Journey of a committed paleodemographer

Farewell to Jean-Pierre Bocquet-Appel

Itinéraires d'un paléodémographe engagé

Hommage à Jean-Pierre Bocquet-Appel

edited by

Anna Degioanni, Estelle Herrscher, Stephan Naji

PRÉHISTOIRES DE LA MÉDITERRANÉE

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ABSTRACTS

This book is dedicated to Jean-Pierre Bocquet-Appel, anthropologist and biologist, one of the founding fathers of palaeodemography in France, who died in 2018. Known and recognised worldwide, he contributed to the development of new techniques for estimating the age at death of skeletal assemblages and promoted the introduction of estimators in palaeodemography. He also participated in the emergence of spatial demography and multi- agent modelling, particularly of Neolithic farmers. We owe him a considerable advance in the understanding of demographic processes linked to the great transitions that humans have experienced in different parts of the world with the discovery of the signature of the demographic transition implied in the passage of societies from a collection economy to an agricultural economy.

This book offers a journey to the heart of his life as a researcher, taking in turn, in a diachronic and multidisciplinary approach, anthropological demography from prehistory to the contemporary period. It also paints a generous portrait of this committed man who has never ceased to work for his discipline, whether through a reflective approach to the history of science and epistemology or the transmission of his knowledge to younger generations. This book invites you to an original and innovative experience on the borders of a rare discipline, paleodemography.

Cet ouvrage est dédié à Jean-Pierre Bocquet-Appel, anthropologue biologiste, l'un des pères fondateurs de la paléodémographie en France, disparu en 2018. Mondialement connu et reconnu, il a contribué au développement de nouvelles techniques d'estimation de l'âge au décès d'assemblages de squelettes et promu la mise en place des estimateurs en paléodémographie. Il a également participé à l'émergence de la démographie spatiale et de la modélisation de type-multi-agent en particulier des agriculteurs néolithiques. Nous lui devons une avancée considérable dans la compréhension des processus démographiques liés aux grandes transitions qu'ont vécu les hommes en différents points du globe avec la découverte de la signature de la transition démographique impliquée dans le passage des sociétés d'une économie de collecte à une économie agricole.

Cet ouvrage offre un voyage au cœur de sa vie de chercheur, reprenant tour à tour, dans une démarche diachronique et pluridisciplinaire, la démographie anthropologique de la Préhistoire jusqu'à la période contemporaine. Il brosse également un portrait généreux de cet homme engagé qui n'a eu de cesse d'œuvrer pour sa discipline, que ce soit à travers une approche réflexive sur l'histoire des sciences et l'épistémologie ou la transmission de ses savoirs auprès de jeunes générations. Cet ouvrage convie ainsi le lecteur à une expérience originale et innovante aux confins d'une discipline rare, la paléodémographie.

ANNA DEGIOANNI (DIR.)

Anna Degioanni is a lecturer in biological anthropology at Aix-Marseille University (LAMPEA). Her research topics focus on developing genetic and demographic models, particularly of the Neanderthal population and its relationship to the environment.

ESTELLE HERRSCHER (DIR.)

Estelle Herrscher is an anthropologist and biologist, research director at the CNRS (LAMPEA). Her research aims to understand the diversity of dietary behaviors in different geographical locations (Europe, Caucasus, Pacific) and this in a diachronic way (recent prehistory).

STEPHAN NAJI (DIR.)

Stephan Naji is a bioarchaeologist affiliated with the Department of Anthropology at New York University, specialized in demographic and health transitions. His current research focuses on cementum analysis within a chronobiology evolutionary context and cementochronology for histology and virtual age-at-death and life-history modeling.

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Camille de Becdelièvre, Jean-François Berger, Tamara Blagojević, Henri Caussinus, Daniel Courgeau, Pierre Darlu, Anna Degioanni, Jean-Paul Demoule, Jérôme Dubouloz, Olivier Dutour, Bernard Formoso, Susan R. Frankenberg, Estelle Herrscher, Zuzana Hofmanová, Jelena Jovanović, Lyle W. Konigsberg, Richard Moussa, Stephan Naji, Christina Papageorgopoulou, Marko Porčić, Denise Pumain, Isabelle Séguy, Sofia Stefanović, Panagiota Xanthopoulou, Konstantinos Zafeiris, Anastasios Zisis.

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AnthroExpert provided the English translation of the original French texts.

We dedicate this volume to Jean-Pierre Bocquet-Appel's family, a testimony of the scientific tribute that his community, colleagues, and friends wished to pay to Jean-Pierre.

We would like to thanks Marion Bocquet-Appel for her poignant rendering of her father. Jean-Pierre always spoke with great pride about all his children and we are grateful that Marion accepted to help us celebrate him.

"Welcome back paleodemography" Deconstructing and innovating in paleodemography

« Le retour de la paléodémographie » Déconstruire et innover en paléodémographie

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Abstract: Jean-Pierre Bocquet-Appel is one of the founding fathers of paleodemography in France. With Claude Masset, he developed new techniques for estimating the age at death of skeletons and promoted the implementation of estimators in paleodemography. Since the 1990s, he has participated in the emergence of spatial demography, dedicating himself in recent years to multi-agent modeling, particularly of Neolithic LBK farmers (Linearbandkeramik). Internationally known and recognized for his work on the Neolithic transition, he discovered the demographic signature of the Transition in the explosion of fertility during the transition from a gathering economy to an agricultural economy. He was also interested in the colonization of Central Europe by the first farmers with a modeling approach integrating several disciplines, such as the study of paleoenvironments, bioarchaeology, cultural archaeology, paleodemography, and economics. Several of his works also deal with the history of science and epistemology, the latest of which deals with the crisis and renewal of biological anthropology.
Keywords: paleodemography, age at death, demographic transition, Neolithic, biological anthropology, history of science

Résumé : *Jean-Pierre Bocquet-Appel est l'un des pères fondateurs de la paléodémographie en France. Aux côtés de Claude Masset, il a développé de nouvelles techniques pour l'estimation de l'âge au décès des squelettes et promu la mise en place des estimateurs en paléodémographie. Depuis les années 90, il a participé à l'émergence de la démographie spatiale se dédiant ces dernières années à la modélisation de type-multi-agent en particulier des agriculteurs néolithiques LBK (Linearbandkeramik). Mondialement connu et reconnu pour ces travaux sur la transition Néolithique, il a découvert la signature démographique de la Transition dans l'explosion de la fécondité féminine durant le passage d'une économie de collecte à une économie agricole. Il s'est plus récemment intéressé à la colonisation de l'Europe centrale par les premiers agriculteurs avec une approche de modélisation intégrant plusieurs disciplines, comme celle concernant l'étude des paléoenvironnements, la bioarchéologie, l'archéologie culturelle, la paléodémographie et l'économie. Plusieurs de ses travaux portent également sur l'histoire des sciences et l'épistémologie, le dernier en date traite de la crise et du renouveau de l'anthropologie biologique.*

Mots-clés : *paléodémographie, âge au décès, transition demographique, Néolithique, anthropologie biologique, histoire des sciences*

"My research focuses on demographic anthropology, particularly paleodemography, both in terms of demographic analyses and bioanthropological techniques... my periods of interest range from Paleolithic Europe to the origin of agriculture in several regions of the world. I am particularly interested in detecting signals of a major qualitative break in human demographic history: the Neolithic demographic transition."
Jean-Pierre Bocquet-Appel (https://sites.google.com/site/beanresearchnetwork/about-us-1)

In August 2018, Jean-Pierre Bocquet-Appel left us after joining Laboratoire méditerranéen de Préhistoire Europe-Afrique (LAMPEA) in Aix-en-Provence to extend his research activities in the framework of an Emeritus. Jean-Pierre Bracco, who was the Director of the Unit at the time, accepted, in 2016, his integration into the Unit because of the ongoing research he was conducting with Anna Degioanni. Anna and Jean-Pierre first met in 1992 at the *Laboratoire d'Anthropologie* de Paris 7, thanks to Pierre Darlu, and in 2011 they began collaborating on issues related to the analysis of the demography of an older humanity, the Neanderthals, a work that they published together in 2013 in the journal *Current Anthropology*. Since then, they have initiated new research on the modeling of demographic structures of this critical transition period between Neanderthals and anatomically modern humans. Jean-Pierre joined LAMPEA when the 2018-2022 Scientific Project was drafted and participated in the development of Program 3 entitled *Human behavior and settlement dynamics in their environmental diversity*, proposing, in addition to the research axis developed with Anna, a theme dealing with the agricultural demographic transition or Neolithic demographic transition. This research theme had already earned him funding from several research programs: the BEAN program *Bridging the European and Anatolian Neolithic: demography, migration, and lifestyle at the advent of civilization* (Marie Curie European Initial Training Network (FP7-PEOPLE-2011-ITN - Marie-Curie Action: "Initial Training Networks") and the ANR OBRESOC *A retrospective observatory of an archaeological society: the trajectory of the Neolithic LBK*, a project funded by the ANR (Agence Nationale de la Recherche, Convention ANR-09-CEP-004-01/OBRESOC) within the framework of the ANR-CEP program (Global Environmental Change), to which many researchers, such as Jérôme Dubouloz, Stephan Naji and Jean-Paul Demoule, have largely contributed.

Because of his broad scientific curiosity, Jean-Pierre collaborated with a variety of colleagues from different backgrounds. In particular, Pierre Darlu, with whom he co-authored works on kinship ties, and Lucienne Jakobi, for their work on the demographic transition in 19th c. England, a significant study that allowed them to highlight the diffusion of cultural innovations, such as contraception. Similarly, his work with his long-time colleague Claude Masset to elaborate and develop their pivotal critics of paleodemography. Or a range of highly specialized statisticians such as Jean-Noël Bacro or Robert Sokal to implement innovative solutions to anthropological problems.

In addition to his widely recognized research on the international scene, taught in many universities, Jean-Pierre Bocquet-Appel (JPBA) cared deeply for the younger generations. This generous spirit led him to establish lasting relationships with many students. Particularly, Estelle Herrscher, in 1996, for her Master's degree in paleodemography, right at the time when JPBA published with Claude Masset a major piece of the paleodemography debate describing an innovative Bayesian iterative method and the juvenility index, an indicator. Then, with Stephan Naji, whom he met at the annual meeting of the *American Association of Physical Anthropologists* in Kansas city in 2001. This was the beginning of a long collaboration, from the co-direction of his PhD to analyzing the agricultural demographic transition in the New World and the publication of numerous articles and books.

Jean-Pierre was eager to participate in the teaching of paleodemography, from the most theoretical foundations to their application. In 1998, as a guest lecturer at the EPHE, Jean-Pierre began to transmit his knowledge, which he then taught for several years at Nanterre university. He had no equal when teaching his art, from the simplest to the most complex aspects, from the foundations of demography (with the theories of Malthus and Boserup) to statistical and Bayesian approaches. Everyone who had the chance to follow his teachings will always keep fond memories. Subsequently, Jean-Pierre joined the EPHE in 2008 as Director of Studies, where he taught new courses on paleodemography and anthropology. Once again, he left his original signature. Curious to see how the intricacies of recruiting young doctors work, Jean-Pierre joined the CNU - National Committee of Universities in Section 20[1] for one term between 2012-2015. There too, Jean-Pierre used this opportunity of having colleagues, including ethnologists, anthropologists, biologists, and prehistorians, to write an article in collaboration with Bernard Formoso and Charles Stepanoff on Anthropology in the broad sense, its definition, its perception, and the evolution of its scope in the current research landscape.

[1] Section 20 brings together several disciplines of the humanities and social sciences such as biological anthropology, ethnology, prehistory.

In this book, we wanted to bring together all these good moments of science, discovery, and reflection to share with you a few selected pieces. More than a biography, for which we suggest you read the notice published in April 2019 in the *Bulletins et Mémoires de la Société d'Anthropologie de Paris* by Jean-Jacques Hublin, his colleague and friend of the first hour, and a bibliography of Jean-Pierre's written production that you will find at the end of the book, we wanted to open the floor to his closest colleagues and to those who followed in his footsteps, to share their perception of the scientific questions and epistemological reflections that marked the whole of Jean-Pierre Bocquet-Appel's career.

From a diachronic and multidisciplinary perspective, the thirteen contributions by collaborators and colleagues are grouped into four thematic sections. The first one concerns *The development of paleodemography: the French school's singularity*. The section begins with an article proposed by Lyle Konigsberg and Susan Frankenberg entitled *Jean Pierre Bocquet-Appel's contributions to paleodemography.* Starting with the most cited and pioneer article by Bocquet-Appel and Masset published in 1982, the authors show how they marked a fundamental milestone for the discipline by demonstrating that no bone indicator was correctly correlated to the real age of subjects and thus justifying their mythical title *Farewell to paleodemography*. This article proposes a step-by-step review of the approaches developed by the "paleodemographic" community to solve the various problems that demographic reconstructions entailed. The authors also revisit the paleodemographic estimators proposed by Bocquet-Appel and Masset in 1977, updated in 2002, explaining how this work became a stepping stone in JPBA's career with his work on the agricultural demographic transition in the Neolithic and the subsequent collaboration with Isabelle Séguy, Luc Buchet, Daniel Courgeau, and Henri Caussinus, published in 2013.

The second article written by Isabelle Séguy is entitled *Jean-Pierre Bocquet-Appel and French paleodemography. The search for the key indicator*. Following the main point inherent in (paleo)demographic studies: what is the best indicator to reconstruct the demography of populations that have disappeared today? The author begins this synthesis by emphasizing that, for JPBA, all the biological indicators derived from skeletons, like all the artifacts provided by humans, were all intended to be used, analyzed, and modeled to infer demographic information and understand the dynamics of human populations. The author succeeds in unraveling this common thread to offer a rigorous and didactic analysis of the methodological approaches developed by JPBA up to its "consecration" with the identification of a worldwide phenomenon: the agricultural demographic transition.

In a third article entitled *Paleodemography and statistics: a tale of uncertainty*, Henri Caussinus provides a technical analysis of the methodological approaches developed by JPBA, which was constantly combining demography and statistics to ensure the best reliability of paleodemographic estimates. The author reviews the use of bootstrap and Bayesian methods in JPBA's work while proposing how their improvement can be pursued using concrete examples from historical populations.

The second part of the book is devoted to *Spatial demography: a new approach to modeling human expansion*. In an article entitled *Is biodemography a science?* Daniel Courgeau, co-author with JPBA and Denise Pumain of a major work published in 1996, presents a historiographical and critical analysis of the contribution of spatial analysis to biodemographic data, questioning the "reductionist" impact of genetics in the understanding of the environmental factors involved in the expression of genes and behaviors. The author highlights with a precise and detailed argument all the particularity and complexity of demographic processes, intimately linked to mortality and fertility, which certainly respond to biological rules, but which are themselves shaped by social and cultural factors sometimes challenging to define *a priori*.

Denise Pumain, in her article entitled *Spatial analysis: a valuable turning point for demography* returns to the reasons that motivated JPBA to use spatial analysis in paleodemographic reconstructions. JPBA was fully aware of the shortcomings inherent in bioarchaeological documentation, and his ambition was to use this new methodological approach to fill the gaps. Through examples of settlement in an urban context with the development of habitats and cities, the author proposes a critical review of studies combining spatial analysis and the integration of computer models and shows how the validation of multi-agent systems offers the opportunity to formulate relevant scenarios on the evolution of urban populations, at different scales.

The third part of the book is devoted to the primary research line that JPBA has been working on for the past 15 years: *The demographic dynamics of transitions*. This part begins with an article by Stephan Naji, entitled *The agricultural demographic transition, a Bocquet-Appel signature*. The author offers a fascinating summary of JPBA's work through a detailed, almost epistemological, description of the evolution of his scientific questioning and his methodological contributions. This synthesis, both very factual and largely supported by arguments, gives an account of Jean-Pierre's place in the history of paleodemography, as well as the exceptionally innovative and original nature of his research.

The following article, proposed by Jérôme Dubouloz and colleagues, is devoted to the study of the Neolithic demographic transition in Europe *Between paleodemographic estimators and "LBK" colonization in Central-Western Europe, c. 5,550-4,950 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"*. The author presents the genesis and the implementation of the collaborative research project in the ANR OBRESOC (dir. JPBA). This article attempts to retrace, from a specific example of the first Neolithic societies in Europe, the authors' incessant quest for the best paleodemographic approach and the best model to explain this universal diachronic phenomenon, the agricultural demographic transition. This paper explores the modeling of a complex phenomenon from contextual data discussed, selected, and finally retained in the analysis because of their reliability and accuracy of the sometimes ungrateful archaeological record. We also appreciate the whole process, presented with rigor and argumentation of the parameters and factors that would be indispensable. The authors also demonstrate, with caution, the difficulty of constraining the model(s) by (*a priori* unknown) parameters and the power of research conducted in collaboration with different specialists in prehistoric societies, whether archaeologists, anthropologists, culturalists, or environmentalists.

The third article proposed by Camille de Becdelièvre and colleagues, entitled *Paleodemography of the Mesolithic-Neolithic transformations in the Danube Gorges*, presents the example of the Balkans the influence of JPBA's research in the interpretation of a specific data set. This geographical area, one of the most documented in the world, has yielded impressive archaeological material allowing the exploration of demographic, behavioral, and health changes in Mesolithic-Neolithic populations. The authors propose an analysis of several bio-archaeological indicators (demographic, health and dietary, DNA) with a set of new radiocarbon dates to better understand the changes over time. The research presented here is original in the multiplicity of indicators used, from demographic parameters to the genetic characteristics of the populations, questioning in passing the crucial question of the "number of migrants" in the populations. These parameters are indispensable for understanding all the mechanisms involved in the biological and behavioral patterns observed.

The last article proposed by Tasos Tizis and collaborators concludes this theme on transitions, on *Ancient Greek colonization in retrospect: population projections from the birth of colonie*s. Using the example of the Corinthian colony of Ambracia, the authors propose to explore four possible scenarios by modulating several parameters, the initial size of the population, the rate of fertility, and migration, using classical methods of demographic projections. Discussing the pitfalls stated by JPBA, the authors demonstrate that fertility and migration contributed positively. Thus, the initial settlers who arrived in the region were close to 100 and 200 individuals with a fertility rate between two and four children on average for each woman.

The last and fourth part, *Epistemology of a discipline, from biological anthropology to paleodemography,* includes four reflective contributions on biological anthropology and paleodemography as Jean-Pierre conceived and defended them through his research, institutional commitment, and teachings. Pierre Darlu's first article, *Thoughts on some manuscripts by Jean-Pierre Bocquet-Appel*, presents a critical and historiographical analysis of Jean-Pierre's publications through four articles, which according to bibliometric standards, have not been the most widely distributed and cited by the anthropological community. Thus, this article attempts to unravel the genesis of Jean-Pierre's thinking while showing his passion for new subjects and his enthusiasm for finding ever more effective and rigorous methods, but which were not all as "revolutionary" as he would have liked. Beyond the original and singular tribute that the author pays between the lines to JPBA, one will appreciate the author's nuanced analysis of the life cycle of publications. Indeed, it is fascinating to note that if we observe a certain universality in the scientific approach/valuation, specific research paths, barely born and yet innovative, can find themselves relegated to the last ranks of possible solutions.

The second article, by Jean-Paul Demoule, entitled *From craniometry to paleogenetics*, is a critical and historiographical analysis of "Anthropology" in France, qualified at the beginning as "physical" and then as "biological." Using numerous bibliographical references, the author outlines the contours of this discipline, from its birth in the 18th c. to its "racial" drifts in the 19th c., and its relationship with the conflicts that Europe and the world experienced during the first half of the 19th c. This analysis is also an opportunity to give an account, through the extraordinary interview of Henri Victor Vallois that JPBA had conducted, of the attacks against our discipline and JPBA's positioning to his discipline and his object of study.

The following article, written by Bernard Formoso and entitled *Jean-Pierre Bocquet-Appel and the interdisciplinary dialogue*, takes up the origin and construction of a reflection developed within the 20th section of the CNU (2011-2015 term) and published in the journal *L'Homme* in 2017. From a historical and epistemological perspective, this reflection questions the perimeter of the section "Social Anthropology-Ethnology, Biological Anthropology, and Prehistory," noting a progressive dissociation of these disciplines' practices, procedures, and objectives. The article concludes with a proposal for the renewal of a collaborative and thematic dynamic between these disciplines.

Finally, this section ends with an article by Olivier Dutour entitled *From the teaching unit "Hommes et Milieux" to the "General anthropology" seminar: Jean-Pierre Bocquet-Appel's commitment to teaching at the École Pratique des Hautes Études (2008-2016).* This article presents JPBA's close relationship with the EPHE, particularly during his life when he felt the need to pass on his knowledge, vision, and anthropology practice. It also seeks to give a subtle account of JPBA's pugnacity and commitment to causes that were close to his heart, such as the defense of a generalist teaching program at the EPHE, encompassing the various approaches that would allow for the analysis and understanding of "the world colonization and demography of our humanity." From verbatims, taken from the author's personal "digital" correspondence, one can recognize the eloquence of our colleague, his language, his turns of phrase, his formulations as original and influential as his thought.

Beyond the legitimate tribute we wished to pay to the international stature of our colleague, we wanted to highlight the plurality of themes and decompartmentalized approaches: demography, archaeology, population genetics, economics... such as JPBA practiced them. We also wanted to highlight JPBA's work on the demographic signature of the Neolithic transition in the Near East and its consequences on the Neolithization of Europe through the Mediterranean and Central Europe, which constitute one of the major contributions to paleodemography.

We wish to thank all the contributors for their participation in this book, witnesses of a committed scientific life that has allowed us to share a moment with Jean-Pierre and extend his discussions that are still relevant today.

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1. The development of paleodemography: the French school's singularity

Jean-Pierre Bocquet-Appel's contributions to paleodemography

Les contributions de Jean-Pierre Bocquet-Appel à la paléodémographie

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Abstract: Bocquet-Appel's most highly cited work was his article with Claude Masset published in 1982 in the *Journal of Human Evolution*: "Farewell to paleodemography." Indeed, this article has been cited over twice as much as Bocquet-Appel's second most cited article ("When the world's population took off") from the journal *Science*. While on the surface Bocquet-Appel and Masset's "Farewell" might be taken as a literal adieu, the article functioned as a clarion call for a paradigm shift in paleodemography. The article pointed out a problem later to be known as "age mimicry," it questioned the statistical basis for age estimation in paleodemography, and it introduced new demographic estimators that were related to life table parameters while being relatively resistant to biases. Had Bocquet-Appel simply stopped at this point, his contributions to paleodemography would have been substantial. Instead, he continued to publish and push for improvements in paleodemographic methods. While others toiled on maximum likelihood methods, Bocquet-Appel was at the vanguard of those developing Bayesian methods in paleodemography. Although these Bayesian methods were crystalized by others, it is questionable whether they would have done so without Bocquet-Appel's work in and following his "Farewell to paleodemography" with Masset.

Keywords: age mimicry, maximum likelihood, Bayesian, juvenility index, age structure, calibration

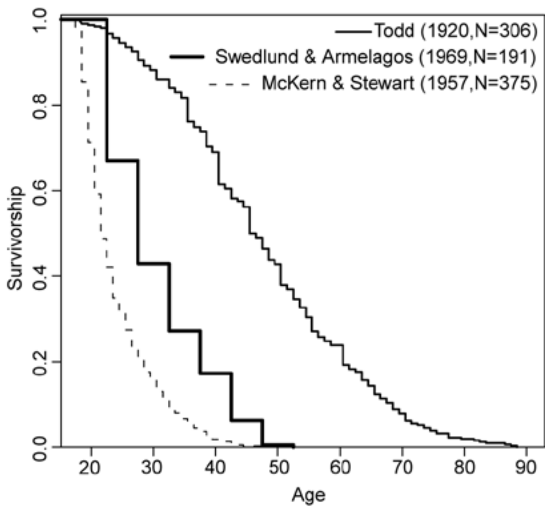
Résumé : La publication la plus citée de Bocquet-Appel est son article avec Claude Masset publié en 1982 dans le Journal of Human Evolution*: « Farewell to paleodemography » (Adieu à la paléodémographie). En effet, cet article a été cité plus de deux fois plus que son deuxième article le plus cité (« When the world's population took off » Quand la population mondiale a décollé) de la revue* Science*. Si, à première vue, le « Farewell » de Bocquet-Appel et Masset pouvait être considéré comme un adieu littéral, l'article appelait à un changement de paradigme en paléodémographie. L'article a souligné le problème de l'influence de la structure de la population sur la répartition des décès par âge connu plus tard sous le nom de « mimétisme de l'âge », remettant en question la base statistique de l'estimation de l'âge en paléodémographie et introduisant de nouveaux estimateurs démographiques, liés aux paramètres de la table de mortalité tout en étant relativement résistants aux biais. Si Bocquet-Appel s'était simplement arrêté à ce stade, ses contributions à la paléodémographie auraient été substantielles. Mais il a continué à publier et proposer des améliorations des méthodes paléodémographiques. Alors que d'autres travaillaient sur les méthodes de maximum de vraisemblance, Bocquet-Appel était à l'avant-garde de ceux qui développaient des méthodes bayésiennes en paléodémographie. Bien que ces méthodes bayésiennes aient été concrétisées par d'autres, on peut se demander s'il en aurait été de même sans le travail de Bocquet-Appel et après son « Adieu à la paléodémographie » avec Masset.*

Mots clés : mimétisme de l'âge, maximum de vraisemblance, bayésien, indice de juvénilité, structure par âge, calibrage

Bocquet-Appel's contributions to paleodemography were many, including analyses of the Neolithic demographic transition and the development of new paleodemographic estimators, both of which were highlighted in his article in *Science* (Bocquet-Appel 2011). But perhaps his greatest contribution to paleodemography was his publication with Claude Masset of "Farewell to paleodemography" (Bocquet-Appel and Masset 1982). Despite the title of the article, which might suggest that Bocquet-Appel and Masset would have nothing more to do with paleodemography, this article served as a signal call for a paradigm shift. Bocquet-Appel was very much involved in forging and contributing to this paradigm shift (Bocquet-Appel and Masset 1985; Bocquet-Appel 1986; Bocquet-Appel 1994; Bocquet-Appel and Masset 1996; Bocquet-Appel and Bacro 1997; Bocquet-Appel and Arsuaga 1999; Bocquet-Appel 2002; Bocquet-Appel and Naji 2006; Bocquet-Appel and Bacro 2008). The 1982 article still serves as Bocquet-Appel's greatest contribution to paleodemography. In fact, of all Bocquet-Appel's publications, the 1982 publication with Masset has the highest citation count (307 *in* Scopus as of November 5, 2019), being over twice the count for his next most widely cited article (143 for the *Science* article). Given the preeminence of the 1982 publication, we focus here on this article as well as on later methodological works in paleodemography from Bocquet-Appel.

Age structure mimicry

Although the term "age structure mimicry" was not used until eight years after the 1982 Bocquet-Appel and Masset article (Mensforth 1990), the subject of "mimicry" was clearly articulated in the 1982 article. As used by Mensforth, the term refers to the tendency of age structure in an archaeological skeletal sample to be similar to that of the known-age reference sample used to estimate individual ages in the archaeological sample. Bocquet-Appel and Masset showed three examples of this effect, one from a United States study on 11th to 13th c. Nubians (Swedlund and Armelagos 1969), one from a Hungarian study, and one from a Japanese study. For the first example, they showed that the Nubian cemetery had an age-at-death structure similar to that of the McKern and Stewart (1957) reference sample. In fact, Swedlund and Armelagos (1969:1293) stated that the age estimates for the Nubian skeletons had been derived "d'après les méthodes de McKern et Steward [*sic*] (1957), et de Todd (1920)…". Van Gerven and Armelagos (1983:354) later noted that "Although the reference population associated with this sample by Bocquet-Appel and Masset was the McKern-Stewart Korean War dead, the system most extensively used was that developed by Todd (1920) and later modified by Brooks (1955). Bocquet-Appel and Masset (1985:107) correctly questioned Van Gerven and Armelagos by stating: "…we may ask ourselves how it is possible to use both Todd's and McKern and Stewart's methods at the same time. What can we do with both of them? Take the mean? What is the subtle dosage of reference populations?" Figure 1 shows the Kaplan-Meier (1958) survivorship for the Korean War dead sample (data from Table 4 in McKern and Stewart), for the 306 males analyzed in Todd (1920; data from his appendix on pages 328-329), and for the Meinarti (Nubian) sample from Swedlund and Armelagos' Table 2 (page 1293). For the Meinarti data we use ages starting at 15 years. These ages are in the form of a lifetable with intervals of 16-20, 21-25, …, 51-55. We rewrite these as interval-censored ages of [15-20], [20-25], …, [50-55]. For the Korean War dead and Todd samples we assume one year interval censored ages.



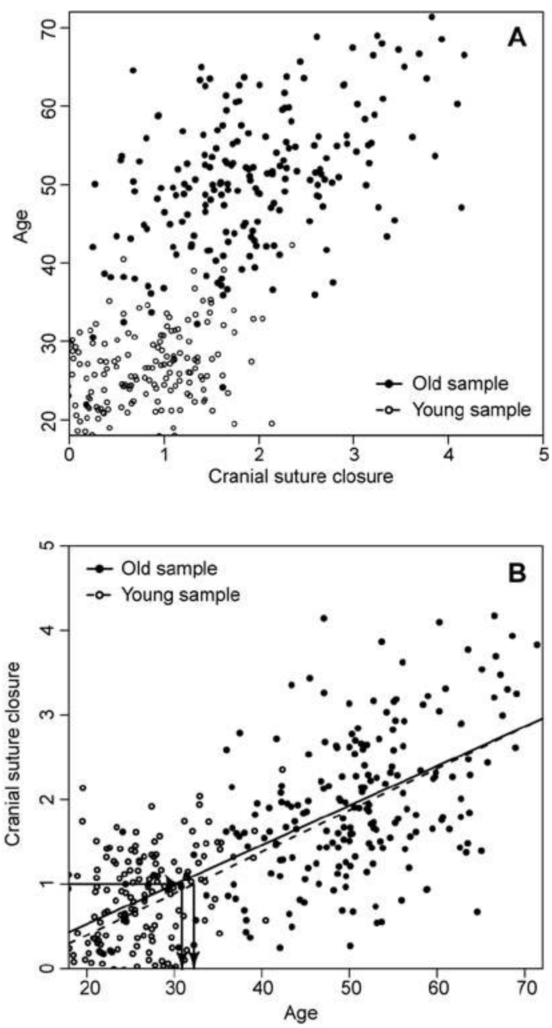
1. Kaplan-Meier survivorship for the Meinarti Nubian sample (Swedlund and Armelagos 1969) and the Korean War dead (McKern and Stewart 1957) and Todd (1920) reference samples. Note that while the Meinarti Nubian sample is more like the Korean War dead sample, all three survivorship lines differ from one another.

From Figure 1 it is clear that estimated survivorship for the Meinarti sample is like neither the Korean War dead sample nor the Todd sample, although the Meinarti sample is closer to the Korean War dead sample. More to the point, and as indicated by Bocquet-Appel and Masset in 1985, we cannot know to what extent the two reference samples were used. Presumably, the Korean War sample may have been used for Meinarti skeletons that were thought to be younger and the Todd sample for those Meinarti skeletons thought to be older. The picture becomes even foggier when we consider that Todd did not use any statistical method to summarize his pubic symphyseal data. He simply stated age ranges based on a very select sampling of his 306 individuals. McKern and Stewart proposed a three component system for the pubic symphysis, but ultimately summed the scores and provided age ranges, mean ages within the total scores (for scores of 0, 1-2, 3, 4-5, 6-7, 8-9, 10, 11-13, 14, and 15), and standard deviations within the total scores. Neither McKern and Stewart's nor Todd's studies could be considered as shining examples of statistical analysis.

A decade after Bocquet-Appel and Masset correctly pointed out the problem of age mimicry, Konigsberg and Frankenberg (1992) demonstrated that cross-tabulating age against stage in a reference sample in order to estimate the number of deaths by age in a target sample was fraught with peril. If done incorrectly, this method incorporated an informative prior for age in the target sample that was based on the reference sample age distribution. This problem had been pointed out earlier in the fisheries literature (Kimura 1977; Westrheim and Ricker 1978). Following on Bocquet-Appel and Masset's treatment of the age mimicry problem, this type of bias has been widely recognized in the paleodemographic and forensic anthropology literature (Müller *et al.* 2002; Prince and Konigsberg 2008; Coqueugniot *et al.* 2010; Langley-Shirley and Jantz 2010; Godde and Hens 2012; Bullock *et al.* 2013; Buckberry 2015; Tangmose *et al.* 2015; Miranker 2016; Dahlberg *et al.* 2019).

