not univocally determined.

#### *Description of the factors or components (Appendices 2-4)*

The detailed analysis of the first three factors of the MCA, then of the factorial maps of their 38 modalities, makes it possible to specify the previous observations (Appendices 2-4, 7 and Figs. 4 and 5).

The first factor (original eigenvalue of F1 = 10.69% or 77.79% in Benzecri correction) is detailed in Appendix 2. It contrasts the sites well documented by excavations, dating to different stages of the LBK (especially St. 2 and 4) and of rather limited duration, with the less well-documented and therefore less reliable sites: France and Poland/Czech Republic respectively embody these two opposing poles which, not surprisingly, dominate the structuring of the data.

The second factor (F2 = 5.55% or 8.45% Benzecri, Appendix 3) mainly articulates the temporal variability around the differential documentary effects of 'Survey' and the 'Collect'.



**Fig. 3. Relative contributions of the six variables to the characterization of the first three components of the MCA (colours shown in Annexes 2 to 4)**

The third factor (F3 = 5.07% or, 5.53% Benzecri, Appendix 4) specifies the variability of the borders of the time sequence, by underlining the opposition of older and long-lived Central European sites, resulting from ‘Survey’ prospection (52.1% of the inertia), to westernmost sites dating to the later stages of the LBK and correctly located (31.2%). It also shows that some countries linked to ‘Collect’ in F2 (Slovakia, Hungary) are additionally associated with ‘Survey’.

*Analysis of maps F1/F2, F1/F3 and F2/F3 (Figures 4–5 and Appendices 5–7)*

● Map F1/F2 (Figure 4 and Appendix 5) shows a qualitative and chronological structure in the data and reveals three main groups of modality associations. It contrasts extreme documentary situations, between France/Netherlands (best information) and Poland/Czech Republic (worst information). In addition, it defines for part of Central Europe an intermediate group of sites with variable documentation and often ‘average’ quality. Germany and Belgium, at the centre of the scatterplot, are linked to all qualities of documentation, but with only a small proportion of the best; Austria has a significant rate of good quality information; Hungary and Slovakia are isolated from the other countries mainly because of their stronger ties to the early stages of the LBK.

● Map F1/F3 (Figure 5 and Appendix 6) identifies, in addition to the extremes already identified in F1, a central cluster of medium to high level modalities; this indicates a fair to good reliability shared by many sites in central-western Europe belonging to the main part of the LBK sequence and of all durations. It also confirms the better documentation of the western trio (Netherlands, Luxembourg, France), and the more varied documentary quality in Ger-

many, Belgium and Slovakia. The cluster of countries gathered around the least positive modalities confirms the singularity of Poland, linked to ‘Survey’.

● Map F2/F3 (Appendix 7) characterizes the database without the influence of poor documentary situations; it shows links masked by the hyper-structuring weight in F1 of the strong correlation of qualitatively weaker or undefined modalities. Hence it confirms the existence of the same poorly or badly characterized sites in the BD\_LBK (here centrally positioned and therefore not very significant in describing this additional variability) and their distinction

with the very well-characterized group in France and the Netherlands in the later stages of the LBK. In addition, this plot underlines a significant and favourable situation with Poland and its systematic ‘Survey’ practices. It also confirms that, at the time of database completion, Hungary and Slovakia stand out strongly from the other European countries in terms of the relative weight of their older, long-term and partially documented sites.

A synthesis of these successive and complementary analyses is quite easy to make, as they provide fairly similar results on the variability of the documentation. Three major poles emerge: first, the group with the best possible combination of documentation, in Western Europe, with sites in France, the Netherlands and Luxembourg; second, the group with lowest quality information, around the Czech Republic and partly Poland; third, the combination of intermediate quality information in Hungary, Slovakia, Germany, and Belgium. The remaining five ‘Country’ modalities are divided between the poor-quality combinations (Moldova, Romania, Ukraine, Switzerland) and the medium-quality ones (Austria).

Apart from the western trio, Poland and Hungary/Slovakia both present a complex situation. They can be regarded as specific versions of poor and moderate documentation. Thus, Poland shares with the western part of Europe a significant proportion of sound documentation (Fig. 4, map F2/F3), thanks to its affinity for high-quality ‘Survey’. In the group of medium quality documentation, Hungary and Slovakia stand apart from others (see Figs. 4–5 and Appendix 7). This may be related to their greater connection to the earlier stages of the LBK. The mid-quality group is also well represented by Germany and Belgium, which possess all the variety of docu-

mentation in significant proportions. Some is rather poor and broadly similar to the qualitatively under-documented Eastern Europe and Czech Republic, where the huge number of entries in the database statistically overshadows the well-documented sites in Bohemia and Moravia. Finally, Austria's documentation lies between the good and medium quality groups, quite close to that of the western countries.

**Quality of the BD\_LBK and overall heuristic validity.**

The overall impact of the observed heterogeneity (Appendix 1) in the BD\_LBK on the investigation of geo-environmental aspects and LBK settlement dynamics will now be assessed.

From the point of view of geography, this diversity is arranged quite clearly along an east-west transect; our information thus gains in quality along this axis and its suitability for interpretation increases at the same time. Apart from language barriers (for Ukraine and Moldova), three logically related constraints con-

tribute to this overall European pattern: the number of sites recorded, the temporal depth of the research and the underlying types of archaeological intervention. Thus, three countries which are major contributors to the database (Germany, Czech Republic, Poland) are characterized by an overall documentary situation of average to mediocre quality; and three other countries, lesser contributors to the database (France, Netherlands, Austria), present much more favourable situations. This dichotomy, which is somewhat counter-intuitive, is probably due to a mass effect. For the first countries mentioned, the temporal and spatial extent of research has produced a high proportion of sites identified 'in the past', while settlements that are well documented by more recent research have in this case relatively less weight than in countries where more recent, more proactive and/or more localized research will have accumulated fewer poorly documented sites.

Several intermediate situations are obviously present. For example, Hungary and Slovakia each illus-

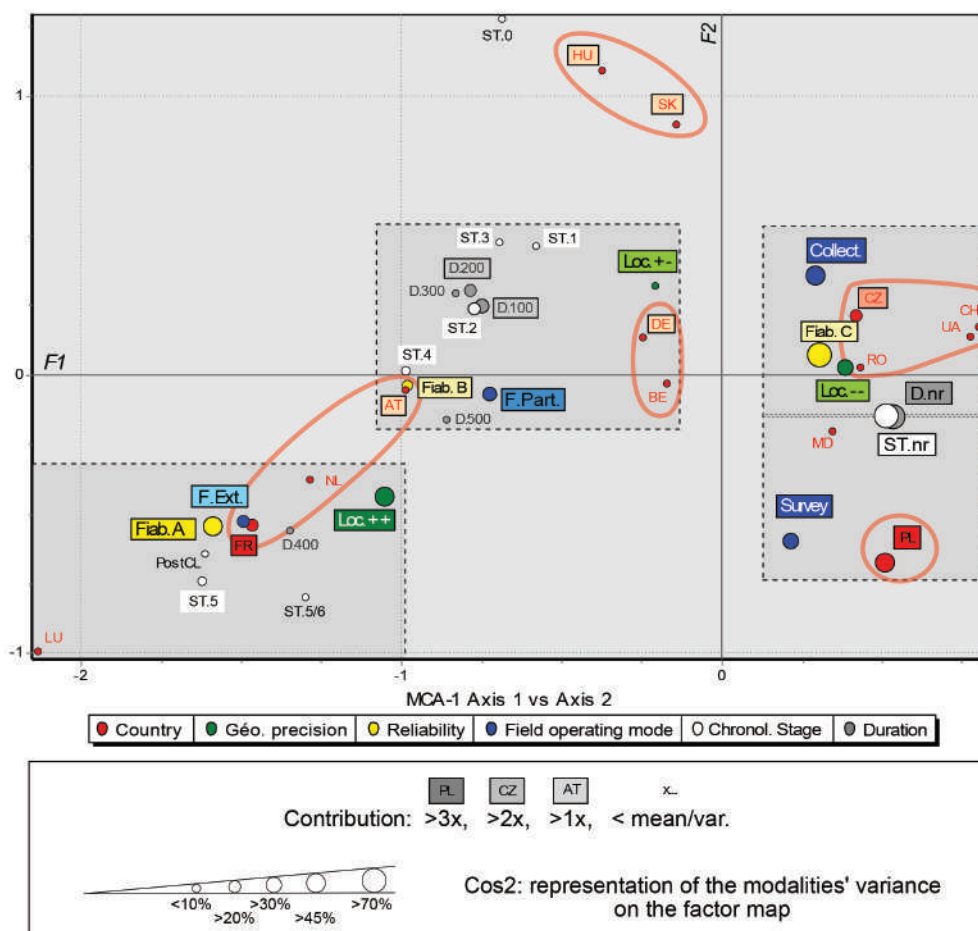
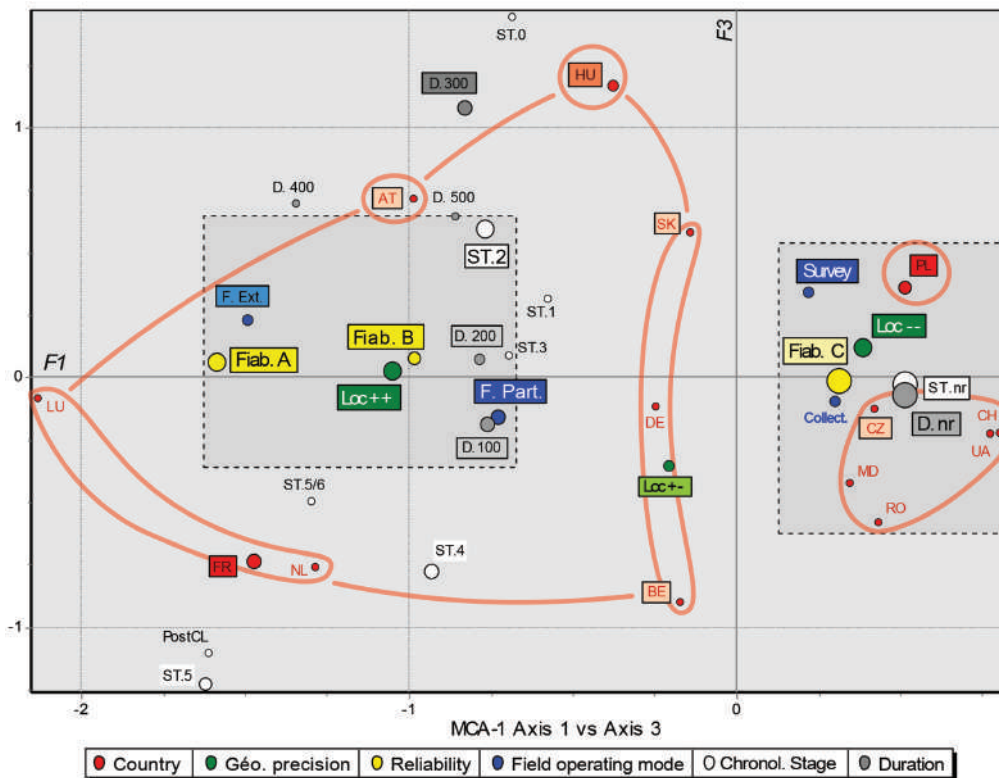


Fig. 4. F1/F2 map of the MCA showing the archaeological descriptors. Size and coloured highlighting of the fonts symbolize the level of the modalities' contribution; radius of the circles shows their representation's rate; red contours underline the particular distribution of the countries.





**Fig. 5.** Graph of the 1/3 factorial map (F3 inertia: 5.07% or 5.53% in Benzecri correction). Same legend as Figure 4.

trate their specificity, and their close positioning seems as much related to the broad trends that structure LBK data as to their own similarity. Thus, their convergence is probably mainly due to the distribution of the chronological variable: these two countries have relatively few well-documented sites and comparable proportions of moderately to poorly documented sites, but their share of later LBK sites, lower than in the other countries, may explain their joint isolation in the results of this analysis.

Finally, at the geographical margins of the phenomenon under study, the situations are broadly opposed. One, in the east, appears to be mediocre overall, no doubt due to shortcomings in the collection of information, but also possibly due to a very different history of research and more limited funding. The other situation, in the west, generally appears to be good, probably due to the geographical limitation of the areas concerned (the Netherlands and Luxembourg) and/or significant and earlier funding of rescue archaeology.

Thus, as was to be expected, the 'Country' variable is not an explanatory descriptor, but is only relevant in highlighting contextual trends. These can be summarized by five fairly well-differentiated classes and sub-classes: (i) the class with little information, main-

ly comprising eastern sites; (ii) the sub-class 'Poland', which has limited information in general, but is often well documented by 'Survey' or extended excavations ('F.Ext.');

(iii) the class of mixed situations, comprising Belgium, Germany, Slovakia and Hungary, with comparable proportions of poorly and moderately documented sites, together with some large to huge archaeological investigations;

(iv) the sub-class 'Austria', which has fairly good information overall;

(v) finally, the class of the most favourable situations, mainly associated with the Netherlands, Luxembourg and France: Austria participates to a certain extent in this last group (F1/2).

This extensive information variability could have a negative impact on the use of the database for research, by restricting the number of comparable sites available in different regions and by blurring the conclusions to a greater or lesser extent, depending on the regional representativeness of the available samples. However, in the broad analysis of the agro-ecological determinants of LBK settlement, it emerges that these documentary limitations have only a marginal impact. Indeed, such an approach mainly requires geolocation in line with the resolution used for the geo-environmental space, and this is often enough to provide a good summary of the main characteristics of the LBK point-pattern. Basic geostatistics

tical techniques such as low-pass filtering will be able to overcome the main documentary weaknesses. On the same geo-environmental level, the characterization by stages of LBK expansion will be more uncertain, particularly in Eastern Europe, a region that will have to be excluded from detailed analyses. But for the large contributors in Central Europe, with considerable medium- to poor-quality documentation, the problem is mitigated by the significant number of available sites and their varied spatial distribution.

The projected research on settlement dynamics is in turn dependent on the quality of information on the chronology and continuity of occupations. The MCA presented in this section has highlighted the weight of the undetermined modalities in the structuring of the data: thus 60% of the sites in the BD\_LBK do not meet the fine chronological aspects. The majority of these sites belong to the eastern regions of Europe, which again cannot be compared with other regions (although there are some pioneering studies such as Dmytro Kiosak (2017) and Thomas Saile (2020)). Among the latter, the three largest contributors to the database (Germany, Czech Republic, Poland) certainly present a significant rate of negative responses (in Thuringia/Saxony/Saxony-Anhalt (Thüringen/Sachsen/Sachsen-Anhalt in graphs), Bohemia (Čechy in graphs), Little Poland (Mało-Polska in graphs) and Kuyavia (Kujawy in graphs)), undoubtedly challenging the representativeness of these samples with regard to the regional temporal variability of LBK occupation; but the distribution of correctly to very well-informed sites overlaps quite regularly with the general pattern of known sites (Fig. 1), giving reason to hope for good spatial representativeness. Unless we can correct these biases, our forthcoming historical-anthropological interpretations will have to take this uncertainty into account.

### Topographical and agro-ecological data

In this section we will focus on site locations (point coordinates) in order to characterize their geo-contexts. The set of variables integrated in the analysis is presented in Appendix 8. Each archaeological site is thus documented by two topographic and six agro-ecological variables for a total of 38 descriptors out of 41 (two descriptors and one modality, not represented in the data, were deleted).

#### Data classification

① Slopes. The slope map is classified into four map units: SL1 (flat) = from 0 to 3; SL2 (low slope) =

from 3 to 9; SL3 (medium slope) = from 9 to 20; SL4 (steep slope) = from 20 to 65; in the analysis, the SL4 modality was grouped with SL3.

② Landscape openness. Classified into three sets, this measure is a morphometric indicator that determines the degree of concavity and convexity of the landform (Yokoyama et al. 2002). It considers for each pixel a line of sight over 8 azimuths ( $r=10\text{km}$ ) which may be redundant with the visibility indicators (total visibility): OP1 (closed); OP2 (open); OP3 (very open).

③ Moisture. This is the variable deduced from the low-resolution (1km) surface water saturation map. The map is classified into four map units: HY1 (low); HY2 (medium); HY3 (high); HY4 (very high).

④ Soil texture. This document, originally classified into seven classes, is simplified into six classes (by combining the <no data> and <organic layer> fields): TX0 (n/a); TX1 (coarse, clay<18% and sand>65%); TX2 (medium, clay<35% and sands>15% or clay<18% and 15%<sands<65%); TX3 (medium, fine, clay<35% and sand<15%); TX4 (fine, 35%<clay<60%); TX5 (very fine, clay>60%).

⑤ Soil thickness. The original five-class classification is retained: PR0 (n/a); PR1 (shallow, <40cm); PR2 (moderate, 40–80cm); PR3 (deep, 80–120cm); PR4 (very deep, >120cm).

