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Between paleodemographic estimators and "LBK" colonization in Central-Western Europe (c. 5550-4950 BCE): A tribute to the theoretical and methodological trajectory of Jean-Pierre Bocquet-Appel in the study of the first farmers of the "Old World"

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Journey of a committed paleodemographer Farewell to Jean-Pierre Bocquet-Appel

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Abstract: Jean-Pierre Bocquet-Appel has reintroduced and renewed the demographic issue in Prehistory, particularly in the analysis of the processes of diffusion of the agro-pastoral economy in the “Old World,” through his deconstruction/reconstruction approach of paleodemography (Bocquet-Appel and Masset 1982, 1996) and his research on the Neolithic/Agricultural Demographic Transition (ADT), carried out on a European (Bocquet-Appel 2002; Bocquet-Appel and Dubouloz 2003, 2004) and intercontinental scale (Bocquet-Appel and Bar-Yosef 2008; Bocquet-Appel 2009). The emphasis on a strong demographic growth linked to establishing a production economy was, therefore, the first stage of Jean-Pierre’s interest in this scientific question (Bocquet-Appel 2008).

This research was the seed of his later investigations into the nature and pace of the diffusion of the agricultural system in Europe (LBK), first through ¹⁴C radiometric dating analysis, then through the analysis of the systemic conditions of this process (Bocquet-Appel *et al.* 2009, 2012). The construction of descriptive models articulating the apparent expansion of LBK with its environmental,

technical, sociological, and cultural components was, therefore, the second expression of his commitment to this highly debated subject. This opened the way to an even more integrative advance, the theoretical modeling and computer simulation of past anthropological processes. Given the good archaeological evidence, the emblematic, self-evident case chosen for this approach was the diffusion of the Linear Pottery Culture (LBK) - the prehistoric period which corresponds to the introduction of the agricultural system in central and central-western Europe during the 6th and early 5th millennia before the Common Era (BCE). Since we have been involved in this endeavor from the early 21st c. and have contributed closely to several of these projects between 2002 and 2018, we shall present the essential elements of this multi-agent approach, the simulated products directly relevant to Neolithic archaeology, as well as the limits of this first simulation.

Keywords: Continental Europe, NDT (ADT), Neolithic, linearband pottery (LBK), agricultural expansion, multi-agent modeling

Résumé : Par sa démarche de déconstruction/reconstruction de la paléodémographie (2012 1982 , 1996) puis ses recherches sur la Transition Démographique Néolithique/ Agricole (TDN), menées à l'échelle européenne (Bocquet-Appel 2002; Bocquet-Appel and Dubouloz 2003 , 2004) et intercontinentale (Bocquet-Appel and Bar-Yosef 2008; Bocquet-Appel 2009), Jean-Pierre Bocquet-Appel a réintroduit et renouvelé la question démographique en Préhistoire, notamment dans l'analyse des processus de diffusion de l'économie agro-pastorale dans le « vieux Monde ». La mise en évidence d'une forte croissance démographique liée à l'établissement de cette économie de production fut donc une première élaboration de son intérêt pour cette question scientifique (Bocquet-Appel 2008). Elle portait en germe ses recherches ultérieures sur la nature et le rythme de la diffusion du système agricole en Europe (LBK) par l'analyse des datations radiométriques ¹⁴C d'abord, puis celles des conditions systémiques de ce processus (Bocquet-Appel et al. 2009, 2012). La construction de modèles descriptifs articulant l'expansion apparente de la LBK avec ses composantes,

environnementales, techniques, sociologiques et culturelles fut donc une seconde expression de son investissement sur ce sujet hautement débattu. Elle ouvrait à une avancée plus intégrative encore, la modélisation théorique et la simulation informatique de processus anthropologiques du Passé. Le cas emblématique choisi pour cette approche — la diffusion de la culture à Céramique Linéaire (LBK) — allait de soi, au vu de la bonne connaissance archéologique sur cette période préhistorique : elle correspond à l'introduction du système agricole en Europe centrale et centre-occidentale au cours du VI^e et au tout début du V^e millénaires avant l'ère commune (BCE). Pour avoir participé à cette démarche dès l'orée du XXI^e s. et contribué de très près à plusieurs de ces travaux, entre 2002 et 2018, nous présenterons ici les éléments de base de cette approche multi-agent, les produits simulés intéressant directement l'archéologie néolithique ainsi que les limites de cette première simulation.

Mots-clés : Europe continentale, TDN, Néolithique, céramique linéaire (LBK), expansion agricole, modélisation multi-agent

The following pages aim to recapture, among the many aspects of Jean-Pierre Bocquet-Appel's (JPBA, as he used to call himself) scientific career, the originality and coherence of his long-term approach (35 years between the end of the 1970s and the middle of the 2010s) to a central issue in the history of humanity: the emergence of agriculture and animal husbandry during the Holocene and its demographic consequences, the Agricultural Demographic Transition (ADT).

Before the "OBRESOC" project

JPBA and Claude Masset have established, since the end of the 1970s, through the modeling of stable pre-industrial populations, that the proportion of subadults in funerary remains provided a good assessment of the shape of the age pyramid of the living on a large scale and, more generally, of the birth and fertility rates (Bocquet-Appel and Masset 1977, 1982, 1996). The juvenility index $_{15}P_5$ could thus be transformed into an increase rate ρ within a fairly wide confidence interval among the paleodemographic estimators resulting from this work.

The implementation of this $_{15}P_5$ index to Meso and Neolithic European burial remains, using a chronological distance relative to the local onset of the agricultural system (dt), has evidenced a demographic transition (ADT) linked to the introduction of the agricultural system. As soon as this new food production system was

introduced, there was an abrupt demographic change from the pre-existing stationary regime and a rapid increase in the proportion of subadults by about 70%; the corresponding population growth rate jumped from -0.3 to +1.3% ($\pm 1.07\%$) in about 500 years (Bocquet-Appel 2002, 2008).

This increase in the birthrate/fertility pair suggests a reduction in the birth interval through a decrease of the weaning age due to dietary change and social factors such as a new division of labor (Bocquet-Appel and Bar-Yosef (eds) 2008).