Age estimation as calibration

While Bocquet-Appel and Masset did not refer to age estimation as a calibration problem in their 1982 publication, their Figure 2 clearly shows the relationship of age estimation to the general statistical problem of calibration. In the calibration problem, there is a precise and generally expensive-to-measure variable that is assessed using an imprecise and less expensive variable (Scheffé 1973). In the age estimation problem the precise and expensive variable is the known age within a reference sample while the imprecise variable is some age indicator, such as cranial suture closure. In the classical calibration approach, so named because it is the older method (Eisenhart 1939), one would regress the indicator variable onto age and then solve the regression for age. This method has the advantage that it takes a uniform prior for age, and as a consequence, does not tend to over-age young individuals and under-age older individuals. This is a problem that Masset 1989:81 later referred to as "attraction of the middle." This problem arises when one regresses age onto the indicator, as is so often the case in both paleodemography and forensic anthropology. Krutchkoff 1967 referred to this as "inverse regression" for calibration, because it regresses the explanatory variable onto the variable that is being explained. In the age estimation setting, a researcher using inverse calibration regresses age onto the indicator variable. That this is "backwards" becomes clear when estimating juvenile



2. A: The regression of age onto suture closure for a young age sample and an old age sample, with simulation parameters and other parameters taken from Bocquet-Appel and Masset's Figure 2. The vertical arrows at suture closure state 1 show the very different age estimates from the two samples. B: As in Figure 2A, but showing the regressions of suture closure on age. Note how the suture closure score of 1 produces very similar age estimates regardless of whether the young age sample or the old age sample is used.

ages from long bone lengths. Biological anthropologists who study human growth would be quite surprised to see age as the dependent variable and long bone length as the independent variable. Such a regression would seem to suggest that a child becomes older because their long bones are lengthening. Similarly, in the adult setting, it is difficult to claim that individuals become older because they gain secondary osteons.

In addition to appearing to reverse causality, inverse calibration places an informative prior on age. Specifically, the reference sample age distribution (represented as a normal distribution) places an informative prior on the target sample age estimate. Figure 2A shows an example of this problem modelled after Bocquet-Appel and Masset's (1982: Figure 2). When age is regressed onto cranial suture closure, a younger reference sample will produce an age estimate of (rounding to the nearest first decimal place) 26.3 years while an older sample will produce an age estimate of 45.8 years for a suture closure score of 1.0. Alternatively (Figure 2B), if suture closure is regressed onto age and the regression equations are solved for age, the younger sample will produce an age estimate of 32.2 years and the older sample an age estimate of 30.8 years for a suture closure score of 1.0. Bocquet-Appel and Masset (1982: p. 232) referred to this problem stating "when aging a cranium by the state of its sutures, one must not use A_1 and A_2, but B_1 and B_2, the inverse regressions". Their lines A_1 and A_2 are our regression lines in Figure 2B (the regression lines of age onto cranial suture closure) while their lines B_1 and B_2 are our regressions in Figure 2A (the regression lines of suture closure onto age). In fact, there is no requirement that inverse regression or inverse calibration be used. Lucy and Pollard 1995 pointed this out in 1995, and two years later both Konigsberg *et al.* 1997 and Aykroyd *et al.* 1997 came to the same conclusion that there was merit to the classical calibration approach.

The estimation of a population structure

Bocquet-Appel and Masset 1982 ingeniously argued that estimation of a population structure was made difficult, if not impossible, because of the relatively low correlations between age indicators and actual age. To demonstrate this problem, they assumed that the age distribution for a target sample was uniform (rectangular) between the ages of 18 and 90 years. Using the well-known equation for the variance of a uniform distribution (Freeman 1963: p. 133), the variance in Bocquet-Appel and Masset's case is:

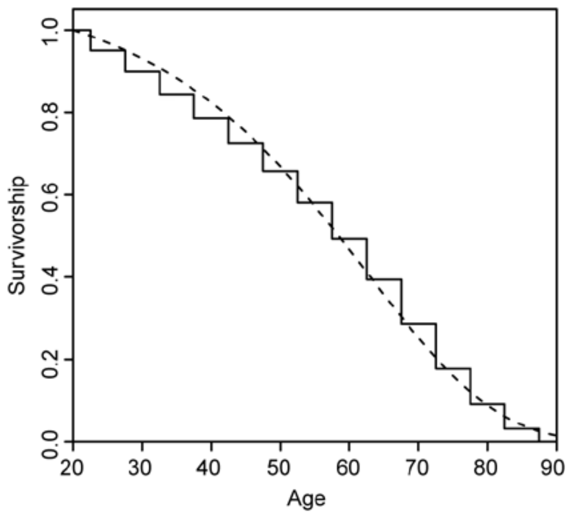
$$\frac{(90-18)^2}{12} \quad (1)$$

Bocquet-Appel and Masset took the square root, obtaining 20.68 on page 324, though the actual value to three decimal places is 20.785, the number that they do appear to have used in their Table 1. From this standard deviation and an assumed correlation coefficient of r, one can obtain the square root of the unexplained portion of the age variance as:

$$20.785\sqrt{1-r^2} \quad (2)$$

For example, at a correlation coefficient of 0.8, the square root of the unexplained portion of the variance to two decimal places is 12.47. In the second column of Bocquet-Appel and Masset's Table 1 they multiply this number by two (obtaining 24.94) and in the third column they multiply this number by four (49.88), arguing that plus or minus two standard deviations gives the range that would correctly contain 95% of the age estimates. With a width of 49.88 years and a total width from 18 to 90 years of 72 years, Bocquet-Appel and Masset argue that only 72/49.88 = 1.4 age intervals can be estimated for the target sample. Indeed, by this argument, at a correlation coefficient of 0.5, only one age interval can be estimated. Taking a similar problem where age is uniformly distributed from 20 to 90 years, the correlation coefficient would need to be about 0.9923 to obtain seven intervals each with a ten-year width. As Bocquet-Appel and Masset show in their Tables 2 and 3, the observed correlations between age indicators and age is well below such a high value.

While the logic Bocquet-Appel and Masset used to calculate their Table 1 appears both correct and quite damaging to the estimation of a population structure, two considerations ameliorate the situation. First, a uniform age-at-death structure, which has a high variance, would be quite unusual in a paleodemographic target sample. To illustrate this, Buikstra and Konigsberg (1985) examined the variances of adult ages-at-death from Coale and Demeny (1966) West model life tables and from Weiss' (1973) model life tables. Séguy and Buchet (2013) have pointed out the deficits in such model life tables in relation to paleodemography, so here we instead use the combined sexes model from Séguy and Buchet's Table 9.1. Figure 3 shows the adult age distribution of this model as a Kaplan-Meier survivorship function and as a Gompertz (1825) survivorship curve fit to the life table data. The mean adult age from this model is 56 years with a variance of 268. The standard deviation is then 16.37 as *versus* Bocquet-Appel and Masset's standard deviation of 20.785. This still produces age interval widths that are excessively large. For example, Bocquet-Appel and Masset's width of 49.88 at a correlation of 0.8 becomes 39.29 under the model in Figure 3. The second ameliorating consideration, also raised by Buikstra and Konigsberg (1985), concerns heteroscedasticity of age indicators. They argued that confidence intervals around estimated ages should increase with increasing age. This is a complication not accounted for in Bocquet-Appel and Masset's Table 1.



3. The Kaplan-Meier survivorship (step function) for adult survivorship in Séguy and Buchet's (2013) "pre-industrial standard" life table (their Table 9.1). Also shown with a dashed line is the Gompertz survivorship fit to their life table.

Demographic estimators

In the section titled "Demographic Estimators" Bocquet-Appel and Masset introduce the death ratio D_{5-14}/D_{20+} which they had previously described in 1977 (Bocquet and Masset). This ratio showed a strong correlation with life expectancy at birth and was relatively resistant to the problems of age estimation. Further, this ratio excluded individuals under age five years, who often are under-represented in archaeological samples either due to mortuary practices or to poor preservation. Bocquet-Appel (2002) eventually switched from using this ratio to using the proportion D_{5-19}/D_{5+}. This proportion had the advantage that its statistical properties were simpler than that of a ratio. The idea of using a proportion appears to trace back to Masset and Parzysz 1985 where they converted the original "juvenility index" of D_{5-14}/D_{20+} to $D_{5-14}/(D_{(5-14)}+D_{(20+)})$. The original juvenility index and the proportion given in Masset and Parzysz were written in life table notation, so in point of fact included individuals up until age 15, just as Bocquet-Appel's (2002) modification included individuals up until age 20 in the numerator. In both Bocquet-Appel (2002) and (2005), he showed that the new juvenility proportion D_{5-19}/D_{5+} was most closely related to the crude birth rate in stable but not necessarily stationary populations. This closer relationship to fertility than to mortality follows on the proof given in Sattenspiel and Harpending 1983 and supported in later works (Buikstra *et al.* 1986; Horowitz *et al.* 1988). Importantly, Bocquet-Appel's careful work with this death proportion led to his groundbreaking finding that fertility increased during the Neolithic transition (Bocquet-Appel 2011). As mentioned above, Bocquet-Appel's (2011) paper, which was published in Science, is his second most highly cited paper after the 1982 "*Farewell to paleodemography*" paper with Masset.

The aftermath of the "Farewell to paleodemography" paper

Much of the aftermath of the "Farewell to Paleodemography" paper has been summarized in section 4.5 of Courgeau's (2012) book and his chapter 12 in Séguy and Buchet's book (2013). These should be required reading for anyone studying paleodemography and particularly for those attempting to trace the history of developments in this field. They also serve as useful introductions to the fully Bayesian methods that have been developed in paleodemography (Caussinus and Courgeau 2010; Séguy *et al.* 2013). There is little point in repeating here the details that one can find in the aforementioned work by Courgeau and others. However, some generalizations are in order.

Following on the rapid back and forth in response to publication of "Farewell to Paleodemography" (Van Gerven and Armelagos 1983; Bocquet-Appel and Masset 1985; Buikstra and Konigsberg 1985; Bocquet-Appel 1986; Greene *et al.* 1986), there was a period of relative quiescence. A paper a decade later broke this quietude (Konigsberg and Frankenberg 1992). In this paper, Konigsberg and Frankenberg argued for applying maximum likelihood methods to estimate the age-at-death structure for anthropological, and in particular paleodemographic, samples. Bocquet-Appel and colleagues (Bocquet-Appel 1994; Bocquet-Appel and Masset 1996; Bocquet-Appel and Bacro 1997) answered this paper by pointing out that they had used similar methods before the Konigsberg and Frankenberg paper, but that they had found the maximum likelihood methods lacking. One area where they found the likelihood method lacking was that it did not account for uncertainty due to fixed sample size in the reference sample. In selecting methods, Konigsberg and Frankenberg had relied on an article from the fisheries literature (Kimura and Chikuni 1987) that indeed did not account for this uncertainty. A similar article from the fisheries literature (Hoenig and Heisey 1987) did account for this uncertainty, but Konigsberg and Frankenberg were initially unaware of this article.

The use of maximum likelihood methods in paleodemography was emphasized in the U.S. and parts of Europe (Konigsberg and Frankenberg 1994; Konigsberg and Holman 1999; Boldsen *et al.* 2002; Herrmann and Konigsberg 2002; Holman *et al.* 2002; Hoppa and Vaupel 2002a; Hoppa and Vaupel 2002b; Konigsberg and Frankenberg 200; Müller *et al.* 2002) while Bocquet-Appel and Bacro (2008) were stressing the applicability of Bayesian estimation methods. Although Bocquet-Appel did not ultimately provide a fully Bayesian method, his work was foundational for others who did provide a fully Bayesian approach to paleodemography (Caussinus and Courgeau 2010; Séguy *et al.* 2013). In providing this approach recent authors have come full circle from the original problem of "age mimicry" first clearly articulated in "Farewell to paleodemography.". In that paper, Bocquet-Appel and Masset (1982) were essentially arguing that there was an implicitly Bayesian approach such that the reference sample age-at-death structure provided an informative prior for the target sample. In the current Bayesian approach, the method is explicit and uses information from the reference sample only on the development of indicators against known age. The prior for the age structure of the target sample may be uninformative or it may come from an external source. Thus, the main problem that Bocquet-Appel and Masset noted in their article has finally been solved and the paradigm shift is complete.

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Jean-Pierre Bocquet-Appel and French paleodemography. The search for the key indicator

Jean-Pierre Bocquet-Appel et la paléodémographie française. À la recherche de l'indicateur-clé

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Abstract: Reconstructing the demography of populations having made little or no use of writing or the recording of key events, such as births, marriages, migration, and deaths, is not a simple task. Ingeniousness is required to establish via material sources a tenuous link with the demographic behaviour of the populations having produced them, naturally for other ends. Drawing on disciplines complementary to demography and archeology, Jean-Pierre Bocquet-Appel produced highly original work. On both a micro and macro scale, his research embraced the long history of *Homo sapiens*. His demographic interpretation of archeological information was based on models and theories stemming from demography, ethnology, and ecology, and on an original approach to primary data.

Keywords: *juvenility index, estimators, Neolithic demographic transition, georeferenced dates, pre-industrial populations, metapopulations*

Résumé : *Reconstruire la démographie de populations n'ayant pas ou que peu recours à l'écriture et à l'enregistrement d'un certain nombre d'événements vitaux (naissance, mariage, migration, décès) n'est pas chose simple. Il faut faire preuve d'ingéniosité pour trouver dans les sources matérielles, un lien ténu avec les comportements démographiques des populations qui les ont produites, pour d'autres usages naturellement. Puisant à la source de disciplines complémentaires à la démographie et à l'archéologie, Jean-Pierre Bocquet-Appel a développé des travaux très originaux. Ses recherches, à la fois à l'échelle micro et à l'échelle macro, embrassent l'histoire longue des* Homo sapiens. *L'interprétation démographique des informations archéologiques est élaborée à partir de de modèles et de théories issues de la démographie, de l'ethnologie et de l'écologie, et d'un traitement original des données primaires.*

Mots clés : *indice de juvénilité, estimateurs, transition démographique néolithique, dates géoréférencées, populations préindustrielles, métapopulations*

Introduction

Reviewing the impact of Jean-Pierre Bocquet-Appel's work, in the various directions he followed to reconstruct the history of human demography based on source materials, is not an easy matter. It calls for a sweeping appraisal of his centres of interest; research into the disciplines having inspired his investigations and opened new pathways; an analysis of the collaborative work initiated in step with the issues explored; an appreciation of the methodological inventiveness he displayed to resolve his investigations; and a concise summary (or an attempt thereto) of what distinguishes his work from the research approaches adopted in other (notably English-speaking) countries.

Because, far from a swansong, *Farewell to paleodemography*, published in 1982 with Claude Masset, undoubtedly stands as the key moment in the emergence of 'French paleodemography'[1]. This article was an alarm call, directing the attention of the international scientific community to the statistical biases inherent to estimating age based on biological criteria. But it failed to produce the intended effect, on the contrary leading to a division of the academic world along a fracture line generally corresponding to linguistic borders. In 1996, realizing that dialogue was impossible (*Paleodemography: expectancy and false hope*), Jean-Pierre Bocquet-Appel turned to other branches of paleodemography, including the spatial approach to prehistoric populations and the search for a 'Neolithic Demographic Transition'. At the same time, he continued to work on improving methods for estimating age at death, which can be used to reconstitute the structure of a buried population and assess some of its demographic parameters. It was not until 2002 and the *Rostock manifesto* (Hoppa, Vaupel 2002: 1-8) that the international community validated the findings made by Bocquet-Appel with Claude Masset some 20 years earlier. At the same time, through new collaborative initiatives and the use of analysis methods borrowed from the natural sciences and geography, Bocquet-Appel revealed new dimensions in paleodemography. The major discoveries resulting from these efforts consolidated Bocquet-Appel's international reputation and contributed to the dissemination of a way of thinking that is highly original yet still grounded in a Cartesian approach.

[1] A discipline that studies past populations based on material remains revealed by archeology (human remains and traces of occupation).

From biological anthropology to paleodemography

All of Bocquet-Appel's work is in the field of demographic anthropology, a discipline arising in the 1980s (Petit 2011) from the hybridization of demography, which measures 'population phenomena', and anthropology, which explains these phenomena through 'cultural differences'. Long divided, and having failed to work together 'to strengthen each other' (Gessain 1948: 500), the two sciences came together to 'understand the reproduction and evolution processes of small groups of humans by using the concepts and methods of anthropology, demography, and population biology' (Bley and Boëtsch 2000).

Jean-Pierre Bocquet-Appel added the dimension of time, the long time span of humanity, and applied some of his themes not at local level, a common characteristic of demographic anthropology, but on a planetary scale. With a research theme that Bocquet-Appel himself defined as 'ranging from paleodemography to contemporary demography, covering the five continents and with an evolutionary perspective'[2], he was required to introduce new (archeological) sources and make use of new methods, including biological anthropology, statistics, modelling, and spatial analyses. This article focuses on this notable aspect of his work, as well as his combined use of archeology, demography, and biological anthropology, along with ecology, ethnology, and statistics. In addition to social and cultural factors, his approach takes account of environmental variables. The systematic study of the influence of these variable and interactive factors has served to boost the momentum of paleodemography, a discipline long ensconced in immobile time frames and static populations.

Bocquet-Appel believed that any source material could contain demographic information. The key was to make it speak. Unlocking this door made it possible to cover the entire history of mankind, or, more modestly, *99.99% of the demographic history of humans*, based on material traces left by human beings well before the invention of writing.

But owing to the extremely weak link between archeological data and the sought-after information, detecting and interpreting a demographic signal calls for an original approach involving three key processes: defining a synthetic demographic indicator that can

[2] https://prosopo.ephe.fr/jean-pierre-bocquet-appel

be measured via archeological or osteological data; reducing space and time into a single variable addressing the four dimensions of latitude, longitude, altitude, and relative or absolute dating; and, with a view to linking these synthetic data to population dynamics, harnessing concepts, models, and theories from diverse disciplines able to address the particularities of populations and their contexts.

Working on pre-industrial populations, Bocquet-Appel drew on the findings of historical demography and adapted the population models of demographers. Exploring prehistoric populations, characterized by small sample sizes, dispersion across vast territories, long observation periods (several millennia), and substantial environmental changes, he borrowed concepts from ecology (including that of metapopulation[3]) and data from ethnology, and also used advanced geostatistical techniques.

Inferring demographic information from archeological data reduced to a synthetic indicator

Archeological data come in two main forms: the remains of dwellings and artefacts (signs of human activity), and skeletons unearthed by funeral archeology. Consistent with its sources, paleodemography lends itself as much to exploring the spatiotemporal distribution of populations, based on cultural markers, as it does to estimating the demographic parameters based on determinations of the sex and age of skeletons. And the thematic focuses of Bocquet-Appel do indeed follow these two directions.

In the early 2000s, he unified these two approaches, these two perceptions of space (local and distant), and these two sources (artefacts and biological data) to highlight what he referred to as the 'Neolithic Demographic Transition' (NDT), or the 'Agricultural Demographic Transition (ADT). This strongly disrupted the balance between fertility and mortality, the two parameters ensuring the natural renewal of populations over the long term (see below).

[3] Metapopulation (population of populations able to exchange genes). Deriving from ecology, this concept designates an ensemble of small populations living in a dispersed manner in a given space (or ecological niche) at a given time. These populations are connected through varying degrees of contact and migration and dispersion flows, closely related to the density of their population.

Archeological data are numerous, diverse, and sometimes difficult to interpret. Which data should be selected to respond to a demographic issue, concerning either a population's spatial distribution or its fertility and mortality behaviour? The common point of all Bocquet-Appel's work lies in the concentration of all archeological information into a single variable: a synthetic indicator.

Space and time, or the georeferencing of ^{14}C dates

Reducing space and time to a single synthetic variable proved necessary when attempting to infer the demography of prehistoric populations observed on a vast scale and over the entire period of prehistory. The small populations concerned are characterized by spatial and/or temporal distance while being interconnected culturally or genetically.

To model the demographic evolution across the European continent of these human groups defined by characteristic technical production, Bocquet-Appel had to consider both the geographic coordinates of the sites occupied by a population and their dates via carbon-14. The idea, then, was no longer to analyze the distribution of material (lithic) remains in spatial terms but to combine localization and dating to obtain what Bocquet-Appel called 'georeferenced dates' (Bocquet-Appel and Demars 2000). Combining these dates with a variable providing demographic information served to depict the dynamic of ancient populations in Europe.

The most elementary variable is the presence or absence of human occupation, observed at some sites. Demonstrating areas of presence or absence on the basis of the 1,500 or so scattered points (sites) on the European continent calls for techniques developed in spatial geography (Bocquet-Appel *et al.* 1996). Combined with genetic calculations on populations, Bocquet-Appel used these geostatistical methods to model and map the discontinuous process of the 'colonization' of Europe by modern humans (*Sapiens sapiens*) between 37,500 and 27,500 BP, as well as the corresponding contraction of native Neanderthal populations, which disappeared gradually with the exception of two 'refuge areas' in central-western France and southwestern Portugal (Bocquet-Appel and Demars 2000).

Based on the same archeological information reduced to georeferenced dates, but using techniques to analyze distribution density, Bocquet-Appel was able to establish a settlement model. Combined with an ethno-archeological approach determining geographic density according to the technical and climatic conditions of the time, he used this model to reconstitute the population density of hunter-gatherers and its trend throughout the Upper Paleolithic period between 40,000 and 11,500 BP in line with glacial and interglacial climate cycles (Bocquet-Appel *et al.* 2005).

A sizeable body of work, theses and collective research programmes has continued in this direction, modelling migrations and the colonization of new territories (Coupé *et al.* 2017; Dubouloz 2017), simulating the consequences of a population's expansion on its genetic diversity (Currat 2004), and exploring the demographic responses of Neanderthal populations subject to strong environmental pressures (Fabre 2004). These approaches require an interdisciplinary approach and advocate close dialogue between geographers, prehistorians, and mathematicians.

The structure by age of a buried population reduced to an index (juvenility index, P indicator, mean age at death of adults)

Human skeletons provide information similar to that used by demographers, notably age at death and sex. To estimate age at death in the absence of civil status documents, bio-anthropologists systematically compare the morphological criteria observed on series of skeletons from archeological digs and on a series of recent skeletons for which age at death and sex are known (the 'reference population'). Several criteria are used, mainly based on bone synostosis and/or stages of tooth development. But individual variability is considerable and no biological indicator of age[4] furnishes a robust statistical link with the civil age of the individuals. To correctly estimate age at death, the margin of error reflecting this meagre relationship must necessarily be taken into account[5].

This margin of error becomes troublesome when seeking to estimate the age at death not of an individual but of a set of buried individuals. Many paleodemographers content themselves with the average values of the estimated age without factoring in all the age probabilities of each of the individuals making up the population. The attraction of the average is one of the systematic biases of the paleodemographic studies reviewed by Claude Masset back in 1971[6]. To circumvent these issues, in his doctoral thesis (Bocquet-Appel 1977) Bocquet-Appel relied on two key points: a synthetic indicator, capable of representing the mortality curve, and a basis of comparison established among pre-industrial populations rather than contemporary anthropological and demographic data. Pre-industrial populations are also characterized by an essentially agricultural lifestyle and had little or no access to modern medicine. Their demographic behaviour was marked by high mortality rates (especially among children aged under five) offset by high fertility rates. On the assumption that the demographic characteristics of pre-industrial populations apply to all archeological populations (including nomadic hunter-gatherers), these models can be used to infer the missing data and establish demographic estimates based on biased or incomplete data.

Life expectancy is the best-known synthetic indicator capable of reflecting the health level of a population. It corresponds to the average number of years that a set of individuals may expect to live, starting from age *x*, if living conditions do not change. The lower the value, the greater the mortality rate among young people. Other indicators measure mortality in the first few years of life, quantifying the risk of dying between two given ages: the mortality quotient between birth and the first birthday (${}_1q_0$), the mortality quotient between the age of one and four (${}_4q_1$), and the mortality quotient between birth and four full years (${}_5q_0$).[7] The difficult aspect in paleodemography is accessing these four parameters, as young people are often under-represented in necropoleis and cemeteries for taphonomic and cultural reasons. And not taking this bias into account equates to underestimating infant and child mortality[8] and overestimating adult mortality.

To remedy this issue, Bocquet-Appel (Bocquet-Appel and Masset 1977) suggested the use of another indicator, the juvenility index (JI)[9], which provides good statistical

[4] Cementochronology is a more precise method as it is based on the number of annual age rings. However, while this indicator has a better correlation with civil age, it also has a margin of error, which has yet to be measured, precisely.

[5] See Séguy and Buchet, 2011, Table 1, page 58.

[6] Claude Masset identified the main causes of systematic errors in the determination of the sex and age of buried populations, notably responsible for the erroneous image of excessive mortality among women aged 18 to 29 and a near total absence of the elderly (Masset 1971, 1973a and b, 1982, 1995).

[7] For example, the child mortality quotient is the number of deaths between 0 and 1 year proportional to the number of live births, generally measured over one year and expressed as per thousand.

[8] Historian-demographers estimate that one-quarter to one-third of children died before the age of one and 30% to 45% before their fifth birthday (Dupâquier *et al.* 1988).

[9] This statistical index is used in demography (and notably anthropological demography) to measure population dynamics through the proportion of young people. It provides an approximative measurement of the structure of the population around a pivotal age corresponding to full age or the age of entering the adult group.

correlations with the variables required (e_0, ${}_1q_0$ and ${}_5q_0$), and adapted it to the funeral context by exclusively considering individuals aged over five. In its initial version, the JI ($JI = D_{5\text{-}14}/D_{20\text{-}\omega}$) also did not consider individuals aged 15 to 19, whose estimated age involved a margin of error that was too substantial to be classified, without an excessive risk of error, into an age group. Bocquet-Appel (Bocquet-Appel 2002; Bocquet-Appel and Bacro 2008) then suggested using the ${}_{15}P_5$ index (${}_{15}P_5 = D_{5\text{-}19}/D_{\text{-}5\text{-}\omega}$)[10], a continuous variable built to factor in deaths between the ages of 15 and 19 and including in the denominator the headcount of the numerator.

Representing the share of young people relative to the population of adults (JI) or the population of over-fives (P), these indicators synthesize both fertility behaviour (through the size of the share of young people) and the mortality rate among the two major age groups. This explains why these indicators are extremely sensitive to variations in population growth and why a high value may reflect a static population with high levels of child mortality (and low life expectancy at birth) as well as a population with a moderate but growing mortality rate.

Neither the JI nor the ${}_{15}P_5$ provides information on adult mortality, which trends fully independently of non-adult mortality. This required the introduction of a further synthetic indicator able to provide information on this segment of the mortality curve: the mean age at death of adults (a_{20}, Bocquet-Appel and Masset, 1996), calculated later according to probabilistic methods (see the chapter by Henri Caussinus in this publication).

Using these synthetic indicators to understand the demographic behaviour of archeological populations

As mentioned earlier, each of the indicators devised by Bocquet-Appel cultivates statistical relationships of varying degrees of robustness with a number of demographic parameters that can be used to assess different mortality and fertility behaviour between different archeological populations. While they cannot be used to measure migration movements, these indicators intrinsically convey population growth, either natural or migration-based. Using this property, Bocquet-Appel posited that an increase in the juvenility index could be the sign of higher mortality for young people, concomitant with natural population growth. Through this hypothesis, combined with an indicator synthesizing space and time, he highlighted a considerable change in the demographic regime corresponding with the sedentarization of Neolithic populations (see below).

Mortality by age and fertility (total number of children per woman)

The juvenility index, the ${}_{15}P_5$ indicator, and the mean age at death of adults (a_{20}) correlate strongly with several demographic parameters. But to understand the demographic behaviour of pre-industrial populations, it is preferable to base these correlations on specific observations rather than (overly) contemporary data less suitable for expressing the weight of the mortality of young children. Working on a set of 40, and later 45, mortality tables attributed to pre-industrial populations, Bocquet-Appel established the regressions[11] connecting these synthetic indicators to infant and juvenile mortality quotients and life expectancy at birth (Bocquet-Appel and Masset 1977), and to female fertility rates and completed fertility per woman[12], calculated on the basis of 30 to 40 initial tables (Bocquet-Appel 1979). Using the mean age at death of adults serves to establish a relationship with life expectancy at 20 and a number of predetermined growth-rate values (Bocquet-Appel and Masset 1996).

A few improvements have since been made. Calculations have been made to factor in random fluctuations generated by the small sample of buried populations, dispersion relative to the regression line shown by the 40 mortality tables used, and the possibility of an increase in the population (Masset and Parzysz 1985). For my part, I have reworked the mortality models for pre-industrial populations by substantially enlarging the sample of mortality tables that form the basis for the regressions and estimated number of parameters, which now target all ages. These new equations were subsequently applied to an archeo-anthropological series studied by Luc Buchet (Séguy *et al.* 2008; Séguy and Buchet 2011, 2013). The successive iteration method used to calculate the mean age at death of adults generated several inconsistencies, as pointed out by Konigsberg and Frankenberg (2002).

[10] This indicator represents the proportion of individuals dying between the age of 5 and 19 out of the total population of individuals dying after the age of 5.

[11] These statistical regressions are often referred to as 'estimators' (see Bocquet-Appel and Masset 1977).

[12] The average number of children per woman during her childbearing years (15–49). In demography, this longitudinal indicator is calculated for a set of women belonging to the same generation.

These issues were resolved by Caussinus and Courgeau (2010) through the development of a Bayesian inference method used to devise a bias-free estimate of the age structure of a buried adult population and deduce the population's mean age at death (Séguy and Buchet 2011, 2013; Caussinus *et al.* 2017; see also the chapter by Henri Caussinus in this publication).

The traces of a demographic transition in the Neolithic

Switching to a macro scale, Jean-Pierre Bocquet-Appel used these same indicators, and notably the ${}_{15}P_5$ indicator, which provides information on the proportion of young people in a population, to detect a major change in the demographic regime. To highlight that change, he posited that 1) the shift from a nomadic lifestyle (hunter-gatherers) to a sedentary lifestyle, linked to an economy based on agricultural and livestock farming, was accompanied by a considerable increase in fertility, as a differential fertility has been observed in the contemporary era between nomadic women (obliged to carry children up to the age of three or four) and sedentary women with much shorter intervals between births (two years on average); and 2) the increase in births was accompanied by an increase in the number of deaths of young children, the assumption being that the laws of mortality of pre-industrial populations also apply to prehistoric populations (see above).

Bocquet-Appel's research is based on a set of sites for which the localization and dating are, once again, combined to form a georeferenced variable. But as the process of neolithization spanned several millennia worldwide, the asynchronous nature of the phenomenon needed to be considered. To that end, Bocquet-Appel introduced a temporal variable no longer absolute but relative to the date at which the first traces of agriculture (and thus sedentarization) can be observed in a given region. Consequently, the relative date t_0 is not the same from one site to the next, making it possible to observe the demographic phenomenon shown by the ${}_{15}P_5$ indicator across the ecumene.

Several paleodemographers had previously attempted to measure the demographic and health consequences of the emergence of agriculture (for example, Jackes 1998), suggesting that it was preceded, or followed, by a sudden increase in the population. But none of them demonstrated this phenomenon across the five continents. The discovery of the signature of a Neolithic demographic transition (or agricultural demographic transition) in burial sites in the Near East, North America and China as well as those in the northern hemisphere (Bocquet-Appel 2002; Bocquet-Appel and Dubouloz 2003, 2004; Bocquet-Appel and Naji 2006; Bocquet-Appel and Bar-Yosef 2008) sealed the international reputation of Jean-Pierre Bocquet-Appel (though not among the archeology community, which was alarmed by the numerous observation and dating biases).

Symmetrically to the modern demographic transition, beginning in the 18th c. in France and still afoot worldwide, Bocquet-Appel identified an imbalance between fertility and mortality rates, leading to a sudden increase in the population, which he detected through the increase in the number of young people at necropoleis. The "demographic explosion" observed by Gordon Childe in the Neolithic lasted only until fertility and mortality levels balanced out and reduced population growth to extremely low levels (undoubtedly within the space of a few centuries).

Conclusion

Jean-Pierre Bocquet-Appel made considerable scientific contributions to paleodemography. Drawing on the advances made in several disciplines, he deftly took advantage of the slightest demographic information contained in archeological and osteological data to extricate paleodemography from a dead end.

The incessant exchanges between the various fields underpinning his work, including ethnology, archeology, bio-anthropology, ecology, demography, population genetics, geography, and statistics, lend it a peerless originality. From a micro standpoint, where only a few 'local' demographic parameters are concerned, as well as from a macro standpoint, where demographic theories are harnessed to explain planetary phenomena, Bocquet-Appel's work focused on reconstituting the demography of archeological populations, with numerous qualities that deserve to be underlined. He was unfailingly inventive when it came to making his sources speak – sources having only tenuous and indirect links with the demographic behaviour of the populations in question. He paid extremely close attention to the living contexts of prehistoric populations (notably sudden climatic cycles and competition for a territory and its resources) and historical populations (pre-industrial and preceding the epidemiological transition that saw the disappearance of infectious diseases and the emergence of chronic and degenerative diseases). He also took account of space and time in his analysis of the dynamic of demographic processes and their evolution, calculating a relative time to track the spatial distribution of a gradual change. Lastly, he explored numerous and diverse disciplines throughout his career, borrowing new methods from them to set realistic limits for his results. He was thus required to assess them in the light of historical, demographic, genetic, ecological, and ethnological knowledge and to test robustness via complex statistics and credibility via modelling (since any experimentation is impossible). Bocquet-Appel's mastery of such varied concepts, tools and methods was the product of extreme intellectual curiosity as well as a substantial amount of work. Through his considerable openness to others, he was able to take multiple collaborative initiatives, to which this publication pays testament.