⑥ Loess. The European loess map (Haase et al. 2007), produced at a scale of 1:2 500 000, contains nine classes distinguished according to their thickness and degree of alteration; this document has been simplified to the extreme to retain only the existence or not of loess in the substrate: LO1 (presence); LO2 (absence)

⑦ Soil group. The 1:1 000 000 Soil Geographical Database of Europe (SGDBE v4) initially presented in 27 classes according to the 1985 FAO classification has been simplified to 11 classes (European Soil Data Centre (ESDAC), esdac.jrc.ec.europa.eu, European Commission, Joint Research Centre): SO1 (Cambisols = brown soils with little typing or differentiation); SO2 (Chernozems, Greyzems and Phaenzems = soils with a high content of organic matter in their upper horizons, clinohumic soils); SO3 (Fluvisols = alluvial soils); SO4 (no data = glaciers, city, rivers, destroyed soils, n/a); SO5 (Gleysols, Histosols, Marshes, Planosols, Vertisols); SO6 (Podzol = soils marked by a true podzolization process); SO7 (Luvisols, Pozoluvisols =

degraded and leached soils characterized by eluvial upper horizons); SO8 (Lithosols, Regosols, Rankers, Rendzinas, Outcrops = thin soils, limited in depth by a coherent and hard material (bedrock or hardened horizons); SO9 (Arenosols = soils with sandy granulometry, not differentiated); SO10 (Salinosols = saline soils of Solonetz or Solonchaks type); SO11 (Andosols = soils of volcanic origin).

③ **Fertility.** The fertility map produced as part of the ANR 'Obresoc' project (Schwartz et al. *in prep.*) was used without regrouping or modification. The simplification of the soil cover carried out by the authors is dictated by an attempt to reconstitute Neolithic soils. As such, this work differs from classic studies – and from those presented here – which are based on the current state of the soil. Nevertheless, the scale (1:5 000 000) means there is great simplification and often arbitrary cartographic limits: FR0 (n/a); FR1 (very fertile); FR2 (fertile); FR3 (medium fertility); FR4 (low fertility); FR5 (not fertile).

#### **Statistical analyses (MCA and HAC)**

All statistical analyses performed on the LBK settlement data are based on the cross-referencing of the point attributes with the set of environmental descriptors operated in matrix form. The characteristics of the locations are at pixel level (100m), but include the very close environment since a low-pass filter has been applied to the raster data. The value of each cell is calculated from the eight surrounding pixels, thus obtaining a smoothed raster where the maximum and minimum values of each neighbour are averaged and local variations are reduced.

A multiple correspondence analysis (MCA) of the topographic and agro-ecological modalities and a hierarchical ascending classification (HAC) on the factorial coordinates (factor scores) enables a description of the settlement choices of LBK populations.

#### **Description of the factors (Appendices 9–11)**

- The strongest contributions to factor 1 (~85% of its total variance or inertia) mainly separate sites in poorly defined or rare contexts from all other sites (Appendix 9). Its relevance to our research questions is therefore very limited.

- The second factor (Appendix 10) is mainly based (~84% of its inertia) on the opposition between leached (Luvisols) or degraded soils, very deep, with a medium-fine texture and good fertility, and brown soils with moderate to deep depth, fine texture, very good or medium fertility, in a closed landscape. This

second statistical summary thus distinguishes two kinds of favourable agro-ecological environments.

- The third factor (Appendix 11) is mainly based (~81% of its inertia) on the predictable opposition between deep and very fertile soils of Chernozem, Greyzem and Phaenzem types and very thin soils or soils with a tendency to waterlogging.

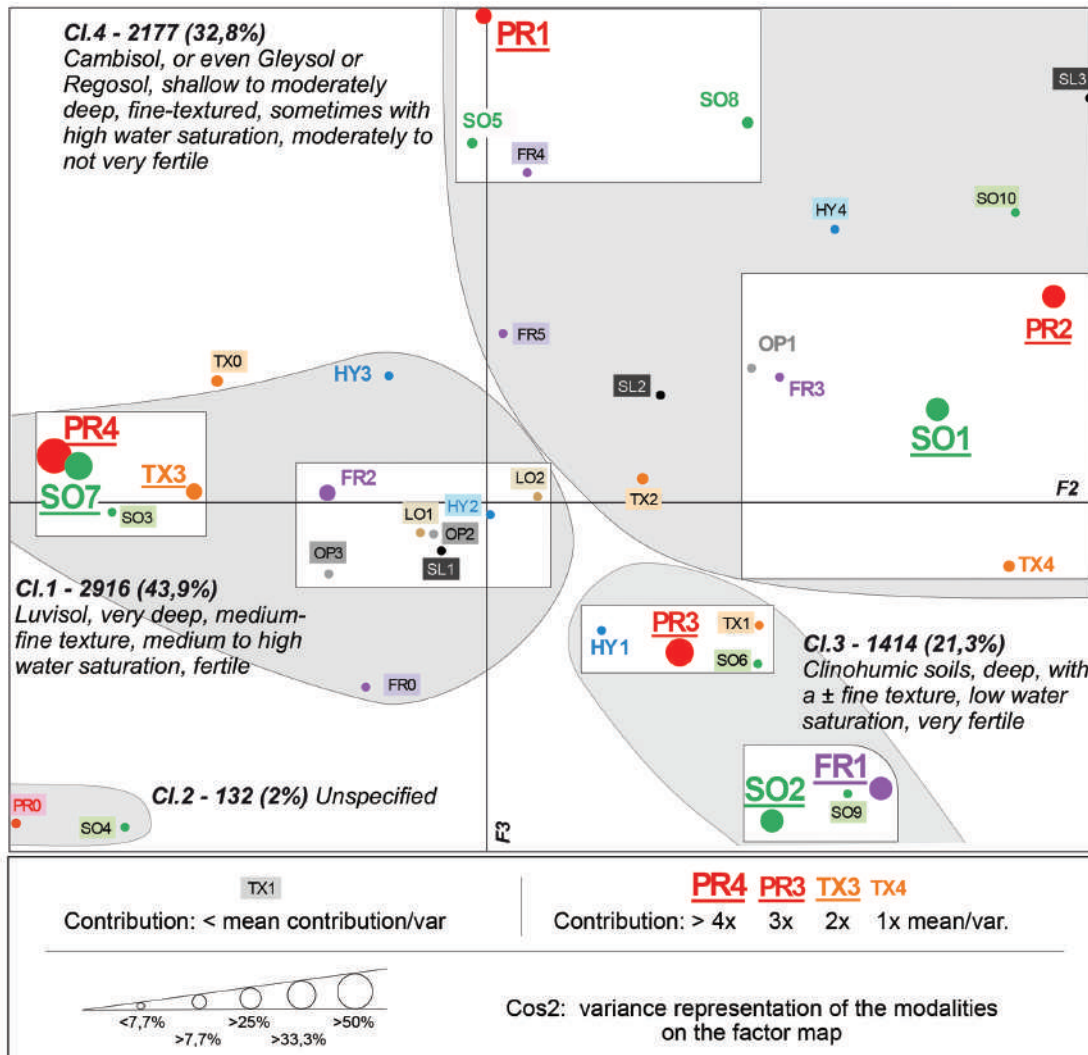
#### **Analysis of map F2/F3 (Fig. 6)**

Because factor 1 is defined by modalities that mainly describe the absence of information, it is more relevant to focus on factors 2 and 3 of the MCA (Fig. 6), despite a reduced inertia (total = 14.3%, 35.7% in Benzecri correction). With the results of the HAC conducted on the factor coordinates of the modalities, it reveals four main classes (Cl.1 to 4).

- Class 1 (Cl.1), with 2,916 sites (44% of the total), is predominately determined (>90%) by sites located on very deep (PR4), degraded (SO7) or alluvial (SO3) soils; then (> 50%) on medium-fine textured soils (TX3), fertile (FR2), humid and tending to hydric saturation (HY3); to a lesser extent (35–50%) by sites located on flat (SL1), open (OP2) to very open (OP3) landforms and medium hydromorphic soils (HY2). Two poles of association of agro-ecological modalities constitute class 1: the first one is very specific, around degraded, very deep, moderately fine-textured soils, and the second one around the most shared modalities, including good fertility, average waterlogging, and flat or very slightly sloping land in an open landscape. The presence of loessic substrates does not seem to be very discriminating, since their absence also contributes to defining this subgroup of CL.1.

- Class 2 (Cl.2) is composed of 132 sites (2%) located on soils for which the depth (PRO) and nature (SO4) are not given. This very marginal class of uncharacterized sites is not very relevant.

- Class 3 (Cl.3) concerns 1414 sites (21.3%) located primarily (>90%) on clinohumic (SO2) or sandy (SO9) soils; then (>50%) on very fertile soils (FR1), or soils marked by a process of true podzolization (SO6) and to a lesser extent (35–50%) on deep soils (PR3), with low surface hydromorphy (HY1) and sometimes with a coarse texture (TX1). Two preferred associations of agro-ecological modalities are also visible in class 3. The first one, very characteristic, concerns sites on clinohumic soils, very fertile, and the second one sites on deep soils with low waterlogging.



**Fig. 6.** Plot of the MCA showing topographic and agro-ecological traits (map F2/F3, inertia F2: 7.69% – 22.95 in Benzecri correction; F3: 6.58% – 12.74% in Benzecri correction) and arrangement of the classes from the HAC. The class boundaries are indicative; they do not exclude other under-represented modalities.

● Class 4 is made up of 2177 sites (32.8%), located primarily (>90%) on moderate depth soils (PR2) or shallow soils (PR1), waterlogged (SO5) or thin soils (SO8) or even saline (SO10); then (>50%) on brown (SO1), moderately fertile (FR3) to poorly fertile (FR4), fine-textured (TX2) soils located in topographic environments marked by a steep slope (SL3) and a closed landscape (OP1); and to a lesser extent (35 to 50%) on slightly sloping (SL2), non-fertile (FR5) and moderately textured (TX3) soils. This very heterogeneous class is structured around two very significant groups of modalities: the first concerns sites on brown soils of moderate depth, fine texture and, in part, average fertility in a rather closed landscape; the second group, very characteristic, but much less represented, is made up of shallow soils of low fertility, such as Gleysols, Vertisols, Rendzinas and Regosols.

*Intermediate conclusions*

The broad analysis of the agro-ecological data thus highlights the great variety of contexts in which LBK settlements are found. Rather than, as has often been assumed, a simple constraint by loess (47.6% of the total number of sites are strictly located on a loessic substrate), it is a set of characteristics favourable to sustainable farming that conditions the most frequent location of these sites: *very good to average fertility, very great to average depth, not too pronounced waterlogging, fine to average textures*. Many different soil types (SO1, SO2, SO7, even SO3 and SO6), whether on loessic or non-loessic substrates and widely present throughout Central Europe, seem to have been acceptable compromises for these early farmers. It is thus clear that they had an ancestral practical knowledge of the agrological properties of the soils, including their natural vegetation and

associated fauna. This background will have successfully guided their settlement choices in the Central European landscape.

### ***Additional analyses***

As regards the importance of loess and major soil types in the choices of location, further analysis can be made on a continental scale in order to identify interregional and/or temporal variability. Uncertainties related to soil evolution over the last 7000 years will be addressed in the course of the analysis and in the conclusions that can be drawn from the current soil cover.

### ***The loess issue***

Loess substrates make up more than a quarter of the surface area occupied by the LBK as a whole (26.2%). This share is greater if one excludes the mountain ranges, largely avoided by LBK agro-pastoralists. Loess is fairly evenly distributed (see Appendix 12), with a particularly marked presence to the northeast and east of the Carpathians, as well as in Hungary, around the Harz mountains and in Belgium/the northern Paris Basin. It is therefore expected that in most of these regions, loess may have been a major substrate for the establishment of LBK settlement.

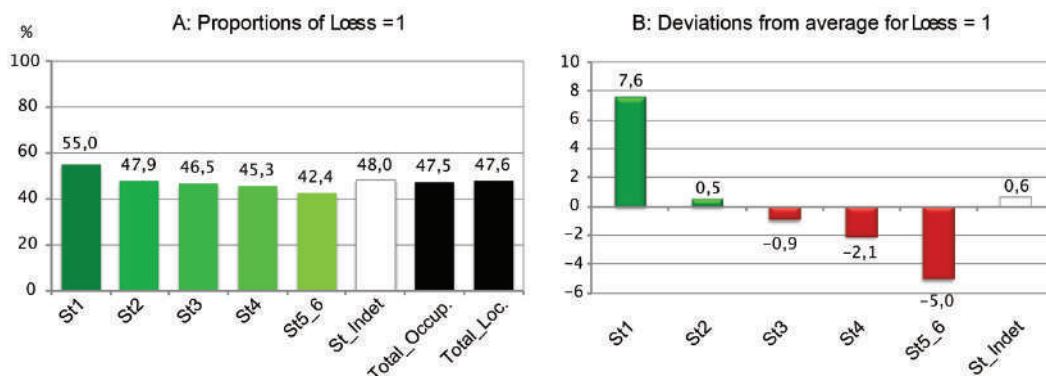
Two approaches have been followed to specify the archaeological impact of these formations. One is based on the geographical coordinates of the sites and the other on a buffer zone of 2.5km around each site. This second approach partly reduces some of the imprecision in locating the sites and mapping the loess areas.

According to the first approach, the general trend between the Black Sea and the English Channel shows (Fig. 7.A) an almost equal number of locations on loess or other substrates (47.5% of occupations and 47.6% of localities). At a more precise temporal scale (Fig. 7.A and B), and therefore at a varying

geographical scale, a trend can be seen towards a lesser dependence on Loess (Chi2: df 4, p. 0.001) between the beginning and the end of the LBK (from 55% to 42.4%), well expressed by the deviation from the mean of the occupations. This overall development thus underlines the importance of loess, but mostly at the beginning of the process, as well as increasing adaptation to the varied geo-pedological contexts encountered.

This space-time trend, identified on the basis of the present-day distribution of loess across Europe, motivated a second approach and further investigations of the geo-pedological composition of the terroir within a radius of 2.5km around each site, by major settlement region. In order to evaluate loess dependence, three surface thresholds in the buffer zone were established: (1) with 80% of loess in the buffer area, the site is considered to be located to maximize the presence of this formation, or has simply benefited from its extensive availability in the area; (2) conversely, with between 0 and 20% of loess in the buffer area the site is considered to be located with no particular interest in the presence of this substrate or has simply suffered from its low availability; (3) an intermediate threshold at 40% of the buffer area is also tested to define a proximity of the site to loess (<1km), but without excluding other substrates. According to this analysis, approximately 30% of all LBK sites are loess-independent, 34% have predominantly a loessic substrate, and 20% have a broad access to other types of geology. The remaining 16% (between 20 and 40% loess surface) represent sites with little attraction to this loess. At this level of geographic and temporal resolution, the importance of loess in the location of LBK sites is clearly variable.

The distribution of this differential access to loess according to major settlement regions (98% of sites), reveals a number of different patterns of settlement (Fig. 8.A-B).



**Fig. 7. A proportions of sites punctual location on a loess substratum; B deviations from average**

① The opposition of the extreme situations (80% vs 20% of the buffer area) creates four groups (Fig. 8.A):

- A first group (green) with 42–64% of sites with over 80% loess and 15–34% of sites loess-independent (0–20% of their buffer area), occurring in regions where the spatial distribution of loess corresponds to large, compact sectors (Niederrhein-Westph./Maas (NWM), Wetterau/Main, Franken, Elbe-Saale, Austria (Österreich in graphs), Southern Vistula, Romania/ Moldova).

- A second group (yellow) with only 12–30% of sites with over 80% loess and 30–48% of sites loess-independent, occurring in regions with smaller and more discontinuous loess sectors (Alsace-Middle Rhine (Alsace-Mittel-Rhein in graphs), Neckar, Lower Saxony/Fulda-Weser (BSFW), South Bavaria/Schwabia (Süd-Bayern/Schwaben in graphs (SBS)), Bohemia, Moravia, Slovakia-Hungary and South-Eastern Poland-Ukraine (SPK)).

- A third group (orange), far western [Paris Basin/Hainaut, Franco-Luxembourg Moselle (BPHM)], where only 5–8% of sites have over 80% loess (mainly the nine sites in Belgian Hainaut) and 67–78% are loess-independent;

- The fourth and last ‘group’ (dark red) is made up of the Kuyavia/Chelmno area (KUJ), where 100% of sites are not located on loess.

② At the threshold of 40% loess in their buffer area (Fig. 8.B), the sites fall into almost the same four groups as above:

- The fourth and third groups (red and orange) are formed by the same regions (KUJ, BPHM), where the attraction of loess concerns only 0% and 11–15% of sites, respectively, except in the small Belgian Hainaut region. This overall statistic confirms the weak association of the LBK with loess in these regions.

- The second group identified above concerns 40–62% of the sites in the same regions, to which are added the Moldavian-Romanian and Southern Vistula regions. By doubling or even tripling the proportion of sites concerned, the ‘mixed’ terroirs thus represent a considerable weight in these regions and reveal a fairly strong link between the LBK and loess (50% ± 10).