In 2003, we confronted these paleodemographic results - the existence of an ADT and its specific European characteristics - with a category of archaeological record whose systemic link with a new social pressure was suspected (Bocquet-Appel and Dubouloz 2003, 2004). The quantitative distribution of Neolithic enclosure sites on the 'dt' chronology thus shows a good concomitance of its general growth tempo with the subadults' profile. This overall coincidence provided physical anthropology with an independent socio-cultural archaeological counterpart, and in turn, improved the hypothesis of the social regulation function of this type of site in the context of significant demographic pressure.

Subsequently, research published in 2009 focused on the statistical detection of the European diffusion of the agricultural system and its tempo on this continental scale (Bocquet-Appel *et al.* 2009). This research revealed the general irregularity of this process through the analysis of

the spatial-temporal distribution of ^{14}C dates recorded for the beginning of the Neolithic in Europe and identified ten geographical areas of renewed expansion and nine areas of stasis, corresponding relatively well to archaeological events based on the material culture and its geography.

The authors "objectify" on a large scale the hypothesis of an arrhythmic expansion of the agricultural system (Guilaine 2000, 2003), from southeastern Anatolia to Portugal, Scotland, and southern Scandinavia, by using the kriging interpolation technique. This geostatistic method makes it possible to estimate the spatial-temporal continuum represented in this case by the local ^{14}C dates by identifying the variation in archaeological density across the isochronous surfaces and constructing a map of the spatial-temporal vectors of the dates' distribution.

In addition to areas of renewal or stasis, this vector mapping also suggests the main directions and axes of this expansion, globally in concordance with the available archaeological interpretations. For the LBK, we can guess the two trends of the Linear Ceramics running from Hungary either towards the West and the North-West, or towards the North and the North-East, and the three zones of renewed expansion in Transdanubia, Germany, and the Parisian Basin.

Building on these global results, JPBA devoted the rest of his research to explaining this general processual pattern. In an article published in 2012 (Bocquet-Appel *et al.* 2012) dedicated to measuring the systemic links between the variability of the rate of expansion (speed), the agricultural system, and the demographic density, JPBA, and his colleagues cross-referenced five geographical variables, five additional climatic and ecological variables, ten cultural variables (including two Mesolithic scenarios: middle and recent dating), combined with the local date of the emergence of the Neolithic period and its rate of expansion (a total of twenty-two (22) variables).

The data are mapped onto a spatial grid applied to the surface of the space-time continuum defined by kriging. The probabilities of meso/neolithic contacts and the rate of expansion on the spatial grid are subject to specific approaches, well detailed in the publication, before being confronted with the other explanatory variables. Thus, the scenario based on the central Mesolithic dating probability values unsurprisingly indicates a much lower potential for biocultural interaction between hunter-gatherers and farmers (<1% of the grid squares) than the scenario based on the lower dating probability margin ($\approx 25\%$ of the squares). This alternative information is factored into the rest of the analysis.

The expansion velocity, calculated at the grid square level, also suggests unsurprisingly different values for the continental and maritime trajectories. This research reveals two main results through a complex statistical analysis procedure: 1) the expansion speed is affected by a deceleration only around the Baltic and North Seas and possibly in the Iberian Eastern Mediterranean in the hypothesis of contact with local Mesolithic populations. Elsewhere, no effect is noticeable or can be analyzed simply; 2) In general, the authors consider it counterintuitive that the speed of expansion appears negatively correlated with the gradient of agricultural intensification as well as with demographic density.

The "OBRESOC" project

This theoretical and methodological research trajectory has obviously weighed in the definition and then the implementation of a project to simulate the LBK agricultural expansion on a European scale: the "OBRESOC" project (OBservatoire RÉtrospectif d'une SOCIété archéologique). This was indeed the restricted and reasonable version of a more ambitious, worldwide intention, for which JPBA wanted one of us (JD) to model the European part. The perplexity expressed at the time in front of the theoretical, material, and financial feasibility of such a program undoubtedly contributed to the definition of a more realistic project concerning the LBK expansion alone, built from partial anthropological and ethnohistoric intermediate models, decontextualized and informed by paleo-environmental, bioarchaeological, cultural archaeology and paleodemography disciplines. The implementation of this project will eventually reveal how it required a team that we have only imperfectly assembled in the final project.

This second project, which emerged a few months later and was submitted to the ANR (ANR 09-CEP-004-01/OBRESOC)¹, was enthusiastically embraced by the authors, and we will now offer a condensed summary of its main features. The first methodological and practical steps have already been presented several times (Bocquet-Appel *et al.* 2014, 2015; Dubouloz *et al.* 2017). Therefore, we will limit the presentation to a brief overview of the underlying archaeological background, the structure of the model as a system of interaction of different sub-models,

¹ This project was submitted as part of a CEP (Changements Environnementaux Planétaires) call for proposals from the INSU-CNRS (Institut national des sciences de l'Univers).

simulated results directly related to the archaeological interpretation, and the limits of the experiment.

Main archaeological bases for the project

The development of the LBK agricultural system over six centuries in continental middle Europe leads to the hypothesis of a migratory process. The expansion tempo is relatively well understood in Central and Western Europe, less so towards its eastern borders (Ukraine, Moldavia, Romania; Dubouloz *et al.* 2017, fig. 1). Much of this process is carried out during the first two chronological stages (LBK 1 and 2, between c. 5,550-5,500 and 5,200-5,175 BCE).

The first phase of expansion, as far as the Rhine and northwestern Ukraine, is rapid, about 100-150 years, after a genesis around 5,550 BCE in Transdanubia, Burgenland, southwestern Slovakia (e.g. Oross and Bánffy 2009; Bánffy and Oross 2010; Brigand *et al.* submitted; Pavlů 2000; 2010; 2013; Pavúk 2004; Quitta 1967; Stadler *et al.* 2019; Stäuble 2005). This region characterized by an agro-ecological barrier (Bánffy and Sümegi 2012; Kertész and Sümegi 2001; Sümegi and Kertész 2001, Sümegi *et al.* 2003; Raczki *et al.* 2010) experienced the economic and social adaptations of the Balkan Neolithic necessary for the environmental conditions of Central Europe. The second stage, up to ca. 5,175-5,150 BCE, extends far beyond the Rhine/Meuse border to the west and already reaches the large plains of the river system beyond the Carpathians to the east (e.g. Gaskevych 2006; Lüning 2005; Modderman 1988).