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Paleodemography and statistics: a tale of uncertainty

Paléodémographie et statistique : une histoire d'incertitude

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Abstract: Jean-Pierre Bocquet-Appel pioneered statistical methods to estimate the age structure of adults in a skeletal population. He was at the forefront of all the major advances: from calculating the estimate's precision (he introduced the recent bootstrap technique into palaeodemography) to the estimate's adaptation to an age classe number greater than the number of indicator stages. This is the *iterage* algorithm based on an original idea that considers prior demographic knowledge of the estimated object. This kind of approach was later developed within a formal Bayesian framework. This context provides a good opportunity to review the evolution of the statistical methodology and offer some guidelines for their further improvement based on Jean-Pierre Bocquet-Appel's fruitful and stimulating work.

Keywords: accuracy, age structure, Bayesian statistics, Dirichlet distribution, estimation, frequentist statistics, maximum likelihood, paleodemography

Résumé : *Jean-Pierre Bocquet-Appel a eu un rôle pionnier dans l'avancement de la méthodologie statistique visant à estimer la structure par âge des adultes dans un site funéraire. On le trouve au premier rang dans toutes les avancées majeures depuis le calcul de la précision d'une estimation (il fait entrer pour cela en paléodémographie la technique alors récente du bootstrap), jusqu'à l'extension de l'estimation à un nombre de classes d'âge supérieur au nombre de stades de l'indicateur : c'est l'algorithme iterage fondé sur une idée originale prenant en compte les connaissances démographiques* a priori *sur l'objet estimé. C'est autour d'une idée semblable que d'autres méthodes statistiques, de nature plus formellement bayésiennes, ont ensuite été développées. A la lueur des travaux de Jean-Pierre Bocquet-Appel nous passons en revue l'évolution des méthodes d'estimation et donnons quelques pistes pour poursuivre leur amélioration en s'appuyant encore sur ses fécondes propositions.*

Mots clés : *distribution de Dirichlet, estimation, maximum de vraisemblance, paléodémographie, précision, statistique fréquentiste, statistique bayésienne, structure par âge*

Introduction

At the request of Daniel Courgeau and later Isabelle Séguy and Luc Buchet, I was drawn to a statistical question raised in paleodemography. I discovered a complex field of research, based on observations that are often few in number and of dubious reliability, often providing only indirect information on the issues studied: a challenge for the statistician (although far from the "big data" that is more fashionable today). I also discovered that some paleodemographers had highlighted the many challenges and paved the way, tackling some notorious errors, insisting on refraining from exaggerated enthusiasm, while looking for tools that would justify a more rational optimism. Jean-Pierre Bocquet-Appel is among them and has a prominent place in reflecting on the estimation of the adult age at death distribution based on aging biological data. The greatest concern for rigor is always present in Jean-Pierre's work, even if the results lead to some disappointments. In statistics, rigor means a reliable method (without methodological bias) and an indication of the estimates' precision level, considering the random nature of the observations. In addition, rigor requires maximizing efficiency by reducing this uncertainty inherent to all estimates as much as possible, without neglecting to broaden the scope of the method application. We will discuss Jean-Pierre Bocquet-Appel's contribution to the implementation of such a program. We will present some recent works, mainly extending his reflections, and suggest how to pursue it further. It should be emphasized that our ambition is not to make a complete survey of the literature or compare in detail the different schools' perspectives at any given stage of research development (see, for example, Hoppa and Vaupel 2002; Courgeau 2013). Nevertheless, we hope to cover the essential points around Jean-Pierre Bocquet-Appel's fundamental reflection and technical contributions.

We will arbitrarily begin this history at the beginning of the 1980s, with the following citation from Bocquet-Appel and Masset 1982 clearly outlining the preceding context:

> *"Historical demography […] succeeded in constructing a picture of life and death among the European peoples of three centuries ago […]. The contrast between the mortality pattern thus obtained and the one arising from our graveyard populations (some of them barely older) was striking. It challenged the quality of the conclusions propounded by the paleodemographers: were the populations they had been investigating actually as peculiar as they seemed to be? Or perhaps were the methods in use warped by some systematic error? The second hypothesis proved to be the right one. In fact, there are several causes of error, of a statistical rather than a biological nature. These causes of error were described in previous works (Masset 1971) […]. Let us only record the most awkward of them: the procedure which leads one to superimpose on the mortality structure of cemetery populations the structure of other populations entirely alien to them."*

There are two main points to be emphasized here: the French school was quick to denounce the severe errors that marred several studies, and the statistical method must be challenged primarily. In order to understand the issue, it is essential to state the problem clearly, i.e., the question raised and the "raw material" available to try to answer it. The latter is of two kinds: available observational data and the halo of prior knowledge on the subject. The question under consideration is the distribution of ages at death on a site, for which it will therefore be necessary to forge the tools to move reliably and efficiently from the available means to the expected answer.

Age estimation from biological data: formalization of the statistical problem

The data

We will present the problem for discrete (or discretized) data, i.e., defined by classes pertinent and often warranted in Jean-Pierre Bocquet-Appel's work. Most of the biological aging indicators are particularly difficult to evaluate in a very precise way, and we know how much chronological ages evade a valid estimation to the extent that it would be foolhardy to expect an estimation within a few months. Moreover, the case where several aging biological indicators are simultaneously available will remain outside our scope. The required statistical methods are undoubtedly different in nature, in particular, because the valuable reference data are not easy to acquire (unless we assume the indicators' independence, which is certainly inappropriate in most cases).

Let r be the number of classes (stages) used for the indicator and c the number of age classes. The available data are:

- the frequencies of the indicator's various stages for a given site, i.e., for a sample drawn from the population corresponding to that site; these frequencies will be noted: $m_1, m_2, \ldots, m_i, \ldots, m_r$ the sum of which m is the observed sample size,

- the frequencies observed in a reference table drawn from a population in which both the indicator stage and the age at death are known for each subject. We will write n_{ij} the number of subjects in the i^{th} skeletal stage and the j^{th} age class. Here again, we refer to frequencies observed in a sample (or rather in *c* samples, noting that it is always possible to compose a sample for each age class without modifying the various implemented methods; this is inherent in the methods themselves).

Only the statistical issue will be addressed here. Therefore, we will assume that the important preliminary question of the quality of the observations has been resolved. For example, the guarantee (to a reasonable degree) that the collected samples represent the corresponding populations, that the coding of the biological indicator is analogous for the reference data and the data collected at the site of study, among others. However, one point should be mentioned regarding the reference data. The data are presumed to have the same distribution of skeletal stages for a given age in the reference population and in the site studied (the hypothesis of biological invariance implies that the reference data belong to the preindustrial period). On the other hand, for the age distribution of a given skeletal stage to be the same in the reference population and the site under consideration, it would be necessary to have an equivalent of biological invariance by permuting the roles of skeletal stage and age, which obviously cannot be achieved. This is precisely because the age structure of the site under investigation is unknown and has nothing to do in theory with the age structure of the reference population. This is another way of expressing the essential point of Bocquet-Appel and Masset's quote from 1982 mentioned in the introduction, where the authors denounce "*the procedure which leads one to superimpose on the mortality structure of cemetery populations the structure of other populations entirely alien to them*."

In addition to the statistical data mentioned before, it is necessary to add the knowledge of the subject previously acquired by the researchers. All this prior knowledge can (and must) improve the statistical study.

Objective

The goals are:

a) the estimation of the age structure of the (adult) population corresponding to the burial site studied, i.e., the estimation of the probabilities $p_1, p_2, ..., p_j, ..., p_c$ of the *c* age classes in this population. However, the estimation of other parameters should also be considered, for example, estimating the average age at death for the adult individuals of this population.

b) the estimation of the level of uncertainty of the previous estimators.

c) the search for a statistical method (as general as possible) that reduces this uncertainty as much as possible.

Before discussing how the methods have evolved to achieve the three objectives above successively, some preliminary notations should be introduced.

We will denote $\pi_1, \pi_2, \ldots, \pi_i, ..., ..., \pi_r$ the probabilities of the various skeletal stages for the site under consideration. It is conventional for these parameters to be estimated by $m_1/m, m_2/m, \ldots, m_i/m, ..., m_r/m$, respectively. We will note $p_{1/j}, p_{2/j}, \ldots, p_{i/j}, ..., ..., p_{r/j}$ the probabilities that the skeletal stage is respectively stage 1, stage 2, ..., stage *r*, for a subject in age class j. These probabilities are naturally estimated by $n_{1j}/n_j, n_{2j}/n_j, ..., n_{rj}/n_j$, where $n_j = \sum_{i=1}^{i=r} n_{ij}$ is the sum of frequencies n_{ij} over all stages *i* (sample size of subjects of age *j* in the reference population).

From point estimation to uncertainty assessment

Bocquet-Appel and Masset 1996 emphasize the importance of going beyond the search for a simple point estimator (valid on average) of the age structure by providing an assessment of its precision. To do so, they achieved a major breakthrough by proposing the use of the bootstrap technique, which had only been introduced into the arsenal of statistical tools recently (Efron 1979). This is a resampling method that appropriately varies the reference data around the observed values to simulate sampling errors on these data and hence on the estimation results. Bocquet-Appel and Masset compared the accuracy of their method, introduced long ago by C. Masset (IPFP algorithm) for point estimation, and the IALK algorithm proposed by Konigsberg and Frankenberg 1992 (following the work of Kimura and Chikuni 1987) on a fisheries problem formally similar to the one faced by paleodemographers. The competing algorithms IPFP and IALK have ultimately been proven identical (Bocquet-Appel and Bacro 1997). The minor differences sometimes observed are only approximations related to the practical implementation of the calculations[1].

[1] An incidental remark on this subject to justify the formalization that may

Several years later, Konigsberg and Frankenberg 2002 insisted on the need for precision analysis, noting that the IALK algorithm provided a maximum likelihood estimate and proposed using the general properties of such estimators. However, these properties are only valid for sufficiently large samples, which is rarely the case in practice (for small samples, evaluating the precision by bootstrap would be more reliable).

However, we notice that, apart from this sample size issue, either previous approach is still insufficient for a valid evaluation of the uncertainty. The data are effectively only samples allowing to approximate respectively the parameters $\pi_1, \pi_2, \ldots, \pi_i, \ldots, \ldots, \pi_r$ (site data) and, for each j, the parameters $p_{1/j}, p_{2/j}, \ldots, p_{i/j}, \ldots, \ldots, p_{r/j}$ (reference data). Therefore, there are two sources of uncertainty in any estimate using these data. However, Bocquet-Appel and Masset 1996 "bootstrapped" only the reference data without considering the variability of the site frequencies. Instead, the IALK method assumes that the reference data estimate the corresponding conditional probabilities without error, only the uncertainty of the site sampling being considered.

Extension of estimation possibilities

The algorithm discussed above requires that the number r of stages is greater than or equal to the number c of age classes. This condition is easily understood with the IALK format based on a statistical model: if $r<c$ the number of estimated parameters is greater than the number of available data, then the model is said to be unidentifiable (which is sometimes translated in the literature to mean that the number of degrees of freedom is negative!).

One way to reduce the number of parameters is to introduce a demographic model for the p_j, thereby reducing the number of parameters from c-1 to the number of parameters of the model (e.g. 2 for the Gompertz model, 3 for the Gompertz-Makeham model). Specifically, with the Gompertz model and the minimum age of a years, the probability of the age class $[b,c]$ years will be

$$\lambda exp(\rho a)[exp(-\lambda exp(\rho b)) - exp(-\lambda exp(\rho c))]$$

depending on the two parameters λ and ρ alone regardless of the number of age classes. Several papers mention this possibility in the referenced volume by Hoppa and Vaupel 2002. Konigsberg and Herrmann 2002 proceeded to implement it. We include this option in Appendix 3 as part of a brief comparative study.

With a similar objective, Jean-Pierre Bocquet-Appel introduces an innovative approach at this stage (Bocquet-Appel and Bacro 2008). Rather than using a model as in classical statistics, the authors seek an estimate in a family of mortality laws that they produce from prior knowledge derived from demographic data. The authors refer to this method as *iterage*, which can be described in the following way.

The parameters of the model are connected by the equation:

$$\sum_{j=1}^{j=c} p_{i/j}\, p_j = \pi_i \qquad \text{for } i = 1,\ldots,r \qquad (1)$$

If $p_{i/j}$ and π_i are replaced by their natural estimates, $n_{i/j.}/n_j$ and m_i/m, respectively, provided by the reference and site data of interest, the system of equations (1) becomes a multiple linear regression from which to estimate the parameters p_j. However, for $c>r$, there are too many unknown parameters, and the system has an infinity of solutions resulting in an ineffective method (this is the problem already mentioned above). Even if $c<r$, the usual least-squares estimation often gives odd or even aberrant results such as a negative probability estimate. Obviously, we can proceed by least squares under the constraints necessary to produce an estimate in the range of possible values for the probabilities p_j; however, we can also produce estimates on the range boundary, effectively a zero probability for some age groups, which is clearly unsatisfactory. This statistical method could probably be further improved on a theoretical basis. However, the subtle answer is to say: "the p_j cannot be arbitrary since it is a mortality law; consequently, we will seek the mortality law which best solves the system (1) (for example, using the least-squares method) among a family of potential candidate laws." Moreover, since the reference data are subject to uncertainty, they can be bootstrapped around the observed values, resulting in as many estimated values as bootstrap repetitions. The mean of these values will provide a point estimate. In contrast, their distribution around this value will evaluate the uncertainty, measured by a standard deviation or any other dispersion index. The authors propose two families of "candidate" mortality laws, one for attrition and one for catastrophe.

seem excessive in our paragraph 2. Konigsberg and Frankenberg 1992 criticize the proposal behind the IPFP algorithm for discarding some of the data (*the main problem with selecting a reference sample with a uniform age distribution is that this requires discarding data, which certainly cannot be an efficient way to proceed*). Bocquet-Appel and Masset 1996 object to discarding data using a uniform distribution argument that is perfectly valid in substance but not entirely in form. A more appropriate argument would have been to say that some data were indeed discarded (the distribution of ages in the reference matrix), but that these were precisely the data that should be discarded! Moreover, this argument becomes irrelevant once we verify that IPFP and IALK lead to the same result.

This method is effective in many circumstances, but two points need to be closely revisited:

- The two suggested mortality law families seem natural, but how to choose between them in a specific case? Should we sometimes combine them? Should we build others?

- For uncertainty calculation it is insufficient to bootstrap the reference data when the site data is itself a sample. Thus, the π_i estimate is also subject to uncertainty. Besides, the assessment of uncertainty presents a slightly more delicate challenge: the family of mortality laws considered is bounded, i.e., "corseted" between "extreme" laws; if the (unknown) law we are looking for is outside this family (more accurately outside the laws that can be derived by combining the members of this family), the solution found for each bootstrap replication will be nearest to (but possibly "distant" from) the same extreme value of the family or some of these extreme values, so that the dispersion of these solutions will be small. Therefore, the point estimate (average of these solutions) will be necessarily inaccurate with the illusion of minimal uncertainty (see Appendix 3).

More recent work

The *iterage* method emphasizes the value of invoking general knowledge about the nature of the estimated parameters, particularly that p_j represents a mortality law. In practice, some parameters are likely to be observed more often than others. For a statistician, this implies the use of a Bayesian method. The methods of classical statistics (or frequentist) consider that the unknown parameter (in fact a vector of several real parameters, in our case, the p_j and the $p_{i/j}$) is fixed in a given space (the parametric space) and that the estimate is a value of this space supposed to approximate it. Specifying a model implies reducing the dimension of the parametric space (for example, by taking a Gompertz mortality model in the framework of the IALK method). In contrast, Bayesian statistics assigns a probability distribution to this parameter on the parametric space to weigh the different possibilities considering the general knowledge on the subject and independently of the observed data. This is why this distribution is called a *prior law*. The observed data indicate the specificity, on the one hand, of the joint distribution of the skeletal index and the age (reference data), on the other hand, of the site of interest (site data). They prompt to revise the vector distribution of the parameters accordingly: this distribution, conditional to the data, is called the *posterior law* of the parameters of interest[2].

In an attempt to improve the previous methods, we have proposed and implemented a Bayesian estimation method. An initial version of the method is outlined in Caussinus and Courgeau 2010 and Séguy and Buchet (chapter 13, 2013). This method is further developed and applied to new examples in Séguy *et al.* 2013. This article demonstrates that the number of age classes can be relatively high without damage (on the contrary): we recommend 13 age classes (one class of 18 to 24 years old and one class of over 80 framing 11 five-year classes). An improvement regarding the prior distribution of the p_j is outlined in Caussinus *et al.* 2017 and applied to new data in Buchet *et al.* 2017.

We refer to the articles mentioned above for details of the method's implementation. We will simply emphasize below the two fundamental aspects: the choice of prior laws and the nature of the results generated.

Prior Laws

With the reference data, the samples we are working on are the *c* samples that provide each age class the frequency of skeletal stages. Their distribution is assumed to be multinomial with parameters $p_{1/j}, ..., p_{i/j}, ..., p_{r/j}$ for the j^{th} one. There is no information on these parameters other than provided by the reference data. Therefore, the prior law must be "neutral", which implies adopting a uniform law, a special case of the so-called Dirichlet laws (see Séguy and Buchet 2013, chapter 13, box 13.1) where all parameters are equal to 1.

The situation is more complex for the prior distribution of the parameters $p_1, \ldots, p_j, ..., p_c$. A first approach can be to transpose the *iterage* principle in Bayesian terms and to consider a prior uniform distribution on a family of mortality laws which could be the one constructed by Bocquet-Appel and Bacro 2008 or the "real" laws

[2] In the literature, several paleo-demographers refer to various methods as Bayesian because they use Bayes' formula in which the parameters p_j are called prior probabilities. However, it is important to recognize that these methods are not Bayesian in the strict sense described in this paragraph, and to be aware of the double meaning and double use of the term "prior" since, in the new framework, the "prior probabilities" p_j will be associated (like any other parameter) with a "prior law". Moreover, the *iterage* method can be considered as intermediate between the classical approach and the Bayesian approach, to some degree.

compiled by Séguy and Buchet 2013. This choice was not the most convincing one (see the referenced articles) but would certainly deserve to be considered again.

A second approach is to start from a more theoretical perspective which leads to select a Dirichlet law since we are dealing (as above) with *c* positive numbers summing to 1. Since the p_j represent one mortality law among all possible laws, the selected Dirichlet law will be centered on a mean mortality law. To do so, we have opted for the preindustrial standard (Séguy and Buchet 2013).

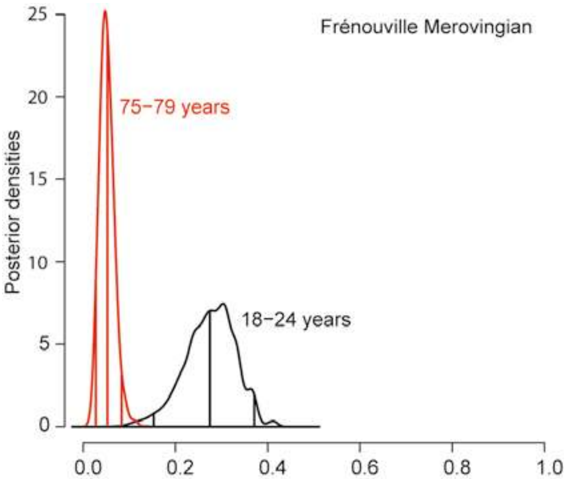
Subsequently, we sought to account for the correlation characteristics specific to all mortality laws. Irrespective of how these are considered, the variations in p_j from one class to another are relatively "smooth", which led to the choice of a "smoothed Dirichlet distribution" as the prior law (constructed by a moving average on a Dirichlet distribution, always keeping the preindustrial standard as the mean: see Caussinus *et al.* 2017. This latter prior law will be used in the following examples.

Nature of the results produced - examples.

The calculations are performed by Monte-Carlo simulation. The desired estimates are derived from the posterior probability law of the parameters of interest. The mean (or median) of this law can be considered as a point estimate (central), its density also providing the degree of uncertainty; this can be quantified by its standard deviation or (rather) by quantiles: for example, the interval between the quantiles 0.025 and 0.975 of the posterior law is an interval, known as the 95% credibility interval, which plays the role of the 95% confidence interval in classical statistics. This procedure can be implemented for all parameters of interest, such as the various p_j, which is the first goal of the analysis, and for any function of these parameters. For example:

- the survival probabilities $\sum_{j=s}^{j=c} p_j$ for *s*= *2, ..., c*
- the mean age at death (of a subject who has reached adulthood) $\sum_{j=1}^{j=c} a_i p_j$ (where a_i is the center of the j^{th} age class), an approximate calculation that requires classes of sufficiently small amplitude,
- individual conditional probabilities $p_j p_{i|j} / \sum_{h=1}^{c} p_h p_{i|h}$ (probability that an individual of stage *i* is in age class *j*).

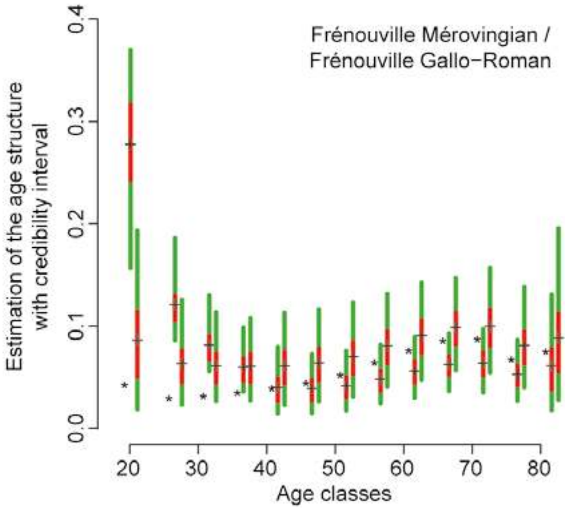
The following figures show some results with various representational methods on the Frénouville, Merovingian period data (for a presentation of this site data and the reference data used, see Buchet *et al.* 2017). The evaluation of aging is done using the cranial suture synostosis adjusted to five stages. Thirteen age classes are considered, namely 11 five-year classes between 25 and 80 years of age framed by one 18-24-year-old class and one over 80 (see Séguy *et al.* 2013 for a justification of this division).



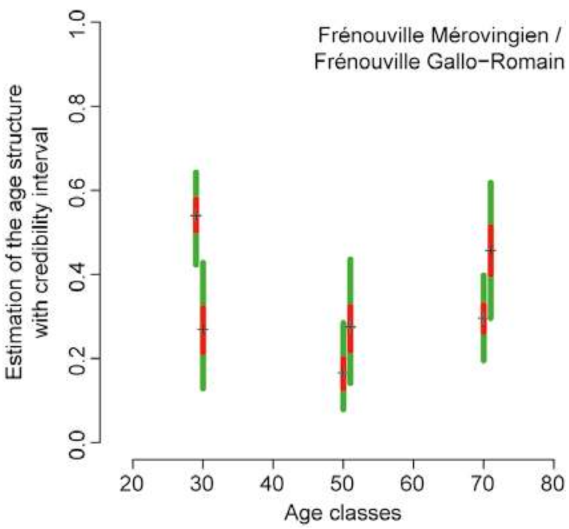
1. Posterior densities of parameters p_1 (black) and p_{12} (red) for the Frénouville site, Merovingian period.

Figure 1 shows the posterior densities of the parameters p_1 (probability of the 18-24 age group) and p_{12} (probability of the 75-79 age group). The central values (point estimates by the posterior average) are respectively 0.27 and 0.06 (indicated by the central vertical line for each density); the tighter pattern of the density suggests that the precision is significantly higher for the second probability than for the first. The quantiles of the posterior laws are a useful summary: the lateral lines specify the 2.5% and 97.5% quantiles, and therefore the interval between them is a 95% credibility interval.

Figure 2 shows the point estimates (+ sign) for each age class with 95% (green between the 2.5% and 97.5% quantiles) and 50% (red between the 25% and 75% quantiles) credibility intervals. The graph provides a synthetic view of the potential differences between the Gallo-Roman and Merovingian periods and compares the preindustrial standard. The Merovingian period shows a clear difference with this standard (over-mortality of the first three classes), while the Gallo-Roman period is relatively similar. However, it is difficult to draw a firm conclusion on a potential difference between the two periods because of the overlap in credibility intervals. This difference is clearer when the age classes are grouped (Figure 3) and will be quite clear through the mean age at death.

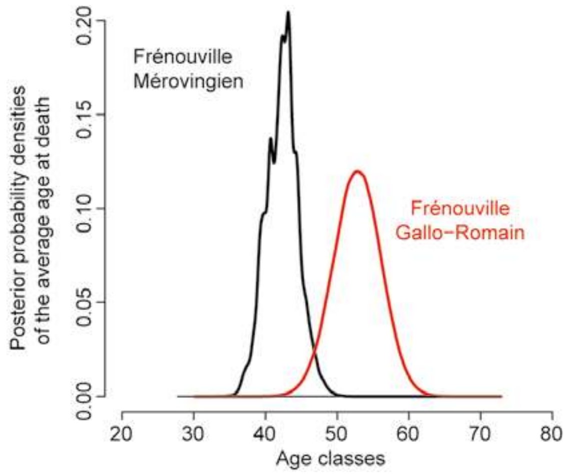


2. Frénouville site, point estimate (+) of the 13 age class probabilities for the Merovingian and Gallo-Roman periods (shifted to the right), with credibility intervals at 50% (red segments) and 95% (green segments). Stars indicate the preindustrial standard probabilities.



3. Frénouville site, point estimate (+) of the three age classes 18-39 years, 40-59 years, and over or equal to 60 years for the Merovingian and Gallo-Roman periods (shifted to the right), with credibility intervals at 50% (red segments) and 95% (green segments)

Figure 4 illustrates the posterior densities of the average age at death for Merovingian Frénouville (black) and Gallo-Roman Frénouville (red). However, calculating a mean age from an age class distribution is approximative, acceptable only for a sufficiently fine subdivision, as seems to be the case with the five-year classes. Moreover, the approximation due to discretization is the same for the two sites and will not affect their comparison. The tighter density for the Merovingian period corresponds to a larger sample size that allows for greater precision. Moreover, the two distributions displayed barely overlap, so that the average age at death is likely to be lower in the Merovingian period than in the Gallo-Roman period. The posterior probability of this event can be estimated from the densities by period and from the two site samples' independence: the probability is estimated at 0.997, which is very close to 1, leading to the conclusion that the two mortality laws are different with great confidence.



4. Frénouville site, posterior probability densities of the average age at death for the Merovingian period (black) and the Gallo-Roman period (red).

Other parameter functions are considered in Appendices 1 and 2.

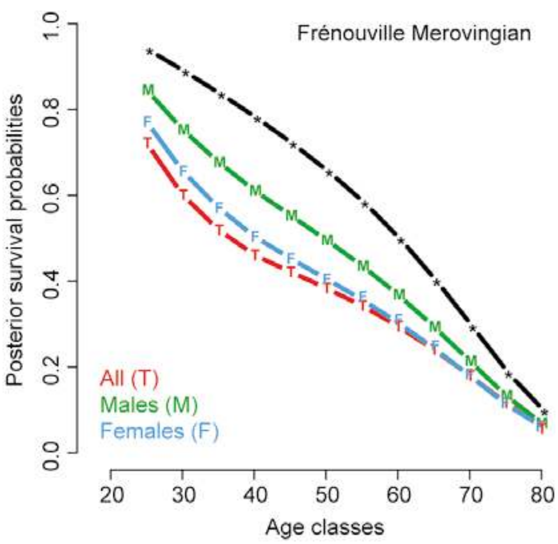
Conclusion and perspectives

About thirty years ago, Claude Masset and Jean-Pierre Bocquet-Appel finally convinced paleodemographers that their perspectives on the age estimation based on an aging indicator were valid.

The fundamental developments on this question, such as evaluating the estimates' precision, expanding the methods to broader situations, and improving their efficiency, could begin. Jean-Pierre Bocquet-Appel was present at each step of this process. With the *iterage* algorithm, Jean-Pierre Bocquet-Appel provided the transition between the frequentist statistical methods exclusively used so far and the Bayesian methods promoted since. We have discussed (see appendix 3, in particular) some challenges of the *iterage* algorithm, such as the choice of "candidate" set mortality laws and boundary problems linked to the set necessarily abrupt edges.

The prior distribution introduced in the Bayesian methods does not present these edge problems, but does it sufficiently consider all the aspects of a mortality law? In competition with *iterage*, Bayesian methods sometimes seem to have lower accuracy. Is this detrimental or simply realistic? In other words, is the higher accuracy illusory or effective? Clearly, both cases are possible, but we never know in which situation we operate. This suggests that the Bayesian methods' prior law could be improved in light of Jean-Pierre Bocquet-Appel's proposals. Although some attempts have been made by constructing a prior law on a family of mortality laws in a simple way (see, for example, Caussinus and Courgeau 2010, 2013; Caussinus *et al.* 2017), all still have drawbacks, and other avenues should be explored. For instance, the proposed Dirichlet law smoothing also follows the same logic but remains very heuristic. How could it be better systematized? How could it benefit from considering lists of mortality laws?

Appendix 1. Note on the results' interpretation from a Bayesian analysis



A1. Point estimates of posterior survival probabilities for the Frénouville site, Merovingian period: males (M), females (F), and sexes combined (T). Stars indicate survival probabilities of the preindustrial standard for all sexes.

The principle of Bayesian statistics is to investigate how the observations require a revision of the prior distribution. Therefore, this prior law plays a pivotal role in interpreting the results of any statistical analysis. We can illustrate this with an example. Figure A1 shows the point estimate of survival probabilities for men, women, and both sexes combined at the Frénouville site (Merovingian period). The survival curve corresponding to the preindustrial standard has been added. We might be surprised that the survival curve for both sexes combined is not just an average of the survivals by sex. However, we must remember that these estimates are always derived by adjusting the prior law according to the observations. As the prior law is centered on the preindustrial standard, if the population age structure is far from the standard, the prior law will be adjusted. However, this adjustment will be increasingly important as the data become more informative, i.e., more abundant. Moreover, the sex-specific sample sizes (at best about half of the total, in this case, 61 and 74 against 200) result in a significantly lower level of information than the total sample, which explains the paradox[3]. Additionally, the figure indicates a lower estimated survival for women, but the sex-specific credibility intervals (not shown) overlap substantially, suggesting that the apparent difference is not necessarily significant. A synthetic parameter such as the mean age at death could be more discriminating. We find a point estimate of 47.85 years for men and 43.72 years for women. The posterior probability that this age is higher for men is 0.812. This value is quite high but still below the levels usually required for a definite conclusion, especially if we use the traditional "level" of the significance test paradigm in the present framework. Nevertheless, from an elementary classical statistic perspective, we observe that a test of homogeneity (chi-square) between the frequencies of the stages in men and women indicates a probability of excess (p-value) of 0.09, not significant at the usual levels. However, the test suggests a strong tendency towards a marked difference between the sexes (although without necessarily explaining why). Somehow, this echoes a point of view that reflects Jean Pierre Bocquet-Appel's (and Claude Masset's) thinking: in paleodemography, the nature and parsimony of the information that can be gathered must lead to the greatest caution and, while it is advisable to seek out the most suitable methods, one must not "believe in miracles".

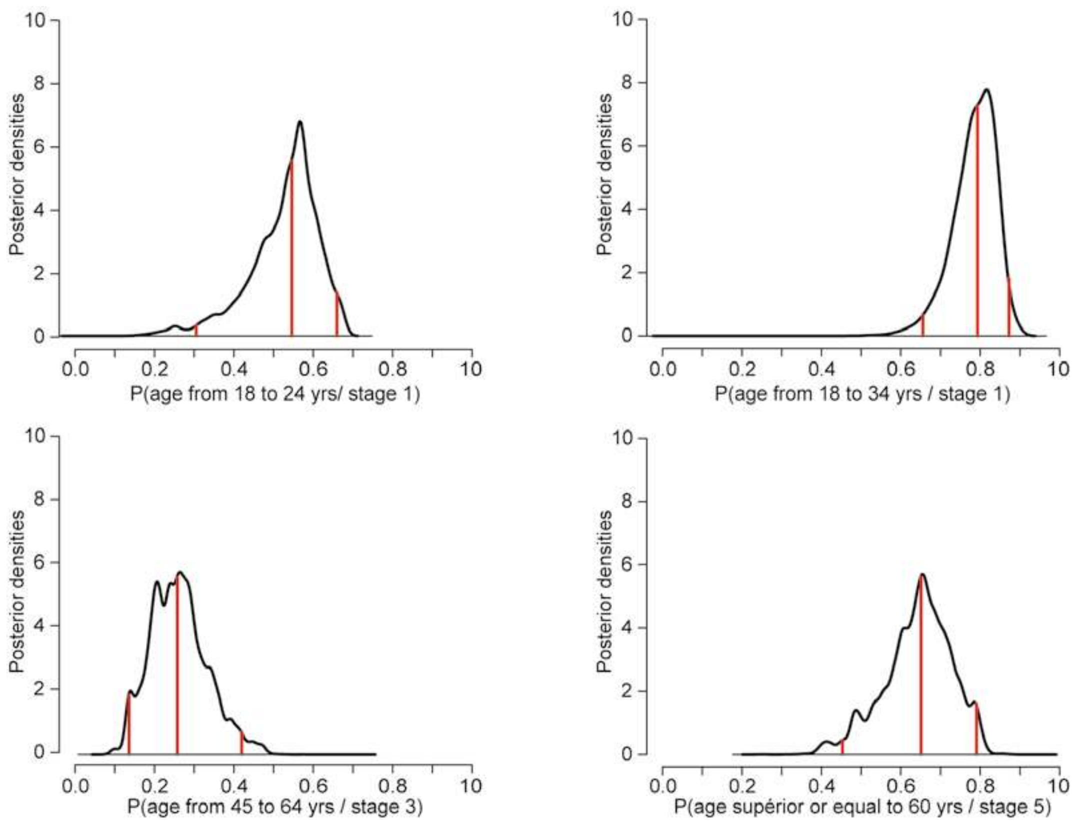
[3] Although the paradigms are different, we can compare the present issue with the hypothesis testing in frequentist statistics with due caution. The null hypothesis is the basic benchmark and the likelihood of accepting a given alternative hypothesis is increased (the power of the test is higher) the larger the sample size.