- The first group retains five of the seven regions with 80% loess, and now includes 72–83% of the sites in NWM, Franken, Wetterau/Main, Austria and Elbe-Saale, which is only a slight increase (1.3 to 1.7 more cases). This weak progression is due to the high spatial availability of loess, which ‘mechanically’ attracts a large number of sites (42–64%). But, by increasing this proportion of sites to 72% and more, the ‘mixed’ sites contribute to the dominant view of the crucial importance of loess for the LBK. This observation remains true for some regions of Germany and Austria, where Eva Lenneis (2001) notes that about three quarters of the settlements are located on loess, from the earliest phase onwards. But in other important regions of Central Europe (Hungarian Transdanubia (Magyar-Dunántúl in graphs), Moravia, Bohemia, South Bavaria/Schwabia (Südbayern/Schwaben in graphs), Middle Rhine/Alsace (Mittel-Rhein/Alsace in graphs), the dominance of loess

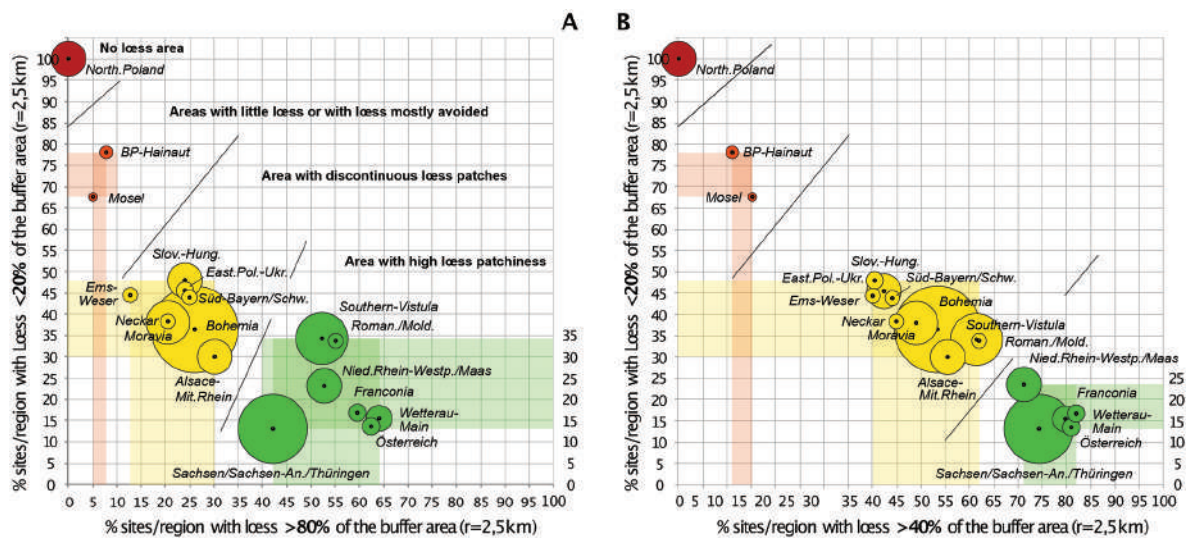


Fig. 8. Geographical distribution of sites according to the proportion of loess area in their 2.5km buffer zone: A <20% vs. >80%; B <20% vs. >40%.

must be tempered by a significant proportion of 'mixed' configurations associating proximity of loess and other substrates.

### Intermediate conclusions

The analyses at supra-regional and regional levels of site position and buffer areas both confirms and moderates the importance of loess in the choice of LBK site location, as already revealed by the MCA (Fig. 6): only 52.3% of the large sample of sites examined (Fig. 8) have over 40% of loess in their buffer areas. As the results show many alternatives, the study indicates a certain independence of the LBK system from loess, even in regions where its presence is high, such as the eastern Carpathians or the Transdanubian Hungary. However, there is a slightly stronger link at the beginning of the sequence (St1) than at the end (St4 and 5–6). These figures suggest that starting from a subsidiary exploitation of non-loessic substrates by the earliest farmers (St1), the LBK's subsistence system has been increasingly adapted to this kind of substrate.

### LBK and present-day soil groups

The geographical distribution of present-day soil groups shows the predominance of Cambisols and Luvi-Podzoluvisols (57% of the total area), far ahead of Clinohumic soils (Chernozems, Phaenzems, Greyzems), Podzols, Fluvisols, Gleysols and Rendzine-Regosols (Fig. 9 and Appendix 12).

Cambisols develop in large continuous areas in the heart of the LBK territory and particularly in the central and central-western parts. Luvisols (and Podzoluvisols) generally border these Cambisols, in rather fragmented patches, and dominate in Poland, as well as in the north-western and western parts of the study area. Clinohumic soils are distributed mainly in the east and south-central regions, on the periphery of the above soils, with some other good patches in the Elbe-Saale region and more modestly in

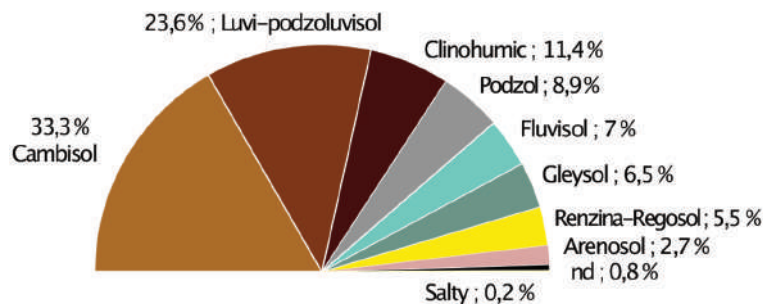


Fig. 9. Distribution of the main types of soils in the geographical area of the LBK.

southern Poland and Bohemia. Gleysols occur between the previous groups, mainly in the northern periphery, like the Podzols, and more in connection with Fluvisols. The latter are distributed throughout the study area, particularly in Moldova/Romania, Poland, Belgium and France. Lastly, Rendzinas essentially show the opposite distribution to Podzols, in the southern half of the LBK occupation zone, with important areas along the Paris Basin, the Austrian Danube and in Hungary, Slovakia and Ukraine: the LBK largely avoided these soils.

This current distribution of the main soil groups, expressing major topographical, geological and morphological factors, appears to be a significant geographical determinant for LBK settlement location. We can nevertheless expect considerable variability, as has been shown for the loess.

### Available soils/selected soils

The distribution of soils at LBK sites shows a good overall correlation with the distribution of soils currently available in the study area (Pearson (0.866) and Spearman (0.7381):  $p < 0.05$ ). This indicates that the early Neolithic farmers made use of most of the possibilities offered by the environment. But the observation of the deviations from the relative distribution of these soil groups in the study area as a whole and at the sites (Fig. 10) shows a stronger relationship (Chi2, df 7,  $p < 0.01$ ) with Luvi-Podzoluvisols (+51.7%), Clinohumic soils (+45.6%) and Fluvisols (+28.6%). The best represented group in the study area, Cambisol (33.3%) is a bit under-represented (-20.4%), and Rendzinas-Regosols, Gleysols, Arenosols and Podzols (between 2.7 and 8.9%) are clearly under-represented at LBK sites compared to current geographical availability (between -34.5 and -88.8%).

The importance of Luvi-Podzoluvisols could be at least partly due to soil developments over the last 7000 years (Lorz, Saile 2011) and could reflect the higher availability of Chernozems (here with Clinohumic soils) at the time of the LBK. This hypothesis can be applied especially around the Harz mountains, as well as in Bohemia and Moravia, judging by the present-day intermingling of Luvisols in the Chernozemic areas and their immediate surroundings. However, Carsten Lorz and Thomas Saile (O.c.) also point out that such a proposal can only be based on detailed pedo-

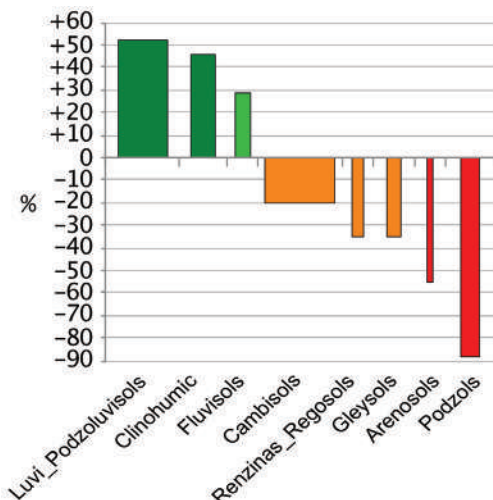
logical studies. The question of Cambisols is even more complex, since this notion covers very diverse soils whose main common feature is an incipient pedological differentiation, and their age is therefore questionable. We will simply note here that more than 80% of the sites located on these formations, very often close to areas where Chernozems and Luvisols are concentrated, avoid their most acidic forms. This is the case in the regions noted above, especially along the secondary, or lesser, watercourses. Here, the ‘absolute’ quality of the soils would have weighed less than the proximity of densely settled areas and site networks.

#### *Loess and selected soils*

Together with these apparent connections, there are significant differences in numbers by substrate for the four main occupied soils (Fig. 11). A Chi-square test confirms (df 3,  $p < 0.001$ ) that the presence of a loessic substrate at the site coordinates tends to favour Luvi-Podzoluvisols and Clinohumic soils in the establishment of LBK sites, especially in the early LBK; conversely, the absence of loess tends to favour Fluvisols and marginally Cambisols, especially towards the end of the LBK.

The weighting of these archaeological observations by the geographical patterns of the three main soil groups attested on loess provides a complementary conclusion (Tab. 1):

- Clinohumic soils, preferred on loess more than on other substrates (18.7 vs. 14.6%), have apparently been exploited in proportions lower than their availability on loess (18.7 vs. 28%), except in their



**Fig. 10. Relative deviations in the proportions of the selected soil types from those of the available soils (horizontal values proportional to the overall availability).**

two main distribution zones east of the Carpathians, as well as in Slovakia and more partially in Moravia and Kuyavia (see Fig. 12).

- Luvisols appear to be the main beneficiary of the apparent choices of LBK settlement location, especially on loess (> 42% of sites).

- Despite the lower overall availability on loess, Cambisols also seem to be readily chosen, and in higher proportions than their overall availability on loess. This trend may reflect an environmental and/or social determinant, *i.e.* a pull of the loessic substrate on the location of LBK sites, irrespective of the soil itself, and/or a desire to be close to a site network occupying the best soils.

Thus, according to these non-exclusive preferential connections, the locational choices of LBK sites as a whole reveal several major alternatives. The ‘Chernozem on loess’ archetype would have been only one of the LBK settlement modes, valid in certain regions and/or at the beginning of the sequence. Elsewhere, according to the gradual spatial variation of environmental availability, LBK settlements seem to have largely found other geo-pedological contexts that were suitable for their farming requirements (Figs. 12 and 13).

#### *Regional variability*

An analysis by major settlement zone (Fig. 12) illustrates this variety of situations in seven main classes:

- Romania-Moldova is distinguished by a preponderance of clinohumic soils (> 80% of cases).

- Slovakia, Moravia (Chernozem) and Kuyavia/Chelmo region (Phaenozem) show a preference for both Luvisols and Clinohumic soils (>66% combined).

- In a large part of Germany Luvisols dominate Cambisols (>70% combined).

- In contrast, in the west and southwest of Germany, Cambisols predominate over Luvisols (>70% combined); in Austria, Clinohumic soils take second place (=89% combined), as already observed by Lenneis (2001, Fig. 6) for LBK 1 in Austria, where present-day Brown soils are preferred to present-day Chernozemic soils.

- Bohemia, Southern Vistula and Silesia show a more balanced distribution of Cambisols, Luvisols and Clinohumic or Fluvisol (>67% combined).



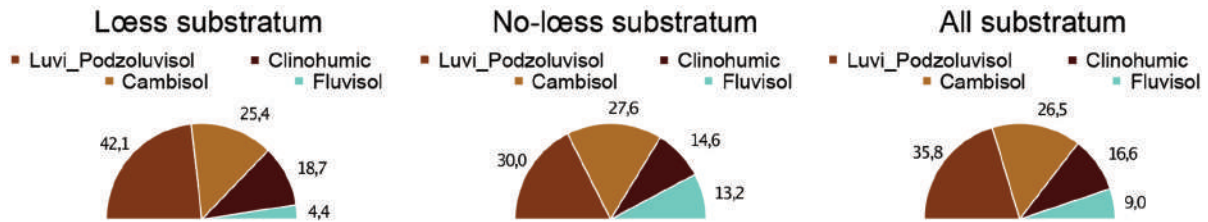


Fig. 11. Archaeological proportions of the four main soil types according to the presence/absence of loess.

Soil groups (%)	% area	% soil on loess/ soil group area	% soil/loess area	% soil-sites on loess
Clinohumics (11.4)		66	28	18.7
Luvi-Podzoluvisols (23.6)		34	27	42.1
Cambisols (33.3)		14	17	25.4

Tab. 1. Proportions of various loess configurations/major soil groups.

- On the periphery, Hungary, Mecklenburg-Pomerania, south-eastern Poland and the Ukrainian borders show a wide variety of soils, including a type that has been encountered rarely until now (only in Kuyavia): Gleysols, associated with Luvisols and Cambisols or Fluvisols (>68% combined).
- In the west, except for Belgian Hainaut (nine sites), Fluvisols dominate, associated with Cambisols (>75% combined) and a variety of other soils.

The cartography of these major classes (Fig. 13 and Appendix 12) shows that, during its spread, the LBK farming system did not focus on a specific geo-pedological niche, but adapted to changing local and regional conditions. In view of this general strategy, the Paris Basin sites appear somewhat distinct, since they underuse the soils developed on the large loess patches occurring in this region. Mainly dated here to the end of the LBK sequence but locally pioneer, the occupation initially tied to the main floodplains was extended, during the early 5<sup>th</sup> millennium (BVSG group), to the loessic plateaus now largely covered by luvisols (Dubouloz et al. 2005; Bostyn et al. 2019). The BVSG farmers seem therefore to have returned to the predilections followed during the European expansion process from which they ultimately resulted.

#### Overall weighting of results

Beyond issues of loess and soils, the distribution of LBK sites highlights their relationship to highly significant sedimentary characteristics. The MCA/HAC (Fig. 6) identifies groupings that are largely defined around variations in water saturation, texture and soil depth (Tab. 2). And it should be remembered here that soil quality not only affects agricultural po-

tential, but also natural plant communities. The influence of these sedimentary characteristics on tree and herbaceous formations implies that the associated vegetation and fauna were most likely important parameters in site location, although such factors remain hidden in our strictly

geo-pedological analysis.

Medium-fine to fine-textured soils thus characterize more than 82% of the sites (Tab. 2.A), and of these about 71% have low to medium water saturation. In the same way, a great to very great thickness of the soils characterizes nearly 80% of the sites, of which nearly 72% have low to medium water saturation. These very high proportions identify the main soil characterization of LBK locations and indicate the skills of already expert farmers. However, a significant proportion of the occurrences (<30%) combines the same characteristics of depth and texture with high water saturation, thus showing that alternative choices were made. This option may have been related to a particular interest in the proximity of specific vegetational areas such as riparian zones or marshes. Concerning the other soil types (Tab. 2.B) on which a minority of LBK settlements are located ( $\leq 20\%$ ), low to medium water saturation also dominates (more than 70% of the cases), thus restating the critical value of this characteristic for LBK agriculture.

From all these observations it can be inferred that, beyond particular types of soil, LBK farmers first sought and found geo-soil formations that were not water saturated, rather fine-textured and quite deep: in other words, a range of situations favourable to their agricultural and gathering needs and widely represented in the territory they explored. These general characteristics provide a better definition than present-day soil types of LBK farmers' main criteria for establishing settlements. According to the statistical study, we must add to this major trend the complementary and less common search for waterlogged soils and their particular vegetation and fauna.