Conversely, human paleogenetics emphasizes the proximity of LBK maternal lineages from Central and Western Europe to the North Balkan and initially Anatolian populations (e.g. Brandt *et al.* 2013, 2015; Deguilloux *et al.* 2011; Haak *et al.* 2010; Lazaridis *et al.* 2014). Ongoing paleogenomics syntheses will elaborate the validity of these findings (e.g. Brunel *et al.* 2020; Lipson *et al.* 2017; Mathieson *et al.* 2017). These findings suggest in part a migrating Balkan population with little or no genetic relationship with local hunter-gatherers in the early centuries, despite a systemically highly mobile system (e.g. Bentley *et al.* 2012; Price *et al.* 2002).

Nevertheless, archaeological funerary selection does not exclude a bias in favor of the population segment directly descended from the first Balkan migrants, possibly distorting our overall vision of the initial settlement dynamics. However, these results are in line with existing evidence on the exogenous (Anatoly-Balkan) character of

the livestock and cultigens of these 6th millennium BCE farmers (e.g. Bollongino and Burger 2007; Colledge *et al.* 2004; 2005; Coward *et al.* 2008; Ethier *et al.* 2017; Salavert 2017; Scheu *et al.* 2015; Zohary *et al.* 2012).

Finally, variations in LBK habitat patterns are well known and support fine-grained parameterization of modeling in terms of domestic structuring and “village-like” local, and supra-local aggregation (e.g. Blouet *et al.* 2013; Boelicke *et al.* 1988; Classen 2008, 2011; Coudart 1998; Dubouloz 2012a, 2012b; Ebersbach and Schade 2005; Gomart *et al.* 2015; Hachem 1999; Hachem and Hamon 2014; Lenneis 2009; Lüning 1998; Pieler 2010; Rück 2009; Soudsky 1969). The dietary foundations are well defined (see, for example, Arbogast *et al.* 2001; Bakels 2009; Bogaard 2004; Hachem 1999, 2011; Kreuz *et al.* 2005; Salavert 2017) and the variability of lithic and bone tool production, ceramics, and milling are already well understood in their raw material supply, technical realization, use, and circulation/exchange aspects (numerous references: e.g. Allard 2005; Blouet *et al.* 2013; Gomart and Burnez-Lanotte 2012; Gomart 2014; Gomart *et al.* 2020; Hamon 2006; Hamon *et al.* 2013).

General simulation principles

Based on this brief knowledge base, the modeling of the LBK system and the spatio-temporal simulation of its expansion throughout continental Middle Europe was therefore the subject of a multi-agent approach in which the model’s agent “is active” in a defined spatial and temporal coherence, interacting with the modeled social and natural environment (Bocquet-Appel *et al.* 2015: 1) the model’s agent is the domestic household with its demographic, economic, and social life; 2) members are born and die following a **pre-industrial and pre-vaccination demographic model** (Bocquet-Appel and Masset 1977, Bocquet-Appel *et al.* 2014, 2015, in prep); and a **specific demography focuses on shortage and famine periods** (Bocquet-Appel *et al.* in prep); Howe and Devereux 2004, Knodel 1978); 3) the spatial frame of the agent’s habitat is the km² with a simulated seasonal weather and environment; 4) the agricultural season, influenced by the environment and climate, is the timespan of the agent’s economic and demographic life; 5) the agent’s annual demographic and economic outcome informs the planning of the following year.

The demographic modeling starts with a simulation of a century of fertility and mortality tables applied to couples (of adjustable number) located in the supposed region of LBK origin to build a “natural” age pyramid and distribution of households as a source of future expansion.

The modeling space is a dual system: i) for climate, a modifiable sub-regional spatial grid smoothes local variability in a realistic continuum; ii) for economic and social aspects, a micro-regional grid, also adjustable in size, adds to local rules a control by supra-local constraints.

Specific field research has produced the data for a paleoclimate reconstruction (Peyron *et al.* in prep), and the climate at the pixel level has been specifically modeled: a seasonal simulation of the WorldClim database calibrated by the reconstruction data. For each season, a draw from the current local variability is calibrated by these "old" values and smoothed regionally. This climate simulation modulates soil fertility, which is itself modeled according to general criteria to approximate adequate prehistoric conditions (Schwartz *et al.* in prep). Thresholds of drought and hydromorphy determine the fertility of each soil type.

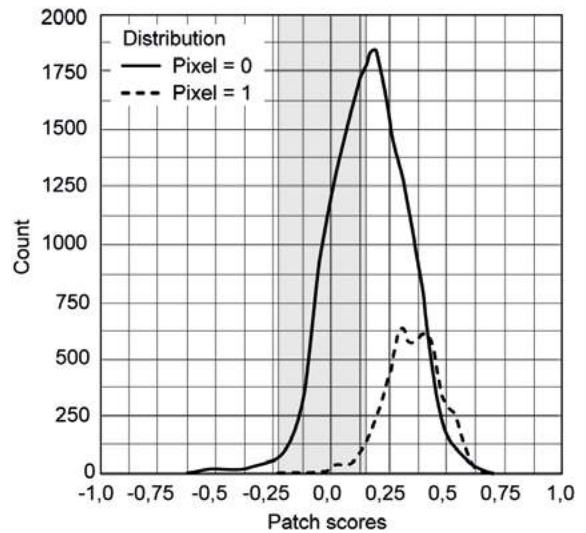
The interaction of the simulated soil environment and climate is used to construct the agent's living surface at a pixel/km² scale. In this example, this so-called Best-Patch geography (Sutherland 1996; Shennan 2009) is derived from the combination of fertility/quarterly temperatures and precipitation (averages and variabilities) in LBK-occupied localities relative to a sample of unoccupied pixels (fig. 1). Therefore, the analysis performed by L. Noiret (Harvard University and PMC-Sorbonne University) defines the LBK-like attraction probabilities of each pixel in the map (Bocquet-Appel *et al.* 2015: figure 2a)².

General principles of the modeled "social process"

The model combines the parameterization of the social and demographic operation of the agent-household, the generated segmentation and splitting processes, and the subsequent mobility rules.

The basic demographic and social unit of this past society (e.g. Hahn 2012) - the domestic household - is designed as a reproductive couple and their children, inserted into their local bi-lateral kinship group of horizontally linked nuclear families through siblings. Thus, the model's family system is the temporary co-resident nuclear family (Todd 2011), generating evolving single- or multi-family households.