Appendix 2. Individual age

Although it may have been tempting to try estimating the age at death of each individual at a site from its skeletal stage and properly aggregate these results to estimate the age structure of the site, this approach was long ago proven to be ineffective. Paleodemographers have therefore considered estimating the age structure directly. However, as mentioned previously, the probability that an individual of stage *i* is of age class *j* is a function of the parameters $p_{i/j}$ and p_j that can be estimated within the framework of the procedure in paragraph 5. This is easily extended to estimate the probability that an individual of stage *i* is of an age falling into any of several classes. To illustrate this, Figure A2 displays the posterior densities of four of these parameters for the Frénouville site (Merovingian period), and Table A2 gives the point estimates and the 95% credibility intervals. First, we observe that the probability of a single age group can be relatively small, even if it is an "extreme" age associated with an "extreme" stage. The probability is obviously higher for a larger age group, although, for a fairly large "central" age group and a "central" stage, the probability turns out to be hopelessly small. Most importantly, the 95% credibility intervals are wide (their length is between 0.228 and 0.355), indicating very imprecise estimates. This result reflects the difficulty of estimating this type of conditional probability correctly. Nevertheless, if it is helpful to estimate conditional probabilities in some cases, it can be done but with great precaution... and the risk of disappointing results.

Estimated probability	Point estimate	95% credibility interval
P (age 18-24 years / stage 1)	0.544	0.302 - 0.657
P (age 18-34 years/ stage 1)	0.795	0.657 - 0.885
P (age between 45 and 64 years / stage 3)	0.257	0.42 - 0.411
P (age greater than or equal to 60 years / stage 5)	0.651	0.467 - 0.783

Table A2. Frénouville site, Merovingian period, point estimate of some conditional probabilities (probability that a subject is in a given age class, or the union of various age classes, knowing its skeletal stage) with the corresponding 95% credibility intervals.



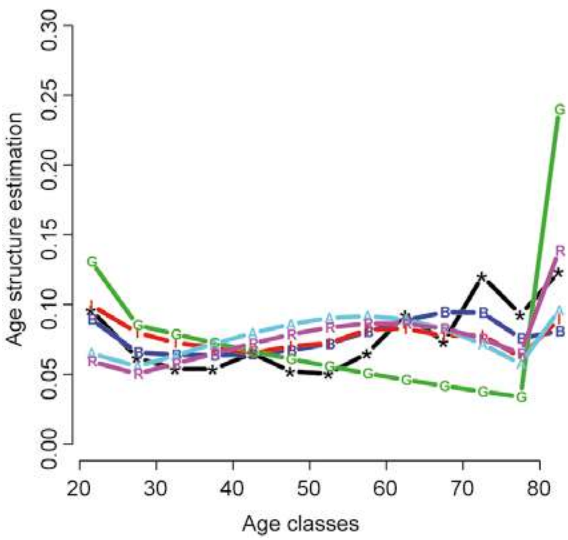
A2. Frénouville site, Merovingian period, posterior density of some conditional probabilities with .025 and .975 quantiles.

Appendix 3. Comparative elements of various approaches.

We have encountered fundamentally different statistical methods in reviewing the methods' evolution for estimating an adult age structure. At the outset, we found the equivalent approaches of ITFP and "basic" IALK. The latter can be extended to any number of age classes by considering a demographic model. The method is based on classical frequentist statistics. The model allows to reduce the number of parameters, i.e., the dimension of the parametric space, and the estimation is done using maximum likelihood. Instead, we have presented a Bayesian approach in which the probabilization of the parametric space replaces the drastic reduction of the frequentist method. The *iterage* method of Bocquet-Appel and Bacro 2008 is intermediate (in time and essence) between the two previous ones. We will compare these three methods on an example where register data exist. The Antibes site (19th c.) is presented in Séguy *et al.* 2013. The biological indicator is the cranial suture synostosis, for which five stages have been selected. We divided the ages into eleven five-year classes, framed by the first class from 18 to 24 years of age and the last class over 80. Since the prior distributions provided by Jean-Pierre Bocquet-Appel were not adapted to this age distribution, we opted instead for the 167 mortality tables compiled by Séguy and Buchet 2013 (we can check their resemblance to the "attri" distributions of Bocquet-Appel). Furthermore, we fitted a Gompertz model on the results provided by methods that do not explicitly use it (nonlinear least-squares fitting). Figure A3.1 and Table A3 reveal that *iterage* and the Bayesian method perform very closely and significantly better than the frequentist method, including when searching for the model that the latter implies. The point here is not to set up an efficiency contest on a singular test that may be biased (for that, a large comparison would have to be organized, probably by simulation, which is outside our scope). However, the consequent results raise interesting questions that deserve to be explored in greater depth. A Gompertz model fits the register data quite well and still approximates the data well when fitted to Bayesian estimates. The same applies when the model is fitted to *iterage* estimates. So why doesn't the maximum likelihood method based on this model provide a good estimate? Is this an intrinsic benefit of the Bayesian method or a similar method, and if so, why? Could it be related to the similarity of the age structure of the site to the standard structure? (We checked that the choice of the model is not the issue: rather, the Gompertz model is the most appropriate here).

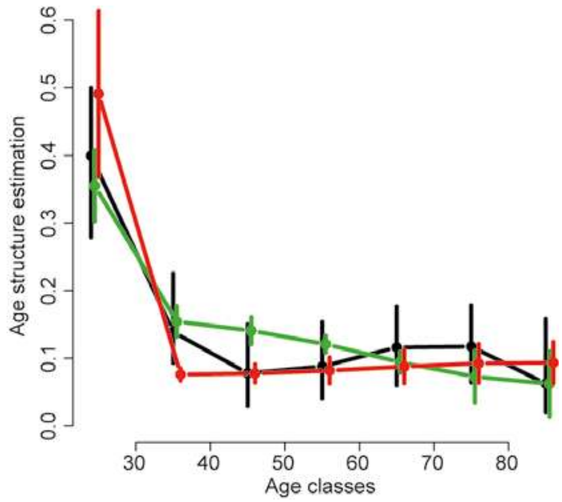
Deviation estimation-registers	maximum	quadratic	quad. relative
Bayes	0.043	0.004	0.052
iterage	0.043	0.006	0.072
IALK-Gompertz	0.111	0.028	0.269
Gompertz adjusted on Bayes	0.049	0.010	0.127
Gompertz adjusted to registers	0.045	0.007	0.090

Table A3. Deviation between estimated probabilities and the registers data measured by the maximum deviation (in absolute value) over the thirteen classes, the squared deviation (sum of squares of deviations), the relative squared deviation (sum of squares weighted by the value of the registers).



A3.1. Structure estimation using three statistical methods: Bayesian method from paragraph 5 (B - dark blue), iterage (I - red), IALK with Gompertz model (G - green). Also, we show the probabilities extracted from the registers (* - black), the Gompertz model fitted to the estimates by the Bayesian method (A - light blue), the Gompertz model fitted to the register data (R - pink).

To examine some aspects of the comparative behavior of the *iterage* algorithm and the Bayesian method, we return to the example of Frénouville (Merovingian period). The age is divided into seven classes: five decennial classes from 30 to 80 years old framed by a "young adults" class and an "over 80" class, to use the two sets of "candidate"mortality laws provided by Jean-Pierre Bocquet-Appel: Attri for attritional and Cata for catastrophic. The *iterage* method is implemented with the modification suggested by our second remark at the end of paragraph 4: implementing a double bootstrap to account for sampling uncertainties on both the reference and the site data. The Bayesian method is applied with 13 classes which are then grouped into seven classes according to the present breakdown. Figure A3(2) shows the estimate of the age structure using the three methods discussed, each time with the estimated precision: 95% confidence interval (approximated by the rule of plus or minus two times the estimated standard deviation) for *iterage*, 95% credibility interval for the Bayesian method using quantile estimation. These intervals are globally longer with the Bayesian method, giving an intermediate point estimate between the two *iterage* estimates. The latter result might be expected to derive from the choice of candidate laws for *iterage*. However, if we apply *iterage* by concatenating the two sets of candidate laws, we arrive at roughly the same results as with the Cata set alone. Hence, the site seems to correspond to this situation (which incidentally raises the question of the prior choice between both Attri and Cata): perhaps it would be better to simply put them together instead. However, the estimation of the precision seems to raise the most interesting questions. Disregarding the fact that confidence intervals and credibility intervals are not quite equivalent, the overall shorter *iterage* intervals seem to argue for this method. However, by examining the set of candidate mortality laws, it appears that for solutions of system (1) with the various bootstrap replicates, the algorithm leads to the choice of laws close to the extremes, for example, in the 30-39 age group, a low extreme with Cata and a high extreme with Attri. However, we do not know which "true" mortality law is being estimated. If the law is at the center of the set of candidate laws, it will be accurately estimated, and the low dispersion warranted. If the law is outside this set, it will necessarily be poorly estimated. All the bootstrap replications will provide a candidate law as close as possible to this law outside their family. Thus, the laws will generally be close to each other, leading to a low variance and thus to the illusion of high precision.



A3.2. Estimation of the age structure for the Frénouville site, Merovingian period (circles), with estimated 95% confidence or credibility intervals (vertical segments): Bayesian method (black), iterage with Attri candidates (green), iterage with Cata candidates (red).

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2. Spatial demography: a new approach to modeling human expansion

Is biodemography a science?
La biodémographie est-elle une science ?

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Abstract: In 1996, the publication of *Spatial analysis of biodemographic data* introduced a new scientific approach to the French readers. This approach quickly developed in the following years, particularly among U.S. researchers. How can we unite these two different sciences? The more negative aspect of this union appeared with the introduction of behaviour genetics at the end of the 20th c., amplified during the following twenty years. Behaviour genetics is based on eugenist ideas and hypotheses formulated by Fisher in 1918, which are no longer valid today but are supported by a powerful current of thought linking genes and behaviour. Among the accomplishments, a more positive aspect of this union resides in the study of mortality and fertility. These two phenomena are at the heart of demographic and biological studies. If properly implemented, the combination of these two approaches could lead to a deeper understanding. However, migration, a purely social phenomenon, is beyond the scope of this analysis. The conclusion extends the reflection to other attempts to unify approaches by focusing on their foundations.

Keywords: biodemography, biology, demography, modelling, research program, axioms, fertility, mortality, migration, behaviour genetics

Résumé : *La parution en 1996 de l'ouvrage sur l'*Analyse spatiale de données biodémographiques*, ouvrait au lecteur français une nouvelle approche scientifique. Elle s'est rapidement développée ensuite, en particulier auprès d'auteurs américains. En quoi l'union de ces deux sciences est-elle possible ? L'aspect le plus négatif de cette union s'est produit avec l'introduction de la génétique du comportement à la fin du* XX*e s., qui s'est amplifié au cours des vingt années suivantes. Elle est basée sur des idées eugénistes et des hypothèses posées par Fischer en 1918, qui n'ont plus de valeur de nos jours mais sont soutenues par un courant de pensée très puissant reliant gènes et comportements. Parmi les succès, un aspect plus positif de cette union se trouve dans l'étude de la mortalité et de la fécondité. Ces deux phénomènes sont au cœur des études démographiques et biologiques. La réunion de ces deux approches permettrait de conduire, si elle est bien menée, à leur approfondissement. Y échappe cependant la migration, phénomène purement social. La conclusion étend la réflexion aux autres essais de réunion d'approches, en s'intéressant à leurs fondations.*

Mots clés : *biodémographie, biologie, démographie, modélisation, programme de recherche, axiomes, fécondité, mortalité, migration, génétique du comportement*

Science without conscience is but the ruin of the soul[1]
(Pantagruel, Rabelais)

Introduction

The publication of the book edited by Jean-Pierre Bocquet-Appel, Daniel Courgeau, and Denise Pumain on the *Spatial analysis of biodemographic data* in 1996 presented the use of biological data in demography (fig. 1). They followed the example of Louis Henry in his family formation models published in 1972, who included biological characteristics in his models, such as the menstrual cycle or the post-partum interval during which a new pregnancy is impossible (non-susceptible period). The focus in our book was primarily on the spatial analysis of these data using multilevel models, analysing the spatial traces and patterns that emerge because these data are not homogeneous across space, and on the genesis of observable structures in geographic space.

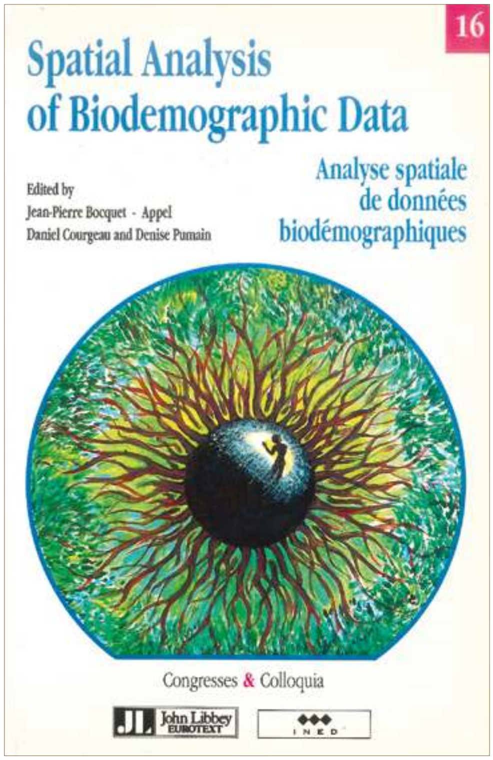
In the following years, several books were published, such as: *Between Zeus and the salmon: the biodemography of longevity* in 1997, edited by Kenneth Wachter and Caleb Finch (fig. 2); *Genetic influences on human fertility and sexuality* in 2000, edited by Joseph Rodgers, David Rowe, and Warren Miller; *Offspring: human fertility behaviour in biodemographic perspective* in 2003, edited by Kenneth Wachter and Rodolfo Bulatao. Subsequently, this biodemographic literature spread very rapidly, especially in the United States.

Consequently, this research's goal expanded. The purpose was no longer to use biological data in demography but to develop a new scientific approach, biodemography, which would synthesise the two sciences. Thus, Carey, in *Biodemography: research prospects and directions*, wrote in 2008 (p. 1754):

> *"The nascent field is becoming a force for unifying biology and demography…"*

However, Rabelais' quotation: "*Science without conscience is but the ruin of the soul*" clearly indicates that this unification requires a conscience. Therefore, we will try to see if this synthesis attempt is rigorous enough to lead to a genuine science.

[1] *Science sans conscience n'est que ruine de l'âme.*



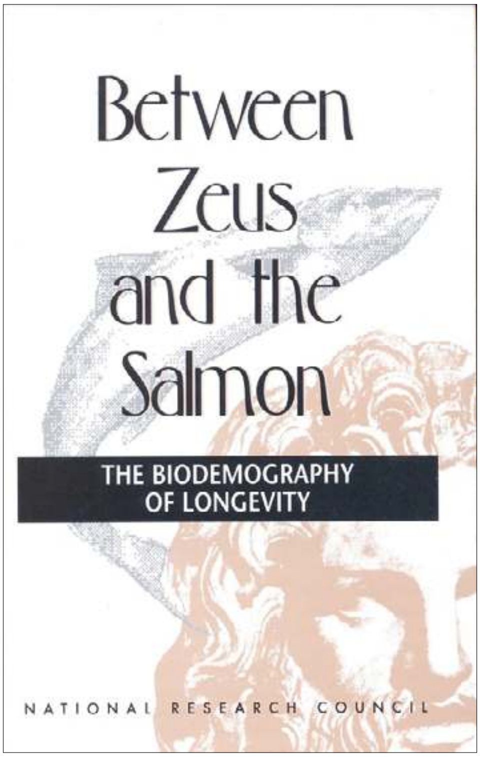
1. Book Cover: *Spatial analysis of biodemographic data*.

To that end, we will first specify the origin and purpose of the two components of biodemography and the changes in definition that they may have encountered over time.

Demography was the first discipline to be created in 1662 with the work of John Graunt, who estimated the population of London using the weekly *Bills of mortality*. William Petty (1690) coined the discipline *Political arithmetic*, following the principles of Francis Bacon (1620) for an inductive approach to science:

> *"There are and can be only two ways of searching into and discovering truth. The one flies from the senses and particulars to the most general axioms, and from these principles, the truth of which it takes for settled and immovable, proceeds to judgement and to the discovery of middle axioms. And this way is now in fashion. The other derives from the senses and particulars, rising by a gradual and unbroken ascent, so that it arrives at the most general axioms at last. This is the true way, but as yet untried."*

Graunt successfully attempted to use this second path by starting from the experience provided by the *Bills of mortality*. Moreover, this designation clearly indicates the growing interest that political power can have for the population.



2. Book Cover: *Between Zeus and the salmon: the biodemography of longevity*.

The name "demography" appeared later in 1855 with Achille Guillard's work *Eléments de statistique humaine ou démographie*, but its objective remains the same. In 1981 Louis Henry, in the multilingual demographic dictionary (p. 10), defined demography as follows:

> *"…the scientific study of human populations primarily with respect to their size, their structure and their development; it takes into account the quantitative aspects of their general characteristics."*[2]

In 2002, the philosopher Robert Franck started a profound reflection in "*The explanatory power of models"* and proposed a mechanistic approach in social sciences. We cannot present this approach in detail here, but the summary he presents (p. 295) will be sufficient for our purposes:

> *"(1) Beginning with the systematic observation of certain properties of a given social system, (2) we infer the formal (conceptual) structure which is implied by those properties. (3) This formal structure, in turn, guides our study of the social mechanism which generates the observed properties. (4) The mechanism, once identified, either confirms the advanced formal structure, or indicates that we need to revise it."*

In this context, the formal object studied by demography is the combination of *fertility, mortality, migration,* and the general structure to ascertain is the principle of all population growth or decline (Courgeau and Franck 2007: p. 40). This research is underway and will be discussed in the conclusion of this article.

Biology appeared later, at the beginning of the 19th c., with the works of Treviranus and Lamarck. Treviranus published six volumes of *Biologie oder die philosophie der lebenden natur*, between 1802 and 1822. He defined the object of this new science at the beginning of his 1802 work (Vol. I, p. 4) as follows:

> *"The objects of our investigations will be the different forms and manifestations of life, the conditions and laws under which this phenomenon takes place and the causes by which it is determined. The science which deals with these objects will be designated by us with the name of biology or science of life."*[3]

Similarly, Lamarck writes in 1802 (p. 112):

> *"All that is generally common to plants and animals, as well as all the faculties which are specific to each of these beings without exception, must constitute the unique and vast object of a particular science which is not yet founded, which does not even have a name, and to which I will give the name of biology."*[4]

These two definitions converge perfectly with the one given by the *Littré* dictionary in 1889:

> *"Science which has for subject the organised beings and which goal is to seek to know the laws of the acts which these beings manifest, by the knowledge of the organisation laws."*[5]

However, the evolution of biology, with the introduction of genetics at the beginning of the 20th c., the study of genes, molecular biology, genome sequencing, and

[2] *« …une science ayant pour objet l'étude des populations humaines en traitant de leur dimension, de leur structure, de leur évolution et de leurs caractères généraux envisagés principalement d'un point de vue quantitatif. »*

[3] *„Die Gegenstände unserer Naturforschungen werden die verschiedenen Formen und Erscheinungen des Lebens sein, die Bedingrungen und Gesetze unter welchen dieser Zustand stattfindet, und die Ursachen, wodurch derselbe bewirkt wird. Die Wissenschaft, der sich mit diesen Gegenständen beschäftigt, werden wir mit dem Namen der Biologie oder Lebenslehre bezeichnen.*"

[4] *« Tout ce qui est généralement commun aux végétaux et aux animaux, comme toutes les facultés qui sont propres à chacun de ces êtres sans exception, doit constituer l'unique et vaste objet d'une science particulière qui n'est pas encore fondée, qui n'a même pas de nom, et à laquelle je donnerai le nom de biologie. »*

[5] *« Science qui a pour sujet les êtres organisés et dont le but est d'arriver, par la connaissance des lois de l'organisation, à connaître les lois des actes que ces êtres manifestent. »*

epigenetics, led biologists to reflect on the meaning of the term "life". Thus, François Jacob could write in 1970 (p. 320):

> *"Today, life is no longer questioned in laboratories. We no longer try to define its outlines. We only try to analyse living systems, their structures, their functions, their history."*[6]

The formal object became the structure of living systems and the characteristic to be studied was the structure's functions, which may be multiple. This is now possible with the concept of mechanism, which applies to both inanimate and animate systems. The above presentation by Franck 2002 applies perfectly to biology by replacing the term "social", as the author was examining the social sciences, with the term "biological", to have a correct view of the demonstration of a biological mechanism. In reality, biology has successfully used these mechanisms since the 1990s (Bechtel and Richardson 1993), and they constitute a new model for explaining these phenomena.

Following this definition of both sciences, we will discuss whether their combination is possible and under what conditions. Could it lead to pseudoscience in some instances? Alternatively, could biology provide useful complementary elements to demography without the two disciplines combining? We will conclude this article by considering what the notion of mechanism can contribute to these two sciences.

Behavior genetics

This approach was developed, long before its use in biodemography, as a result of the work of John Jinks and David Fulker 1970. They tried to demonstrate the possibility of separating the effect of genes from the effect of the environment, using the hypotheses formulated by Ronald Fisher 1918, which we will develop below. This hypothesis has been used in many previous studies on psychological, medical, or biological traits such as intelligence measured by IQ (Pedersen *et al.* 1998), alcoholism (Blum *et al.* 1990), homosexuality (Eckert *et al.* 1986), fruit juice and soda consumption (de Castro 1993).

However, several geneticists criticised the very basis of these studies from the start, such as Lewontin 1974 and Kempthorne 1978, who wrote (p. 1):

> *"The conclusion is that the heredity IQ controversy has been a 'tale full of sound and fury, signifying nothing'."*

Demography remained reluctant for a long time to use this approach to investigate any of its topics. Social, economic, climatic, geographical, and political conditions have been the primary focus of their research.

The advent of biodemography will change this position. Why ignore the effect of genes on demographic behaviour? Obviously, this effect exists, but we must measure the "magnitude" of this influence to demonstrate it. This implies admitting that a measure can be defined and calculated to characterise the contributions of "nature" and "culture" in defining the trait in question. This measure will be the one already proposed for behavioural genetics. In the late 1990s, behavioural genetics became one of the spearheads of biodemography.

As early as 1997, Wachter writes in his introduction to *Between Zeus and the salmon* (p. 13):

> *"It is tempting for demographers who model hazard rates as functions of age to imagine that genes "know about" ages beyond development and reproduction. In caricature, it is tempting to imagine a set of genes influencing the probability of dying between 50 and 55 and another set influencing the probability of dying between 80 and 85. Results that bolster or undermine this picture will shape the next generation of demographic models."*

This idea of specific genes that influence a demographic phenomenon is thus introduced and will be the subject of many articles and books on biodemography.

Thus, the article by Hans-Peter Kohler *et al.* 1999 *Is fertility behaviour in our genes?*, which prefigures the book mentioned in the introduction: *Genetic influences on human fertility and sexuality* 2000, will develop this idea more precisely.

In this article, the authors ask two specific questions: (1) is there an influence of genetics on fertility? (2) Does the relative magnitude of **nature** *versus* **nurture** impact change over time?

The answer to the first question is obviously affirmative because every trait has a genetic component, and this question is only rhetorical. To answer the second question, the authors used a regression method directly related to the hypotheses formulated by Fischer in 1918 and can thus answer "yes". But we can ask, justifiably, whether these hypotheses are effectively supported to provide such a positive answer?

[6] *« On n'interroge plus la vie aujourd'hui dans les laboratoires. On ne cherche plus à en cerner les contours. On s'efforce seulement d'analyser des systèmes vivants, leurs structures, leurs fonctions, leur histoire. »*

Fisher assumed that the combined action of genes was additive and that the environment's effect was independent of this action. The hypotheses he formulated, which can be considered as axioms of this behavioural genetics, include the following:

1. Polygenes act additively;

2. Polygenes segregate independently;

3. Environment is independent of genes and random;

4. The population is in Hardy-Weinberg equilibrium, which means that there are no inbred individuals, no migration, no mutations, nor selection;

5. The number of polygenes is infinite.

If Fisher's assumptions are verified, then the variance of a phenotypic trait: *Var P*, can be decomposed into additive parts:

$$Var\ P = Var G + Var\ E = Var\ A + Var\ D + Var\ E$$

where *Var G* is the genetic variance, which is decomposed into its additive part *Var A*, and its part due to dominance *Var D*, and another part due to the environment *Var E*.

For example, if assumption (3) is not verified, then interactions between the various characteristics must be added, destroying the simple structure we have suggested.

However, we will first proceed with the reasoning of the behavioural geneticists and define their basic concept: heritability.

We define h^2 the "heritability in the strict sense of the term" as the ratio of additive genetic variance to phenotypic variance:

$$h^2 = \frac{Var\ A}{Var\ P}$$

and H^2, the "heritability in the broad sense of the term," as the ratio of genetic to phenotypic variance:

$$H^2 = \frac{Var\ A + Var\ D}{Var\ P}$$

These concepts have been used in strictly controlled animal and plant experiments that attempt to test some of Fisher's hypotheses extensively. However, given the complexity of the underlying gene action and the failure to test Fisher's hypotheses, we will describe later that the additivity of effects is never actually tested.

Kohler and colleagues use these definitions to calculate these heritabilities for fertility by regressing the number of children of one twin against the other. These heritabilities seem quite high and lead the authors to conclude for a strong predominance of the nature effect on fertility. But we will demonstrate that Fisher's hypotheses underlying these regressions are absolutely not supported for human populations. This will lead to entirely incorrect results from this work.

First, the authors ignore marriages between relatives because they state they have no information on them. This coefficient of assortative mating for the trait "number of children born in a family" is actually approximately equal to 1, to account for infidelity! Unfortunately, this hypothesis is now replicated for most biodemographic analyses of fertility!

Furthermore, these hypotheses were put forward by Fisher in 1918 when nothing was known about the genome. The discovery of DNA in 1953 and the subsequent gene count revealed less than 20,000 genes in humans. Therefore, hypothesis (5) is not supported because how can we produce more than a million proteins with so few genes?

Fisher was also unaware that genes are grouped in 23 pairs of chromosomes. In this case, we cannot claim that the polygenes act additively (hypothesis 1) and are subject to independent segregation (hypothesis 2). If some of these polygenes are located on identical chromosomes, they cannot act independently.

Since controlling the effects of the environment is impossible in human science, hypothesis (3) is also not supported. Finally, since human populations engage in mate choice, migration, mutation, and selection, hypothesis (4) is not supported either.

As biologist Gottlieb said in 2001 (p. 6123):

> *"It is now known that both genes and environments are involved in all traits and that it is not possible to specify their weighting or quantitative influence on any trait […] this has been a hard-won scientific insight that had not yet percolated to the mass of humanity."*

Nevertheless, behavioural geneticists remained oddly silent about this result and similar criticisms from geneticists such as Lewontin, Kempthorne, Jacquard, and Vetta, and continued to make the same mistakes.

The advent of the genomic era around 2001, and the post-genomic era, especially epigenetics, around 2010, revealed that DNA no longer acts as a genetic program, capable of forming a trait, but as a random generator of proteins. This discovery hardly deterred this pseudoscience and instead raised new hopes, which soon faded away.

For example, Tan and colleagues wrote in 2015 (p. 138):

> *"By treating epigenetic measurements […] as a quantitative phenotype, the classical twin model can be applied to estimate the genetic and environmental components in the epigenetic control of gene activity […]."*

Once again, the authors disregard the complexity introduced by post-genomics and rely on the simplistic pathway from genotype to human phenotype that we condemned earlier.

At this stage, there is no need to pursue this critique further. For more details, readers are referred to the paper I published in 2003 with geneticist Atam Vetta: *Demographic behaviour and behaviour genetics* expanded in 2017 in *La génétique du comportement peut-elle améliorer la démographie?* I also welcome Ken Weiss's explicit recognition of the serious epistemological problems posed by genetics and behavioural genomics, as well as the lack of a theory that prevents prediction. In the chapter *Genomic and evolutionary challenges for biodemography* of the book celebrating 20 years of biodemography: *Sociality, hierarchy, health: a collection of papers* 2014, Weiss writes on this subject (p. 97):

> *"The approaches rest essentially on generic statistical association and regression models, which are mechanism-free approaches that, in the presence of the kinds of complex causation I will try to outline, can lead to conclusions so indirect as to provide weak predictive power and hamper understanding of causal mechanisms at the genetic or evolutionary level."*

This statement clearly signals the need to go beyond behavioural genetic studies.

Finally, we would like to point out that this topic has been highly politicised since the introduction of eugenics at the end of the 19th c. and the beginning of the last century by Galton and Fisher, and that behavioural genetics represent this trend's current extension. Eugenics can be defined as the use of genetics for the qualitative and quantitative improvement of humanity.

We only have to remember the monstrous aberrations that eugenics led to between the two world wars. However, despite the dismissal of the concept after the Second World War, the purposes of eugenics are still present today. Thus, coercive birth control was implemented by developed countries for developing countries and led to a new slaughter of the innocent, as John Aird said in 1990. Matthew Connelly's *Fatal misconception. The struggle to control world population* 2008 describes perfectly the institutions created, the policies implemented, and their consequences.

Behavioural genetics is just an extension of eugenics in our contemporary society. Although condemned by the best geneticists and philosophers of science, the field has managed to survive against all odds by supporting specific political factions.

Using biological data in demography

While behavioural genetics is a significant impediment to the validity of a biodemographic approach, other elements may support it.

For example, when demographers do not know a person's civil age, which is an essential variable for this discipline, they can use their biological age, measured by various growth indicators. We will not review these methods presented by Lyle Konigsberg, Isabelle Séguy, and Henri Caussinus in this edited volume, but we will discuss their limitations below.

The invariability of biological phenomena both in space and over time is posited in the biological uniformity hypothesis. For past populations, Isabelle Séguy and Luc Buchet 2013 introduce it as follows (p. 24):

> *"It posits that (a) the biological processes relating to human mortality and fertility in the past are similar to those observed at the present day by demographer-anthropologists and that (b) biological development takes place within the same timeframes for all populations, irrespective of time and place."*

For existing populations (the case of young undocumented migrants, for example), we must postulate this hypothesis for all ethnic groups. This assumption is far from being accepted by all researchers, and its verification is intimately linked to the available sources.

We could verify its validity on the population of the Maubuisson nuns (17th-18th c. France) because we had both biological data on 37 skulls and data from registers on the whole population (Caussinus and Courgeau 2010). However, such a case is uncommon, and testing this hypothesis is generally impossible in the past or would require, for current populations, surveys with large samples.

Another area where biodemography has advanced is in the study of longevity and mortality.

Conventional demographic studies model mortality using population variability over time and across circumstances. Their models, now based on biographical and multilevel analysis, involve many individual and societal characteristics.

However, the more fundamental mechanisms that affect this phenomenon are not explored. This is where biology could be relevant.

For instance, once the maximum number of known characteristics has been included in a biographical model, one possibility is introducing an individual biological "frailty" into it. This biological "frailty" would correspond to a hidden heterogeneity, which is not necessarily independent of the observed characteristics.

The problem is that this underlying process is unknown. Depending on the distribution selected for this "frailty," the estimated parameters may change significantly. In this context, a robust theory of the individual mortality process is essential. I would argue that the various theories for biodemography proposed by Kenneth Wachter in 2014, such as "stochastic vitality" (p. 22) or "genomic approach" (p. 23), cannot provide a foundation. Indeed, this "vitality," which tries to measure individual vulnerability to death, is too complex to provide useful evidence. Also, the "genomic approach" is too intricately linked to behavioural genetics to understand these processes.

The statisticians Aalen and colleagues described this issue in their book *Survival and event history analysis* 2008 (p. 425):

> *"As long as there is no specific information about the underlying process, and observations are only made once for each individual, there is little hope of identifying what kind of process is actually driving the development."*

Consequently, this approach is, for the moment, purely speculative, and only a complete axiomatisation of the mortality process could provide an answer. We are not there yet.

Therefore, we need to seek another breakthrough to improve biodemography: the use of biomarkers could provide such progress (Strimbu and Tavel 2010).

These biomarkers are objective indicators of a given patient's medical and biological status, which can be measured accurately and reproducible. These include blood pressure, blood sugar, cholesterol levels, and many other far more complex laboratory tests. These variables are now increasingly collected in large biodemographic surveys, such as MIDUS (Midlife in the United States), which has been following 12,000 Americans for 20 years, or the SEBAS (Social Environment and Biomarkers of Aging Study), which has been following a sample of 1023 Taiwanese since 2000.

The results, published in *The Oxford handbook of integrative health science* in 2018 (Ryff and Krueger 2018), provide an overview of the assorted data that can be used in the life sciences: socio-demographic factors (i.e., age, gender, socio-economic status), psycho-social factors (i.e., emotion, personality, social networks), behavioural factors (i.e., wellness and health practices), biological factors (i.e., blood pressure, medical tests), and stressors (i.e., divorce, discriminations, responsibilities).