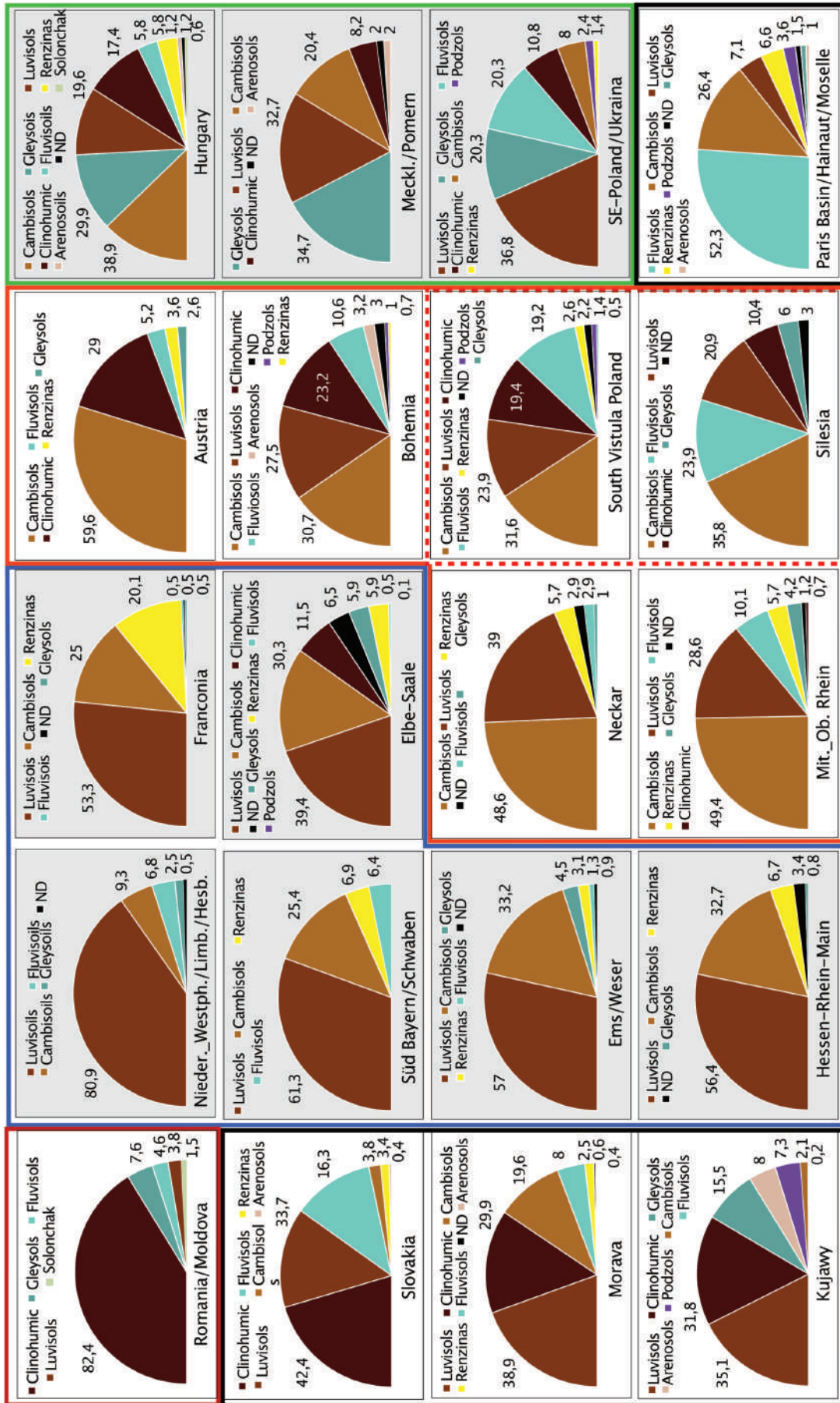
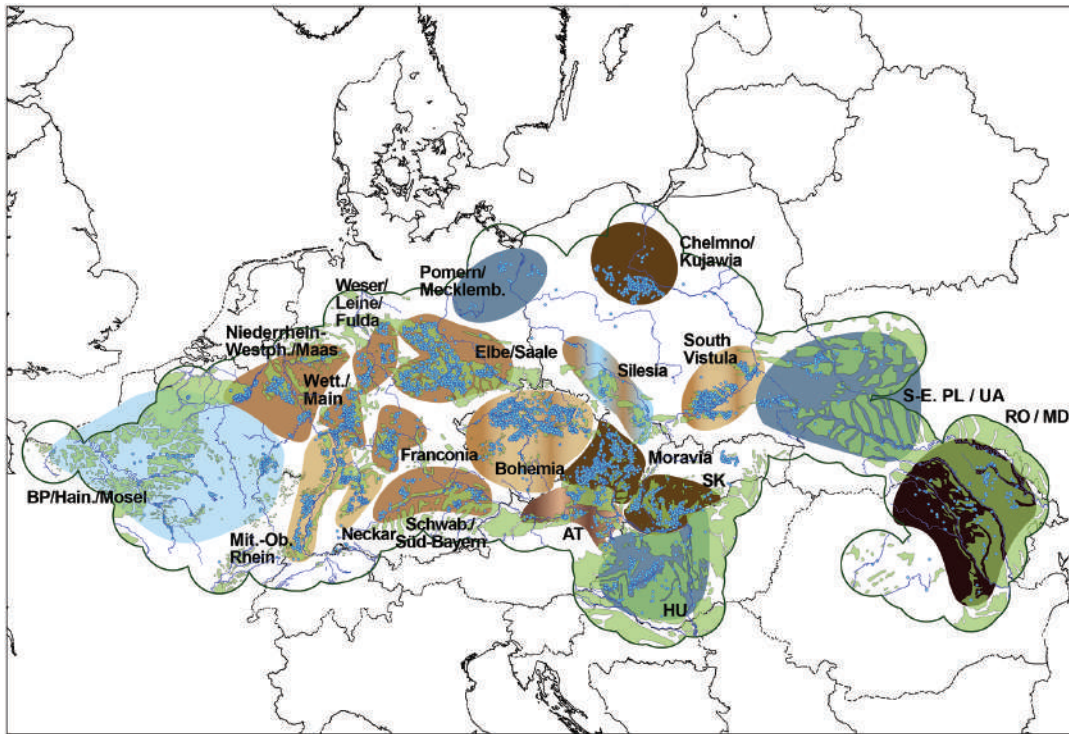


Fig. 12. Proportions of the different types of soil for the LBK sites of twenty settlement areas.



**Fig. 13. Geographical distribution of the dominant soil configurations of twenty LBK settlement areas: very dark brown: predominance of Clinohumic soils; dark brown: predominance of Luvisols/Clinohumic soils; medium brown: predominance of Luvi Podzoluvisols/Cambisols; beige: predominance of Cambisols/Luvisols or Clinohumic soils; blue-gray: importance of Gleysols; light blue: importance of Fluvisols; light green: Loess.**

These findings are at least partially in line with the conclusions of Michael Kempf (2020a), whose research is not really comparable to that developed here, as differences in spatial scale, temporal perspective, size of the samples examined, resolution of the basic environmental data and the descriptive system of the geo-pedological units make this comparison rather impractical. However, we note a convergence of our observations with some results of his analysis, especially the importance of low-medium water saturation in the choice of settlement location.

On the other hand, the study by Lorz and Saile (2011) on the genesis of the Chernozems, restricted to southern Lower Saxony, also reaches some conclusions compatible with those produced here on a continental scale. This is the case for the partial disconnection that can be observed between site location, loess and the presence of Chernozems, which has already been proposed by various researchers cited by these two authors. Thus, their database clearly shows the major importance in LBK site location of contact zones be-

tween geo-pedological ensembles, recalling our definition of ‘mixed terroirs’ (section 2.3.1 and Fig. 8). Due to the fine resolution of their environmental data, they ultimately draw the conclusion, unattainable at the resolution of our own study, “[...] that LBK settlers preferred highly productive and light soils with easy access to water courses (Sabel 1983). These conditions are provided in the dry Loess landscape of the investigated region with a distinctly incised, dense drainage network.” (op. cit. p. 278, underlined by authors). This specific environmental configuration might be the actual source of our observations (section 2.3.2a) concerning site distribution in the intertwined Chernozems-Luvisols-Cambisols of the loessic region around the

	% of total (N)	Low-medium sat. (N)	Strong and more sat. (N)
A			
Txt. fine to medium-fine	82.2 (5455)	70.7 (3832)	29.8 (1623)
Depth + and depth ++	79.8 (5200)	71.7 (3730)	28.3 (1470)
B			
Other textures (very fine, medium, coarse)	17.8 (1184)	79.5 (941)	20.5 (243)
Moderate and shallow depth	20.2 (1317)	70.1 (923)	29.9 (394)

**Tab. 2. Overall statistics of site distribution by soil water saturation, texture and depth (NB: 1.8% of soils are not characterized by depth).**

Harz or in Moravia. As much as the search for a dense and socio-economically supporting neighbourhood, the need for easy access to water, identified at the meso-regional scale and at higher spatial resolution (see also *Končelová 2005*), appears to be a strong complementary determinant of this site distribution that is partly disconnected from the best soils.

### Settlement dynamics

Much has already been written on settlement dynamics and no attempt is made here to challenge the interpretations and conclusions drawn from previous research. Rather, we will try to show how large-scale geo-spatial statistical analysis can identify and weigh the different factors underlying this space-time phenomenon.

#### *Chronology of settlements*

The phasing of the overall extension of the LBK, at least in broad stages, is a necessity for this research project, as it enables continuities and discontinuities across time and space to be considered together. But this ambition is particularly sensitive when the western and central-eastern zones are compared. Despite the predictable discomfort of many specialists, we have nevertheless attempted such a chronological standardization, according to a six-stages (St. 0 to 5) sequence (Appendix 13).

The information in the archaeological database can then be used to reconstruct probable settlement dynamics on a continental scale. This first approach is based on the 2559 locations with LBK occupations that can be dated to a stage (4535 different occupations), excluding both extremities of the sequence (St. 0 and St. 5–6) as the occurrences are very low and/or their definition very specific. Indeed, the ‘5–6’ and ‘Post CL’ (or ‘6’) stages only appear in the database as marginal information that we did not want to lose at first. The ‘5–6’ stage is related to the Paris Basin where it extends the LBK occupation (early BVSG) and the ‘Post-CL’ stage was taken into consideration only for subsequent occupations on LBK sites: this stage is therefore not really listed as such and cannot be considered here. The total sample thus represents about 39% of the database, but is unevenly distributed among the different regions. In addition to far Eastern Europe, this limitation is likely to be noticeable for Poland, the Czech Republic and Belgium, for example (Appendix 1).

Several elaborations of the database are necessary, in the form of simple aggregations by major stage:

(1) the total number of occupations; (2) the number of newly created sites, *i.e.* without immediately preceding occupation; (3) the number of enduring occupations (total number of occupations excluding site creations); and lastly (4) the number of abandoned sites during stage ‘t’, previously occupied during stage ‘t -1’.

In order to compare settlement trends over similar time periods, these values have been weighted by the approximate duration of the different stages (Appendix 13). Each is split into ‘n’ periods of twenty-five years (a human generation), according to the following division (the cut-off effect remains unavoidable): St. 1  $\approx 7 \times 25$  y., St. 2  $\approx 6 \times 25$  y., St. 3 =  $2 \times 25$  years, St. 4  $\approx 4 \times 25$  y., St. 5  $\approx 4 \times 25$  y. Lastly, a renewal rate is calculated (ratio of new creations to total numbers) that allows an overall summary of settlement dynamics.

The resulting curves (Figs. 14 and 15) reveal singularly different dynamics, depending on which of the parameters is considered.

Apart from the few settlements of the formative LBK stage (St. 0), the number of creations is similar during St. 1 and St. 3, around 19% for each stage. However, almost 39% of the dated sites (Fig. 14, red curve: Creation) are established during St. 2. Creations then decline and fall to about 5% during St. 5.

At first glance, settlement density is relatively stable between St. 2 and St. 4 (Fig. 14, black curve: Total), with the latter appearing as a clear stage of equilibrium, in view of the highest number of enduring sites (Fig. 14, yellow curve: Stability). The process that emerges, already well identified, is one of an expanding pioneer front that was particularly marked for stages 1 and 2.

However, these trends as perceived through the numbers of occupations per 25-year period offers a different reading (Fig. 15). The curves highlight the St. 3 stage, where the density (black curve) is clearly higher here than in the St. 2 and St. 4 stages, despite a significantly decreasing renewal rate (in green, 42.9 *vs.* 87.6%) and an increase in abandonments (in light blue, 215 *vs.* 61 per 25 years). New creations and a great stability of previously existing sites (in red and yellow) explain this counter-intuitive result. At the 25-year generation rate, St. 3 probably represents, at the mid 52<sup>nd</sup> century BCE, the climax of the expansion process, before a pause at St. 4 which remains at a high level of settlement density.

At St. 5, all factors considered except ‘abandonment’ reach unprecedentedly low values and indicate the exhaustion of the LBK.

As stated earlier in this chapter, this overall reading of the chronological processes is obviously related to the state of the basic information in the database and its representativeness. It is therefore still fragile in terms of detail and should be considered with a margin of error that cannot be easily assessed.

**Geocentres and standard deviation ellipses**

First, a method is applied to assess the overall dispersion of sites and analyse the similarities at each chronological stage: the measurement of centroids (barycentres or geocentres) and deviation ellipses. This approach has long been used in spatial geostatistics (Lefever 1926; Pumain, Saint-Julien 2001) and in spatial archaeology (Hodder, Orton 1976; Gauthier 2004; Poirier 2010; Nuninger et al. 2012). It enables the comparison of distributions based on a number of indicators:

(i) The geocentre corresponds to the average coordinates of the dispersion by period and the distance between each of these centroids is a way to assess the rates of population movement (Tab. 3).

(ii) The deviation ellipse encompasses sites whose location shifts by no more than one standard deviation from the centroid and therefore allows a measurement of dispersion at each stage of the LBK culture (Fig. 16). For the reasons mentioned in the conclusions of section I.3, the eastern expansion in Moldova and Romania has not been included in these analyses.

The centroid of the LBK formative stage (St. 0, <5500 BCE), located on the shores of Lake Balaton, involves only a very small set of settlements. The orientation of the deviation ellipse (in white) shows the dispersion gradient along a SE-NW axis. Then,

a shift in polarities is very marked in the next stage St. 1: the roughly 350km distance between the two geocentres (Tab. 3 and Fig. 16) undeniably evokes territorial expansion during this founding stage of the colonization of Central Europe (in yellow). Indeed, between c. 5500 and c. 5325 BCE settlement extended from Transdanubia to the Rhine (nearly 900km of maximum extension) and the upper Vistula valley, then towards the end of this stage Kuyavia and northwest Ukraine (nearly 800km). This settlement expansion, with standard deviation ellipses increasingly orientated east-west, remains at least until St. 3 (c. 5175–5125 BCE, in blue) very close to that of St. 2 (in purple), with a small extension to the west (lower Rhine/Meuse region, the Moselle and eastern Champagne).

The westward expansion restarts with St. 4 (c. 5125–5025 BCE) during which further parts of the Seine Basin and the Belgian Hainaut are colonized. Nevertheless, the geocentre shifts less than a hundred ki-

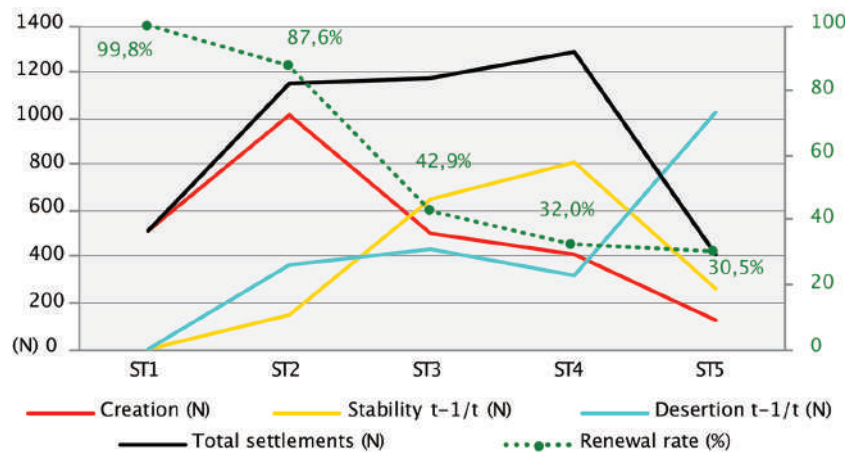


Fig. 14. Summary of the population dynamics (excluding the reoccupations after hiatus as Creation), combined with the renewal rate (right-hand scale); colours are the same as in Figure 22 (maps).

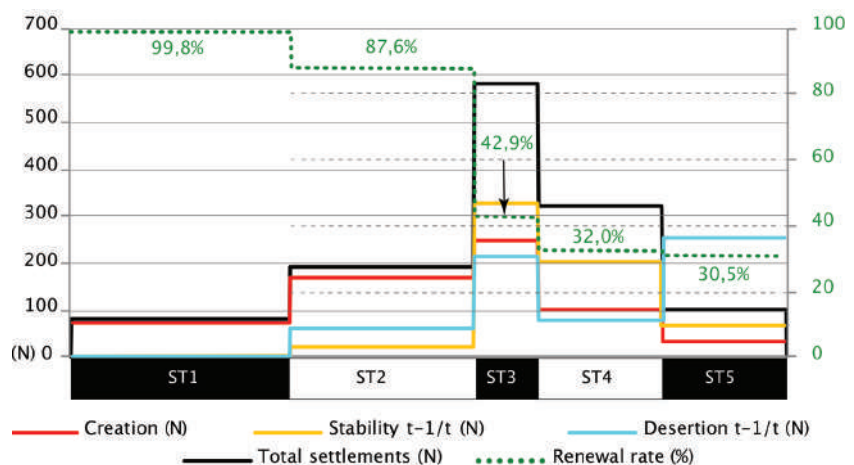


Fig. 15. Summary of the settlement dynamics by 25-year period.

lometres (Tab. 3), settlement being largely maintained in the former foci of Central Europe. The situation changes radically in St. 5, at the very end of the 6<sup>th</sup> millennium and the beginning of the 5<sup>th</sup>, with the weakening of the Transdanubian and central-eastern LBK foci. This is clearly underlined by a 308km shift of the barycentre (Tab. 3) and by the change in orientation of the deviation ellipse towards a NE-SW axis. It can be assumed that a rather similar process would be observed in Eastern Europe when the dating is better established there, and it will be interesting to compare the rates and average distances of progression there with those measured for the western expansion.

### Density and transition maps

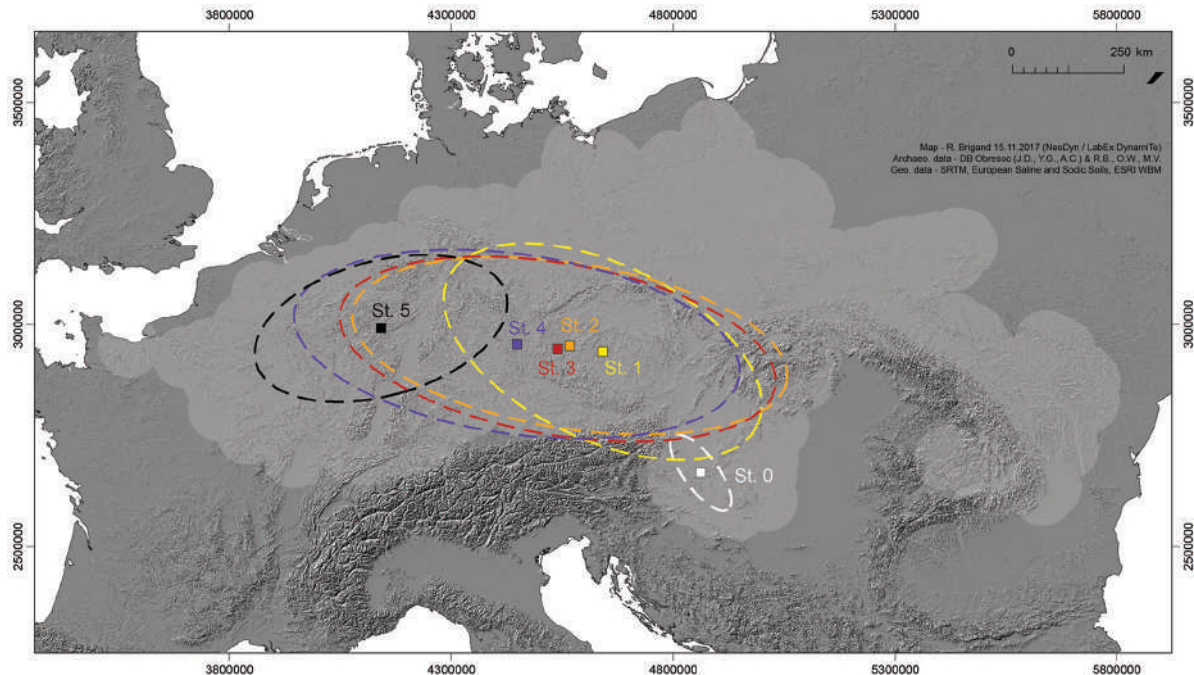
In order to go beyond the point distribution of sites, the 'kernel density estimation' tool (KDE) analyses the data in a continuous surface, reflecting the intensity of the occupation of the space. This method provides an estimate of the density of sites in a moving window and the resulting values include the situation in the neighbourhood. Thus, an area surrounded by other densely populated areas will have its own density increased. This method has been well known to geographers since the 1980s (*Silverman 1978; 1986; Wand, Jones 1995; Zaninetti 2005*), and widely used by archaeologists working at site scale (*Baxter, Beardah 1997; Beardah 1999*).