The domestic household's growth is conditioned by the cycle of Chayanov's Consumption/Production Ratio



1. Distribution of best patch scores for the sample of pixel-km² coded 0 "no known site" (solid line) and pixel-km² coded 1 "presence of a site" (dashed line). Note: the shaded area delimits the first quintile of the scores of distribution 1, poor for LBK; it only includes 5% of the pixel-km² (total 6543 pixels), but covers nearly 50% of those of distribution 0 (total 25978 pixels). This difference in proportion indicates the lack of interest of the "LBK" agro-pastoralists for around half of the European area, and the precision of their preferential choices.

(C/P; Chayanov [1923-25] 1986; Hammel 2005), which was evidenced in the domestic split among Russian peasants' households in the 19th c. This ratio evolves cyclically according to the arrival of new mouths to feed and their entry into full production age. When this ratio is close to 1 ($C \approx P$), the years are conducive to the departure of a segment of the household to establish a new household that remains to be located.

Ethnography teaches that a large availability of suitable land promotes **village splits** in 50-150 person settlements to regulate their internal, interpersonal conflicts (Carneiro 1967, 1978; Cohen 1977, 1985; Rappaport 1968). The social density growth increases the conflicts, while the group splitting can relieve them. The parameterization of this local density determining village splitting and the agents' mobility is based on "Scalar-related Social Stress" (Johnson 1982), which considers the interaction issue at the sociological unit level.

In a domestic split, the local densification solution is first tested. If the odds are not in favor, then a displacement towards a distant 'best patch' is implemented, reflecting the village split. However, if the unavailability of favorable land prevents such a solution, then densification is imposed on the original hamlet, which reaches a first critical level of internal tension.

² For unfortunate reasons of legend's switch, the legend of figure 2a is that of figure 1 and vice versa.

From an adjustable social density threshold, the densest hamlet in a micro-region (10x10 km by default) becomes a “leader-hamlet,” a very rough metaphor for the emergence of individual “leaders”; such hamlet’s domestic households can store their surplus production for three years and consequently gain greater stability. Following a coarse analogy with the ethnographic logic of “feasting” (Dietler and Hayden 2001), this hamlet-leader thus becomes a “supra-local social and political leader,” an “economic buffer” for the neighborhood and a “demographic attractor.” The micro-regional density can increase to a new threshold.

General principles of the modeled food economy

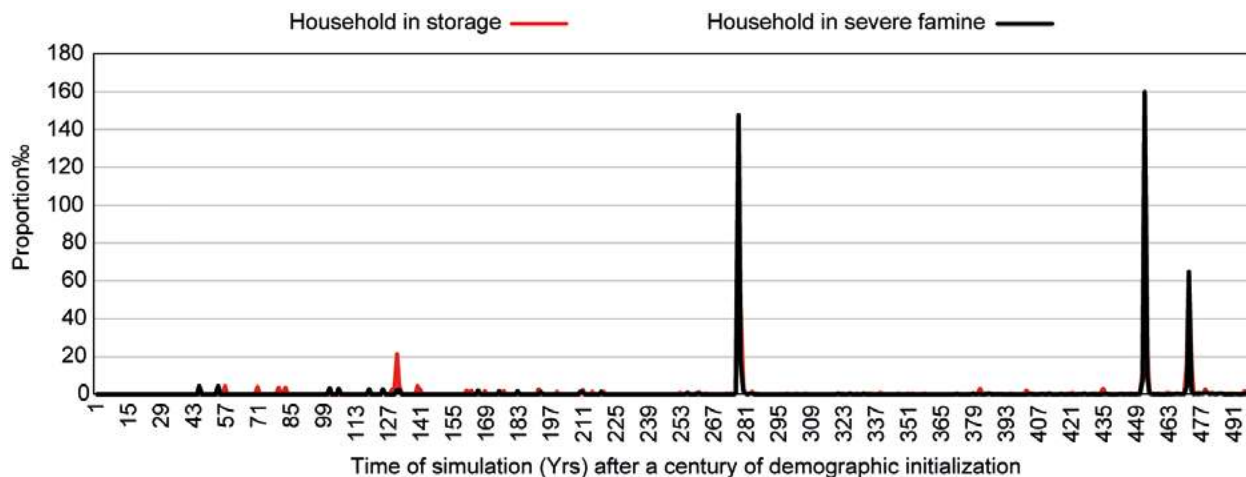
The household food production model can be summarized in the following main elements: 1) the agent’s needs depend on the household’s demographic composition, in kcal; 2) production strictly ensures the annual demand plus a security trimester; 3) agriculture is intensive with manuring after two years of slash and burn; 4) yields and productivity are calibrated within paleo-agronomic and experimental margins; 5) winter planting reacts to the weather and emergency planting in spring is possible; 6) the livestock, sensitive to climatic events, is dominated by cattle and provides the share of its annual growth, in kcal and $\frac{1}{4}$ of its milk production for human consumption; 7) hunting and gathering depend on agricultural success: the yield is a function of forest state, labor force, and catch probabilities.

A pattern was designed to simulate climate-food crises, which were very likely to occur during the six LBK centuries (fig. 2).