However, these studies do not yet include all the elements that influence people's lives. This is because the elements included are not isolated, as biographical analysis assumes, but are strongly interwoven with social structures that will influence their future. Ignoring these structures will bias the results of a biodemographic analysis.

The multilevel analysis provides a solution to this problem by integrating into the same statistical procedure the various levels of aggregation in which humans live. Under these conditions, as the philosopher Robert Franck said in 1995:

> *"...it no longer makes sense to choose between holism and atomism and, as regards the social sciences, between holism and individualism."*[7]

For example, holism in demography will consider that all events experienced by individuals are shaped by the society in which they live. On the other hand, methodological individualism will consider that events are determined by people's individual conditions throughout their lives. Once individual characteristics and the pressures of social groups are incorporated into the same model, the two approaches will no longer conflict. In this case, there is no longer an ecological error generated by holism, nor an atomistic error, generated by methodological individualism. There is also the possibility of introducing more than just two levels to distinguish various groups and social networks, or for example, we could introduce biological levels below the individual.

[7] *« ...il n'y a plus de sens à choisir entre holisme et atomisme, et, pour ce qui est des sciences sociales entre holisme et individualisme. »*

As a result, I have emphasised that in addition to the statistical individual concept used in demography for a long time, we must also introduce the concept of statistical social network (Courgeau 2018). Given the complexity of individual life, we must construct a statistical individual with a reduced number of characteristics to reason with. Similarly, the complexity of social networks leads to a reduction of their characteristics to reason about themselves.

While the concept of statistical social network in demography is derived from multilevel analysis, it stems from other analyses in biodemography. For instance, in the book *Sociality, hierarchy, health: comparative biodemography* celebrating 20 years of biodemography, the chapter by Maxime Weinstein, Hillard Kaplan, and Meredith Lane states (p. 13):

> *"All aspects of people's lives, from birth to death, are affected by their social relationships and their larger social context."*

However, the structure of human social groups is hardly studied in biodemography, which mainly considers intergenerational transfers and cooperation between individuals (Lee 2014). Thus, among the existing hypotheses, which provide a basis for future research in biodemography, one focuses on the parent most involved in children's care or transfers: this parent should live longer than the others. This hypothesis has previously been tested in both humans and baboons (Alberts *et al.* 2014). While such studies are valuable, they do not include the structure of the social groups in question but only the relationship between individuals.

If the most visible part of biodemography has been studying mortality and longevity, the study of fertility and nuptiality appeared simultaneously with Kohler and colleagues' work 1999, discussed in the first part of this article. However, in the book *Offspring: human fertility behaviour in biodemographic perspective* (2003) by Wachter and colleagues, Michael Rutter already warns the reader, as we did with Atam Vetta 2003, about the use of behavioural genetics (p. 31):

> *"Finally, there is the crucial point that evidence of a significant heritability for fertility is completely uninformative with respect to causal mechanisms."*

Nevertheless, Kohler and Rodgers 2003 continued to promote behavioural genetic approaches to fertility in the same book.

The more constructive part of these studies is searching for biological fertility indicators, similar to what has been done for mortality. Previously, I mentioned the pioneering role of Louis Henry in 1972 on models of family formation, where he already made use of various biological characteristics, such as the length of the menstrual cycle, even though he was not referring to biodemography yet. Techniques to measure and control hormone levels and fluctuations and endocrine signalling systems are significant improvements for the study of fertility.

In contrast, when studying human migration, this phenomenon is so social, political, and economical that it would be nonsensical to include biology. In fact, few biodemographic studies deal with this phenomenon. Instead, they are mainly those that seek to synthesise the different demographic concepts: mortality, fertility, and migration.

As Maxime Weinstein, Hillard Kaplan, and Meredith Lane 2014 (p. 2) pointed out:

> *"Notably missing from among the papers in this volume is consideration of migration. Surely, migration is linked to social connection, given the large remittances that migrants often send to their natal home, and to hierarchy, given the variable social and economic niches that migrants occupy."*

Migration is clearly intimately related to social networks, but demography with multilevel analysis did not need biology to introduce these networks into its models. Once again, the lack of social network studies in biodemography is evident, as discussed previously.

Conclusion

Can we provide a more straightforward answer to the question raised at the beginning of this paper: can we imagine unifying demography and biology? The review of over twenty years of trials and experiments in this field should help us answer this question more conclusively.

Naturally, when specific characteristics, such as civil age, are missing in paleodemography, we need to relate them to other characteristics, such as biological age, to use them. However, this does not qualify as a new scientific approach.

Moreover, in this paper, the contribution of biology to demography was perceived either as dangerous, in the case of behavioural genetics, or as providing beneficial characteristics to consider in the case of biomarkers. These new characteristics can then be introduced into a biographical analysis but still do not constitute a new approach.

Faced with these negative responses, we must recognise that the object of demography, the combination of fertility, mortality, and migration, cannot be assimilated to the object of biology, the structure of living organisms. Therefore, we must resist the inclination to scatter our efforts, as in biodemography, and instead focus our efforts on the specific objects of these two disciplines.

First, we will consider what this means for biology. We have already indicated in the introduction how the notion of mechanism constitutes a new and productive explanatory model of biological facts since the 1990s. Mechanism has freed biology from the search for empirical laws by deducing biological facts from a conceptual and mathematical system that explains such facts. Philosopher William Bechtel 2011 describes how the mechanistic approach provides an understanding of living organisms' complexity by expanding its scope (p. 554):

> *"Mentally rehearsing operations sequentially is not sufficient to determine how such a mechanism will behave, and the basic mechanistic account must be extended in the direction of dynamic mechanistic explication in which computational modelling and dynamic systems analysis is invoked to understand the dynamic behavior of biological mechanisms."*

These mechanisms will explain specific biological phenomena such as protein synthesis or natural selection. Illari and Williamson's 2010 article, *Functions and organisation: comparing the mechanisms of protein synthesis and natural selection*, provides a remarkable and very educational philosophical explanation of this approach in biology. The authors summarise their viewpoint as follows:

> *"Mechanistic explanation begins with a specification of the phenomenon to be explained. At the least, this consists in an isolated description of a behaviour. Explanation then proceeds by identifying two kinds of parts – activities and entities – which contribute to producing that phenomenon. Entities and activities are both individuated in part by their roles in higher level mechanisms, so that they have role-functions derived from the characterisation of the phenomenon being explained. The explanation is not complete until the organisation of those entities and activities – the relations they stand in which allow them to produce the phenomenon – is also identified."*

This perspective is strikingly consistent with Robert Franck's summary of the mechanistic approach in the social sciences, quoted in the introduction.

In demography, a comparable movement simultaneously emerged from the early 1990s. Thomas Burch published in 2018 a book on *Model-based demography*, which contains many of the articles he wrote in the past on the role of demography theory and proposes a new approach to this discipline. Thus in 2002, in *Computer modelling of theory,* he will adopt and develop Meehan's 1968 (p. 48) thesis for the explanation of demographic phenomena:

> *"The instrument that makes explanation possible is here called a system. It is defined as a formal logical structure, an abstract calculus that is totally unrelated to anything in the empirical world. The system, as a system, says nothing whatever it generates expectations within its own boundaries."*

This perspective is perfectly in line with the semantic approach in the philosophy of science (see, for instance, Suppe 1989), which leads to a mechanistic approach. However, it leaves the question of realism in science without a clear answer. However, Burch will try to go beyond this approach to provide more realistic results, particularly with the approach that we will present next (Burch 2003).

In 2003, Francesco Billari and Alexia Prskawetz proposed to use an approach based on agents' behaviours, already used previously in sociology, for example. In their introduction, these authors state:

> *"Different to the approach of experimental economics and other fields of behavioral science that aim to understand why specific rules are applied by humans, agent-based computational models pre-suppose rules of behavior and verify whether these micro based rules can explain macroscopic regularities."*

This is a mechanistic tool that seeks to link individual behaviour at the micro-level to demographic trends at the macro level. However, the question remains whether we can ignore the aggregate levels and be satisfied with an individual approach to demographic phenomena. The application of this type of model in sociology by Schelling 1971 to the problem of residential segregation indicates that we can. Based on a simple hypothesis about an individual's tolerance threshold for racial mixing, Schelling demonstrates that in most cases, this leads to clear residential segregation. However, other more complex cases show the need to involve several levels of aggregation.

For example, Courgeau 2003 used a multilevel analysis of Norwegian farmers' migration to illustrate the impossibility of explaining their behaviour by individual characteristics alone. The individual biographical analysis clearly showed that a farmer had a much lower probability of migrating than other professions, while an aggregate analysis showed the opposite in an equally significant way. Only a multilevel analysis can synthesise these seemingly opposite results: a high density of farmers in an area will increase the probability of migration of other professions.

Therefore, the challenge of generating macroscopic regularities by simply using individual rules is evident. Conte *et al.* 2012 (p. 340) clearly describe the challenges faced by these models:

> *"First, how to find out the simple local rules? How to avoid ad hoc and arbitrary explanations? As already observed, one criterion has often been used, i.e., choose the conditions that are sufficient to generate a given effect. However, this leads to a great deal of alternative options all of which are to some extent arbitrary."*

Consequently, if these models based on agents' behaviour alone have resulted in significant advances in demographic analysis, more complex models will be needed to avoid these various drawbacks.

In *Model-based demography: towards a research agenda* 2017 (p.41), we propose, together with Jakub Bijak, Robert Franck, and Eric Silverman, the implementation of a fully mechanistic approach to demography that overcomes the limitations of models based only on agents' behaviour:

> *"The resulting research agenda we would like to propose for demography is based on three key pillars: (1) adherence to the classical program of scientific enquiry; (2) enhancement of the ways in which demographic phenomena are measured and interpreted; and (3) the use of formal models, based on the functional- mechanistic principles, as fully-fledged tools of population enquiries."*

By "function modelling," we mean the general conditions that are implied by the phenomena we seek to explain, *without which these phenomena would not be what they are or would not take place as they do* (Courgeau and Franck 2007: 44). This program is being developed and will make it possible to consider demography as a genuine science similar to biology.

Therefore, there can be no question of merging disciplines whose objects are designed to account for their different characteristics. However, instead, the method, which starts from these characteristics to model their mechanisms, is sufficiently general to be successfully applied to the natural, biological and social sciences.

Nevertheless, each discipline, taken in isolation, misses a considerable part of the phenomena investigated. As Suppe 1989 (p. 65) puts it:

> *"A science does not deal with phenomena in all their complexity; rather, it is concerned with certain kinds of phenomena only insofar as their behavior is determined by, or characteristic of, a small number of parameters abstracted from those phenomena."*

Consequently, the analysis of more complex objects is tempting and will help us better understand the world: this is what biodemography is attempting to do. However, trying to merge these two disciplines is pointless because their formal objects are tailored to account for different properties of the more complex object. Confronted with this challenge, Robert Franck 1999 (p. 140) proposes to operate as follows:

> *"Through analysis, we can build a* ***new*** *formal object, able to give an account of a complex of* ***properties*** *that* ***intuitively*** *challenges us and which existing* ***formal*** *objects cannot solve, a new formal object which is not contradictory with the existing formal objects which individually give an account of specific properties that appear in the complex."*[8]

Clearly, this is a very complex task, and the biodemography advocates have not addressed it adequately. In particular, behavioural genetics, which alone could represent this new formal object, does not represent a breakthrough because it is built on unverified axioms.

If the mechanistic approach advocated for the two disciplines becomes equivalent, their union in a single biodemographic vision is far from reality today.

[8] Par l'analyse on peut construire un objet formel nouveau, capable de rendre raison d'un complexe de propriétés qui nous interpelle intuitivement et dont les objets formels existants ne viennent pas à bout, un objet formel nouveau qui soit non contradictoire avec les objets formels existants qui eux rendent compte isolément de certaines propriétés qui figurent dans le complexe.

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Spatial analysis: a fertile ground for demography

L'analyse spatiale : un tournant fécond pour la démographie

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Abstract: For Jean-Pierre Bocquet-Appel, spatial variations were an intermediary in a multidisciplinary reasoning to fill the gaps in our information on past populations. We are following a parallel path to overcome our ignorance of the multiple *spatial interactions* that preside over past and present changes in settlement systems, especially for cities that became the dominant form of human habitat. I would like to show how spatial analysis coupled with computer models that make strong assumptions about spatial interactions could reconstruct urban populations' evolutionary trajectories. Today, emerging methods for validating multi-agent systems allow us to identify which assumptions are not only sufficient but also necessary for this reconstruction, while the incremental construction of models allows for variable granularity in the transition from the general to the local.

Keywords: spatial analysis, urban geography, spatial interaction, cities trajectories, evolutionary theory of urban systems, modeling, simulation

Résumé : *Les variations spatiales étaient pour Jean-Pierre Bocquet-Appel un intermédiaire dans un raisonnement pluridisciplinaire pour remplir les lacunes de notre information sur les populations passées. Nous suivons un chemin parallèle pour pallier notre ignorance des multiples* interactions spatiales *qui président aux changements passés et actuels dans les systèmes de peuplement, en particulier pour cette forme d'habitat devenue majoritaire que sont les villes. Je voudrais montrer comment l'analyse spatiale couplée à des modèles informatiques posant des hypothèses fortes sur les interactions spatiales permet de reconstruire des trajectoires d'évolution des populations urbaines. Les nouvelles méthodes de validation des systèmes multi-agents nous mettent désormais en position de déterminer quelles hypothèses sont non seulement suffisantes mais aussi nécessaires pour cette reconstruction, tandis que la construction incrémentale des modèles autorise une granularité variable dans le passage du général au local.*

Mots-clés : *analyse spatiale, géographie urbaine, interaction spatiale, trajectoires de villes, théorie évolutive des systèmes urbains, modélisation, simulation*

Introduction

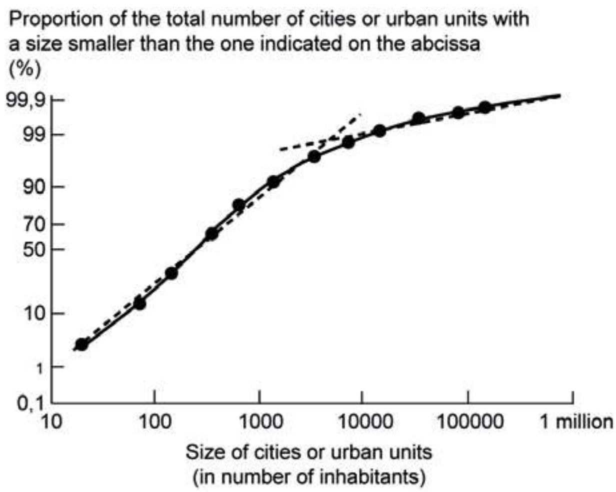
The Neolithic demographic transition, the spatial diffusion of agriculture in Neolithic Europe, the spatial diffusion of contraception in Victorian England, the wombling method for detecting discontinuities and barriers, the use of kriging to analyze the fertility transition in India, trend surface analysis, and autocorrelation... Jean-Pierre Bocquet-Appel has never stopped using spatial analysis to build his research in historical demography (Bocquet-Appel *et al.* 1996). However, spatial analysis, and more generally geography, can also clarify the mystery of urban growth and the sustainability of cities, so much questioned in the context of the ecological transition and the latest pandemic. The goal of the research sketched in this summary is to make intelligible the progressive concentration of population in these historical but universal objects, which surprisingly persistent evolutionary dynamics can be explained by their spatial interaction processes. I have sufficient affinity with demographers to present a first-person narrative chapter. The point is to describe the approach that guided the construction of a theory of the evolution of urban systems. For demographers, this approach has all the flaws and perhaps does not deserve its name because it does not respect any of the canons that demographic science has established for its scientific construction, which clearly leans towards a proper methodological individualism. However, was it necessary to wait until we had all the individual data on the behaviors and intentions of *homo geographicus* required to provide a geographic theory of urban evolution? In the absence of any other solution, we have provided one with the available mesoscale resources.

Meso-level geography in need of a microphone

When I worked in the 1970s with the team led by Philippe Pinchemel on urban growth in France, I was struck by the prominence given to the urban development agents in many of the explanatory speeches: the actions of mayors, of housing builders, were often invoked as the key to the expansion of cities. However, the first statistical analyses of city growth and migration between cities (Robic and Roger-Pumain 1968) showed the widespread nature of the process. Similarly, Philippe Pinchemel, who deplored the excessive tendency of monographic research, was often irritated when the notion of a "favorable site" was promoted to explain urban success. Pinchemel ingeniously listed all the "favorable sites" devoid of any urban settlement... Thus, we were looking for less idiographic explanations and for a nomothetic construction in geography. Following the English geographer Brian Robson (1973), I was able to demonstrate the interest of simple, stochastic statistical models, such as Gibrat (1931), to describe, to a first approximation, the shape of the growth rate distribution in a system of cities (Pumain 1980, 1982a). The main interest of this model was to propose a dynamic explanation of the shape of the distribution of city sizes by indicating that this famous "Zipf's law," a portion of a lognormal distribution of the number of inhabitants of all the settlement units in a territory, was the result of a generalized growth process. The probability in the long term is that all the highly connected cities will have the same growth rate (relative growth, proportional to the size of the cities) but with strong spatial and temporal fluctuations.

One of the first components of this research was creating a database that identifies and delimits coherent geographical entities, defined as multi-communal agglomerations in France (Vincent 1952), to consider the process of city expansion in both demographic and spatial dimensions. This database reconstructs urban agglomerations systematically over a long-term period, making it possible to measure growth over reasonably short time intervals. This is possible because of the frequency of population censuses in France between 1831 and 1975 (Pumain 1982a - see also Pumain and Riandey 1986; Bretagnolle 1999; Guérois and Paulus 2002 for subsequent updates). The second component of the approach is the match between the data analyzed and the model's assumptions, which unfortunately has not always been achieved in some of the countless studies dedicated to "testing" Zipf's law and Gibrat's growth model (Pumain 2012b).

Three major conclusions resulting from this initial research performed with limited statistical and computer resources have been confirmed by subsequent work. The first is that Gibrat's model is, to a first approximation, a good descriptor of the growth process in urban systems composed of "integrated" territorial frameworks, i.e., guaranteeing strong interactions between cities over the long term. The second finding is that the observed deviations from the model indicate a historical increase in inequality between city sizes greater than predicted by the stochastic model, indicating a trend toward metropolization that we have subsequently observed in several territories (Pumain and Moriconi-Ebrard 1997; Cura *et al.* 2017). The third conclusion shows that the French settlement system can be described according to not one but two lognormal distributions. The one corresponding to the cities, which have been growing for a long time, is more unequal. In contrast, the hamlets and villages, which on average had their population peak around the last third of the 19th c. with low or negative growth rates since then, have a lower standard deviation of the distribution of the logarithms of their population size (fig. 1).



1. Two lognormal distributions for the French settlement system (modified from Béguin and Pumain 2017: 212).

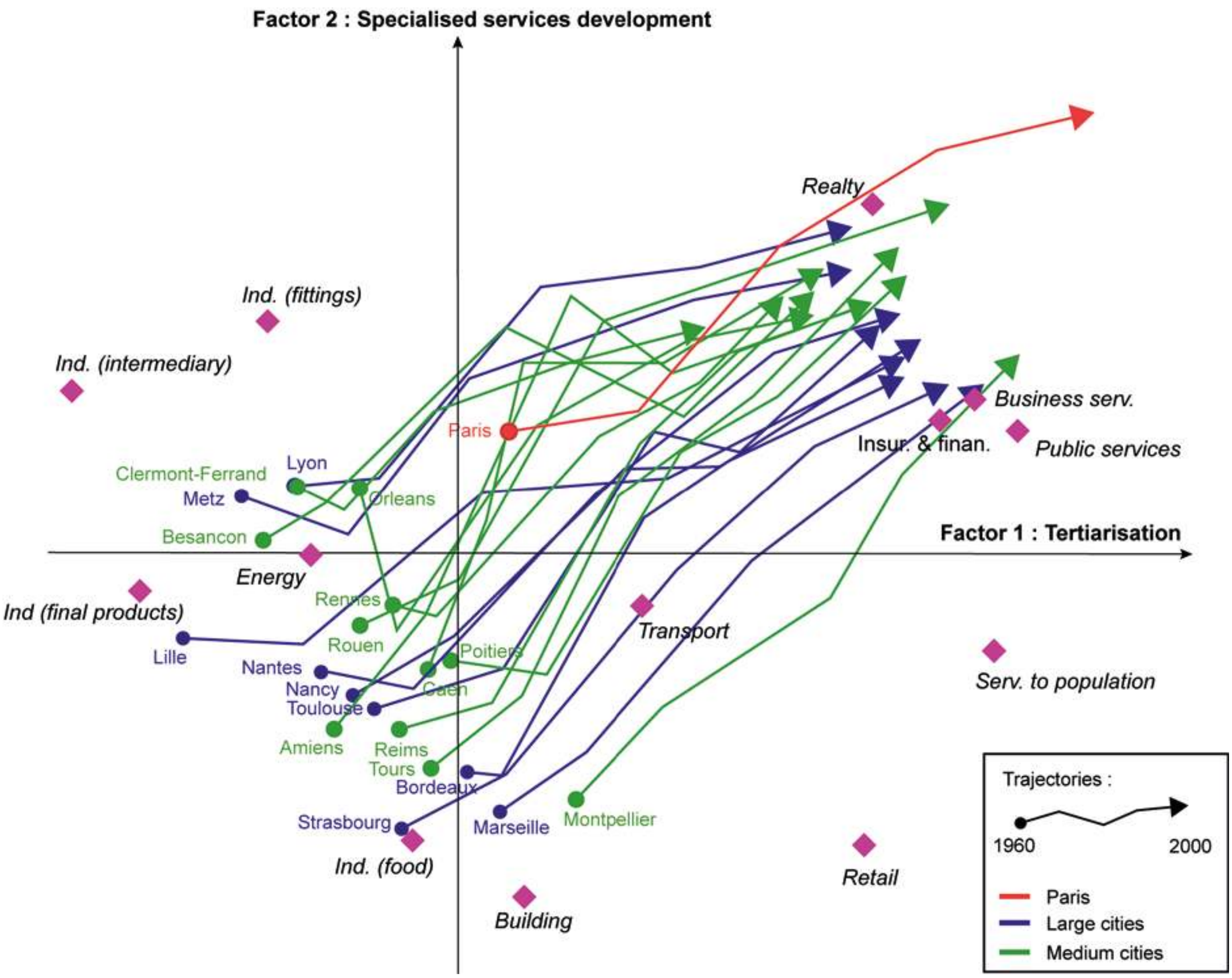
However, the most important result is the return to the theoretical development deviations from the model allow. The substantial similarity of the cities' growth rates over the long term raises the question of the apparent autonomy of the growth process from individual decisions. However, substituting a purely statistical explanation, which also assumes that cities behave as independent units, for the social processes involved in city growth and, instead, demonstrate their multiple interactions, is not the way to build a theory of their evolution. The deviations from the model clearly reveal that these interactions are relevant, given that they are not entirely independent of city size.

From population growth to economic transformation

This approach led to exploring explanations for city dynamics, not necessarily in local conditions favorable to their development or in the specific vision of some officials, but in the comparative observation of their transformations over time. The work initiated with Thérèse Saint-Julien on changes in job composition in all French cities with more than 20,000 inhabitants between 1954 and 1975 demonstrated not the unique nature of these trajectories but, rather, a surprising similarity in the evolution of socioeconomic profiles. This result suggests strong interdependencies between cities in the same territory, which "form a system" (Pumain and Saint-Julien 1978). Moreover, the modalities of change observed in this system of cities are similar to those described by self-organization physical theories, inferring an "order by fluctuations" that maintains an overall configuration of the system from the interactions between its components (Allen and Sanglier 1979). The persistence, or slow transformation, of the system structure (macro-geographical state of the urban system described by the shape of the distribution of city sizes, the main factors of the differential activities and social composition of the cities...) is associated with considerable fluctuations in its elements' relative situation. Therefore, at the meso-geographic level, each city transitions rapidly between "stages" of demographic growth, stagnation, and decline. Alternatively, cities may experience slower changes in their rank in the size hierarchy over the medium term. Also, they may display decennial changes in their socioeconomic profile, which are sometimes leading, sometimes in step with, or lagging behind a common transformation (Pumain and Saint-Julien 1979). While some of these inflections can be interpreted as "local" singularities or bifurcations, it is only when the system becomes unstable, as a result of an external disturbance (e.g. for cities, a new wave of socioeconomic innovations) or the magnification of internal fluctuations (e.g. a persistent, differential rate of adaptation that occurs between groups of cities) that bifurcations can emerge at the macro-geographic level of the system of cities.

Most of the fluctuations in individual city trajectories do not affect the system's overall structure, which we characterized at the time by the principal components identified by factor analysis and combining many interrelated city descriptors. We have proposed an interpretation of these components by linking them to the diffusion process of socioeconomic innovations affecting all cities to a greater or lesser extent. However, these processes leave traces of variable length in the form of specializations more or less related to the city size, depending on the degree of selectivity and the scale of the innovation waves. Thus, we had a first dimension of the socioeconomic differentiation of cities, expressing their "brand image" in the second half of the 20th c., which reflected a reversal of the cities' attraction since the 19th c. The working-class cities that concentrated manufacturing activities in the north and east of the country became the poorest and least attractive, while the cities growing since the 1960s were mainly located in the southern and western regions neglected by the first industrial revolution. Furthermore, we have highlighted the emergence, through the gradual magnification of small fluctuations, of another component, indicative of the selections made between cities by the innovations of the *Trente Glorieuses* period, which we described as "technical modernity." This factor generated stronger growth in the main metropolises and in the most dynamic cities of the Rhône-Alpes region, where industry and the innovative tertiary sector were associated, as opposed to the cities in the interior that were losing ground. This "bifurcation," which lasted several decades, supported a process of metropolization and generated a rather exceptional temporal autocorrelation in the growth rates of French cities, illustrating a singularity in a general dynamic of "coevolution" linked to the size of the cities and their location (Paulus 2004; fig. 2).

Therefore, the shifts in various singular cities' trajectories are explained through faster growth at a given time or through a degree of specialization in particular activities. Consequently, the "singularities" that produce these individual developments are understood as resulting from dynamics common to all cities in an urban theory that is no longer structuralist but is now evolutionary (Pumain 1997).



2. Socioeconomic coevolution of French cities 1960-2000 (modified from Paulus 2004).

The difficulty of direct observation of most intercity interactions

My geographical analysis of urban growth is based on the observation of cities as urban agglomerations (defined by the continuity of constructed areas) or as urban areas (daily commuting areas according to the French definition). These territorial entities combine varying numbers of individuals and companies and a diversity of institutions, which can be described at this micro-geographic level by all sorts of distinct attributes, including intentions and strategies, which are partly similar or convergent and somewhat contradictory and conflicting. Demography and sociology are mainly focused on this level of analysis of cities at the individual level. However, the observation of cities at the mesoscale, when the selected borders make sense at this level, reveals a set of characteristics specific to each city entity: for example, a recognizable urban morphology, a specific range of activities and skills that geographers translate into the identification of "urban functions" in the system of cities (Pumain and Saint-Julien 1976), or particular "urban atmospheres" according to architects, urban planners and urban ethnologists (Péneau 2000; Augoyard 2011). Moreover, these city identity expressions (Debarbieux 2006) illustrate the persistence of interurban differences over time, far beyond the timespan of the generations and cohorts of people who have worked and lived there. Social sciences that focus more on methodological individualism are therefore interested in "place effects" likely to interfere with individuals' behavior and trajectories and explain certain inflections.

Nonetheless, geographers also claim an interest in examining these cities' characteristics independently. Although individual human actions and intentions are "ultimately" responsible for the observed effects, the practical impossibility of capturing all of them justifies not seeking to identify this level of detail to develop an authentic "urban science," contrary to a certain recent international doxy (Batty 2013). This epistemological pragmatism is essential when the research aims to explain the other "location effect" produced, on this average level of urban phenomenon spatial organization, by the observable entity on a macro-geographical scale that we call "system of cities" (Pumain 2006). The hypothesis of the genesis of this macro-geographical object from interactions between cities logically emerges from observations at this level, which observe coherent and partly predictable developments.

The most directly available statistics for measuring interactions between cities are the migratory flows observed from population censuses, which are one of the components of urban growth. We have systematically analyzed migration flows between French cities in collaboration with INED (Pinchemel *et al.* 1972; Balley *et al.* 1974). Migration is clearly the most discriminating component in the growth disparities, even if its weight has decreased proportionally over time relative to the natural balance rate. Incidentally, we have retraced the main characteristics of the territorial migratory fields identified by Daniel Courgeau (1970) after Torsten Hägerstrand (1957). Different gravity models summarize the effect of the demographic weight of geographic entities and their distances on the volume of migration flows. The first dedicated algorithms allowed us to test and compare their explanatory power (Pumain and Poulain 1985). The deviations from the models were then indicative of contrasting population dynamics according to age structure, with the strong attractions of the most urbanized regions on the active population lasting longer than those on the population as a whole (Pumain 1986). This observation underlined the importance of urban economic functions in the differentials of attraction between cities, summarized by the concept of migration filter (Balley *et al.* 1974), and raised questions about the differences in the migration flow patterns, economic activity, and occupation of migrants.

I carried out multivariate analyses of the socio-professional composition of migration flows between French urban agglomerations (Pumain 1980) and compared it with the resident population (Pumain 1976). One of the main results of this work is the strong similarity between the occupational specializations of cities and the compositions of incoming and outgoing flows (Pumain 1982b). Migration flows, at the level of precision described by the socio-professional categories, are either almost entirely determined in their composition by the socio-professional profile of the cities, or they simply replace outgoing flows with incoming flows. My demographer friends paid little attention to this result, which they considered highly inaccurate to measure the effect of migration on urban change. Since the socio-professional situations of migrants were only observed during the census, and couldn't determine any potential individual employment changes or when they occurred. Only large-scale surveys could establish the importance of these interactions at the individual level (Courgeau 1999). However, the heuristic interest of recognizing the persistence of urban specializations and attempting to understand and model their coevolution strikes me as highly relevant when it comes to interpreting territorial changes, and no doubt also to better understand the major inflections of individual mobilities. However, I remain frustrated as a geographer to insufficiently promote the interest of mesoscale research to consolidate the epistemological status of intermediate-level socio-spatial units, as advocated now by some sociologists (Grossetti 2020).

The very low "effectiveness" of migration on urban socioeconomic change has been confirmed many times (Baccaïni and Pumain 1998). Only 1 to 2% of all exchanged flows result in quantitative population shifts or qualitative changes in the city's activity profiles, which only occur incrementally. From an urban theory perspective, this probably means that changes in the local population's skills also contribute to the adaptation of cities to socioeconomic change, which is probably triggered as much by information exchange and financial investment as by human transfers. For example, subsequent research has revealed that large cities with universities send more qualified people to the rest of the country than they receive, despite evidence that jobs in these cities have shifted towards a greater concentration of skilled populations during this "metropolization" period (Pumain and Saint-Julien 1990). However, Olivier Finance's observation of transnational corporate investment at the level of settlements in urban areas indicates that "investment stocks and flows tend to select or exclude a certain number of cities on a long-term and short-term basis." This trend favored large cities but also specific regions, according to varying hierarchical scales across sectors. However, "cities with a less dynamic reputation have managed both to attract more investment than expected given their long-term size and to attract more recent new investment" (Finance 2016: 312).

Today, the bulk of the knowledge about interactions between cities is still inferred from the observation of their differential changes. It was only possible to combine a range of interurban flows to highlight the multi-scale organization into strongly or loosely connected subsystems of cities in the French territory recently (Berroir *et al.* 2017). From a dynamic modeling perspective, it remains exceedingly difficult to obtain sufficient direct information on the city-to-city interactions to have any hope of representing them in models and simulating their consequences on the evolution of cities. Flows occurring between cities based on the interactions implemented in the models cannot represent migrants or investments; they are "second-order interactions" built from state variables describing each city, adjusted by parameters (Pumain 2008). The point is not to claim that we can dispense with micro-scale work to model the evolution of cities and systems of cities. Instead, such knowledge is essential to identify which city attributes are relevant and how to structure their connections when modeling the inter-city interactions expected to occur in the genesis and evolution of systems of cities. The results of individual-level surveys are crucial (and sometimes sorely lacking) for determining plausible orders of magnitude and estimating parameter values that characterize inter-city interactions.

From differential equation models to multi-agent models to improve exploration of the urban interaction space

The notion of self-organization suggests no explicit political or economic purpose, either in institutional terms or interpreted according to an optimized function, to explain urban systems structuring according to an architecture that is identifiable because it is persistent. The structure is instead the involuntary product of multiple interactions between multiple agents. Everyone acts according to their individual goals and strategies, but there is no need to know each one in detail to predict (or simulate) the system's general architecture. The dynamics of change contribute to the shaping of the system through internal and external dynamic processes. If a structure emerges and is maintained long enough to be identifiable, this structure is nonetheless the product of that evolution. From this perspective, temporary changes in the trajectory of a particular city can be interpreted as local "bifurcations," the succession of which produces the unique trajectory of each city. The longer-term spatial and temporal correlations between these trajectories define the "bifurcations" in the structure of systems of cities that can confer a particular configuration to each system. For example, the primacy of Paris in the French system of cities has persisted over centuries since the very early and lasting organization of a highly centralized territory in this part of Europe. This organization represents a singularity that distinguishes France by a significant difference in size that is rarely observed in the urban systems of developed countries. Nonetheless, the French system of cities does not escape the "trivial" generic dynamic that builds the evolutionary interdependencies between the cities of a single system from their interactions resulting in a gradual adaptation through incremental changes in their society and activities.