Stages	ST. 0/ST. 1	ST. 1/ST. 2	ST. 2/ST. 3	ST. 3/ST. 4	ST. 4/ST. 5
Inter-centroid distance (km)	350	75	28	92	308

**Tab. 3. Spacing of centroids over successive stages (in km).**

The results depend on two parameters: (i)  $h$ , the value of the radius, fundamental since it determines the degree of smoothness of the data that offers the best representativeness, between the point scatter and a non-discriminating mesh (*Silverman 1978*); (ii)  $k$ , the chosen function, here a quadratic function. In our study, a graphical approach inspired by the ArchaeDyn program (*Nuninger et al. 2012*) and already proven (*Brigand, Weller 2018a*) is exploited. This involves plotting the maximum values obtained from a series of calculations according to a given interval, here 5000m. The inflection point of the curve corresponds to the best window size, which in our situation is 12.5km, a value between 10 and 15km (Fig. 17) corresponding to about half a day's walk.

At a radius of 12.5km, the KDE density value (in km<sup>2</sup>) is therefore calculated for each stage and compared with another relevant indicator: the average observed distance (AOD) (Fig. 18). These values are considered from stages 1 to 5 (formative St. 0 AOD = 51km and KDE = 0). In the graph combining these two parameters, the values of AOD and KDE are respectively very high and very low for stages 1 and 5. It is clear that during these two periods the occupation is the least dense. Conversely, the occupation is more concentrated during stages 2 to 4, with the



**Fig. 16. Geocentre and standard deviation ellipse of the LBK settlement (stage-dated sites, 39%).**

average distance being lowest and the maximum density being higher: the values of stage 4 show a slightly higher AOD, reminiscent of the situation highlighted in Figure 14.

In order to evaluate the differences between periods following the density curves and maps (Figs. 19–20), an approach based once again on methodological advances from the *ArchaeDyn* program (Nuninger et al. 2012) is proposed. This method exploits the relative difference in density between two periods through the use of the Normalized Differential Ratio (NDR), defined in the same way as the Normalized Difference Vegetation Index, namely:  $NDR = (T1 - T0) / (T1 + T0)$ . This calculation makes it possible to visualize the dynamics of settlement between two chronological sequences, and thus to distinguish the newly created sectors from those more stable or in disuse. A precise example of such a protocol is proposed in Appendix 14.

This *modus operandi* was thus implemented on a European scale (excluding Romania, Moldova and a large part of Ukraine), and a synthesis of the proportions and areas relative to the created, stable or abandoned sites by stage is presented in an analytical diagram (Fig. 19) and five maps (Fig. 20).

- Between St. 0 and St. 1, the newly colonized areas (Figs. 19 and 20.a, red) are the most extensive, since

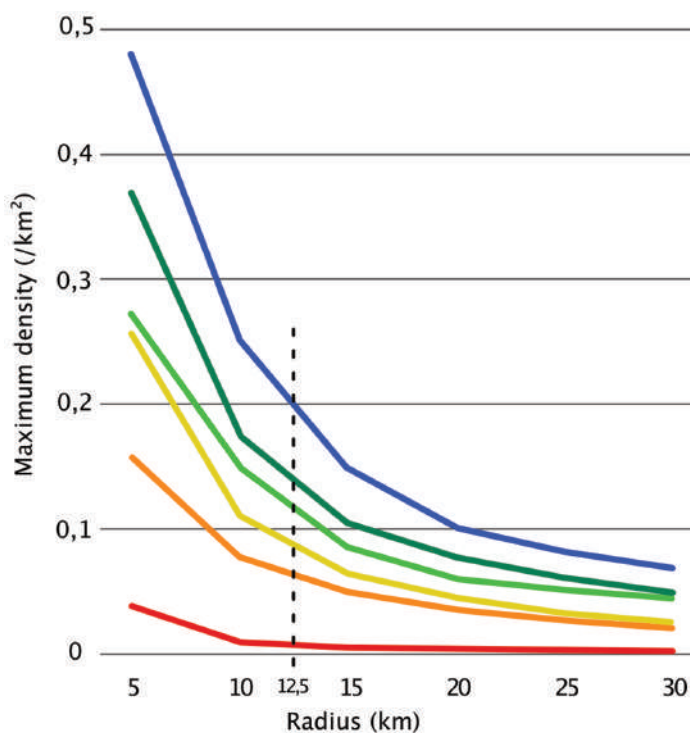


Fig. 17. Evaluation of optimal radius

the LBK leaves its initial focus to reach Moravia, Bohemia, Saxony/Thuringia and the Rhine valley in the west, Little Poland, Transcarpathian Ukraine and the upper Bug valley in the north and northeast.

- Between St. 1 and St. 2 spatial expansion remains substantial both outside and inside the previous occupied areas (Figs. 19 and 20.b, red or orange). The main features are: expansion or densification of settlement in the Rhine-Meuse-Moselle valleys (Fig. 20.b, red-orange), colonization of the hilly areas of the western Carpathians (Fig. 20b, red), and a decline in southern Transdanubia and the Elbe-Saale area (Fig. 20.b, light blue). In Saxony, Saxony-Anhalt and Thuringia, for example, the small number of very 'reliable' and well-dated sites (Figs. 1 and 2) relativizes the significance of the results proposed here, especially for the abandonments.

- Between St. 2 and St. 3, the dynamics of colonization decrease and stability dominates (Figs. 19 and 20.c, yellow), in spite of some mobility of settlement in the occupied spaces (orange) and limited expansion out of the already colonized zones (red), such as the southern foothills of the Western Beskids up to the confluence of the Vah and the Danube (Slovakia). This is the beginning of a stability that will be strengthened with the passage to St. 4 (Figs. 19 and 20.d), especially north of Lake Balaton, during which the internal and external 'conquests' are weak.

- The dynamics between St. 4 and St. 5 (Figs. 19 and 20.e, light blue) have already been observed in sections 3.1 and 3.2 (Figs. 14–16) and indicate a massive decline in Central Europe and a refocusing on western Germany, Benelux and the Paris Basin, whose centre is now occupied.

### Brief synthesis and perspectives

Although many meso- to macro-regional studies have already been carried out on both the settlement dynamics and land-use patterns of the LBK, our study is the first to tackle these questions on a continental scale using a large geo-referenced database and GIS.

As archaeologists, we are well aware that understanding the outputs of such an analysis depends largely on analytical studies at the lower scales. Due to the higher spatial and temporal resolution of the available

information, these more localized studies can often produce a better description and understanding of particular situations. Fortunately, much of this kind of research has already been done so that it is possible to adjust some of the results of our broader approach using these more specific cases and observations (among many others: *Bakels 1978; Bogaard 2004; Bogaard et al. 2016; Ebersbach, Schade 2005; Koncelova 2005; Kreuz 1990; 2008; Lenneis 2001; 2003; 2010; Lenneis, Pieler 2016; Pieler 2010; Saile 2009; 2010; 2020; Tóth et al. 2011; but see also Kempf 2020b*). It is also notable that our results are essentially an estimation of the processes underlying the current distribution maps, as were most of the synthetic narratives already proposed. It is to be hoped that the overall approach and methodological tools applied here will provide a more comprehensive basis for drawing conclusions. One of the main limitations of this approach, which is difficult to quantify globally, lies in the importance of the natural and anthropic phenomena which, since the 6<sup>th</sup> millennium BCE, might have masked and caused the disappearance of numerous settlements: direct erosion and colluvial cover and burial. These types of processes can appear, when analysed at a local scale, to be of considerable importance and therefore constitute one of the most problematic biases of the available spatial distributions. The overall assessment of this impact on the archaeological record remains to be made through further detailed local research. Nevertheless, at this stage of our general knowledge of the LBK phenomenon, the analysis proposed in these pages can represent a satisfactory framework for future improvements.

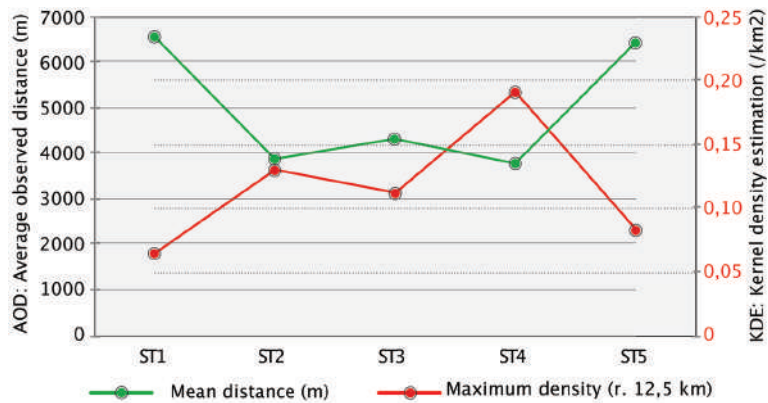


Fig. 18. Comparison of the observed average distance and density.

Three main topics were thus addressed for testing the overall capacity of archaeological research, as reflected in our database, to deal with some important issues: (1) the homogeneity, quality and limitations of the archaeological data; (2) the definition of agro-ecological determinants, if any, in the expansion process of this culture; (3) the highlighting of settlement dynamics that will have affected a significant part of temperate Europe between mid 6<sup>th</sup> and early 5<sup>th</sup> millennia BCE.

❶ The evaluation of the archaeological documentation gathered here delivers a rather complex verdict regarding its potential for description on a continental scale. The easternmost part of LBK Europe can only partially answer the questions raised and cannot be fully incorporated into an overall synthesis, mainly because of the lack of chronological precision on the occupations (see sections Archaeological descriptors and Quality of the BD\_LBK and overall heuristic validity). The other settlement areas of the BD\_LBK seem to be suitable for joint analysis; some of these are less well-documented, but still have sufficiently detailed samples in terms of number and space-time distribution. In this respect, the effect of

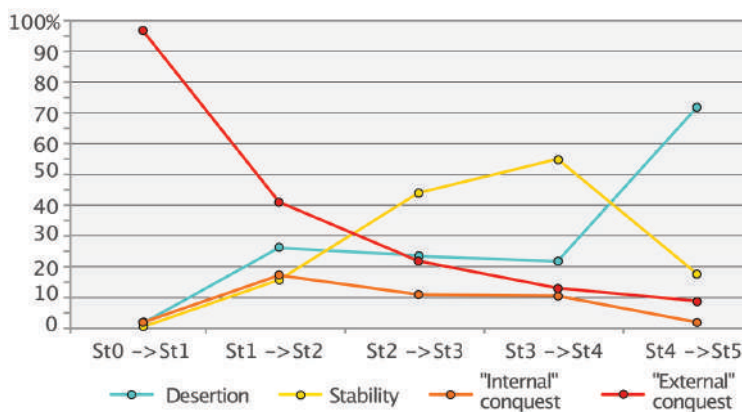


Fig. 19. Percentage representation of the areas concerned by the transition maps.

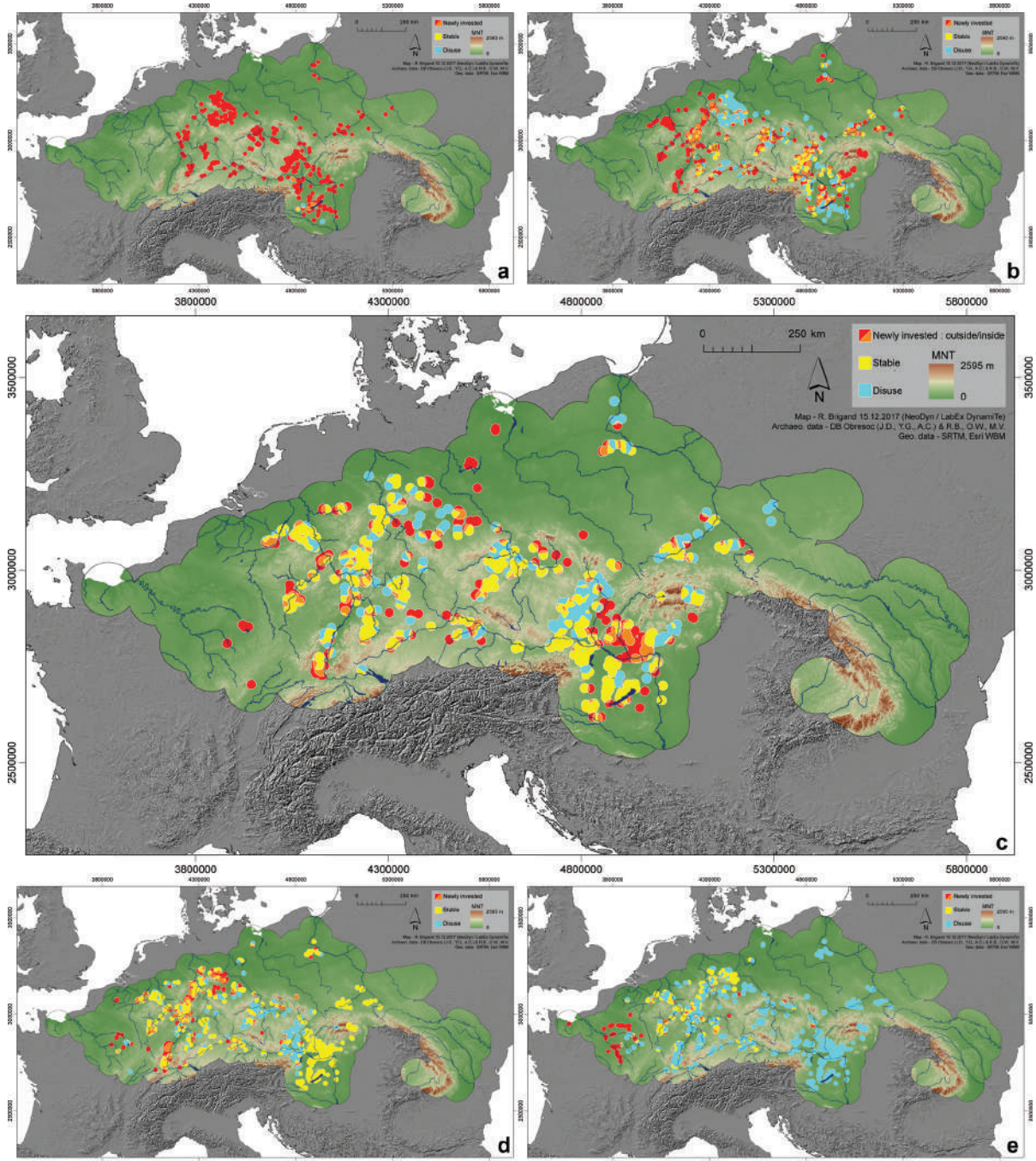
the information deficit in the Neckar Basin on our results (see section The archaeological data) can be briefly mentioned here. First it can be assumed that the analyses are not really affected in their chronological dimension, since most of the non-selected sites are 'Survey-' or 'Collect'-sites probably lacking reliable chronological information. Conversely, there is a concern that the regional statistics on agro-ecological determinants may be affected. Yet on a continental scale this impact can be assessed as marginal, without signifi-



cant impacts on the robustness of the overall observations (see below).

② The analysis proposed in this article does not seek to describe the exact variability of LBK settlement agro-ecology in each region, but rather the dominant trends that have ruled it across Europe. And the general conclusions of our study appear to be supported by some higher resolution research: the importance of ecological transition zones (ecotones),

the only relative relevance of the presence of loess, and the targeting of favourable soil characteristics, with no exclusive focus on their exact soil type. By examining the LBK settlement process in terms of the current geo-pedology, we can show that a major characteristic was the absence of exclusive preferences for particular formations. Thus, the LBK system was adaptive to the changing conditions available across temperate Europe, proof of a farming culture honed by centuries of practice. Here again, evalua-



**Fig. 20. Transition maps between developmental stages: a St. 0 (c. 5550–5500 BCE)/St. 1 (c. 5500–5325 BCE); b St. 1/St. 2 (c. 5325–5175 BCE); c St. 2/St. 3 (c. 5175–5125 BCE); d St. 3/St. 4 (c. 5125–5025 BCE); e St. 4/St. 5 (c. 5025–4925 BCE).**

tion of the documentary bias in the Neckar region suggests that our rejection of many sites there, equivalent to about 5% of the current database, has only slightly weakened the rate of loessic substrates and of Luvisols and Cambisols in LBK's settlement system. This situation does not therefore profoundly affect the validity of our general observations, nor their relevance in describing the overall expansion process. Better still, their presence in the statistics would support the highly variable and adaptive character of the LBK agro-sylvo-pastoral system as a whole. It therefore appears that the current database, despite its limitations noted in the first part (section 1), is indeed a suitable sample for a reliable analysis of the geo-pedological components of the LBK expansion.