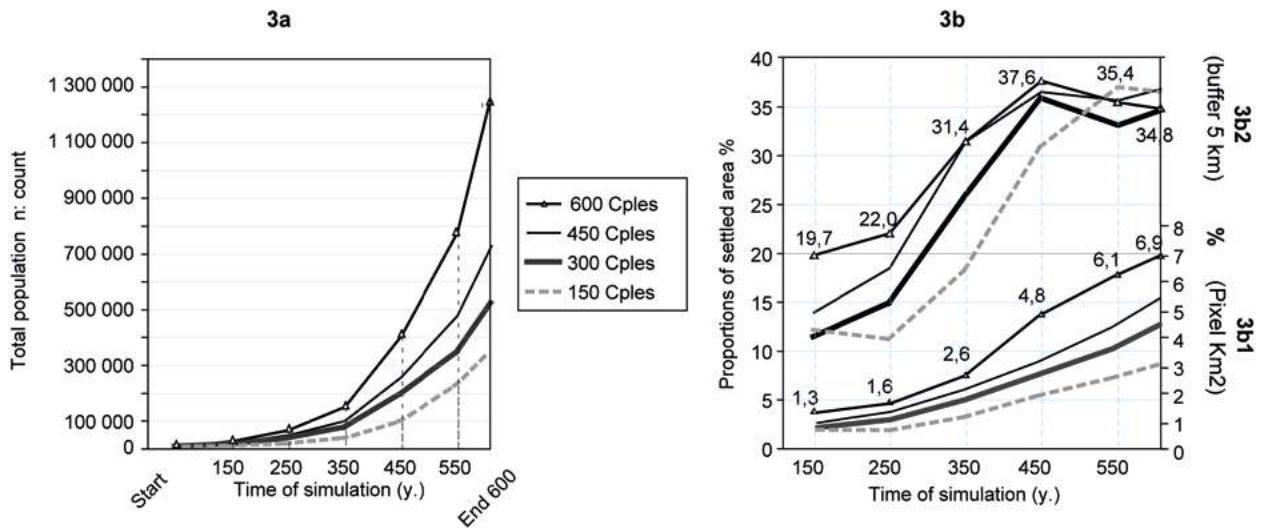
The pattern is based on a typology of sequences of unfavorable seasons, extracted by A. Guillaumont (CNRS-UPR 2147) from the research of E. Leroy-Ladurie on the Early Glacial period (Le Roy Ladurie 2004; Le Roy Ladurie *et al.* 2003). Rainfall and temperature thresholds from the 20th c. provide a basis for implementing this crisis typology (Strasbourg-Entzheim weather station, F. [www.infoclimat.fr]). Response behaviors to these critical states, derived from Social Anthropology (Corbett 1988; Cutler 1984, 1986; Hartog den 1981), are then enabled, and the demographic crisis tables are applicable (see above).

Model sensitivity

Based on a large number of simulations performed by varying multiple parameter values, some “runs” result in a satisfactory similarity of the spatial-temporal tempo of the expansion simulated with the archaeological reconstructions (Bocquet *et al.* 2015: fig. 2B). The runs also result in a satisfactory distribution over the pixels/km² of “patch” with moderate to excellent climatic-pedological fertility. The detailed analysis highlights the importance of several parameters, which, first, include the starting population (fig. 3).



2. Example of the distribution of climatic-frumental crises over 500 years linked to the annual variation of simulated precipitation. Their spacing is due primarily to the low temporal resolution of the reconstructed climate data. The peaks of severe drought-related famine and starvation, which are noticeable at 278, 453 and 472 years after 5,550 BCE, are reminiscent of the onset of identified archaeological phenomena (e.g. end of LBK 1/beginning of the “Flomborn”; cultural changes around the Hinkelstein and STK in some regions; expansion to the far west). The repetition of such crises over one or two decades around these dates could have contributed to these important changes.



3. Demographic (3a) and spatial (3b) variability of the model, as a function of initial pair count. From 150 to 600 initial pairs, the population follows an exponential evolution and varies by a factor ≈ 4 in 600 years. The colonized areas show a more complex process. Depending on whether we consider the pixels finally occupied (3 to 7% of the available pixels) or a buffer of 5 km around them (12 to 37.5% of the available area), the aggregation of the settlement manifests itself differently; at the pixel (3b1), the trend is rather exponential except for the curve initiated by 600 pairs; at the 5-km buffer (3b2), the evolution is clearly logistic and shows a plateau of occupied areas starting at 450 years (occupied neighboring pixels aggregated in the buffers).

In addition to this essential variable, the minimum and maximum distances allowed for the projection of splitters, the maximum distance for the selection of marriage partners, the number of livestock per inhabitant of the household, and their annual reproduction rate (available manure and meat) have a strong influence on the expansion and its rhythm. However, the model seems to be less sensitive, or even not very sensitive, to climatic conditions as well as to grain yields or land productivity per hectare - although the shortcomings of the reconstruction on this point have been observed - in the latter case, the adjustment of production to needs is achieved through variations in the cultivated areas in a context of abundant quality land.

Selected simulation results

One of these satisfactory simulations is based on the following settings: 1) A rather mild random climate "rail"; 2) An initial 5012 people distributed in an age pyramid resulting from the demographic tables applied to 600 young couples for a century before simulation; 3) A 225 km **maximum** radius of knowledge, to choose the 'best patch' during a split and a 70 km **minimum** settlement distance beyond the original pixel during 225 years, to accelerate the first phase of expansion in the absence of other attractors in the model than the 'best patches';

4) A 200 km **maximum** marriage radius to compensate for the initial scarcity of opportunities for matrimonial alliances; 5) A 500 kg productivity per hectare and a ratio of cattle/household equal to 1.

Adjustment signals

The final population after 650 years is 1,800,000 people, between Moldavia and Normandy: annual growth stabilizes at around 1.1%. Simulated climatic disasters and famines were expected to help regulate growth in the absence of other sources of morbidity than those included in the demographic tables. However, the climatic trend used in the model is obviously too uninformed to create sufficient food crises to influence population growth. In addition to its spatial-temporal rhythm, this simulation produces a temporal distribution of household types that accumulates at the end of the sequence as observed archaeologically. This provides compelling evidence of the simulation's reasonable fit, as does the annual distribution of households at the hamlet/pixel scale and the accumulation of surface features left by their house reconstruction every 20 and 30 years (Dubouloz *et al.* 2017: figs. 5 and 7). Furthermore, beyond these indications of adjustment of the simulation to specific archaeological data, this model is first and foremost a tool for experimentation to evaluate our

knowledge which, in return, can be improved. The model provides a basis for the migratory hypothesis on controllable variables. However, and perhaps even more importantly, it can feed the archaeological data interactively through its virtual outputs.

Simulated results informing archaeology

The impact of a climatic-frumental crisis in the absence of a 'leader-hamlet' is noticeable, on a regional scale, during a generation or so (Bocquet-Appel *et al.* 2015: fig. 7-9). This effect is noticeable in the household size, as in the hamlet size, and implies a visible archaeological signature in the distribution of house size - assuming its correlation with the sheltered household size - and in the number of houses variation contemporary with the hamlet (a decrease of about 25%).