Theories of self-organization provide mathematical models to understand the compatibility of these "disordered," random" fluctuations (this does not mean that these actions are irrational or inexplicable, but that they are impossible to describe in detail, for each element simultaneously, in the totality of the system defined at the higher level of observation) with the persistence of the system's structure, to reconcile the fast dynamics of the micro-level and the slow dynamics of the macro level, (Pumain and Sanders 2013). These models of nonlinear differential equations represent the temporal evolution of the state variables that define the macroscopic structure of the system, the microscopic interactions being represented by mathematical functions or by parameters. The advantage of these models is to shift the usual perspective in the study of geographical object transformations.

History and geography change their interactions in the applications of dynamic models to regions (Allen and Sanglier 1979; Weidlich and Haag 1988) or cities (Pumain *et al.,* 1989; Lepetit and Pumain 1993; Sanders 1992). Geography is no longer the theater of operations on which history records events. History is no longer the ultimate expression of local identity, conceived as the reconstruction of the irreversible temporal process that necessarily led to the geographical object observed today, in its indivisible singularity.

Both disciplines are mutually informative by focusing on the morphogenesis of socio-spatial structures, on the processes that generate and maintain the shape of geographic space [...]. From this standpoint, we lose the notions of uniqueness and non-reproducibility associated with historical objects, but we consider the irreversibility of their singular trajectory. Thus, we recognize that processes may be formalized, that geographic objects may have a "trivial dynamic" in a historical trend that remains irreversible" (Pumain 1998: 64).

Despite the heuristic interest of self-organization theories and associated mathematical models, such models' practical application in geography is difficult (Pumain *et al.* 1989; Sanders 1992; Pumain and Sanders 2013), mainly due to the lack of flexibility of nonlinear systems of equations to represent spatial interactions. Consequently, we quickly resorted to multi-agent simulation models that allow a detailed reconstruction of these interactions, which are supposed to generate, through their recurrent operations, the differential dynamics that characterize systems of cities. Therefore, with the help of computer scientists, we designed the series of SIMPOP[1] models intended primarily to test the theoretical proposals of an evolutionary theory of cities (Pumain 1997), formulated to account for the accumulated empirical observations resulting from the statistical processing of large comparative databases on different urban systems (Pumain 2012a).

The first of the SIMPOP models (Bura *et al.* 1996; Sanders *et al.* 1997) allowed for the representation of three different types of spatial interactions according to the urban functions studied: gravitational for commercial exchanges, delimited by borders for administrative functions, and in specialized networks for activities such as manufacturing or tourism. This model suggested that a hypothesis of interactions between cities was necessary to generate their coevolution. According to the highly characteristic "rank-size law", the system's hierarchy does not occur without interactions between cities. However, even with a few hundred trial-and-error simulations performed "by hand" on the parameters that were not directly observable, we could not prove that this minimum condition was also necessary.

The second version of a SIMPOP model, developed by another computer scientist, Benoît Glisse, allowed us to identify some of the processes that generate diversity in urban systems, based on a comparison between Europe and the United States (Bretagnolle *et al.* 2010). An initial version of the model, adjusted to the evolution of European cities over four centuries, required significant qualitative modifications to account for the evolution of American cities over almost three centuries. The singularity of a system of cities from the "New World" was thus evidenced, or at least confirmed in its broad outlines, from the necessary transformation of the multi-agent model's rules representing the interactions between cities. Such a transformation was possible by imposing the "pioneer front" notions in territorial colonization and reliance on the "colonial metropolis" external demand to ensure the development of the system under the dynamics revealed by the empirical data calibration. Somehow, a complex system dynamic model provided a "singularity" example in the classical geography definition, linked to the geohistory of the urban system.

At the city level, Thomas Louail's work (2010) has the benefit of demonstrating the possibility of simulating the emergence of singular urban spatial structures, despite similar constraining dynamic processes, at the cost of defining some rules and initial conditions to differentiate the morphologies of European and North-American cities. The European structure is radioconcentric and characterized by strong internal differences in densities and prices (according to center-periphery gradients). The American structure is more homogeneous and far more widespread, according to orthogonal patterns that

[1] https://web.archive.org/web/20181224152427/simpop.parisgeo.cnrs.fr/

reduce accessibility differentials. This difference illustrates a "bifurcation" in terms of distinct alternative trajectories compatible with the same dynamic process (Prigogine and Stengers 1979).

Modeling to test theories

Much closer collaboration between computer scientists and geographers allowed us to take a qualitatively significant step in identifying what constitutes the specificity of a system of cities beyond the genericity of the dynamic processes implemented in models designed to be as parsimonious as possible. One of the main problems of multi-agent simulations is their validation step, given that calibration cannot readily guarantee the unicity of results, either on empirical data or on theoretical hypotheses (Banos 2013).

Following the development of the OpenMOLE simulation platform, designed to integrate sophisticated model validation processes, including genetic algorithms and a large capacity for parallel grid computing, we were able to achieve higher confidence in the quality of parameter estimation of a generic model (SimpopLocal, prepared in Clara Schmitt's thesis (2014) with the help of the SimProcess platform developed by Sébastien Rey-Coyrehourcq (2015). The almost complete exploration of the parameter space required some 500 million replications of the same model (Schmitt *et al.* 2015). Thus, the theoretical assumptions tested and hypothesized to lead to the emergence of urban systems based on interactions propagating innovations between settlement centers could be considered sufficient and necessary to reconstruct an urban hierarchy. We have developed a new procedure for rigorously exploring the behavioral space of a model, which complements our ability to dynamically distinguish between the particular and the general (Reuillon *et al.* 2015). Moreover, a more sophisticated model calibration of the relatively singular example of the system of cities in post-soviet space (Cottineau 2014) led to an incremental method of developing such models, based on decreasing parsimony in considering the system's generating mechanisms and its environmental constraints. A novel conception of geographic singularity is thus suggested, identifying it at different precision levels, according to an adaptable interval assessing the degree of specificity of a regional development in a generic process, for a given level of description granularity (Cottineau *et al.* 2015).

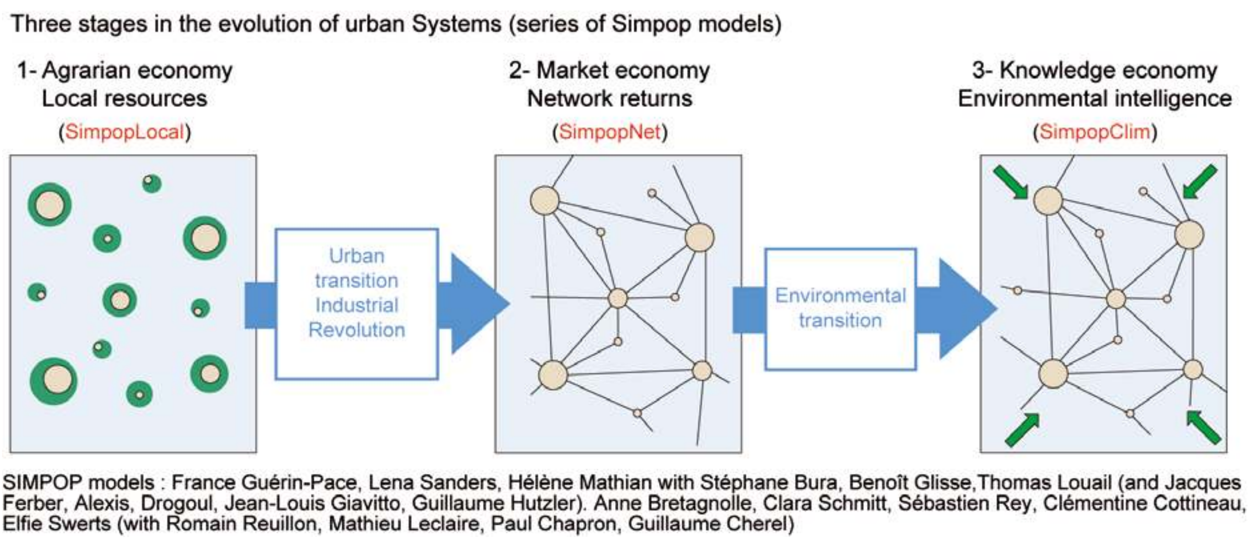
We should explain this progress, which strikes me as important, both for the validation of multi-agent models and for strengthening the reliability of their implementation in the social sciences. Based on these new validation methods, this modeling allows us to obtain results that are, if not predictive, at least capable of more strictly delimiting the universe of possible developments. The SimpopLocal model used initially to test these methods identified parsimonious key parameters to generate an urban system that could evolve according to highly plausible or "average" observations during the first major transition in the history of cities, some 3-4,000 years after the Neolithic. The key parameter for urban dynamics in this model is social innovation, which emergence is effectively endogenous to the model by scaling it to the number of interactions in the population (Schmitt 2014). This choice is confirmed in retrospect by a recent article in the journal *Nature Communication*, which proposes generic models and explanations of the thousand-year-old evolution of settlement systems on this principle (Shin *et al.* 2020). Furthermore, by deploying genetic algorithms and distributed supercomputing to explore the model's outcome data space, we were able to demonstrate, for the first time in the HSS field, that our hypotheses for reconstructing the emergence of a system of cities were both necessary and sufficient (Schmitt *et al.* 2015).

The integrated modeling work, which includes theoretical proposals, harmonized empirical data, and adapted methods, has been extended by Juste Raimbault, not only on hypothetical examples but using empirical data to calibrate the models. A first model analyzes the coevolution of a system of cities and a transport network. This model incorporates network effects by assuming that their development depends on the (gravity-like) strength of interactions between cities and performs flow feedback on city growth rates (Raimbault 2020). An additional step allows the network to evolve dynamically according to flow values, following a threshold self-reinforcement process (Raimbault 2021). This model applied to the French system of cities, and the railway network between 1850 and 2000 generally supports the idea of a strong relationship between urban growth and the development of networks that support interactions between cities while showing a wide variety of coevolutionary regimes, with varying degrees of lag between the two processes. Calibration over successive periods provides information on the network interaction and growth dynamics and reproduces typical stylized features such as the tunnel effect. A similar approach has been used to show the tight relationship between population density and road network growth in Europe by reproducing the diversity of morphological organizations of the system of cities (Raimbault 2018, 2019).

Conclusion: spatial analysis and demography to anticipate the future of cities

For geographers, studying the spatiality of societies implies considering the planet's organization with human requirements and assumes a clear understanding of the settlement's interactions with their environment. Figure 3 represents a schematic of the evolution of these relationships since the emergence of cities. By definition, cities base their development on networking more distant resources than the villages of the sedentary Neolithic period. However, during the four or five millennia following the emergence of cities in agrarian economies, their development remained strongly constrained by the availability of local resources and was influenced by the climatic and seismic fluctuations of their immediate environment. Besides, conflicts between neighboring cities or invasions of more distant origin often led to destruction, sometimes permanent, at least until the 14th c. The full realization of the amplifying role of the networks developed by the cities only emerged with the demographic and economic boom that prepared the first industrial revolution, spreading urbanization and its processes -including capitalism- all over the world in just two centuries. The power of urban networks may have seemed limitless until we recognized the depletion of specific resources, particularly in energy, or their excessive consumption or degradation, increasing at a higher rate than their renewal. But the established urban networks are now much more stable and universal in their coverage of territories. The interactions that support them and that they ensure should make it possible, in a system powered by science, technology, and territorial intelligence, to facilitate the necessary information exchanges to achieve the "ecological transition" and urban sustainability that are part of the United Nations' programs (UN Habitat 2020).

With our models, we invert a "sedimentary" perspective that conceives geography as "the last layer of history." We no longer seek to explain a location, a "geographical entity," by taking into account its entire history, by reconstructing its unique genesis. We no longer construct history as a path that we follow backward to find an "explanation" in the biography of a place. Initially, we have been able to hypothesize that in some features, geographic objects represent specific achievements, among a range of possible achievements, of general dynamic processes with models that concede the existence of multiple solutions to the same dynamic process. Subsequently, we could postulate theoretical hypotheses describing the interaction patterns between cities through multi-agent simulation models. These interactions are difficult to observe directly in the medium and long term but are consistent with available empirical observations of changes in urban systems of different types (Pumain *et al.* 2015). The construction of models that are constantly improved by adding empirical data and methodological innovations within a program whose name deliberately



3. Diagram of the evolution of systems of cities (modified from Schmitt 2014).

highlights urban geodiversity[2] contributes to identifying geographical singularities in the "classical" sense at different spatial and temporal scales.

The question of the future of cities entails answering the following question: will the interurban dynamics observed so far continue in a context of slowed or even negative demographic growth and more restricted economic growth? Our research on the role and power of interactions in the morphogenesis of systems of cities tends to predict continuity of their hierarchical organization and a progression of their inequalities that only war periods have slowed down until now. Only massive and costly political interventions in small and medium-sized cities could lead to a complete reversal of the current dynamics.

The evolutionary theory considers "urban systems" as complex, multi-scalar, and open social adapters. While always requiring a time and space context, the dynamics of these urban systems include regularities that allow them to be partly comparable and predictable across systems and time scales. Micro-geographic level interactions, resulting from the multiple interventions of many agents, produce the "behaviors" of cities and systems of cities at meso- and macro-geographic levels due to the complex and reflexive feedbacks introduced by the agents' activities. Nevertheless, these individuals and institutions must be informed of this urban collective dynamic's knowledge to benefit from the collective territorial intelligence they represent and to succeed in the essential adaptations required by our time's ecological and social tensions.

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3. The demographic dynamics of transitions

The agricultural demographic transition, a Bocquet-Appel signature

La transition démographique agricole, une signature de Bocquet-Appel

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Abstract: Jean-Pierre Bocquet-Appel (JPBA) had a broad anthropology vision focused on understanding human and pre-human population dynamics from an evolutionary demographic perspective. He was one of the rare paleodemographer in France with a robust understanding of cultural and biological anthropology and a solid experience in statistics. His large-scale, 'top-down' approach led him to test the hypothesis of an abrupt population growth in the major centers of agriculture invention worldwide. The signal of this Agricultural Demographic Transition (ADT) was identified in Europe, North America, and the Levant and characterized by a rapid fertility increase. Also, JPBA was the principal promoter of cementochronology as a solution to individual age estimation techniques.

Keywords: demographic transition, Neolithic, fertility, maternal energetics, cementochronology

Résumé : Jean-Pierre Bocquet-Appel (JPBA) avait une vision large de l'anthropologie axée sur la compréhension de la dynamique des populations humaines et pré-humaines dans une perspective de démographie évolutive. Il était l'un des rares paléodémographes en France à posséder une excellente compréhension de l'anthropologie culturelle et biologique et une solide expérience en statistiques. Son approche à grande échelle et « descendante » l'a conduit à tester l'hypothèse d'une croissance démographique abrupte dans les principaux centres d'invention de l'agriculture dans le monde. Le signal de cette Transition Démographique Agricole (TDA) a été identifié en Europe, en Amérique du Nord et au Levant et caractérisé par une augmentation rapide de la fertilité. En outre, le JPBA a été le principal promoteur de la cémentochronologie comme solution à la technique d'estimation de l'âge individuel.

Mots clés : transition démographique, Néolithique, fertilité, dépense énergétique maternelle, cémentochronologie

Introduction

I was introduced to Jean-Pierre Bocquet-Appel (JPBA) by Estelle Herrscher at the 2001 American Association of Physical Anthropology meeting in Kansas City while studying in the USA. I had just completed a paleodemography course and studied the influential "Farwell to paleodemography" debate articles. JPBA's immediate enthusiasm to meet a random French graduate student abroad completely surprised me. Later, I would discover that this curiosity was indeed one of JPBA's genuine reactions as a true anthropologist when traveling and meeting people. This encounter was a formative moment in my curriculum. JPBA is one of the three researchers with Henry Duday and Jane Buikstra, who shaped my training and career, as well as my vision of science. After having kept a short correspondence with JPBA, he invited me to his office on the first week of my Paris return in September 2002. During this meeting, JPBA spent over an hour outlining what *he* could do to help *me*, even though I had never asked for anything. I was once again stunned by his generosity that I am still trying to emulate today. This chapter is my account of JPBA's contribution to the Neolithic Demographic Transition (NDT) question during the seven years I have spent in his laboratory, on the other side of his office door. For more information on JPBA's life, I will refer the reader to Hublin 2019 for an insightful necrology.

Theoretical framework

JPBA had a robust understanding of cultural and biological anthropology and a solid experience in statistics, refined at the LISH laboratory in Paris (Hiernaux and Bocquet-Appel 1987) and later in the USA with Robert Sokal at SUNY-Stony Brook (Bocquet-Appel and Sokal 1989). JPBA principal research interest was focused on the understanding of human and pre-human population dynamics (fertility, mortality, and migration) from an evolutionary demographic perspective - the combination of a life history approach (the effect of natural selection on how organisms allocate their resources through the course of their lifetime), and optimal foraging theory (a set of evolutionary principles concerning the costs and benefits of daily resource choices), within a Malthus-Boserup demographic model (Lee 1986). He was a paleodemographer, and to my knowledge, the only one in France working within this theoretical framework.

JPBA had a global approach to science. As a pragmatist, JPBA regularly argued with me that local narratives only clarified local behaviors and thus had limited explanatory power for our species as a whole. Rephrased in theoretical terms, JBPA was often more concerned about large scale 'top-down' approach by testing specific hypotheses derived from evolutionary theory; rather than the 'bottom-up' approach more common to the social science of demography, which seeks to explain a particular phenomenon (Blurton Jones 1986; Sear *et al.* 2016). However, JPBA always pleaded for a "common anthropological project" (Bocquet-Appel *et al.* 2017), defined as an interpretative system simultaneously rendering physical, physiological, psychological, and sociological variables. This vision is illustrated with regular contributions on a range of anthropological topics such as disciplinary knowledge (Bocquet-Appel 1989; Bocquet-Appel *et al.* 2017), history (Bocquet 1989; Bocquet-Appel 1996), behavior (Hiernaux and Bocquet-Appel 1987), contemporary demography (Bocquet-Appel *et al.* 2002), statistics, (Bocquet-Appel and Sokal 1989; Bocquet-Appel and Bacro 1994), or genetics (Bocquet-Appel and Jakobi 1990; Bocquet-Appel 2012). JPBA was always grounded in empirical observations and used a dynamic interaction between data and theory to test hypotheses about larger anthropological questions. This process was never done blindly, randomly, or selectively, however. JPBA's scientific honesty and desire to understand the data instead of massaging them to validate his intuitions were, as far as I am concerned, unequivocal.

The origins of agriculture: from the Neolithic Revolution to the Agricultural Demographic Transition

> *"[…] sedentism can set into motion a number of interrelated biological, behavioral, and psychological changes that can result in increased fertility and decreased child mortality, and an increase in the population growth rate, even if such growth increases work efforts in the long term. The scenario we have outlined here, however, is speculative and requires testing against archaeological data."*
> (Kelly 2013: 212)

I wasn't part of the genesis for JPBA project on the European Neolithic diffusion first presented at a Spanish conference in 2000 with his colleague M. Paz de Miguel Ibanez and followed by its companion publication in 2002. The subsequent articles on this topic regularly spanned the pages of Current Anthropology, from 2002 to the last summary of results in 2011, in addition to other articles and book chapters (see the NDT chronological bibliography at the end of the chapter).

I want to emphasize that despite having been a seemingly solitary researcher who could lock himself up for days with a noise-canceling headset to pour over dozens of articles ardently, write algorithms or put together brilliant (if dense!) PowerPoint presentations, JPBA knew how to build interdisciplinary teams to solve specific issues. For an illustration, see the acknowledgment of 23 specialists on the first page of the 2002 Current Anthropology NDT article or the large international teams funded by national or European grants afterward. Finally, when authors openly debated JPBA's methods or results, these exchanges often inspired creative responses and ultimately promoted a more robust scientific approach that JPBA always welcomed, if only grudgingly (see the comments section in Bocquet-Appel and Naji 2006).

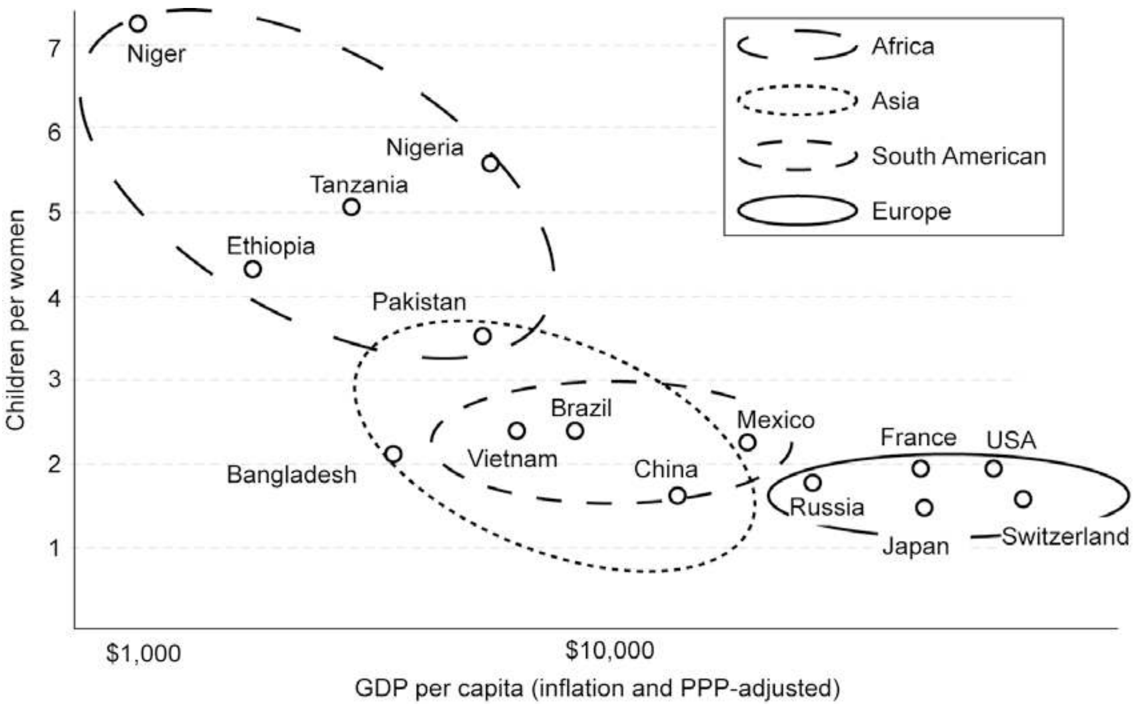
Demographic transitions

Decades of archaeological research have been consistently supporting V. Gordon Childe's hypothesis of a "Neolithic Revolution" (Childe 1925), describing a sharp increase in various archaeological features, including skeletal remains, with the transition from food procurement to food production and the advent of village life (Bellwood 2005; Bellwood and Oxenham 2008; Bocquet-Appel 2008; Hassan 1980; Kuijt 2009). Increasing site size or density of settlements was among the primary archaeological indicators of human subsistence changes and organization associated with the agricultural revolution (Price and Bar-Yosef 2011). This increase was a reflection of population growth as well as new forms of settlement and social organization. These Neolithic remains were most visible since they contrasted dramatically from the absence of archaeological record from hunter-gatherer populations.

JPBA, among others (Binford and Chasko 1976; Cohen 1977; Livi Bacci 1992; Simoni *et al.* 2000), hypothesized that a demographic transition with an abrupt growth change was either the cause or the effect of the technological and economic shift and subsequent geographical expansion. This population growth was thus akin to a Neolithic Demographic Transition (NDT) in demographic European language (Bocquet-Appel 2002: 1). If we assume that any natural population lives in quasi-homeostatic equilibrium (Wood 1998; Bocquet-Appel 2002: 646), then this hypothetical increase in the birth rate entails that it was closely followed in time by a comparable increase in mortality, unless we assume a demographic growth rate that would rapidly reach a cosmic number (Bocquet-Appel 2002).

This hypothetical two-stage NDT scenario mirrors the historical, contemporary demographic transition (CDT) well documented by historians and historical demographers (Caldwell 2007; McCaa 2002; Wood 1998). The industrial revolution created the economic and technological conditions for the initial stage of a rapid mortality decline with the advent of modern sanitation, the demonstration of germ theory, and the invention of the vaccine, among other discoveries, starting in the 18th c. in North-Western Europe and still happening today in some areas of the world (Caldwell 2007). Because fertility rates remained unchanged for several decades, the mechanical outcome was an unprecedented increase in population size via an accelerated growth rate. The second fertility stage was a comparable drop in the birth rate when populations started to adopt various effective birth control strategies to cope with the rapid increase in children to feed as a tradeoff between quantity and quality of offspring - JPBA always referred to Dickens novels for very poignant descriptions of what was happening in England during this industrial "baby-boom" - Once a population reached a homeostatic equilibrium, the growth rate would stabilize and oscillate around a demographic regime of low mortality and low fertility that most industrialized countries are experiencing today. As JPBA outlined in 2005 (Bocquet-Appel 2005), the drop of the birth rate below population replacement level is ongoing in correlation to some countries' positive economic growth rate (fig. 1), and as access to education increases (fig. 2), among other factors.

This contemporary low-pressure system of fertility and mortality is in stark contrast with the preindustrial farming regime also well documented as far back as the 17th c., and more sporadically from older medieval or antique accounts (Lee and Anderson 2002; Séguy and Buchet 2013b; Wood 1998). Pre CDT populations with high-birth and high-mortality rates experienced a typical growth rate of about 0.2 to 0.1% per year. The lack of data for older periods, and certainly for cultures with no written records, left most specialists to hypothesize that this demographic regime had been the norm for all pre-CDT populations outside of a few isolated forager groups, probably since the invention of agriculture and perhaps even before (fig. 3). However, since direct demographic variables were out of reach using standard archaeological evidence, the preindustrial demographic regime's origin was never directly documented or measured (Cohen 1977).

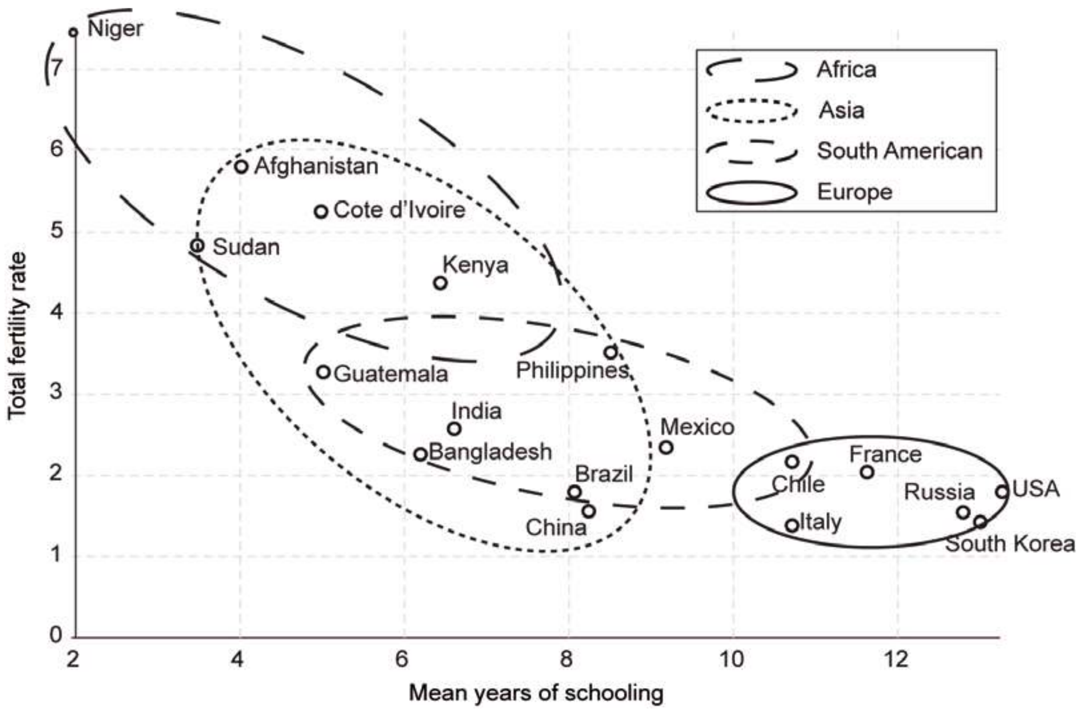


1. Children per woman (total fertility rate) by Gross Domestic Product (GDP-in dollars) per capita. Source: ourWorldInData.org/fertility. Ellipses represent around 95% of continental countries. Based on data from Roser 2020.

Demographic proxy indicator of fertility

Paleodemography has been fraught with methodological biases and misconceptions almost from the start. Nevertheless, because archaeological evidence from skeletal samples is the only direct way to observe mortality/fertility patterns of populations with no surviving records, each skeletal assemblage becomes a critical piece of the human demography puzzle and requires direct investigation whenever possible (Kelly 2013). I will not describe the development of JPBA's initial focus, alongside Claude Masset, to solve the deadlock that anthropologists and paleodemographers were facing since the fifties with skeletal age estimation (Bocquet and Masset 1977). I will refer the reader to another series of seminal articles (Bocquet-Appel and Masset 1982, 1996) and detailed historical summaries of the "Farewell to paleodemography" debate written by Frankenberg and Konigsberg 2006 and Buchet and Séguy 2013a, from the US and French perspectives respectively.

Suffice to say that confronted with the inherent biases in anthropological age estimation methods, Bocquet-Appel and Masset developed several non-conventional demographic proxy indicators (Bocquet and Masset 1977; Bocquet-Appel and Masset 1982), ultimately resulting in the ${}_{15}P_5$ ratio (Bocquet-Appel 2002). The ${}_{15}P_5$ ratio (P) is calculated by dividing the number of skeletons found in a non-catastrophic (attritional) cemetery, aged 5 to 19, by the number of skeletons aged five and over. This ratio is highly correlated with the birth rate (adjusted $r^2 = 0.963$) and strongly correlated with the growth rate (adjusted $r^2 = 0.875$) in a stable population model (Bocquet-Appel 2002: table 2; Bocquet-Appel and Naji 2006: figure 6). This relationship describes a critical yet counter-intuitive correlation between funerary assemblages and life variables, rather than with mortality parameters as it was previously assumed (Johansson and Horowitz 1986; Harpending *et al.* 1990). This ratio was explicitly developed for archaeological investigations of funerary sites with taphonomic or ritual biases of children under-representation. Also, the cutoff age at death of 20 years could be safely estimated using anthropological standards (for an extensive critical summary, see Séguy and Buchet 2011 in French and 2013a in English).



2. Fertility rate vs. mean years of schooling. Source: ourWorldInData.org/fertility. Ellipses represent around 95% of continental countries. Based on data from Roser 2020.

Using a relative chronology to contextualize global patterns.

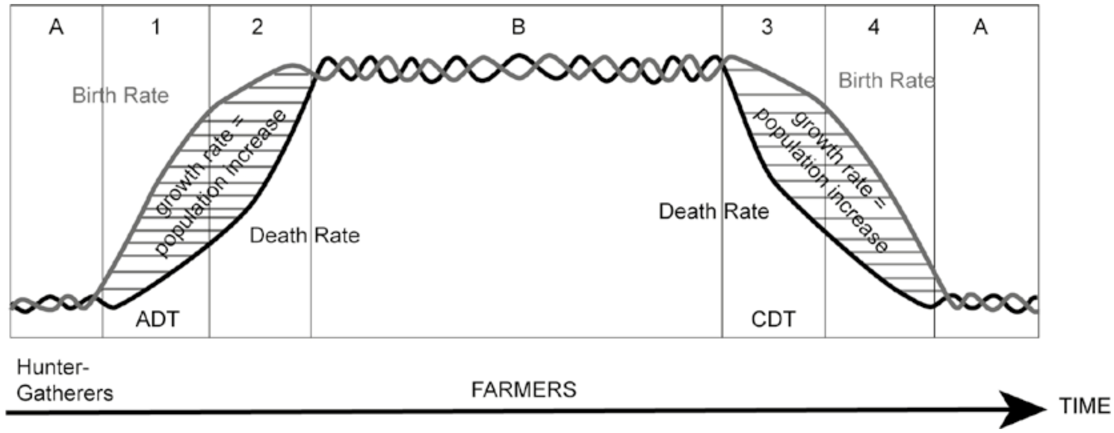
To test the NDT hypothesis on a large scale, JPBA developed a relative chronological framework (*dt*) to compare archaeological sites with different NDT absolute dates simultaneously (Bocquet-Appel and Paz de Miguel Ibáñez 2000, 2002; Bocquet-Appel 2002). With *d*t on the x-axis and P on the y-axis, the use of a loess fitting procedure is sensitive enough to track small variations of P (and thus of the birth rate) in multiple sites relative to the local introduction of the agricultural package (*dt*=0), in foragers (*dt*<0) or farmers (*dt*>0) groups (Bocquet-Appel and Paz de Miguel Ibáñez 2002). This approach was a conscious tradeoff between the lack of granularity on the map (e.g. scarcity of archaeological data, missing points in large geographical areas) and the statistical power to detect a signal at a large enough scale.