⊕ In the light of different geo-statistic approaches, the LBK expansion dynamics ultimately appear as a combination of two major quantitative trends distributed over time. From stage 1 to stage 4, there is a rapid and steady decrease in the creation of sites beyond the previous colonization front, at the same time as an ever-stronger growth in the stabilization of places already occupied. The second trend is the fairly regular process of site abandonment, partially balanced by a roughly stabilized rate of creation within already occupied areas. Then, with stage 5, the number of site abandonments soars while the other settlement dynamics further decline, clearly demonstrating the weakening and increasing scarcity of the LBK cultural expression on a continental scale. The analyses also showed that stage 3 of our chronological framework (centred around 5150 BCE) may be considered as the climax of LBK expansion. This composite stage, formed, as noted in section 3.1, by compilation of an identified stage 3 in the west and a reconstructed middle/late transitional stage in the east, determines a state of equilibrium in stage 4 (and in the late LBK/post-Notenkopf in general). Then in stage 5 (or the latest LBK) a gradual dissolution occurs, as if the driving forces of expansion (demography, networks of socio-cultural exchange, sense of common identity) had after four centuries reached the limit of their capacity to maintain basic unity at such a large spatial scale. Thus, in our view, this overall trajectory is firstly and mainly indicative of a socio-cultural process.

It might be tempting to relate this trajectory to the 'boom and bust' pattern identified by Stephen Shennan *et al.* (2013) and Adrian Timpson *et al.* (2014) in their analysis of  $^{14}\text{C}$  data covering the whole European Neolithic. Yet, for several major reasons, it

seems clear that our LBK trajectory cannot be strictly linked to the pattern proposed by Shennan and colleagues, and in fact does not really match it at all. The authors of the population model under consideration themselves state that their results can only have a good statistical significance on a multi-millennial scale, with a time step of more than two centuries (Timpson *et al.* 2014:550). However, the time scale analysed in the two cases is very different, with the duration of the LBK representing a small fraction (10–13%) of the span envisaged for Neolithic Western Europe, and occurring very close to its onset. Thus, the LBK trajectory alone (400–500 years, depending on the regions considered) cannot corroborate a model built according to other methodological requirements and with a much more general aim. In fact, it would not be logical to seek in the LBK trajectory highlighted by our own work confirmation of a model developed for a process that was taking place over about two millennia.

At the same time, it can be observed that the  $^{14}\text{C}$  data of the eight European regions involved in the LBK expansion do not clearly illustrate the pattern. Indeed, on closer inspection of the curves proposed by Shennan *et al.* (2013) and Timpson *et al.* (2014) in their respective Figure 3, we can see considerable heterogeneity of the results and three different patterns. (i) The Paris Basin, Rhineland-Hesse and Moravia-Austria show a statistically valid start of a pronounced 'boom' approximately concomitant with the onset of LBK. However, this 'boom' lasts for about one millennium, *i.e.* twice the duration of the LBK itself. (ii) South Germany and Kujavia show a short and slight LBK-related 'boom', then two bigger ones many centuries later. (iii) The third pattern is represented by central Germany, Little Poland and Bohemia, where there is no LBK-related 'boom' but a few short 'booms' occurring 1500 to 2000 years after the end of the LBK itself. Curiously, these three regions have some of the most numerous LBK occupations known, so that these results appear very counter-intuitive. As for the 'bust', it appears statistically very significant in only three out of the eight regions, yet around 1700 to 2200 years after the end of an initial LBK-related 'boom' (Paris Basin, Rhineland-Hesse, South Germany). A fourth region (Moravia) displays a very short and slight 'bust', occurring at the same pace of time. This regressive phenomenon is therefore not directly related to the disappearance of the LBK. Moreover, in central Germany, a 'bust' seems to occur about 750 years after the end of a flourishing LBK that did not produce the signal of a 'boom', though logically predictable. Lastly, in two

regions where the strong settlement dynamics of the LBK are very apparent (Bohemia and Little Poland), we observe the absence not only of any ‘boom’, but also of any ‘bust’ over the four millennia considered.

In short, the overall heterogeneity of these results, where one would expect a good coherence, does not provide firm support for the population model defended by Shennan and colleagues and in our view raises doubts about the real adequacy of the proxy used in their study. Such an approach using a category of information that has become an expensive standard in scientific protocols is undoubtedly legitimate for defining new hypotheses, but it is up to researchers to confront them fully with the basic data, which should themselves be critically evaluated. The least that can be concluded, from the point of view of our work, is that the trajectory identified by our approach to the LBK cannot provide solid evidence for the population model promoted by Shennan *et al.*, at both methodological and factual levels.

In this respect, the final LBK dissolution should probably not be directly interpreted as an overall population collapse without an assessment at the same time of post-LBK cultural developments. Indeed, the trajectory identified here on the basis of the distribution of LBK sites alone cannot say much about the subsequent situations in the same regions (Stichbandkeramik (Stroke-ornamented ware), Lengyel, Hinkelstein/Grossgartach, BVSG). It is clear that the spatiality of these cultural developments must also be analysed in detail, as closely as possible to what is proposed here for the LBK. This is one of the reasons why it seems to us that the attempt to create demographic scenarios on the basis of radiocarbon dates alone is probably only a stopgap measure of very relative reliability. Indeed, such an approach cannot easily escape the heterogeneity of research focuses and their intensity, nor the varying archaeological visibility of different settlement modes; it cannot therefore guarantee a comparable representation of the different chrono-cultural aspects at stake. Under these conditions, statistical corrections, however rational and sophisticated they may be, cannot in our opinion replace basic archaeological information of the same reliability as that provided by the LBK. Since we have found that even the LBK data may be deficient for some specific analyses and interpretations, the results of radiocarbon analysis alone, disconnected from more or less uniform knowledge of chrono-spatial dynamics, are likely to be somewhat illusory with regard to long-term population dynamics (see *Crombé, Robinson 2014*).

For reasons of limited space here, we are developing elsewhere a complementary study- about the agro- ecological factors and their related settlement dynamics, through a spatial-temporal modelling (*Brigand et al., in prep.*). In a third contribution, special attention will be paid to the distribution of salt resources, the importance of which for Neolithic communities is now well identified (*Munteanu et al. 2007; Weller, Dumitroaia 2005*), especially for the relatively more complex societies of the 5<sup>th</sup> and 4<sup>th</sup> millennia (*Weller 2015; Brigand, Weller 2018b*). While some salt production centres have been studied in Eastern Europe (*Sordoillet et al. 2018*), we know much less about the early LBK farmers in Western and Central Europe. And as already raised in the literature for several geographical areas (*Bánffy 2013; Geschwendt 1958; Pyzel 2016; Saile 2012; Weller 2015*), to what extent did salt resources contribute to the rapid LBK expansion and the development of its main settlement areas throughout Europe? As we can see, there is still a lot of research to be done on this famous LBK culture, both on a local and European scale, in order to understand this unprecedented phenomenon.

#### ACKNOWLEDGEMENTS

*This work has received financial support from the LabEx “Dynamite. Territorial and Spatial Dynamics” (ANR-11-LABX-0046), as part of the French “Investissements d’Avenir” program, and from the “Neo-Dyn Project. Dynamiques migratoires des premiers paysans en Europe: Le rôle clé des ressources salifères dans la néolithisation” (University Panthéon-Sorbonne, Paris).*

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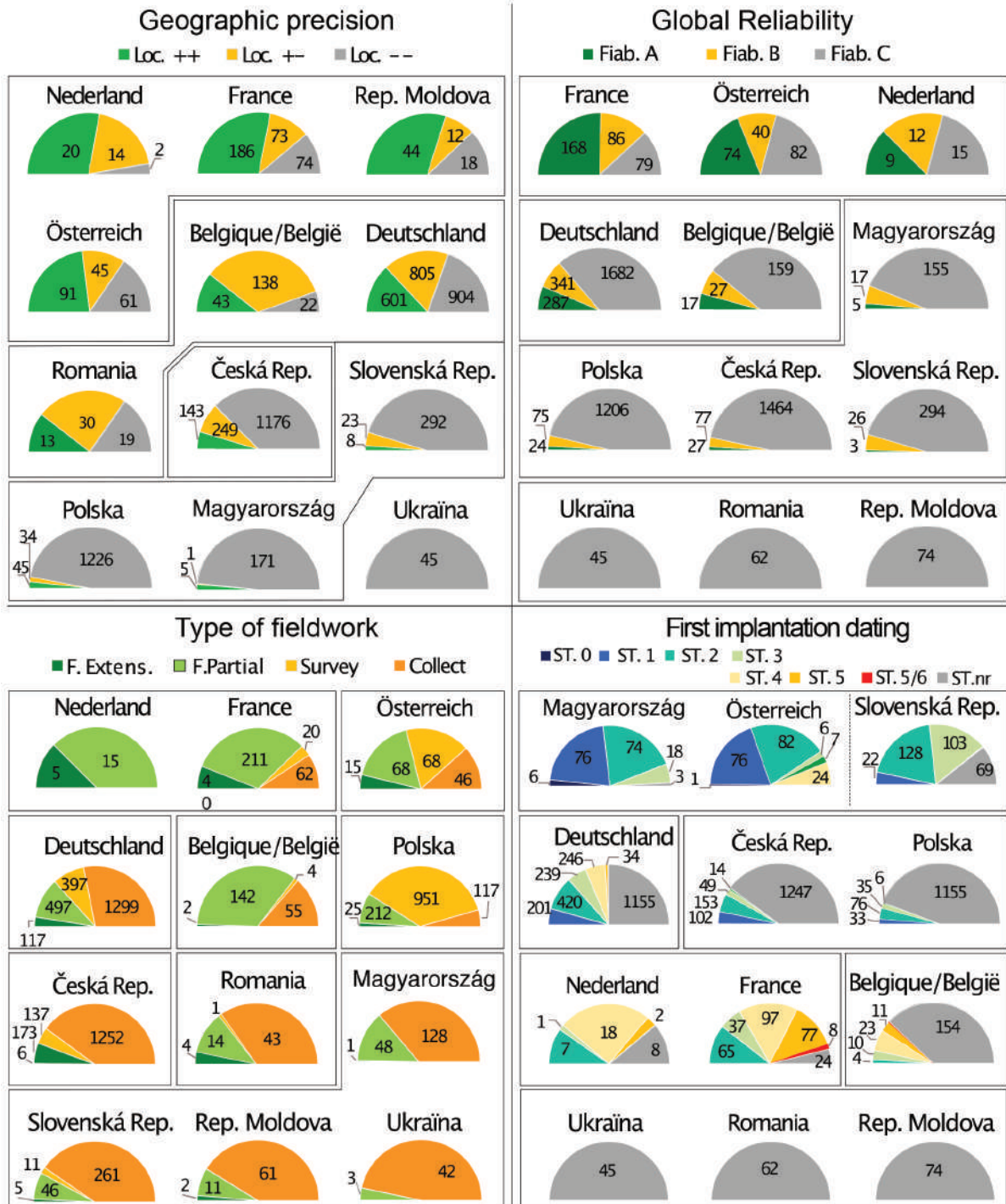
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## Appendices

### Appendix 1. Variability of site data (BD\_LBK) across major countries.

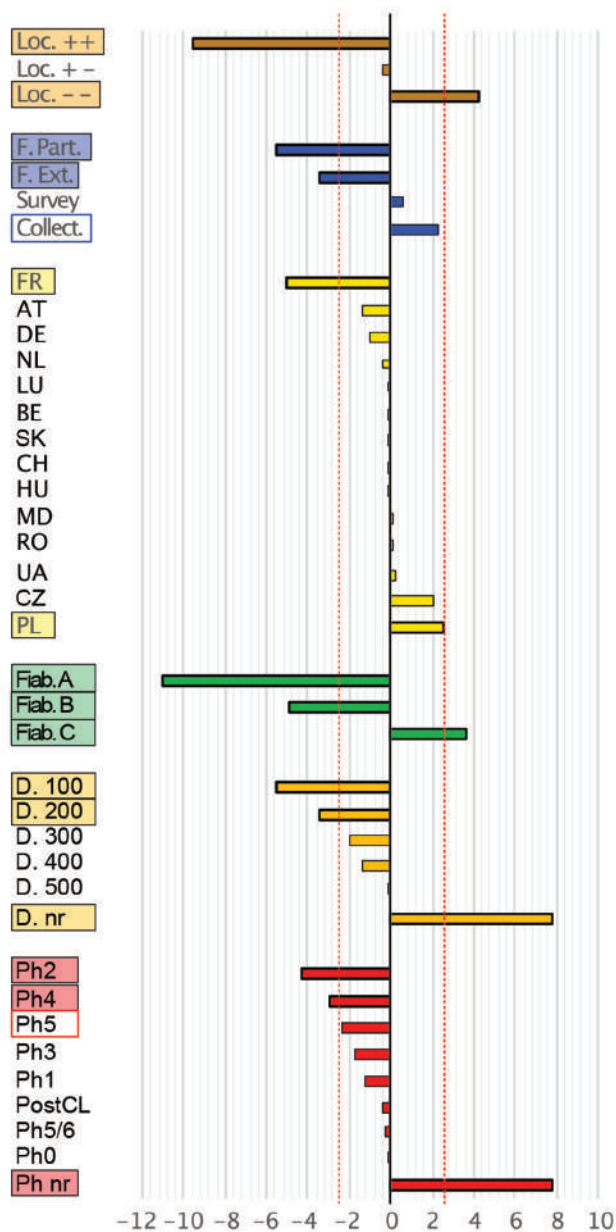


**Appendix 2. Contributions of the modalities to the first component (F1) of the MCA on the archaeological information of the database. The vertical dotted lines represent the average theoretical contribution.**

The first factor (F1) is based on 15 modalities at or above the average theoretical contribution (81.7% of the total inertia). Five of these (positive, 26.2%) belonging to 5 out of 6 different variables define a weakly documented cluster; it is significantly represented in Poland and even in the Czech Republic. Ten other modalities characterise the opposite pole (negative, 55.6%); they belong to all the variables and combine geographical precision, extensive and partial excavations, short/medium duration of occupation, datation at LBK stages 2, 4, 5, and as a whole, good to very good documentary reliability: France contributes more than the other countries to this configuration, due to its strong link with the modalities 'Loc. ++', 'Fiab. A' and 'D. 100'.

F1 thus reveals a maximum and not very surprising variability of the data around documentary reliability and precision. There is a clear correlation between the most superficial types of intervention (prospecting, collecting), imprecise location (Loc --), undefined chronology and duration of occupation (St.nr and D.nr).

Contributions to F1



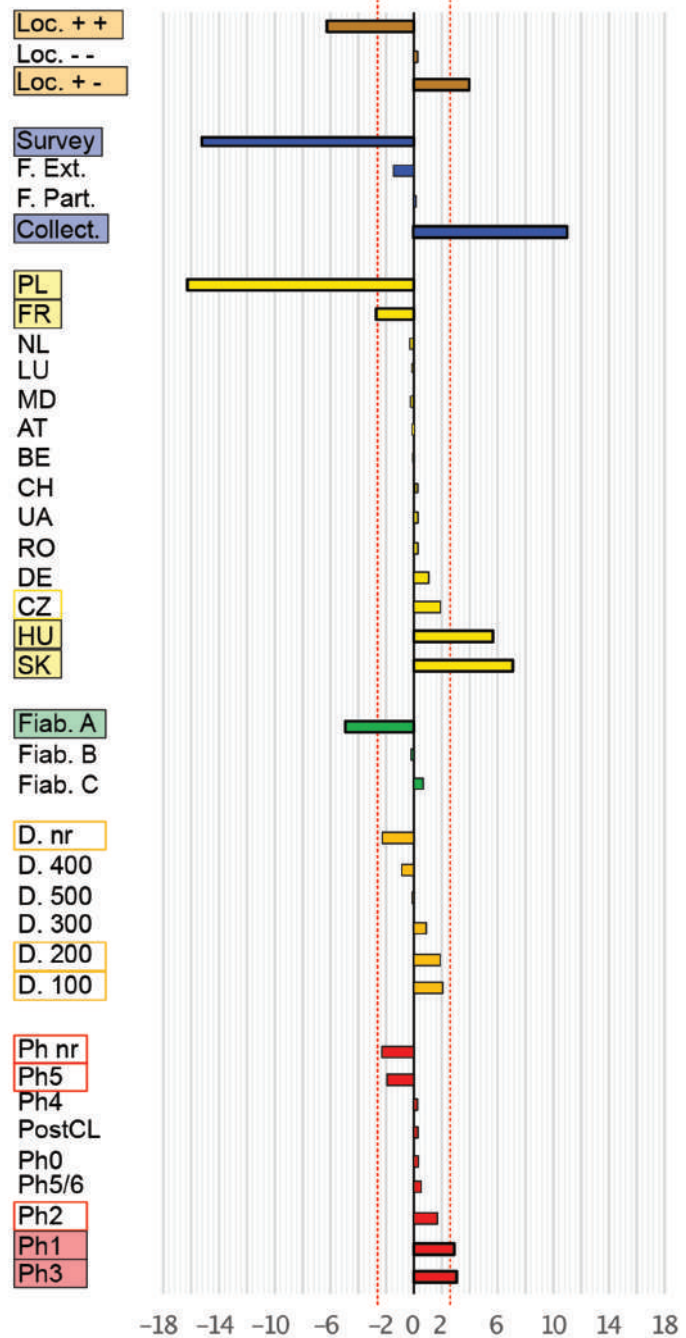
**Appendix 3. Contributions of the modalities to the second component (F2) of the AFCM.**

The second factor (F2) is based on 11 modalities at or above the average contribution (79.2% of the residual inertia). Of these, six are positive (33.6%) and belong to four out of six different variables. They define a pole representing early and middle LBK sites (Ph.1-3) from surface collections, with short/medium duration, correctly located and on the whole limited in reliability. Two countries contribute particularly to this cluster: Slovakia and Hungary.