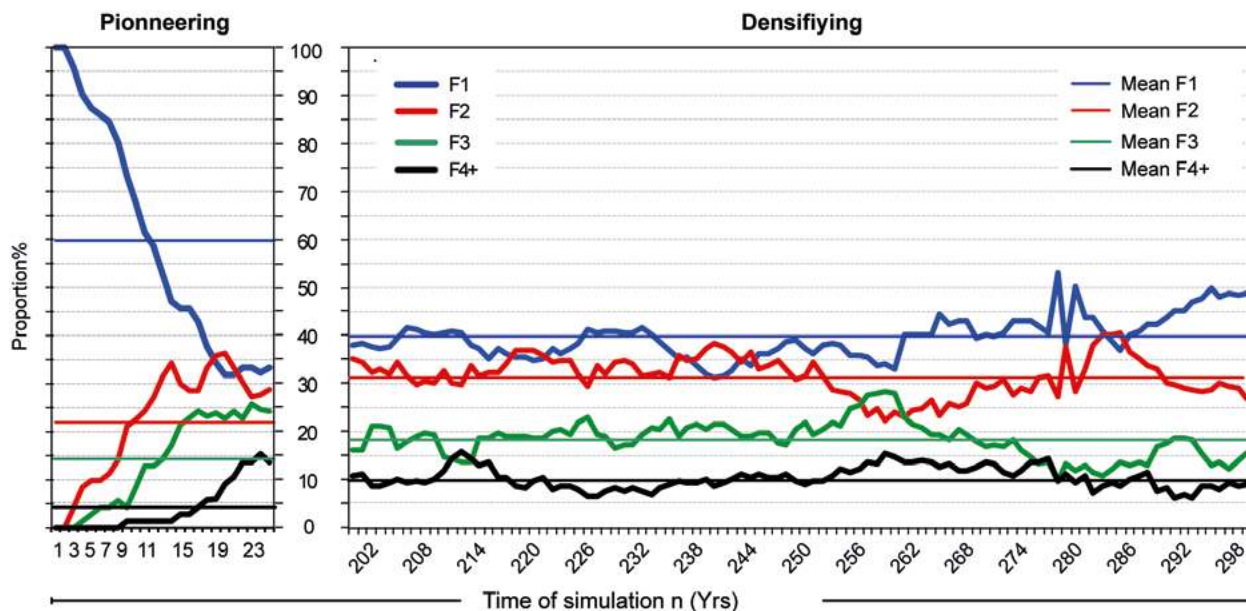
The change in supralocal and regional densities is weak. Its archaeological signature, particularly dependent on the sampling quality, is unfortunately not entirely reliable, except for well-prospected geographic sectors. Thus, the

two signals, household-house, and hamlet-site do not reflect the crisis equally well. However, we suspect that the simulated sequence of a few bad harvest years over 1-2 generations would have a more marked impact, visible in the field.

Meanwhile, a system of socio-demo-economic 'leadership,' as implemented in the model, strongly reduces the impact of a climatic-wheat crisis, possibly to the extent of hiding it archaeologically. The high probability of a weather/climate crisis and the concomitant absence of its archaeological population markers could then indicate the existence of a damping system and supra-local economic solidarity.

The singularity of the pioneer front in relation to the densification sectors can also be addressed through the evolution of the household type proportions in a sample representative of each situation (fig. 4).

The F1 type (single-family) is ultra-dominant at the outset and is practically overtaken by the F2 and F3 types after only 20 years, as is most often the case in a

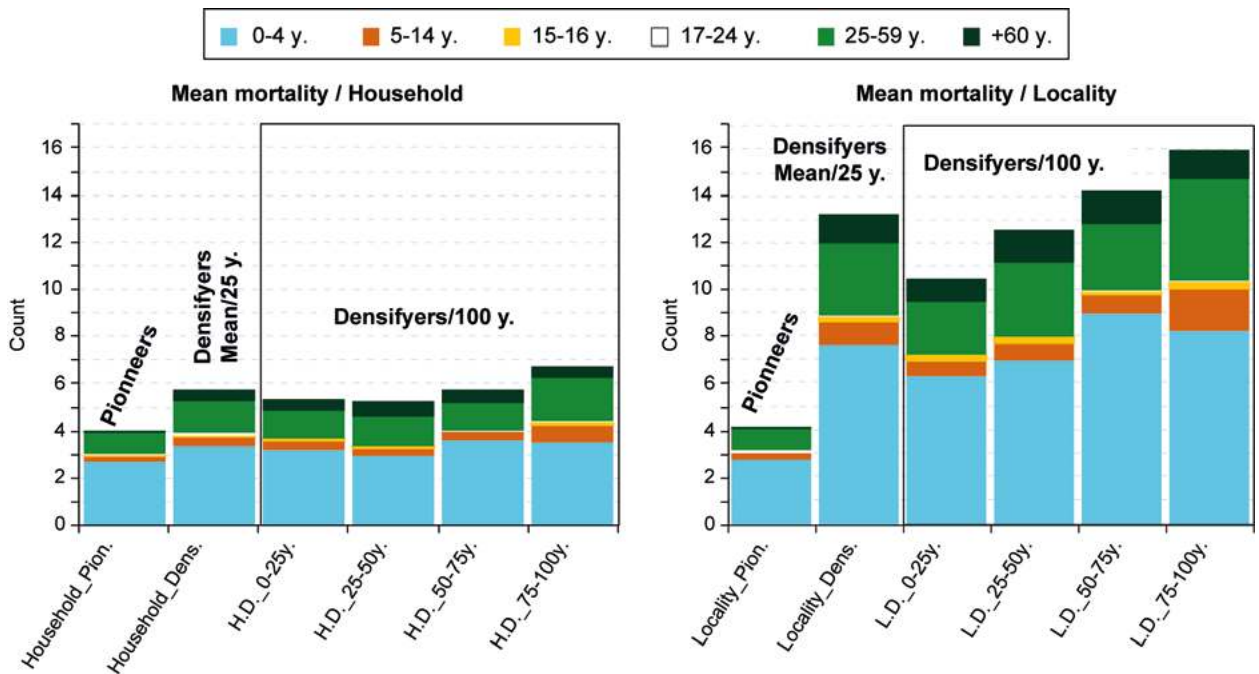


4. Proportions of household types (1 to 4+ families) in two samples, according to the pioneer scenario (first 25 years; sample spread over all of Europe) or the densifying scenario (a century after 100 years of installation of a large regional sample).

context of perennial occupation. Therefore, the pioneer front will produce far more single-family households, which should be reflected in a greater number of small archaeological houses (on average 60% F1 for a period of one generation, 22% F2, 14% F3, and less than 5% F4+).

This pattern would only be recognizable archaeologically for short-lived pioneer sites.

The simulated mortality also illustrates the singularity of the pioneer front (fig. 5).