The demographic signature of an NDT

Europe and North Africa

JPBA implemented the first test on a European and North African database with a skeletal demographic proxy and a relative chronological framework (for a complete description, see (Bocquet-Appel and Paz de Miguel Ibáñez 2000, 2002; Bocquet-Appel 2002) as well as Dubouloz and colleagues in this volume).

The results described an average pattern for an NDT signature characterized by a noticeable increase in the proportion of immature skeletons during the forager/farmer transition corresponding to a growth rate increase from -0.3% to 1.3% (±1.07%) over 600 years. This transitional first stage of an unprecedented rise in fertility was hypothetically followed by an inferred second stage of mortality increase to reach homeostatic



3. Schematic changes in the birth (gray) and death (black) rates from hunter-gatherers (left) to modern time (right). A: low-pressure system; B: high-pressure system. The lag in stages 1-2 & 3-4 creates an accelerated growth rate resulting in a net population increase. Stage 1-2 mirrors stage 3-4. ADT: Agriculture Demographic Transition; CDT: Contemporary Demographic Transition.

equilibrium in the new high-pressure demographic regime of high fertility and high mortality characteristic of farming communities until the 19th c. This signature was interpreted as mirroring the CDT in reverse order of demographic stages (Bocquet-Appel 2002: figure 3).

A Worldwide test of the NDT: North American and the Levant

In his 2002 article, JPBA predicted that the NDT signature should be observable in all centers of agriculture inventions. At the time, the most likely candidate for skeletal data was the American continent. However, cemetery distribution and density were disparate at best, especially for South America. Also, for Mesoamerica and South America, the chronology of local domesticates' adoption was not fully documented nor consensual (Piperno and Pearsall 1998; Smith 2006). JPBA hired me to go to the Smithsonian museum and the Library of Congress to access archaeological reports and build the necessary database to test the worldwide NDT signature hypothesis. This was the start of three years of uninterrupted contracts on the NDT project. Generous discussions with Bruce Trigger and Dolores Pipperno at the Smithsonian institution led us to focus our test on North America (present-day Mexico, USA, and Canada) to avoid unresolved debate about the origin and development of agriculture in the rest of the continent (Bocquet-Appel and Naji 2006).

Results for the North American data indicated an increase of about 30% in the proportion of immature skeletons over roughly 500 years during the transition from forager to horticulturist-farmer populations, similar to the shift observed in European and North African (Bocquet-Appel and Naji 2006: 346, fig. 3). Of course, the dynamics of New World colonization implied a slightly different timing corresponding to local adaptations. The resulting discussions in the comments section (Bocquet-Appel and Naji 2006: 350-355) motivated JPBA to consider ethnographic data of transitioning forager groups to integrate total fertility rate estimates to evaluate fertility variations at the time of the transition (see below).

The Harvard symposium on the ADT

With two major agriculture centers describing a comparable pattern of an abrupt increase in population's growth rate at the onset of the NDT, JPBA started to reach out to the larger community specialized in the agricultural transition and consolidate the evidence from various lines of evidence. The Harvard symposium was co-organized and hosted with Ofer Bar-Yosef to present the outcome of this global outreach. The results were published in 2008 in an edited volume, "The NDT and its consequences" (Bocquet-Appel and Bar-Yosef 2008), bringing together archaeologists, zooarchaeologists, biological anthropologists, and paleodemographers.

During the symposium, we presented the third test attempted in the Levant region, with Emma Guerrero's help, at the time specialized in Levantine funerary archaeology. Levantine cemeteries revealed an increase in immature skeletons as high as in the rest of Europe but for more than 2000-2500 years, three times as long as the 600–800 years found in the Northern hemisphere (Guerrero *et al.* 2008).

Multiple lines of evidence

JPBA relative framework benefited from combining multiple lines of evidence to test the tempo and magnitude of variables relative to the NDT. The first implementation of such a comparative test was done in 2003 with Jérôme Dubouloz. In two articles (Bocquet-Appel and Dubouloz 2003, 2004), the authors compared the evolution of the temporal distance of Neolithic enclosures site density from the start of the "Neolithic" way of life in Europe (for a summary, see Dubouloz *et al.* this volume). The analysis revealed that the sample of 700 sites varied quantitatively according to the demographic transition detected in cemeteries. The phenomenon reached a peak about 500 years after the transition of a given region for the anthropological data and about 600-900 years for the enclosure data. Similarly, the Levant's gradual increase in archaeological site size was concomitant with a gradual decrease in gazelle remains (the primary protein source for local hunters) over a similar length of time. This trend supported the hypothesis of a slower tempo of change in the center of agriculture invention (the Levant) compared to secondary transition zones (Europe and North America; Guerrero *et al.* 2008: figures 3 & 4).

In addition, the second mortality stage of the NDT is theorized to have been related to increases in regional population density and the size of human settlements, in turn, produced by the rapid growth of the first stage. The increase in mortality in the second stage resulted in a decrease in the rate of population growth. This decrease was documented in a preliminary fashion using archaeologically measured population growth rates in three Latin American regions (Bandy 2008). Bandy's data show that the decrease in population growth in the second stage, at least for the areas in his sample, took place between *dt* = 600 and *dt* = 800, a tempo that matches previous independent sources of information.

Finally, we took the opportunity to test the model's complementary predictions, namely the deleterious consequences of agriculture on human health. This hypothesis mainly stemmed from the biological anthropologist's community (Cohen 1977; Cohen and Armelagos 1984; Larsen 1995; Cohen and Crane-Kramer 2007). We implemented the analysis in our North American database using three common paleopathological "stress indicators" as reported in the literature, in addition to sexual dimorphism, to test the evolution of their frequencies in cemetery populations along our relative chronological timeline *dt* (Bocquet-Appel *et al.* 2008). Results mimicked the ADT signature and supported the interpretation of biological stress during the shift of economy.

Interpreting the ADT

> "*Dramatic demographic changes can be related in a provocative manner to changes in fertility as conditioned by shifts in labour organisation and diet.*"
> (Binford and Chasko 1976: 142-143)

Anthropologists of all theoretical backgrounds debated the interpretation of the archaeological evidence Gordon Childe had initially outlined, from global descriptions to local narratives, explained in terms of cultural or population diffusions. However, recent studies of whole-genome ancient DNA data have considerably shifted our perspective on decades of inconclusive debate on understanding the European spread regarding the demic expansion of farmers originally from southeast Anatolia (Isern *et al.* 2017). Regardless, the empirical data describes a common underlying process where several independent cultural centers developed and spread the use of domesticated plants and animals within a short (in evolutionary scale) window of time (Piperno 2018). Kavanagh *et al.* 2018 suggested that their hindcast model of population density during the ADT supports a common global factor named the "surplus hypothesis." This hypothesis describes an increase in atmospheric CO_2 and temperature at the end of the Pleistocene that improved environmental conditions for successful plant cultivation and higher resource productivity. This led to human population density and the near synchronous emergence of domestication in the major centers of agriculture invention (Piperno 2018: figure 1).

Once agriculture was in place, populations quickly densified and rapidly spread (again, on an evolutionary scale) to all geographical niches on the planet, from the initial Pleistocene expansion to the American continent's historical colonization and remaining pacific islands (Bocquet-Appel 2005). However, the lack of archaeological evidence and robust method to directly test the tempo and magnitude of the origin of the agricultural demographic regime remained relatively unchallenged with few local exceptions (Binford and Chasko 1976; Ellanna 1990; Gomes 1990; Hitchcock 1982; Roth and

Ray 1985). How could we explain comparable patterns in such diverse ecological environments, with so many different local narratives around the ADT time?

The relative metabolic load model

The initial causal variable JPBA invoked to interpret the observed first stage (increased fertility) of the ADT was the reduction of the interbirth interval. The mechanism involves decreased breastfeeding and earlier weaning age that follows the decrease in residential mobility and a greater reliance on stable food sources (Bocquet-Appel 2009). Mechanically, the second stage (increased mortality) of the ADT, necessary for the return to a homeostatic equilibrium, was the consequence of increased sedentism with the accompanied development of zoonoses, infectious diseases, as well as the lack of sanitation in nascent fast-growing village life (Bocquet-Appel 2002: 647). Subsequently, the developing literature linking fertility (Henry 1961; McNeilly 1993) and energy expenditure (mobility and maternal energetics) in the relative metabolic load model (Ellison 2008; Valeggia and Ellison 2009) provided a broader theoretical framework to interpret the data in addition to the shift in food production alone.

The observed signature of the NDT makes it possible to answer the question, was demographic pressure the cause (Boserup) or the effect (Malthus) of the cultural change? For JPBA, the population was simultaneously the cause and the effect of the cultural shift, which rapidly increased the population growth rate, locally or regionally (Bocquet-Appel 2008; Bocquet-Appel and Naji 2006). The cause is linked to the pressure on the hunter-gatherer production system's carrying capacity, and the population increased probability of a system shift. The consequence can be understood by the rapid growth towards the new carrying capacity of the horticulturist-farmer system as soon as the new economic system is introduced, as illustrated by the resulting fertility explosion. This self-catalyzing process triggered the geographical expansion (e.g. individuals, nuclear families, demic) from the centers of the agricultural invention to the peripheral zones of adoption, conforming with the predictions of the Malthus-Boserup demographic model (Lee 1986; Wood 1998).

Finally, the apparent paradox of health decline with increased fertility after the NDT should also be seen in the broader framework of nutrition and maternal care. The forager system sustained a very low demographic density (Bocquet-Appel *et al.* 2005) apparently qualitatively better nourished, but the system was fragile to stochastic environmental fluctuations. The hypothesis is that the tradeoff between offspring quality and offspring quantity could account for the combination of increased ill-health with more successful recruitment during the transition (Lawson and Borgerhoff Mulder 2016). Also, Quinlan's (2007) cross-cultural analysis found that maternal care increased with increasing pathogen stress then declined. Overall, improved infant survival and greater reproductive success can still be consistent with poorer health and lower life expectancies for the population (Pennington 2001). In summary, the ADT is the positive effect on fertility of a relatively abrupt change in maternal energetics that occurs mainly during the transition from a mobile forager economy to a farming economy in any period (Bocquet-Appel 2011: S502).

Exploring pre-agricultural "natural" fertility

Building on this hypothesis of population growth with the advent of agriculture, JPBA became more focused on the demographic variables *before* this transition. Demographers refer to populations not influenced by modern medicine and effective contraceptive as following a "natural" fertility and mortality schedule, including all groups before the invention of agriculture and, to a certain degree, contemporary pre-farming nomadic food collectors. Few data exist on natural fertility for Pleistocene populations. The only proxy demographers have been using are contemporary groups defined by their subsistence strategies as Hunter-Gatherers, Farmers, or Transitional (from Collectors to Producers).

Campbell and Wood 1988 looked at 70 different populations and found that the average number of children from females surviving to mean childbearing age, represented by the total fertility rate (TFR), varies significantly from 3.5 to 9.8. This variation is more than three times the variance observed in "controlled-fertility" populations (TFR = 1.5-4.5). Wood concludes that: "there is no typical level of natural fertility" (Wood 1994: 32). However, other analyses identified a significant difference between agriculturalists (TFR>6.6) and non-agriculturalists (TFR<5.5) (Bentley *et al.* 1993; Blurton Jones 2016; Hewlett 1991). All these studies point out that hunter-gatherers do not necessarily have fertility as low as the level we see after the Contemporary Demographic Transition (Campbell and Wood 1988). Sellen and Mace 1997 tried to tease out these differences by distinguishing each subsistence strategy and relate them to fertility. They concluded that "differences in dependence on agriculture were the strongest predictors of the differences in fertility between closely related cultures" (Sellen and Mace

1997: 886). However, the main body of data for these contemporary groups is limited on many levels.

The demonstration that these populations were free of any influence from agriculturist neighbors, or colonialist interaction, is inconclusive at best (for examples and discussions, see (Early and Headland 1998; Hill *et al.* 2007; Hurtado and Hill 1996; Kelly 2013). Also, there is a potential confounding factor in the availability of modern medicine and antibiotics as well as the rapidly expanding post-industrial culture, where sexually transmitted diseases had a significant impact on sterility and fertility rates (Pennington 2001).

Besides, several ethnographic studies have documented the shift from mobility to sedentism specifically, with a subsequent increase in fertility (Binford and Chasko 1976; Ellanna 1990; Gomes 1990; Hitchcock 1982; Roth and Ray 1985). JPBA had directly tested the metabolic load hypothesis in the archaeological record (Bocquet-Apel and Naji 2006) and 172 ethnographic populations of North American Indians (Bocquet-Appel 2008: table 1). In both datasets, results supported the prediction that energy intake (diet) and energy expenditure (mobility and lactation) are good predictors of low fertility for female nomadic hunter-gatherers (high mobility, high carrying loads, and low-calorie diet) and high fertility for sedentary farmers (low mobility, no carrying load, and calorie-dense food). Also, when applied to 138 archaeological sites (Bocquet-Appel *et al.* 2008: 39), the use of the P ratio clearly differentiated nomadic hunter-gatherers (P=0.2228) from sedentary farmers (P=0.2536), with semi-sedentary shell mound foragers in between (P=0.2292).

The main conclusion of this natural fertility analysis is the understanding that the ADT is a within-population shift. To detect the impact of the ADT, what needs to be compared is not the absolute values of the averages of fertility indexes between subsistence groups but the rates of change within those same populations when they experience an economic transition (Bocquet-Appel 2011).

Cabbages and Storks

Following a series of articles with crafted titles ("Farewell to paleodemography" 1982, "Paleodemography, resurrection or ghost" 1985, "The Blind leading the lame" 2001), JPBA contextualized the outcome of the ADT project in 2011 with a "cabbages and storks" metaphor! In his last Current Anthropology article, JPBA highlighted that the major difference between the agricultural and contemporary demographic transitions is that the ADT's cause was *unconscious*, determined by the mechanical effect of the agricultural economy's invention on maternal energetics. In other words, through natural selection, humans, like all animals, have a propensity to maximize their reproductive success given their local environmental factors, and the strategies for higher reproductive success are likely to spread at the expense of less successful ones (Bocquet-Appel and Degioanni 2013). On the other hand, the fundamental cause of the CDT was *conscious*, i.e., the will to control mortality and reproduction (Bocquet-Appel 2011). The Industrial Revolution emerged simultaneously as these two controls on mortality and reproduction, each localized in a zone of the Western cultural space. However, it did not cause them: a correlation, not causation. With its high fertility and mortality, the agricultural populations' demographic regime appeared 10,000 years ago with the mechanical impact of the farming system on the energetics of fertility. This regime started to disappear with the emergence of conscious post-Enlightenment control over demography during the CDT, leaving cabbages and storks with no further influence on human progeny (Bocquet-Appel 2009: 659).

Expanding the tests

Following the NDT signals' publication twenty years ago, several researchers started to refine and expand JPBA signature method in other parts of the world. I will only mention a couple here. Notably, Kholer and Glaude (Kohler and Glaude 2008) tested the NDT hypothesis in the US Southwest. They identified a strong signal in the mid-first-millennium AD in most subregions, following by a few hundred years the introduction of well-fired ceramic containers, more or less contemporaneous with the first appearance of villages. Kohler and Reese 2014 followed up to reconstruct the NDT process in greater detail. They revealed an anomalously long and spatially variable NDT dependent on environmental conditions (dry vs. irrigation farming) that resulted in a two millennia process for farmers to reach the agricultural niche's carrying capacity in the Southwest. Willis and Oxenham 2013 presented oral health data from Neolithic An Son in southern Vietnam. The authors observed a clear pattern of elevated rates for oral disease in the Neolithic followed by a marked improvement in oral health during the Bronze and Iron Ages. In light of local archaeological contexts, this pattern was interpreted in support of the NDT mechanism of increased levels of fertility during the Neolithic, followed by a decline in fertility during the subsequent Bronze and Iron Ages. Downey *et al.* 2014 expanded on the European analysis using the summed calibrated date probability distribution of radiocarbon dates from archaeological sites, which confirmed increased growth rates after the introduction of agriculture. They validated the use of ^{14}C dates as a demographic proxy. When Lesure *et al.* 2014 analyzed the P ratio in over 6,700 pre-Hispanic burials in Mesoamerica, they suggested that the demographic transition and associated fertility rates rose gradually during both the second and the first millennia BC, probably because of the low initial productivity of maize. However, the authors departed from the strict relative chronological framework (*dt*), which may have influenced the results due to the lack of precise data on agriculture's local shifts. More recently, McFadden and Oxenham 2018 were inspired by JPBA's P ratio and NDT scenario and proposed an alternative index to estimate the rate of natural population increase from skeletal remains and applied the method to ancient Southeast Asian samples.

Wait...what about cementochronology?

I couldn't conclude without mentioning JPBA's contribution to cementochronology, the analysis of seasonal deposits of cementum on dental roots, for age-at-death and season-of-death estimations on humans and animals (Naji *et al.* 2016).

Since individual skeletal age estimation is a central variable for understanding populations demography, JPBA has been continuously trying to solve the challenges associated with age estimation methods in anthropology (Bergot and Bocquet 1976; Bocquet and Bergot 1977; Bocquet-Appel and Bacro 2008; Bocquet-Appel *et al.* 1980). Even though Bocquet-Appel and Bacro 2008 were amongst the first to offer a viable solution to unbiased collective age estimation (see also the later expansion by Caussinus and Courgeau 2010, JPBA was hopeful that cementochronology could yield significant result at the individual level. Once again, his intuition was well-founded.

When cementochronology's protocol was finally dusted off and robustly validated (Kagerer and Grupe 2001; Wittwer-Backofen *et al.* 2004; Wittwer-Backofen and Buba 2002), JPBA immediately supported Joël Blondiaux to validate the method in France (Blondiaux *et al.* 2006; Gabard *et al.* 2007). Consequently, the clear implication of this precise and accurate aging method boasting success rates above 90% (Naji and Koel-Abt 2017) convinced me to train with Blondiaux to include cementum analyses in my Ph.D. dissertation (Naji 2010).

Motivated by these positive initial results, JPBA funded the first workgroup on cementum with Thomas Colard, Joël Blondiaux, and myself in 2010. This group will then become the Cementochronology Research Program during the first symposium on cementochronology organized at the AAPA in 2012 (Naji *et al.* 2016). Our group has since developed reliable protocols to promote cementochronology as a reliable and accurate method (Colard *et al.* 2015) and motivated several significant advances in cementum biology, protocols, and applications in anthropology. Cambridge University Press is publishing these results in an edited volume entitled "Cementum in Anthropology" (Naji *et al.* accepted). This is yet another legacy of JPBA. The most exciting area to explore demographic variables stems from noninvasive synchrotron 3D analysis (Le Cabec *et al.* 2019; Newham *et al.* 2019). This technology allows us to identify innovatively individual stress events (Mani-Caplazi *et al.* 2019; Newham and Naji, accepted) and potentially female fertility in the past (Naji *et al.* accepted).

Concluding thoughts

The debate around the origins of agriculture is still open but seems to be closing rapidly. Between the recent contributions in evolutionary demography, expanding archaeo-botanical research, the development of metagenomic data, and the drastic increase in modeling complexity (see Dubouloz *et al.*, this volume), speculations of the past are rapidly transforming into a robust theory. Local environment-specific narratives might elude us for a little bit longer (Piperno 2018), but the broader outline of our demographic origin is filling up steadily.

The lack of direct skeletal evidence has logically favored a more recent heavy computational modeling trend to tease out causal variables (e.g. environmental, demographic, cultural) from the multiplicity of specialized archaeological datasets now available. For example, in 2018, an innovating hindcast model using newly available climate reconstructions and predictors of human density (residential mobility and resource ownership) in 220 foraging societies, discussed the role of demographic changes in the origins of agriculture (Kavanagh *et al.* 2018). The authors concluded that the potential for increasing population density was an essential enabling condition in all regions that developed an innovation that changed the course of human history (Kavanagh *et al.* 2018: 483; but see Weitzel and Codding 2016 for a different perspective). This result is fascinating, but I was surprised by the lack of references to the NDT debate that directly tested these exact predictions using a direct proxy of human fertility.

On the other hand, other modelers have clearly acknowledged JPBA's contribution. In his latest book, Shennan 2018 (2018: 2) singled out JPBA as a major contributor to explaining the processes involved in becoming a farmer using evolutionary demography within a Malthus-Boserup framework. Similarly, Henderson and Loreau 2019 established an ecologically driven theory of demographic change that uses resource accessibility as a proxy for socioeconomic factors. These authors explicitly used JPBA empirical data to fit their model and to combine multiple concepts to represent 12 millennia of past population dynamics through simple human-nature relationships.

Even though I wouldn't claim the prominence of JPBA's hypotheses in paleodemography, these nonoverlapping trends in publications were always puzzling to me and seemed somewhat counterproductive. My point is not to naively expect JPBA's publication to be systematically cited, despite the combined Google Scholar citation metric for JPBA's NDT articles (around 1455 on 05/05/2020, see NDT bibliography below). Even if this contribution isn't trivial in anthropological publications, this one metric still seems relatively low compared to JPBA's 682 citations from his most cited article, "Farewell to paleodemography" (1982). In the English literature, articles such as "The osteological paradox" (Wood *et al.* 1992; G-index=1480) in biological anthropology, or Bellwood "First farmers: the origins of agricultural societies" (2005; G-index=1371) in archaeology, clearly have a wider audience. I fully recognize that JPBA had an unorthodox approach, often taking short-cuts exasperating data-driven archaeologists in particular. JPBA's incisive logic and focused mindset created many "lively" debates. However, the lack of cross-disciplinarity on the origins of agriculture and associated demographic change, and the perception that specialists discuss past one another or deliberately ignore some contradictory body of evidence, seems to be a depressing illustration of confirmation bias and discipline's conservatism.

For some, JPBA was an outlier in the data cloud of anthropologists, too often dismissed for the wrong reasons. For others, as illustrated in the present volume and his international standings, his global vision of Anthropology and Research placed him far above the mundane and always above the boring. I would like to conclude by relating my last lunch with Jean-Pierre a couple of months before his departure. I was fortunate to spend this afternoon during which he could still behave in his usual busy manner and sharp wit. Even after confessing having calculated his (low) survival probability, he could still comment on various science news, institution gossips, and even express regrets for not pushing me more in my professional career! From my first introduction to our last meeting, Jean-Pierre Bocquet-Appel always left me with a feeling of generosity, passion for science, brilliance, and always humor. He is missed terribly.

Farewell!

Acknowledgments: I would like to thank Anna Degioanni and Estelle Herrscher for inviting me to the symposium organized by LAMPEA in memory of Jean-Pierre Bocquet-Appel. We had a wonderful moment amongst friends and colleagues. I wanted to thank again, Nathan, Marion, and Eugénie for kindly attending the entire symposium and diner with us. It was a pleasure seeing them again. I hope this edited volume will help them understand Jean-Pierre's contribution to anthropology and his influence on our lives.

References

Demographic transition bibliography (in chronological order)

In bold, Google scholar citation index (05-05-2020): total = 1455

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Between paleodemographic estimators and "LBK" colonization in Central-Western Europe (c. 5,550-4,950 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"

Entre estimateurs paléodémographiques et colonisation « LBK » en Europe centro-occidentale (c. 5550-4950 BCE) : hommage au parcours théorique et méthodologique de Jean-Pierre Bocquet-Appel dans l'étude des premiers fermiers du « Vieux Monde »

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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 ^{14}C 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* ^{14}C *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 o 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% (±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 (≈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

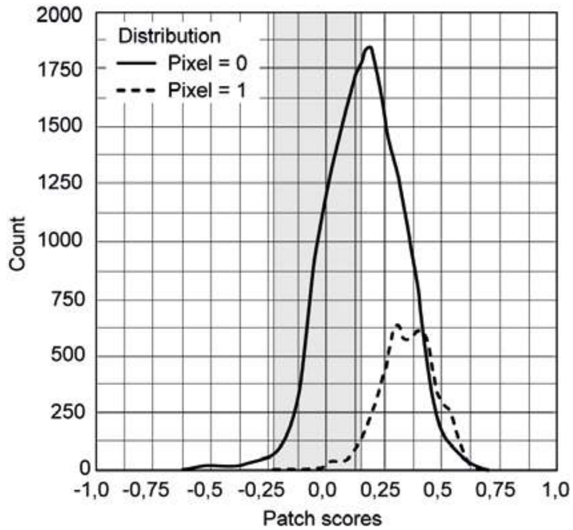
Based on this brief knowledge base, the modeling of the LBK system and the spatio-temporal simulation of its expansion throughout continental Middle Europe was therefore the subject of a multi-agent approach in which the model's agent "is active" in a defined spatial and temporal coherence, interacting 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 km^2 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/km^2 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].



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.

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 (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 ≈ 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

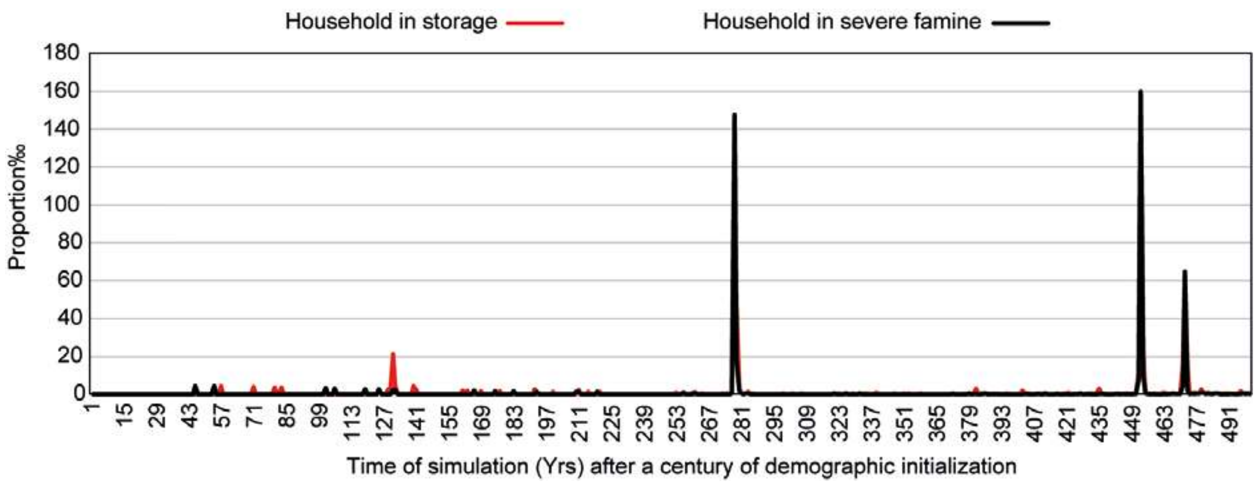
The household food production model can be summarized in the following main elements: 1) the agent's needs depend on the household's demographic composition, in kcal; 2) production strictly ensures the annual demand plus a security trimester; 3) agriculture is intensive with manuring after two years 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 ¼ 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).

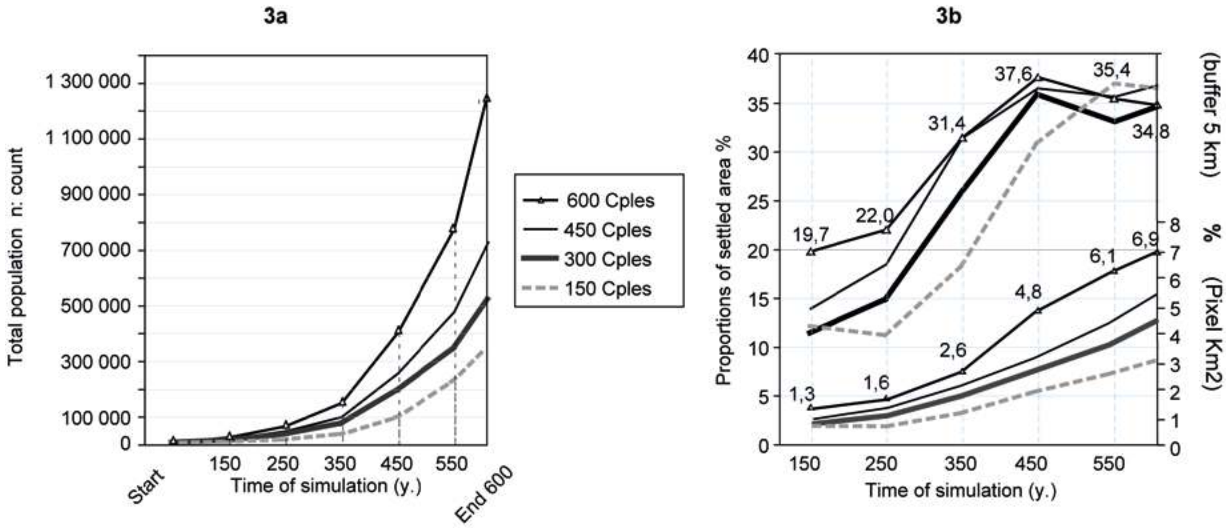
The pattern is based on a typology of sequences of unfavorable seasons, extracted by A. Guillaumont (CNRS-UPR 2147) from the research of E. Leroy-Ladurie on the Early Glacial period (Le Roy Ladurie 2004; Le Roy Ladurie *et al.* 2003). Rainfall and temperature thresholds from the 20th c. provide a basis 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/km^2 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%).

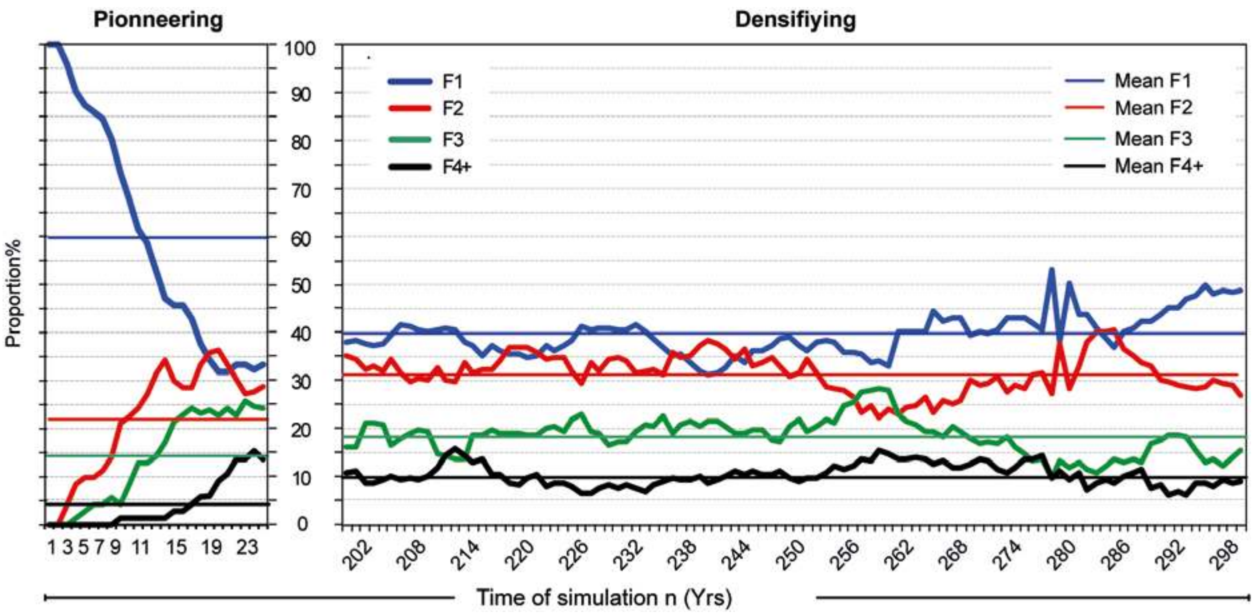
The change in supralocal and regional densities is weak. Its archaeological signature, particularly dependent on the sampling quality, is unfortunately not entirely reliable, except for well-prospected geographic sectors. Thus, the two signals, household-house, and hamlet-site do not reflect the crisis 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.