Five other negative modalities (45.5%) characterise the opposite pole; they belong to four of the six variables analysed and combine geographical accuracy, surveys and good to very good documentary reliability. Only two countries determine this configuration, Poland in particular and France more slightly.

This second summary on the remainders of variability not described by F1, therefore reveals the contributions of four new descriptors: two modalities of the variable 'Type of intervention' (Survey and Collect.) and two of the variable 'Country' (Slovakia, Hungary). It contrasts sites mainly Northern and Western sites with good documentary reliability, resulting from 'Surveys' and very well located, with a group of early sites in the chronology from southern central Europe, resulting from more or less random collections ('Collect'), but correctly located.

Contributions to F2

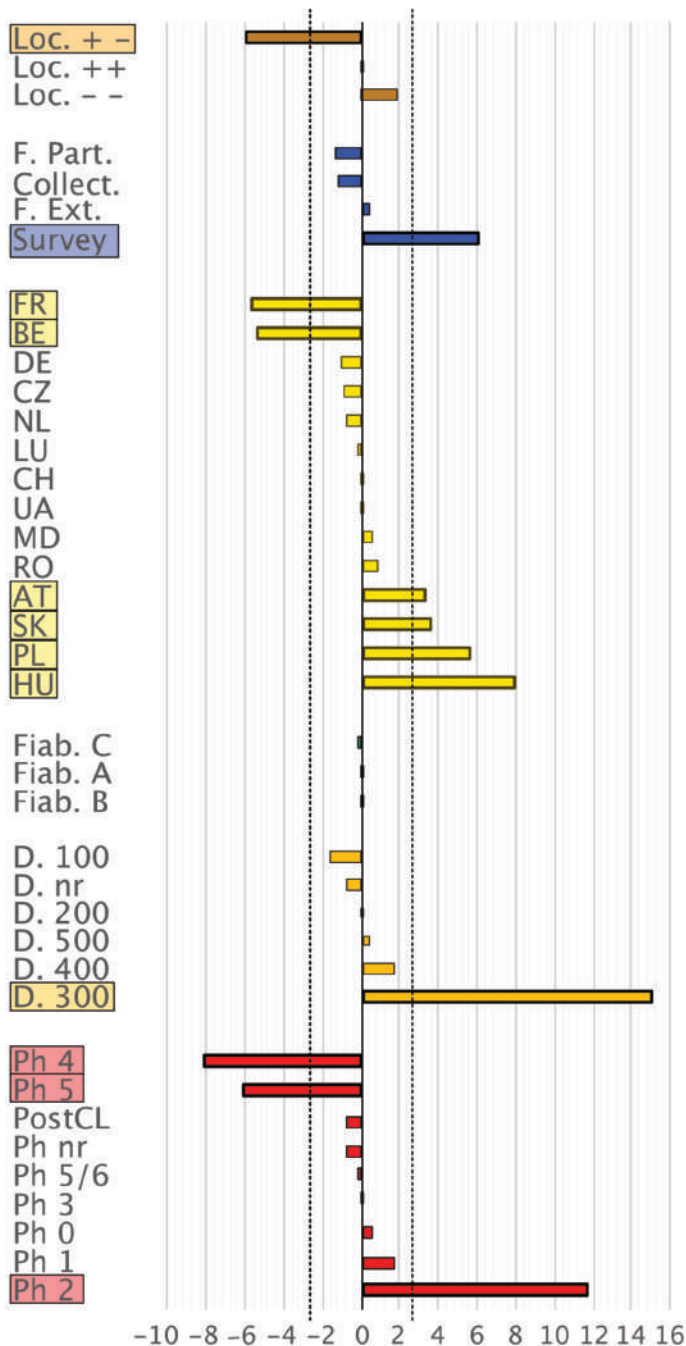


**Appendix 4. Contributions of the modalities to the third component (F3) of the MCA.**

Finally, the third factor (F3) summarize a residual fraction of the total inertia of the data, not yet taken into account. In this way, it adds complementary components to the global design of the data variability. It is constructed by 12 modalities at or above the average contribution (83.3% of the residual inertia). Seven of these are positive (52.1%) and belong to 4 out of 6 variables. They define a cluster of central-eastern sites (Hungary, Poland, Slovakia, Austria) resulting from 'Survey', belonging rather to stage 2 of the LBK (Ph.2) and showing a long duration (D. 300). Five other negative modalities (31.2%) define the opposite pole; they belong to only half of the variables analysed and combine late LBK stages with a correct location: this configuration is found mainly in France and Belgium.

This third complementary synthesis thus marginally contrasts early and long-lived Central European sites, not very well located and resulting from 'Collect', with Far-Western sites belonging to the recent stages of the LBK and correctly located. It also tells us that the main countries concerned in F2 by the 'Collect' modality are also concerned in F3 by the 'Survey' modality (Poland, Slovakia, Hungary).

**Contributions to F3**



**Appendix 5 (see Figure 4, Map F1/F2)**

The analytical data set is displayed in the factorial space around the most discriminating modalities of the first two summaries of the MCA. They oppose, in a ternary system, Poland, Hungary/Slovakia, and France.

- To the right of axis 1, are grouped the modalities representing sites which are relatively poorly documented (Fiab. C), both chronologically (St.nr and D. nr) and geographically (Loc --). Among them are those resulting from the lightest archaeological investigations (Collect. and Survey). Many Polish, Czech, Swiss, Ukrainian, Romanian and Moldovan sites share these characteristics: the first ones particularly linked to the 'Surveys' and all the others rather to the 'Collect' variable. It is therefore a large group of mostly central-eastern and eastern sites, which are generally less well documented than those in other regions of LBK Europe.

- In contrast, to the left of axis 1 and at the bottom of axis 2, are the well documented sites (Fiab. A), with good geographical precision (Loc ++), resulting from extensive excavations (F. Ext) and dated to the latest stage of the LBK (St.5). The countries concerned by this high-quality documentation are mainly France, the Netherlands and Luxembourg.

- As an intermediate to the previous clusters but still to the left of axis 1, meaning not being dominated by low quality documentation, the average archaeological information from Germany, Belgium, Slovakia, Hungary and Austria seems to be relatively well documented and localised (Fiab. B and Loc +-); it appears to be linked particularly to partial excavations (F. Part.), to the main stages of the LBK (St.1 to St.4) and to the most common occupation duration modalities (D. 100 to D. 300). This average position applies thus to countries that present in moderate proportions the whole spectrum of research types and a great variety of documentary realities. Austria is rather better documented than Belgium and Germany, where there is a significant proportion of less well-informed sites. These are therefore similar to those widely encountered further east, notably in the Czech Republic. Finally, Hungary and Slovakia, linked to partial rather than extensive excavations and to the early stages of the LBK, are isolated from the other regions of Europe and particularly from Poland with its particular link to 'Survey'.

Actually, the structuring of the data revealed by this first and most distinctive synthesis of the data, is not surprising at all. Main opposition between poorly documented groups of sites and others is a kind of truism; similarly, the correlations between location accuracy, chronological characteristics and type of investigation are also predictable. But it was not taken for granted that all these possible variations should be organized in coherent sequences, evident for almost all the descriptors together. Under these appearances, the ordering of the countries on the factorial map draws an almost perfect east-west progression, which we believe is related to the temporal depth of research on the one hand and its funding on the other. Such a spatial configuration could rapidly change under an unlikely common elevation of the economic and technic standards of archaeological research in Europe. Poland, Hungary, eastern Lands of Germany, for example, have finally implemented effective and promising practices (rigorous survey programs, broad scientific Rescue Archaeology) that show a way forward. But at the same time West Germany has been slowly regressing in these respects, while other regions (Belgium, Slovakia, Romania) have remained behind. We cannot yet be sure whether the recent evolution of practices in France will impact the results upwards or downwards. Therefore, the harmonisation of data on a continental scale is still a long way off, or could be achieved at a frustrating intermediate standard.

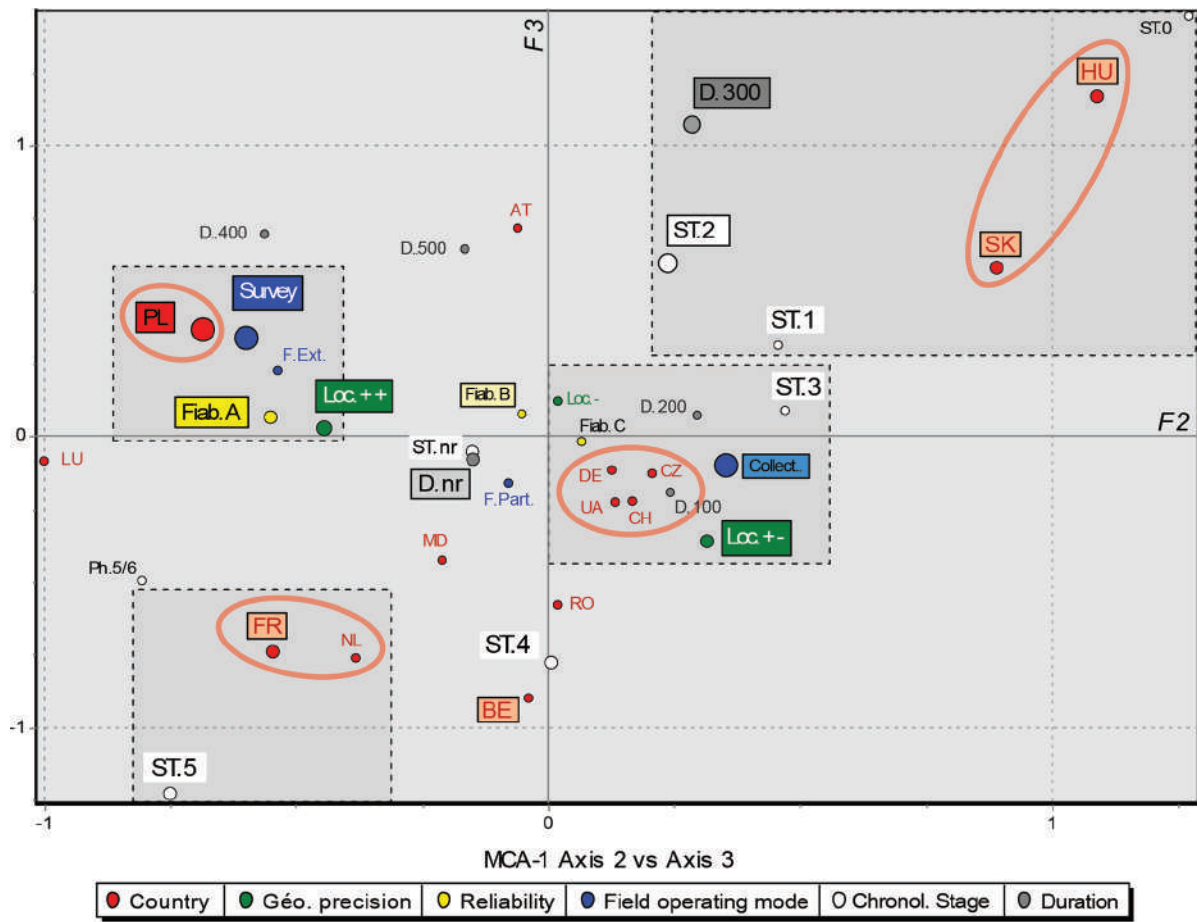
**Appendix 6 (see Figure 5, Map F1/F3)**

Following the methodological principles of MCA, map F1/F3 (Fig. 5) modulates the previous conclusions. It presents only two groups of opposite modalities: to the right of axis 1, the same set as before is shown again, due to the decisive weight of their modalities in the characterization of the first factor, and confirms the singularity of Poland; but it redistributes the other modalities in a single second group around which gravitate the other modalities of 'countries' and those, extreme, of the LBK 'chronology' (St.0 and 4-5): this map confirms Austria, linked to the long-lived durations (D.300-500), in a positive situation; France and the Netherlands, around late chronological stages and short durations, appear again as more often better informed and the Belgium-Germany-Slovakia trio still show their intermediate quality.

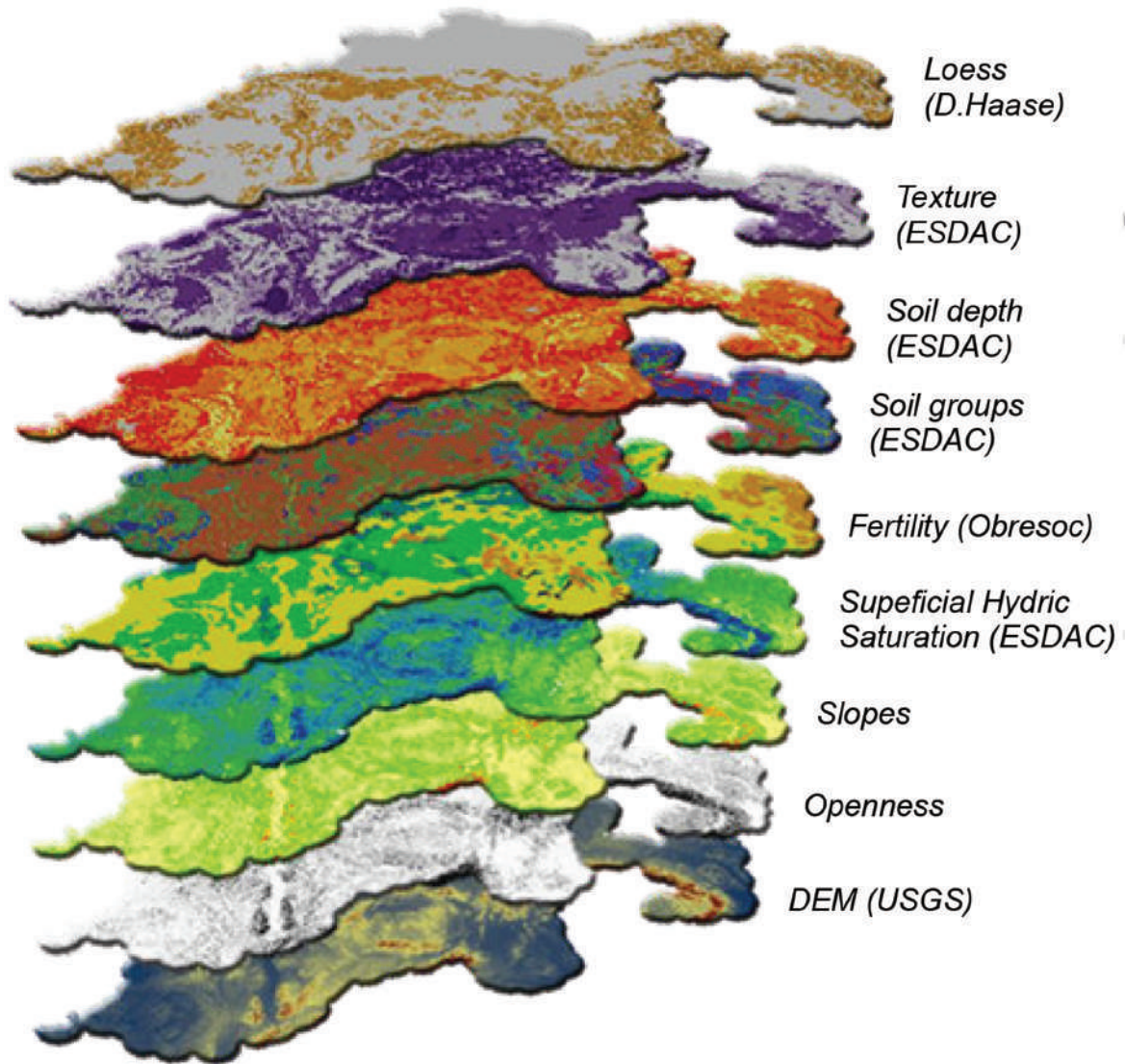
**Appendix 7 (map F2/F3)**

The F2/F3 map characterises the database without the influence of poor documentary situations; it can thus show some secondary links previously masked by the hyper-structuring weight, in F1, of weaker or undefined modality values. The main point of this map is, on the one hand, a significant and favourable configuration around Poland and its systematic 'Survey' practices; on the other hand, a clear highlighting of the Hungary and Slovakia's specificity re-

lated to the weight of their older and long-lived sites. The group of sites of the BD\_LBK with limited or scarce documentation is logically in a central position and therefore not very significant in this secondary statistical summary. But interestingly, a part of the German sites belongs to this group, as already suggested by the previous diagrams. At last, the western trio (FR, NL, LU) remains linked to the best modality values, while part of the excavated Belgian sites are close to them, probably because of their links with the late stages of the chronology.