5. Average mortality/25 years at home and at the locality according to the pioneer or densifying setting. A century in a "densifying" context was analyzed by 25-year increments (on the right of each graph) to account for the variability of mortality at the same time step as in a pioneer context. The average of these 25-year averages (second column of each graph) was calculated for comparison with the pioneer situation (first columns).

The number of deaths per generation in the household is very low in a pioneer or densifying context, except for those under five years of age, rarely observed in archaeology. On average, we can only hope to recognize the death of one adult under 60 years of age per generation. However, through households' aggregation, the locality level signals a clear difference. In a densifying context, mortality produces a significantly higher average number of deaths per locality every 25 years, including one individual of 5-15 years of age, approximately three others of 15-60 years of age, and at least one over 60 years of age (total \approx five deaths). Nevertheless, archaeology fails to recover these numbers ($5 \times 4 = 20$ deaths per century, 60 for a locality lasting three centuries!), thereby highlighting the well-known taphonomic and cultural dimensions of differential burial treatment in LBK village contexts.

On the scale of the overall hamlet's history, the simulation reveals the significant instability of the local settlement, in terms of individuals and households present year-round: the duration of the latter, their size, and composition are constantly changing (Dubouloz *et al.* 2017: figs. 6 and 8) and there is a remarkable succession/rotation of the main households. This constant variation is not easily deduced from the archaeological data yet

it should have important consequences for the house size and the consumption level reported by the remains found in the field. Therefore, there is a line of data inquiry to explore further.

A model output about the annual composition details of domestic households can provide the age distribution and family numbers, the cadence of deaths and their ages, the marital entries/exits rhythm, and the splitting cycle with its number of departures. This information makes it possible to model the household's requirements in terms of consumption and living space, to observe that their rhythm is not regular. Thus, does the number of occupants per variable period influence the volume of consumption discards? Also, can the hypothesis of a monotonous reconstruction every 17-25 years be questioned, or can the spouses' inflows fuel the investigation of some innovations' introduction, such as in ceramics (Gomart *et al.* 2015) or milling tools (Monchablon in press)?

Simulated domestic meat consumption can, in turn, be directly compared to the best archaeological estimates (Hachem and Bedault 2008; Hachem, *personal oral communication*). Under the archaeological model of a 3-5-year accumulation (Allard *et al.* 2013), we observe that the

simulation usually favors the lower half of the estimates. The conclusion is that the simulated livestock/per capita ratio is too low, or that the archaeological consumption represents more than five years of consumption, or even that the best-known archaeological sample is not representative enough. An interesting simulated/expected feedback is therefore possible for this question. Regarding the hunted wildlife, identified preferentially in small archaeological houses and particularly the oldest ones (Hachem 1999, 2001, 2011), the simulation reinforces the interpretation by concentrating this food source on single-family households, particularly pioneers with a small number of cattle.

Finally, to conclude this overview of the modeling's heuristic qualities, we will address the question of storing the annual harvest per household, recorded in kilo-calories. After converting this measurement unit³, grain storage in bags or containers⁴ seems unlikely: the considerable number of containers needed, bulk, weight, and low mobility effectively eliminate such a solution. Storage in ceramics is particularly implausible if we consider the scarcity of large vessels capable of performing this function. For example, for an average household (F2), there would be 65 vases of 20 liters or 26 vases of 50 liters; we are still looking for archaeological evidence of such quantities, probably renewed once or twice per house lifetime. Conversely, the calculation on the simulated data suggests that seed storage, very temporary in time, is conceivable in this form: between 6 and 15 containers of 50 or 20 liters would be necessary on average (min. 3-9, max. 8-20). However, for most of the crop, storage in spikelets with appropriate daily husking seems the most likely (Bouby 2003). Besides the natural protection benefits conferred by the different seed husks, particularly for hulled species, the calculated volumes are compatible with the surface area of attics available under the roof⁵.

Final comments on the modeling

Beyond the satisfaction of correctly mimicking the LBK expansion and revealing the capacity of such an approach

³ A conversion directly into weight, then into volume by the weighting of a kilogram of modern einkorn.

⁴ This paper explores a possible alternative, in the absence of identified dedicated silage structures, either underground or above ground.

⁵ We can imagine attics with raised floors, leaving few recognizable traces: however, consider the doubling of posts at the entrance of some large houses, known on the LBK European scale, which could have served as supports for such floors, massive in these configurations.

to virtually flesh out the archaeological remains, we will conclude with a general methodological perspective and a quick presentation of the model's limitations.

Under the aegis of experts in this type of modeling (REEDS-UVSQ) and for a first model (Obresoc 1.0?), the primary challenges were to build a controllable system that does not stall quickly while approaching the spatial and temporal rhythm of the targeted prehistoric process. To achieve this, the state-of-the-art favors the initial construction of an “eternally” stable model by default, which we will then try to destabilize by the controlled variation of a few parameters, considered (or demonstrated) as significant. A “reasonable” proportion (here about 50%) of parameter values of intrinsic origin, therefore self-fulfilling, or of extrinsic origin, therefore potentially explanatory, should be maintained at this stage of the design to guarantee adequate control of the results. Therefore, the question of the model's internal coherence, in terms of the components' interactions, their programming, and the concern to control the results, essentially took precedence over considerations of the wealth and subtlety of these interactions.

To demonstrate the difficulty of such a construction, the systematic audit of the multiple intermediate versions revealed several often-surprising bugs and almost unforeseeable calamitous deviations that had to be corrected. Regarding the parameter settings, they required much tinkering. The “marriage” radius, for example, was the subject of multiple tests. Ultimately, we discovered that there were never enough opportunities for marriage alliances in the immediate surroundings (up to one or two days walk) to sustain population growth. Without a drastic extension of this radius, the simulation stalls in a few short decades due to a lack of births. This result must raise questions about the actual conditions of demographic viability of the expansion process analyzed. Unless one considers a prior, numerous, well-distributed and always available indigenous population, which does not seem to be the case, and/or a regular peri-Balkan contribution, conceivable for example, from the Vinča culture, we must admit that the demographic viability of the LBK farmers initially relied on a very extensive flow of humans and their skills. Once these methodological limits have been outlined, we can proceed to the best-identified limitations of this model. They impact all the sub-models within the model.

There are two reasons for the limitation of the exercise in terms of weather-climate: the western location of the seasonal data source is not sufficient to capture the ancient variability of the LBK territory fully. Furthermore, this

data's temporal resolution, which is still low in relation to the model's time span, does not frequently or regularly enough inform the simulated weather-climate "rail." The crises triggered by an absolute threshold effect (1/0) correspond to the maximum effects of the selected typology. They are too sudden and punctual to serve as effective constraints during the entire expansion. The fertility variations are also limited to a few rare, informed instances. Having said this, the punctual effects on the settlement presented above (§B.3.2.) remain useful as they reveal the fragility of the simulated society and its archaeological legibility.

From an environmental perspective, the first limit lies in the data quality implemented in strict spatial terms. The modeled soil map (fertility in the 6th millennium BCE) defines rather coarse surfaces: the characteristics of most small and medium-sized alluvial valleys are smoothed out. Particularly in some regions, the choice of agents in the model and their dispersal pace can be distorted: the inversion of the agents' order of arrival in the east and the center of the Paris Basin is an obvious example to identify. Another limitation, probably preferable to poorly controlled variations, is the absence of any real modeling of the forest environment variability itself (plant and animal bio-mass), but its fixation in an "average" position, to the detriment of the potential impacts of the latter on the agents' lives.

The demographic process is based on a single source - the initialization in Austro-Hungarian Transdanubia - and does not benefit from any flow outside its logic. However, recurrent inflows from the Balkans or the local Mesolithic settlement may have contributed to the expansion kinetics. Despite the absence of these complementary sources, we notice that using a few specific parameters - *maximum radius of "marriage," minimum and maximum radius of environmental and geographical knowledge* - the demographic trajectory produces convincing results. These specific constraints, not yet systematically grounded (e.g. diffusion by women (?) of decorative concepts over 200 km away; possible direct flint supply also over 200 km away), must still be further evaluated to ensure a robust parameterization.

The modeled economic system also has its limits. As programmed, the model essentially targets an average agent's behavior, appropriate to guarantee its reproduction. The absence of an individual or collective memory system linked to the origins and experience acquired over the past decades smoothes the variability of economic behavior.

For example, this memory should lead to "reasoned" choices for sowing einkorn or emmer wheat, a reinforcement/reduction of livestock farming, or relocation in the event of repeated failure. Thus, the agro-pastoral model does not differentiate the specific qualities of the two wheat species with the climatic-environmental potential; nor does the model include the risks of infestation by viruses or parasites: only the yields vary according to the soil/meteorological/climatic pairing.

Meanwhile, animal husbandry is based on an equivalent share of all caloric needs resulting from domestic meat consumption: a livestock head averaged in terms of vegetable consumption and meat weight, identical beef/sheep/pig proportions for all, and supposedly efficient management of these animals' demographics on a collective scale. All these factors lead to an average and routine domestic use of this livestock. In contrast, the most detailed archaeological analyses now reveal a relative variability in consumption practices, and probably in livestock composition, given socio-cultural constraints that have not been modeled. The trading of goods per se is also not considered, mainly because the model assumes that domestic households are self-sufficient. Therefore, economic trade only appears during crises, in the form of the transfer of mouths to feed to available family partners or neighbors. Therefore, an anthropological model of redistributive and/or reciprocal exchange remains to be introduced to approximate a possible past configuration more efficiently. In short, the agricultural and livestock sub-models are currently only outlined to guarantee the agents' preservation in normal times.

Regarding social organization, we can also mention some rules' imprecision that applies to everyone, regardless of context, individual or collective. This is particularly true for all aspects of the probable lineage and clan structure of LBK society, the emergence of supra-local poles of power, which are undoubtedly unstable but effective during their existence, and the related mobility rules. Mobility structuring through alliance and genealogy networks is not very well developed: this memory's programming beyond two generations and its products' control was considered too complex for this initial modeling stage. Domestic and village division rules are relatively finely modeled on well-identified archaeological and/or anthropological bases. However, when a split leads to an outer-village relocation, one of these rules requires a minimum distance (adjustable), which is primarily intended to accelerate the initial expansion in the absence of other attractors than the agricultural 'best patch' (e.g. salt, lithic materials).

The necessity for such a mobility constraint, created during the model's audit, possibly confirms the existence of reasons that are not strictly food-related in the long-distance mobility of LBK households. Therefore, an anthropological settlement model linked to the search for sustainable access to these different strategic resources remains to be constructed: who, in the region, the hamlet, or the household, oversaw this expansion aspect, and what relationship network did they introduce? Regarding the leadership emergence as "hamlets-leaders," the main merit of this metaphor is introducing the possibility of a break in the model's routine with its socio-demo-economic correlates. In this case, the 'leadership' refers to the locality and its agents able to respond to such development conditions, rather than to an individual (e.g. head of a family, lineage, clan) who represents their group in a relatively competitive social context, which removes us from the ethnographic reference (leader, aggrandizer, great-man, big-man). Thus, this is truly a "conceptual trick" to generate primary effects similar to more academic "leadership."

Despite these limitations, the OBRESOC model provides a renewed narrative of the colonization process of Middle Europe by the LBK socio-natural system; some variables appear, through the interactions they define, to be more important than others, and their identification can influence archaeological research. Therefore, the simulated outputs at the model's main level, the domestic household, provide essential and new insights for analyzing and interpreting the basic data.

Final comments

The scientific trajectory led by Jean-Pierre Bocquet-Appel that we have outlined illustrates the complexity of the necessarily collective approach to global phenomena in prehistory clearly. The issues of data elaboration and their application scale and the construction of tools to implement them shape all of Jean-Pierre's works; thus, the chronology of their achievement describes an uncommon intellectual path in our disciplinary fields. From the general process to the particular mechanism of its components, we proceed from the abstract and disembodied global description to the tentative explanation by experimentation.

Equipped with the intellectual, scientific, and cultural assets necessary for such a path, Jean-Pierre Bocquet-Appel has always been concerned, beyond his permanent tropism for global interpretations, with the primary conditions of verification/falsification of the explanatory hypotheses produced at various research stages. Through controlled feedback between the general and the particular, through mastery of the interweaving of the validity levels for various observed variables and finally through experimenting the effects of variability in the interactive components of the analyzed processes.

The authors of these few paragraphs want to testify to the interest in contributing closely to this intellectual adventure they have experienced. So long, Jean-Pierre, hasta luego.

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