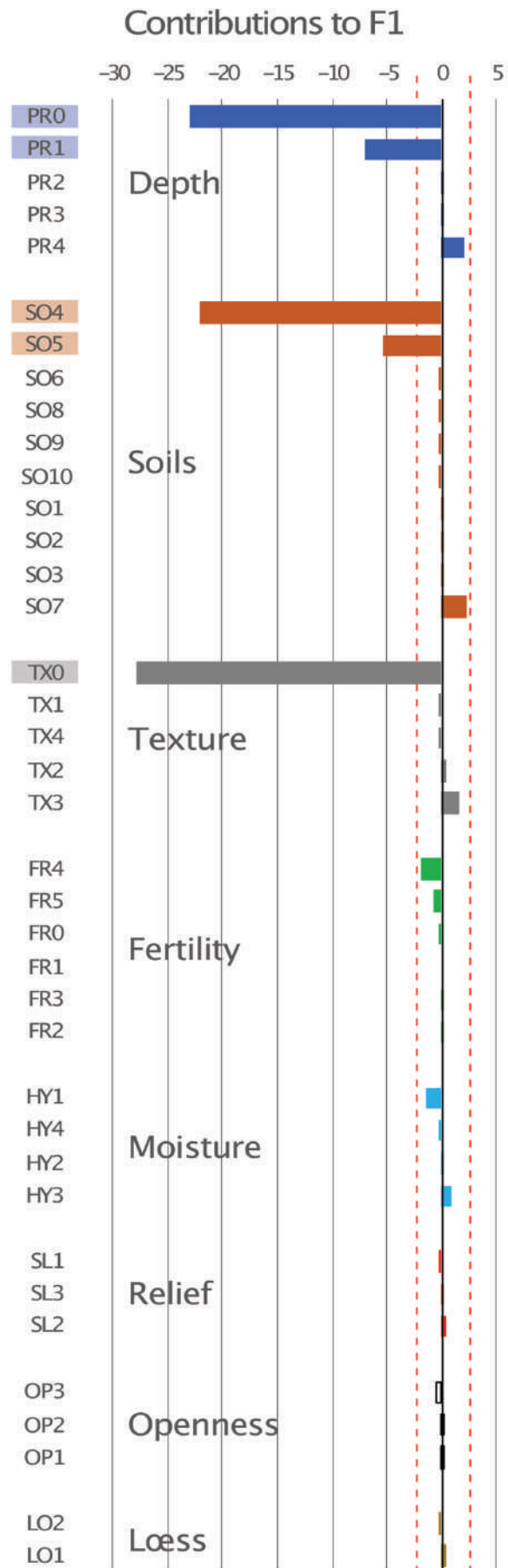


**Appendix 8. Topographic and agro-ecological data of the GIS.**



**Appendix 9. Contributions of the agro-environmental modalities to factor 1 of the MCA. Vertical dotted red lines show the average theoretical contribution.**

The highest contributions to Factor 1 (~85% of its inertia) are all negative. They relate to the ‘undefined’ modalities PR0 (n.r.), SO4 (no data) and TX0 (n.r.) which almost exclusively construct this first statistical summary (respective contributions of 22.9%, 22%, 27.8%, *i.e.* ~73% of the variability summarised by this factor). The other negative modalities PR1 (7%) and SO5 (5.3%), *i.e.* shallow soils and Gleysols or Vertisols, contribute only a little. The first factor therefore mainly separates sites in poorly defined or rare contexts from all other sites. Its relevance to our questions is therefore very limited.

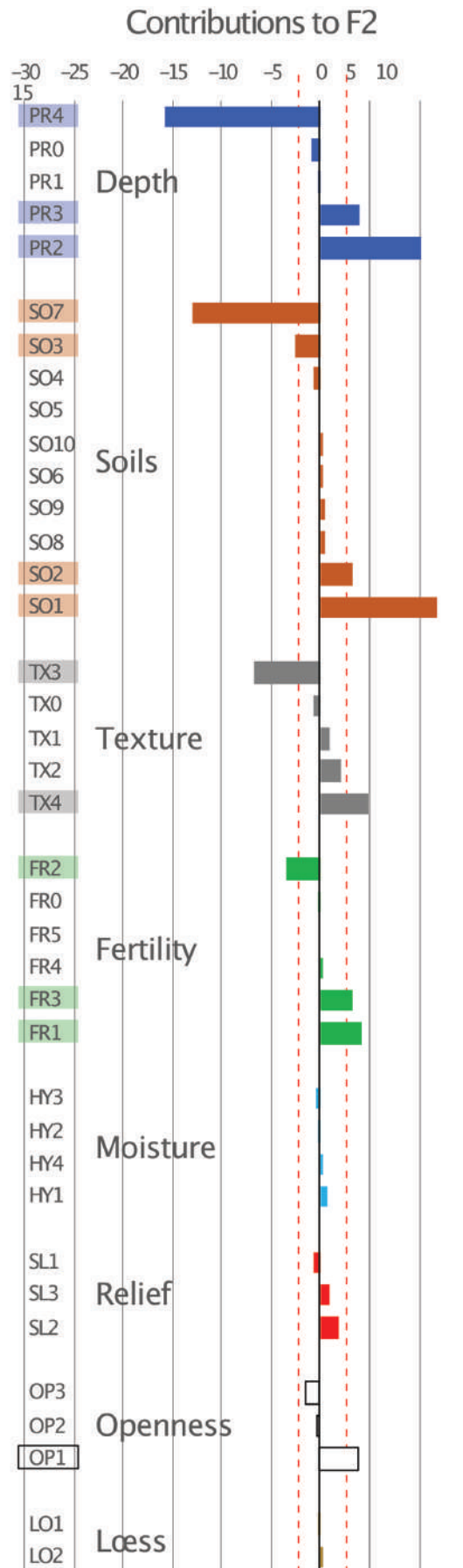




**Appendix 10. Contributions to F2 of the MCA.**

The second factor is mainly built (~84% of its inertia) upon the opposition between negative PR4/very deep soil (15.7%), SO7/degraded and leached soil (13%) and also, very moderately, TX3/medium-fine texture (6.7%) and FR2/fairly good fertility (3.4%), for a total of ~38% of the factor's inertia; facing the positive modalities PR2/moderate depth (10.3%), SO1/Cambisol (11.9%), and very moderately TX4/fine texture (4.8%), FR1/very good fertility (4.2%), OP1/closed landscape (3.9%), PR3/deep depth (3.9%), FR3/medium fertility (3.2%) and SO2/clino-humic soil (3.2%) for a total of ~40%.

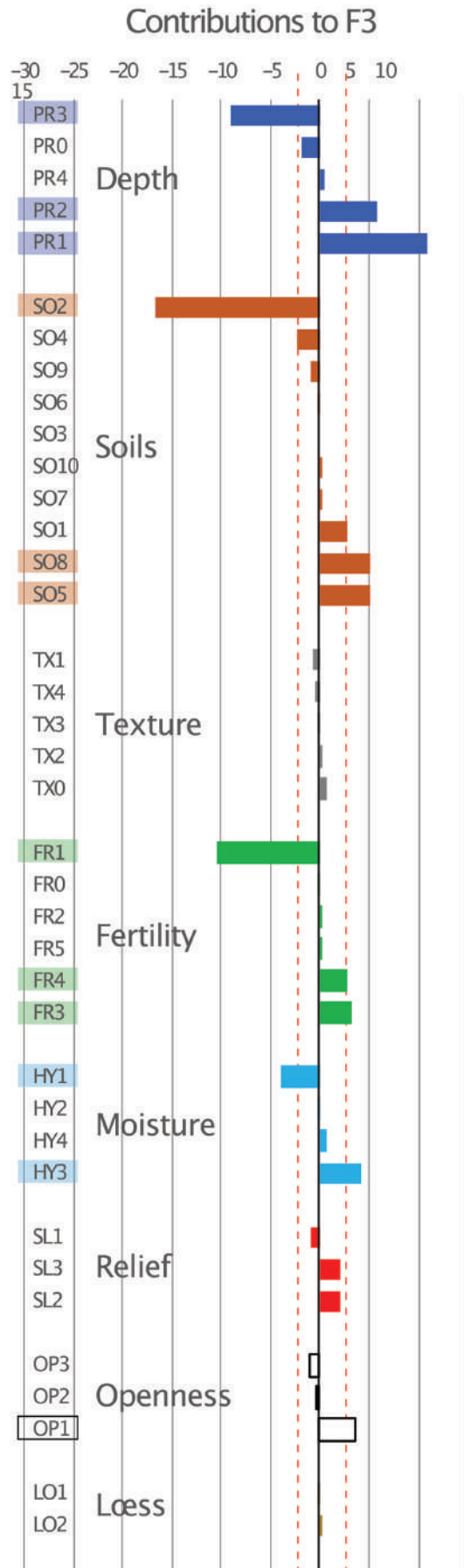
That is to say, an overall opposition between settlements on leached (Luvisols) or degraded soils, very deep, with medium-fine texture and good fertility; and those on brown soils slightly evolved or even clinohumic, with moderate to deep depth, fine texture, very good or medium fertility and in a closed landscape.



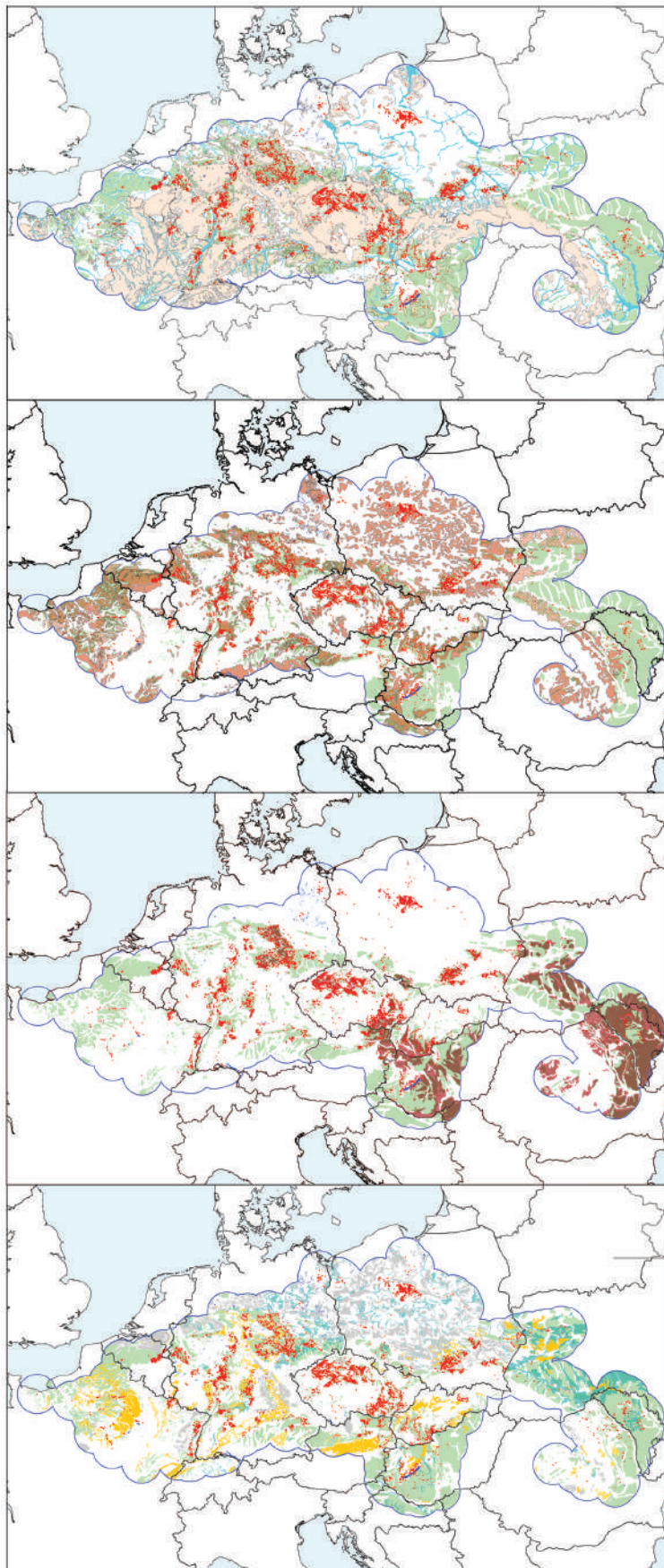
**Appendix 11. Contributions to F3 of the MCA.**

The third factor is mainly built (~78% of its variance) upon the opposition of the negative modalities SO2/clinohumic soil (16.6%), FR1/very good fertility (10.5%), PR3/deep depth (9%), and HY1/low hydric saturation (3.8%), for a total of ~40%; against positive modalities PR1/shallow depth (10.9%), PR2/moderate depth (5.8%), SO8/thin soil (5.2%), SO5/gleysol-vertisol (5.2%), HY3/high hydric saturation (4.1%), OP1/closed landscape (3.7%), FR3/moderate fertility (3.2%) and FR4/low fertility (2.7%), for a total of ~41%.

This is an expected contrast between settlements on deep and very fertile soils of Chernozems-Greyzems-Phaeozems types and those on very thin or water-logged soils.



**Appendix 12. Geographical distribution of the main soil groups in the LBK' occupation area.**



Cambisols (SO1 : beige),  
fluvisols (SO3 : light blue),  
loess (light green),  
and LBK sites (red)

Luvi-podzoluvisols  
(SO7 : light brown),  
loess (light green),  
and LBK sites (red)

Clinohumic soils  
(SO2 : brown),  
loess (light green),  
and LBK sites (red)

Gleysols (SO5: green),  
Podzols (SO6: light grey),  
Renzinas-Régosols (SO8: yellow)  
loess (light green),  
and LBK sites (red)

### Appendix 13. Chronological stage-system in this paper.

Unified phasing of the whole LBK's extension, at least in large stages, is required for this research project: continuities and discontinuities across time and space have to be considered at once. However, this

ambition is particularly sensitive between the Western and Central Eastern chronological systems. Although many specialists may not be satisfied, we have nevertheless made such an attempt at chronological standardisation, according to the following approximative six stages sequence.

Approx. cal BC	5600– 5500	5500– 5325	5350– 5325	5325– 5150	5175– 5125	5125– 5025	5025– 4925
This paper	St 0	St 1	St 1/2	St 2	St 3	St 4	St 5
<i>Meier-Arendt 1966; 1972</i>		I		II	III	IV	V
<i>Dorhn-Ihmig 1979</i>		1a		Ib-c	Id-Ila	Ilb-c	Ild
Lorraine-Bassin-Parisien ( <i>Blouet et al. 2013</i> )				Rubané Ancien (Flomborn)	3–4 – Rub. Moyen	5–7 – Rub. Récent	7–9 Rub. Final/ Termin. –
Alsace ( <i>Denaire et al. 2017;</i> <i>Lefranc 2007</i> )				Rubané Ancien (Flomborn)	Rub. Moyen	Rub. Récent	Rub. Final
Mit./Nied. Rhein ( <i>Dohrn-Ihmig 1979</i> )			I/II? (Nieder Kass.- Uckend.)	Ib-c II- Ältere (Flomborn)	Id-Ila III-Mittlere	Ilb-c IV-Jüngere	Ild V-Jüngste
Württemberg-Neckar ( <i>Strien 2000; Lindig 2002</i> )		Älteste	2a ?	2b-5	6–7	8	Hi
Hessen ( <i>Kneipp 1998</i> )		Älteste	2 ?	3–5	6	7–8	9
Nied. Sachsen-Elbe/ Saale-Sachsen ( <i>Behrens 1973; Kaufmann 1987;</i> <i>Quitta 1970</i> )		Älteste	?	Ältere (Flomborn)	Mittlere	Jüngere	Jüngste/ SbK
Südbayern/Schwaben ( <i>Pechtl, Land 2019</i> )		Älteste	?	Ältere	Mittlere	Jüngere	Jüngste SOB (SbK)
Český ( <i>Pavlu 2000</i> )		Ib-c Ältere	I/II (Áčkový ?)	Ila-b-c/ (Áčkový)	IIIa-b	III/IV IVa-b; šarka	IV?/SbK
Morava ( <i>Čížmář 1998</i> )		Ia-b Ältere LBK	1b2 (Áčkový ?)	Ila-b Jung LBK	IIc NKK/Zseliz	III šarka	?
Niederösterreich/Burgenland ( <i>Lenneis, Pieler 2016</i> )	Älteste Forma- tive	Ältere LBK	Übergangsph. I/II	II Jung LBK Notenkopf	II? Zseliz/ Keszthely	III šarka/ Zseliesovce	?
Centra a západ Slovensko ( <i>Pavúk 2004; 2005</i> )	Forma- tive?	Ältere LBK Biňa	Milanovce	Jung LBK – Notenkopf	Zseliesovce	Zseliesovce	Z.
Magyar Dunántúl ( <i>Oross, Bánffy 2009</i> )	Forma- tive	Ältere LBK Bicske- Biňa	Milanovce	Jung LBK Notenkopf/ Keszthely	Zseliz/ Keszthely	ZI-II Zseliz/ Keszthely	ZIII/L.
Malopolska ( <i>Czekaj-Zastawny 2009; 2013</i> )		Ältere LBK	Zofipole?	Jung LBK Notenkopf	Zseliz	Zseliz	LPC/SbK
Kujawy/Chelm. ( <i>Pyzel 2006; 2010</i> )		Ältere LBK	Zofipole?	Ila-b Jung LBK	III?	III	LPC/SbK

**Appendix 14. Protocol for the elaboration of transitional maps (example of the Upper-Rhine Valley).**

As shown in the figure below, the colonization sectors for a period  $t+1$  are divided into two groups: the one (orange) that develops (at  $t+1$ ) inside an area already settled during the previous period ( $t$ ); and the one (red) that develops outside a previous-

ly occupied area. In this way we can better identify true expansion from densification.

Left and centre: density maps (r. 12.5km) and 12.5km buffer zone (St. 3 and St. 4); right: transition map. The area of slightly less than 500km<sup>2</sup> delimited around sites from a radius of 12.5km is only a study protocol aimed at optimizing the density maps and allowing for a synoptic representation of settlement dynamics.