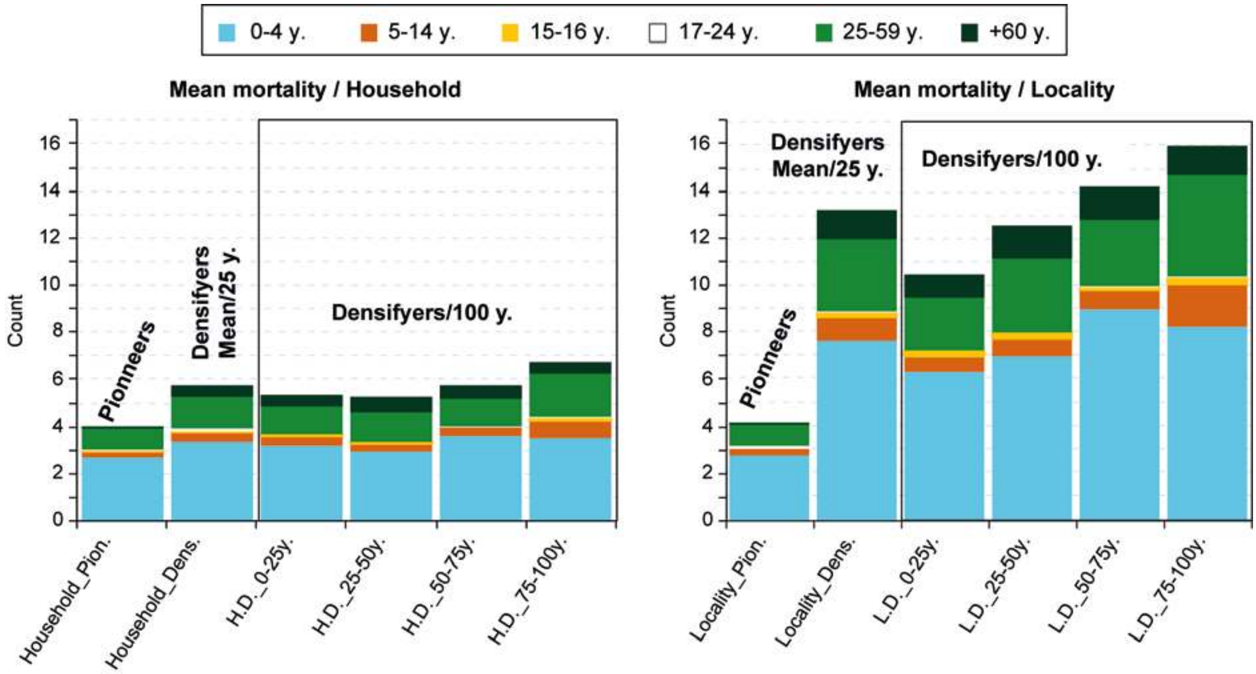
The singularity of the pioneer front in relation to the densification sectors can also be addressed through the evolution of the household type proportions in a sample representative of each situation (fig. 4).

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 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).



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).



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 ≈ five deaths). Nevertheless, archaeology fails to recover these numbers (5 x 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 unit[3], grain storage in bags or containers[4] 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 roof[5].

Final comments on the modeling

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

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[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.

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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Palaeodemography of the foraging to farming transition: insights from the Danube Gorges Mesolithic-Neolithic transformations

Paléodémographie de la transition chasseurs-cueilleurs agriculteurs : transformations Mésolithique-Néolithique dans les gorges du Danube

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Abstract: The diffusion of the farming way-of-life into environments occupied by Mesolithic hunter-gatherers in Europe has been associated with two major demographic events: the migrations of farmers originating from the Near-East and an unprecedented population increase, the "Neolithic Demographic Transition" (NDT). The Mesolithic-Neolithic transformations in the Danube Gorges provide a context of particular importance for tackling issues of Neolithization, due to its location, temporal depth, and highly contextualized osteo-anthropological record. This chapter compares complementary palaeodemographic proxies and bioarchaeological markers in order to assess the demographic response of local foragers to the Neolithic expansion. Interpreted together, these lines of evidence confirm the predictions of the NDT, and shed light on the relationships between subsistence intensification, sedentism and population growth, between migrations, cultural transmission and adaptations, and between dietary strategies, fertility and morbidity – i.e. on some mechanisms, benefits and costs of the farming transition – in the Central Balkans.

Keywords: agricultural demographic transition, Mesolithic – Neolithic, Danube Gorges, Central Balkans, ^{14}C summed probability distribution, juvenility index, ancient DNA, strontium radiogenic, stable isotopes, health status

Résumé : La diffusion du mode de vie agro-pastoral en Europe, notamment dans des milieux occupés par des chasseurs-cueilleurs du Mésolithique, est associée à deux événements démographiques majeurs : les migrations d'agriculteurs originaires du Proche-Orient et un accroissement sans précédent de la population, la « Transition Démographique Néolithique » (TDN). Les sites mésolithiques-néolithiques des gorges du Danube constituent un contexte particulièrement important pour aborder les questions de néolithisation, en raison de leur localisation, de leur profondeur temporelle et de la découverte d'une série ostéo-anthropologique unique. Ce chapitre compare différents marqueurs paléo-démographiques et bioarchéologiques afin d'analyser la réponse démographique des chasseurs-cueilleurs locaux à l'expansion du Néolithique dans la région. Interprétées ensembles, les diverses sources de données examinées confirment les prédictions de la TDN et informent sur les relations entre intensification du mode de subsistance, sédentarisation et croissance démographique, entre migrations, et processus de transmission et d'adaptations culturelles, et entre stratégies alimentaires, fertilité et morbidité au cours du Néolithique ancien dans les Balkans.

Mots clés : transition démographique agricole, Mésolithique - Néolithique, gorges du Danube, Balkans centraux, ^{14}C distribution des probabilités cumulées, indice de juvénilité, ADN ancien, strontium radiogénique, isotopes stables, état de santé

The paradigm of the Neolithic demographic transition (NDT)

The emergence of the farming system and its sprawling expansion – the Neolithic Transition – induced major changes in the demographic and social structures of human societies and created a new platform for our biocultural evolution during the Holocene (Cohen 2009; Pinhasi and Stock 2011). Population dynamics are central to our understanding of the mechanisms beyond the transition to farming: the appearance of the agro-pastoral lifestyle has been associated with population agglomeration and with a considerable increase in anthropogenic remains (Deevey 1960; Bocquet-Appel and Bar-Yosef 2005), the demographic structure of hunters and farmers has long been observed to differ (Binford and Chasko 1976), and, whether cultural or demic, the expansion of the Neolithic way of life necessarily implied some migrations (Ammerman and Cavalli-Sforza 1971; Bellwood 2005; Fort 2015). As asserted by Bocquet-Appel (2001: 637), "the number of humans is at the heart of this so-called Neolithic Revolution, either as a cause or as an effect of its geographical expansion".

Methods to extract demographic information concerning prehistoric populations mainly relied on three types of data: cultural data, such as the density of archaeological sites or phases of occupation (Shennan *et al*. 2013); cemetery data, such as mortality profiles, growth rates, health status (Bocquet-Appel and Bar Yosef 2005); and genetic or biomolecular data, such as DNA, skeletal proxies for genetic information or isotopic analyses (Ammerman and Cavalli-Sforza 1971; Pinhasi and Pluciennik 2004; Borić and Price 2013). Relying on direct paleodemographic information – growth rates inferred from the proportion of immatures in a skeletal population – Bocquet-Appel has demonstrated that the emergence of agro-pastoral activities was related to a major event of worldwide population growth, caused by an important increase in females' fertility (Bocquet-Appel 2002; 2011). For many regions, the analyses of the probability distribution of radiocarbon dates have further confirmed the unprecedented population growth (Downey *et al*. 2014) and have additionally evidenced frequent events of population collapse in the 100-500 years after the appearance of agro-pastoral practices (Shennan *et al*. 2013).

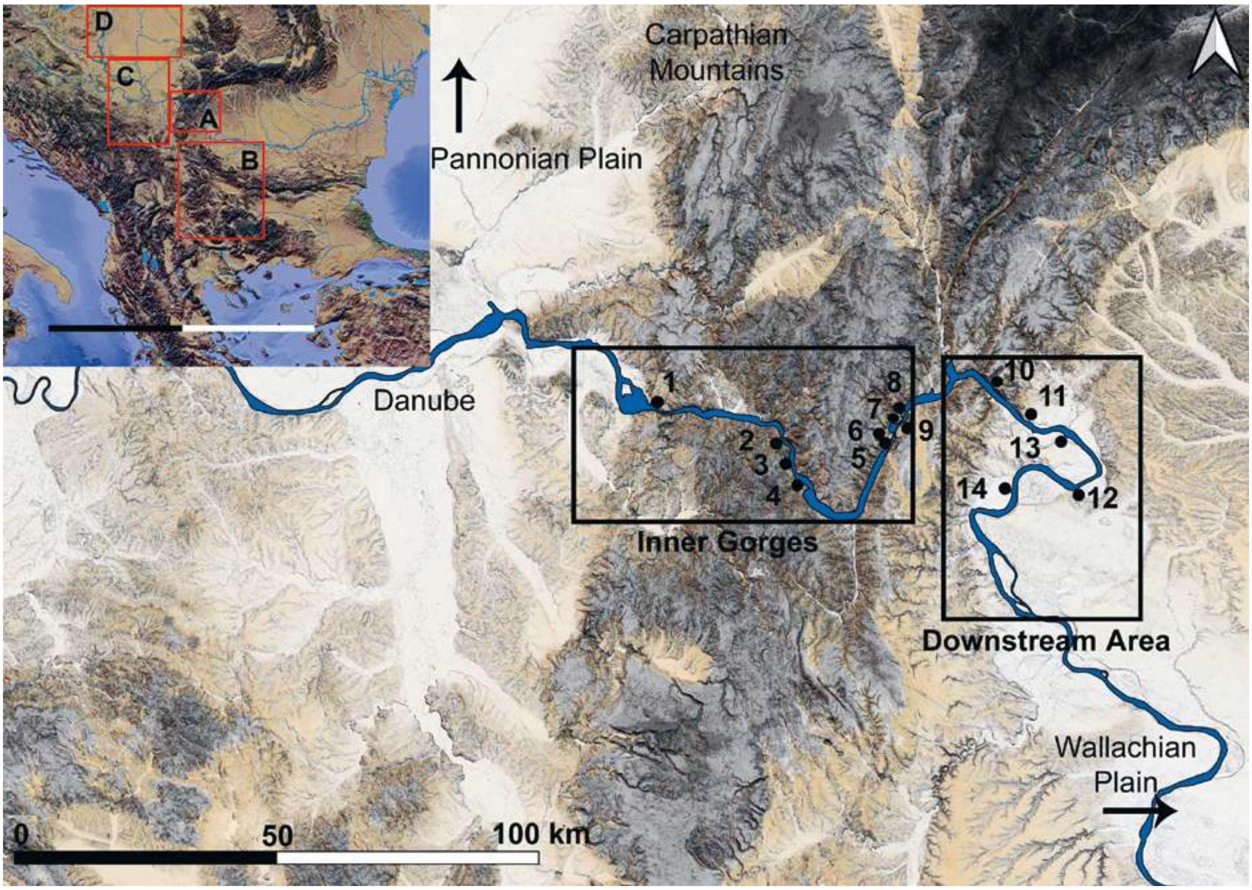
Whether the Neolithic population growth has stimulated the subsistence shift or should be considered as a primary consequence of agro-pastoral innovations has been a long-standing debate and remains controversial (Boserup 1965; Cohen 2009). It is possible that subsistence innovations, resulting from the behavioral adaptations of sedentary, growing foraging communities, were selected because they contributed to the reproductive success during periods of climatic variability, and thus participated to increase population growth. To explain the positive effect of the agro-pastoral lifestyle on females' fertility, Bocquet-Appel (2008) notably suggested, among others, that a set of factors may have collectively contributed to increase birth stacking: changes in mobility and work-load patterns associated with the sedentary lifestyle, an increase in carbohydrate-rich food consumption, a reduction in the duration of breastfeeding and changes in children allo-parenting practices with the village life. These young children in greater number were also the primary victims of the nutritional deficiencies caused by farming subsistence shift and of the appearance of new pathogens (Larsen 2003; Cohen 2008), which may have contributed to "buffer" the farming growth rate (Downey *et al*. 2014).

In many regions, the demographic growth should have been one of the driving forces for the agro-pastoral geographic expansion. The farming system has indeed the advantage that it can be exported outside of the original heartland, modified to cope with the new environments, and hence considerably extended, including into regions where hunter-gatherers had their own niche (Zvelebil 2001). Genetic and cultural data demonstrated the role of migrations in the spread of the Neolithic (Fort 2015; Hofmanovà *et al.* 2016); beyond being a vector of Neolithization, migrations may have also contributed to the demographic transition by emptying areas of Neolithic development and, contrastingly, by stimulating the population growth in secondarily populated areas.

The Neolithic transition in the Central Balkans

After several millennia of development in the Central Anatolian Plateau, the Neolithic way of life – materialized by a fully developed package (domesticated species, ceramics and ground stone technology, household organization, symbolic practices and aesthetics) – was quite suddenly dispersed into Europe, through Western Anatolia and the Balkan Peninsula from the mid-7th millennium BC (Krauß, 2011; Reingruber 2011). The spatial analyses of substantial sets of radiocarbon dates and cultural material data have indicated that a continental route took the Neolithic package to the Southern Balkans around 6,500-6,200 cal BC and rapidly spread through the Central Balkans and the Southern Pannonian plain around 6,100-6,000 cal BC, where it stabilized for a longer time until 5,500 cal BC (Brami and Zanotti 2015; Fort 2015; Blagojević *et al.* 2017). This expansion is chronologically associated with the onset and the end of the Rapid Climate Change, cooling conditions which culminate around 6,200 cal BC (the 8.2 cooling event; Weninger *et al.* 2014). Given the chronological priority of South-Eastern Europe in the spread of the Neolithic into Europe – a receptacle for its adaptation and transmission from Mediterranean to Temperate Europe – the reconstruction of underlying demographic mechanisms in this region has a prominent role in formulating and testing the models of the agro-pastoral expansion.

The Early Neolithic sites in the Northern and Central Balkan region are related to the Starčevo-Körös-Criş cultural complex. This cultural complex is characterized by cultural similarities with the Southern Balkans and Western Anatolian Neolithic, in various aspects of the Neolithic package and by local specificities in flint industry, settlements and species representations (Garašanin 1982; Trigham 2000; Krauß, 2011). The analyses of the SCPD from substantial dataset from Starčevo sites indicated two significant occupation's intensity increase ca 6,200-6,000 and 5,700-5,550 cal BC, followed by a significant decline confirming the broad pattern of the NDT (Porčić *et al.* 2016; Blagojević *et al.* 2017; Porčić *et al.* 2021). While there is evidence to suggest exchange of material and knowledge between Neolithic incomers and the Mesolithic groups in Western Anatolia and the Southern Balkans (Reingruber 2011), the Mesolithic presence remained elusive in comparison with the rich documentation available for the Danube Gorges region of the Central Balkans (e.g. Radovanović 1996; Bonsall *et al.* 2008; Borić 2011).



1. Maps of the sites of Danube Gorges and the different regions of South-East Europe mentioned in this chapter. Regions: A. the Danube Gorges (in present day Serbia and Romania); B. Rhodopes-Balkans mountains and South of Wallachian Plain (in present day Bulgaria); C. Central Balkan and South of Pannonian Plain (in present day Serbia); D. North of Pannonian Plain (present day Hungary). Sites of the Danube Gorges: 1. Alibeg; 2. Padina; 3. Lepenski Vir; 4. Vlasac; 5. Cuina Turcului; 6. Climente II; 7. Razvrata; 8. Icoana; 9. Hajdu□ka Vodenica; 10. Ostrovul Banului; 11. Schela Cladovei; 12. Ostrovul Corbului; 13. Ajmana; 14. Velesnica

Located in the southern fringes of the Carpathian Mountains, the Epipalaeolithic/Mesolithic – Neolithic complex of sites in the Danube Gorges (aka "Iron Gates") usually refers to two distinct landscape settings: after the Pannonian plain, the Gorges stricto sensu (referred here as "the Inner Gorges") and the "Downstream Area", an environment more open on the Wallachian plain (fig. 1). After an Epipalaeolithic occupation in some rock-shelter sites (circa 13,000 – 9,500 cal BC), the human presence is documented on open-air sites in river terraces from the 10th millennium cal BC (Early Mesolithic period, ca. 9,500-7,300 cal BC). During the Late Mesolithic period (ca. 7,300-6,200 cal BC), foragers started to build trapezoidal-shaped buildings and were already probably at-least semi-sedentary (Radovanović 1996; Borić, 2011; Dimitrijević *et al*. 2016). Numerous palaeodietary studies have indicated that the local population substantially consumed fish, as well as wild games (e.g. Bonsall *et al*. 1997; Borić and Dimitrijević 2005; Jovanović *et al*. 2018).

At end of the 7th millennium cal BC (ca. 6,200-5,900 cal BC, Transformation/Early Neolithic period), the Gorges' inhabitants developed intensive contacts with the Early Neolithic communities recently settled in the neighboring regions. This is archaeologically evidenced by the adoption of some Neolithic technologies, raw materials, and ornaments (Borić 2011). This period saw the complexification of trapezoidal buildings and the creation of unique artistic artifacts (Srejović 1969). Also, some novelties in the funerary practices during this period recall the Anatolian Neolithic sphere, such as burials of neonates under the buildings' red-plastered floors at the Inner Gorges site of Lepenski Vir (Borić and Stefanović 2004).

In the Downstream Area around 6,000 cal BC, some Early Neolithic sites display greater cultural affinities with the Starčevo groups than with Inner Gorges' sites, notably funerary practices such as "multiple burials" with individuals in crouched position (Stalio 1986; Vasić 2008). Further important socio-cultural changes occurred in the Inner Gorges after ca. 6,000 cal BC (Early/Middle Neolithic period, ca. 5,900-5,500 cal BC) in terms of settlements (abandonment of the trapezoidal buildings, new types of domestic structures), material culture (intensified presence of Neolithic technologies), symbolic repertoires (Neolithic inhumations in crouched position; new ornaments and grave goods) and subsistence economy (Neolithic suite of domesticated animals; Borić 2011). Recent archaeobotanical studies also indicate that some micro-plant remains recovered from the dental calculus of individuals dated to the Transformation/Early Neolithic and Early/Middle Neolithic phases could have derived from cereals (Filipović *et al*. 2017; Jovanović *et al*. 2021).

A palaeodemographic approach of the Danube Gorges Mesolithic-Neolithic Transformations

While the chronology of the Neolithic expansion into Europe is now well-documented, we still have little knowledge on how local foragers experienced the transition, and on the mutual influences between the two groups. Considering the temporal depth of the archaeological sequence and the continuity in human occupation, as well as the complex evidence for Mesolithic and Neolithic interactions, the archaeological context of the Danube Gorges plays a central role in the study of Neolithization. These sites are also unique with more than 500 individuals remains, spanning the whole chronological sequence (Roksandić 2000). This skeletal record has provided researchers the opportunity to explore different palaeodemographic issues related to migrations, fertility, mortality, nutritional health and morbidity (Nemeskéri 1978; Grga 1996; Bonsall *et al*. 1997; Roksandić 2000; Jackes *et al*. 2008). Today, the constant reassessment of graves' chronological assignment through the publication of new radiocarbon dates (e.g. Borić 2011; Bonsall *et al*. 2015b) enables us to reconsider the results of these studies, for instance, concerning health (Radović and Stefanović 2013; Jovanović 2017). Also, the application of isotopic and ancient DNA analyses have recently shed new lights on Mesolithic-Neolithic demographic transformations (Bonsall *et al*. 1997; Borić and Price 2013; Mathieson *et al*. 2018; Jovanović *et al*. 2018). This chapter reviews these complementary bioarchaeological lines of evidence in light of the new available chronological information to assess the local experience and the demographic response of Central Balkans' foragers to the Neolithic expansion. Particularly, we synthesize the results of:

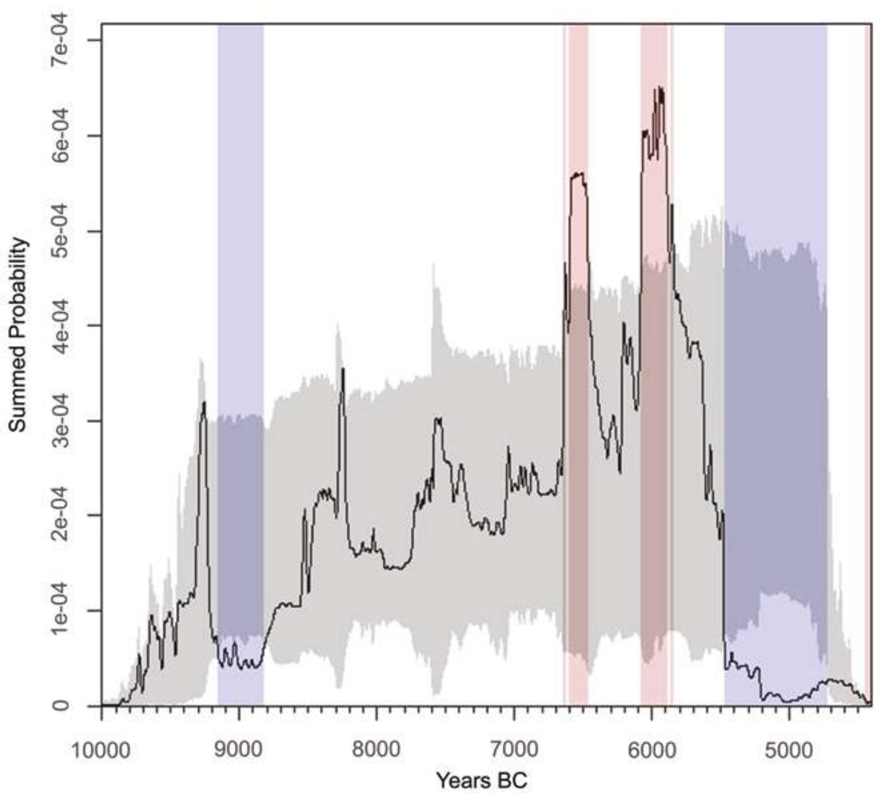
1. New SCPD analyses as a chronological proxy for population dynamics.

2. A chronological reassessment of the juvenility index, as indicator of the Neolithic Demographic Transition; Available morphological (skeletal biodistance studies), isotopic (strontium radiogenic), and genetic (ancient DNA) evidence about migrations.

3. Available biochemical (stable isotopes) and macroscopic (caries, and non-specific bone and teeth markers of physiological stress) information about dietary adaptations and health status.

1. Radiocarbon dates, intensity of occupation and population dynamics

During the past 40 years of research on the Danube Gorges, a long-lasting debate focused on the interpretation of the chronological sequence, required condition to understand the origin of farming in the region (e.g. Srejović 1969; Garašanin and Radovanović 2001; Borić *et al*. 2018). Large radiocarbon dating programs undertaken at the end of the 1990's have confirmed the very long span of the Epipalaeolithic-Mesolithic-Neolithic human occupation of the Gorges, clarified the chrono-stratigraphy of settlements and refined the chronology of the adoption of different cultural components of the Neolithic package (Cook *et al.* 2002; Borić 2011; Bonsall *et al.* 2015b; Borić *et al.* 2018). Beyond chronological advances, the local radiocarbon record may also provide valuable information related to the long-term demographic patterns. Based on the assumption that one can use "dates as data", summing the probability distribution of different radiocarbon dates (SCPD) at a given site should inform about the most probable period(s) of occupation. Consequently, summing similar information for numerous phases and sites at the regional level should draw a rough picture of the occupation's intensity fluctuation, in other words, periods of population growth and/or decline (Shennan *et al.* 2013). Bonsall *et al.* (2015a) reconstructed SCPD on the Danube Gorges radiocarbon dataset to specifically explore the local human response to climatic oscillations and local hydrological fluctuation. They found marked discontinuities in the SCPD curves circa 7,500-7,000, 6,700-6,000 and after 5,800 cal BC, corresponding to major climatic anomalies: the 9.3 and 8.2 ky cold events, and possibly colder temperatures circa 5,800-5,500 cal BC. Thus, they suggested that dips in the local SCPD curves should "reflect periods of higher annual river discharge and an increase in flood magnitude during Holocene "neoglacial" events, associated with generally cooler, wetter conditions in the Danube catchment upstream of the Iron Gates, and that the increased flood risk led to a reduction in the intensity with which people used certain sites or the lower parts of sites bordering the river" (Bonsall *et al.* 2015a: 6).



2. Statistical tests of the SCPD of the Danube Gorges radiocarbon dataset.

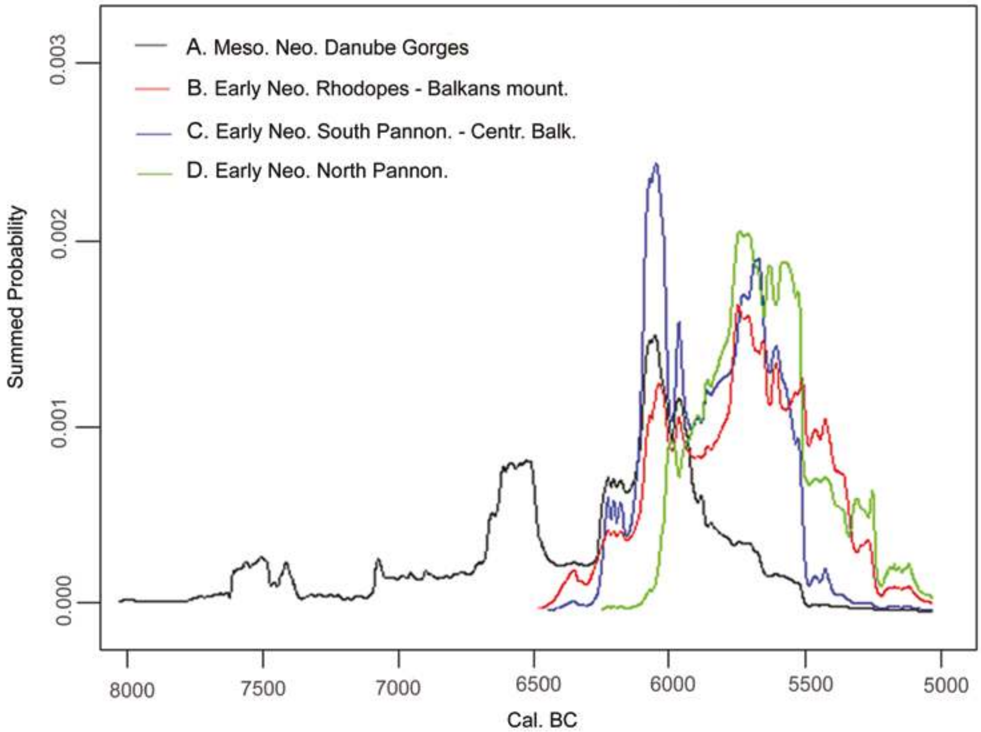
However, the version of the SCPD method used by Bonsall *et al.* (2015a) did not account for sampling bias – an important issue in the Danube Gorges – or taphonomy, and did not provide a statistical test for the significance of the observed patterns. To address these issues, we used the SCPD approach formulated by Shennan *et al.* (2013) and Timpson *et al.* (2014)[1]. In addition to applying a more rigorous statistical analysis, we also include 31 new radiocarbon dates (Penezić *et al*. 2020; Porčić *et al*. 2021; Jovanović *et al*. 2021; Jovanović *et al*. in prep.). A total of 312 audited dates from 12 Danube Gorges sites is included in the analysis. A correction for the freshwater reservoir effect was performed for all the samples with $\delta^{15}N$ values above the threshold following Cook *et al*. (2002).

In general, the SCPD curve shows significant deviations from the null model (global $p<0.001$; fig. 2). After the onset of the Holocene, the SCPD curve begins to increase slowly and irregularly, suggesting the presence of small and fluctuating population size in the Gorges, which is broadly consistent with archaeological information (Radovanović 1996; Borić 2011). The first significant drop can be observed between 9,200 and 8,800 cal BC and might coincide with a slight decrease in the NGRIP $\delta^{18}O$ palaeoclimate proxy (Bronk Ramsey 2009). The drop associated with the 9.3 ky cold event is less pronounced than in Bonsall *et al*. (2015a) and it is not statistically significant ($p= 0.276$) according to the specific SCPD test (Edinborough *et al*. 2017). The intensity of occupation as reflected by radiocarbon dates then statistically increases again after 7,000 cal BC, reaching its maximum ~6,500 BC (6,700-6,400 cal BC). Changes in the patterns of occupation of the sites during this period are also supported by the discovery of the earliest forms of trapezoidal buildings at sites such as Vlasac and Schela Cladovei, and of the first forms of red-plastered floors at Vlasac (Borić 2011). This episode of intense occupation is followed by a rapid and significant decline after 6,500 BC (ca 6,400-6,200 cal BC; specific SCPD test $p=0.0218$), roughly coinciding with the Hudson Bay Rapid Climate Change (6,600-6,000 cal BC) and particularly with the beginning of the sharp cooling episode of the 8.2 ka event (Weninger *et al*. 2014). Although the possibility that this drop in the SCPD curve could have been caused by a dramatic demographic crisis cannot be rejected (pathogen?), this scenario appears quite unlikely in the light of the age structure of the buried population and of available information on health status (*cf* infra part 2 and 4). A simpler interpretation might imply the possible departure of part of the local (semi-)sedentary population to settlements located outside, in the immediate vicinity of the Danube banks (or temporary return to a more nomadic lifestyle?). Such depopulating could have been caused by climatic oscillations and increased risks of floods, by temporary changes in the availability of some fish species, and/or by particular social tension or structural/territorial reorganization, perhaps in relation with the increased demographic expansion of the first Early Neolithic groups settled in the south of the Balkan Peninsula.

The main increase in the curve occurred around 6,200-5,900 cal BC, during the Transformation-Early Neolithic phase in the Gorges, concomitantly with the arrival of Early agro-pastoralist communities in the surrounding areas of the Central Balkans (figs. 2 and 3; Porčić *et al.* 2016; Blagojević *et al*. 2017; Porčić *et al*. 2021). This phase represents the apex of Lepenski Vir culture which reflects an original cultural identity featuring at some sites unique architectural elaborations, artistic creations and symbolic ways of expressions, and Mesolithic-Neolithic cultural hybritization (Borić 2011; Borić *et al.* 2018). The contacts between these two worlds should have thus contributed to intensify the occupation at localities such as Lepenski Vir. The foragers' knowledge of local environmental conditions may have represented an important advantage for agro-pastoralists' adaptations to the new biomes of Temperate Europe, which may have contributed to the fast rate of the Neolithic spread into the Central Balkans.

However, while this "contact phase" may have stimulated the growth of population grouped at some localities, the subsequent Early Neolithic demographic expansion in the surrounding regions of the Balkans ca 5,900-5,500 cal BC coincides with a gradual decline in the intensity of human occupation in the Danube Gorges (fig. 3). Although further socio-cultural changes occurred in the region after 6,000 cal BC, including the adoption of animal husbandry, the Gorges environment may not have been suitable (rugged topography) or attractive (new Neolithic social ethos) enough for the demographically expanding Starčevo groups and their agro-pastoral practices. After 5,500 cal BC, the entire Early Neolithic population of the Central Balkans also experienced a rapid demographic collapse, either caused by important emigrations or by some catastrophic events (fig. 3; Porčić *et al*. 2016; Blagojević *et al*. 2017; Porčić *et al*. 2021).

[1] This version of the SCPD method accounts for the research (sampling) bias by applying a binning procedure (we used 100 radiocarbon years as a threshold, resulting in 102 bins). The effects of taphonomy are accounted for by setting the taphonomic model as the null model for the Monte Carlo simulation. We used the exponential decay model published in Surovell *et al.* (2009) as the taphonomic model – the null model that assumes stationary population size with exponential effects of taphonomic loss on the SCPD curve (see Porčić *et al.* 2016 for details). The method also provides a test for the statistical significance of the deviations of the empirical SCPD from the null model by means of Monte Carlo simulation (10000 iterations). The method is implemented in the R (version 3.6.3), using the Rcarbon package (Crema and Bevan 2020).



3. Comparison of the SCPD of the Danube Gorges with the SCPD of neighboring regions presented in figure 1 (results of Porčić *et al*. 2016 and Blagojević *et al*. 2017).

2. Mortality profiles, growth rates and female fertility

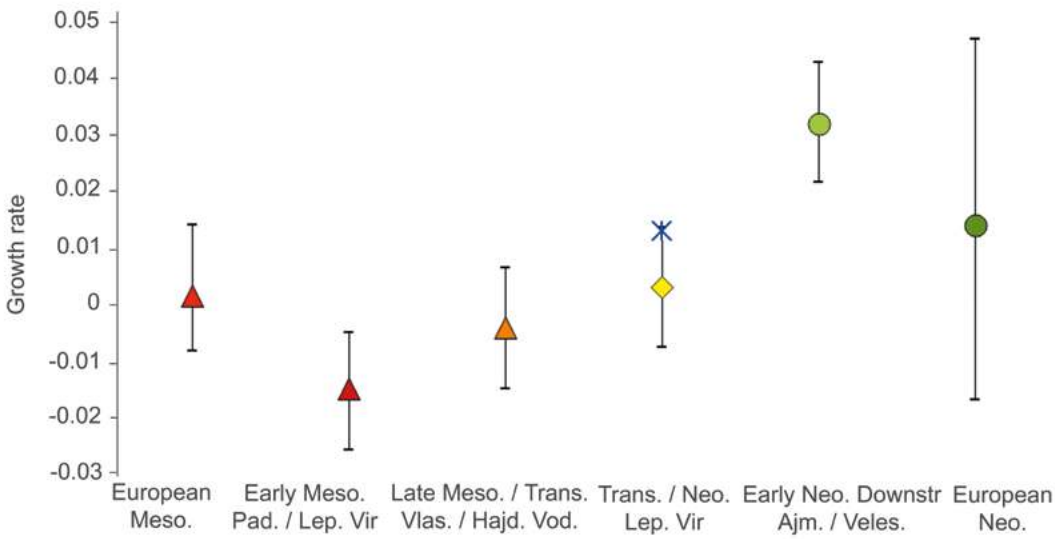
The evidence for an intense occupation of the Gorges during the 7th millennium BC calls into question the possibility of an important local population growth prior to the adoption of agricultural practices. Several authors applied diverse palaeodemographic indices on the grouped osteoanthropological sample and inferred a rather stable and stationary population with both low fertility and low mortality, comparable to other European Mesolithic population (Meiklejhon *et al*. 1997; Bocquet-Appel 2002). Jackes *et al*. (2008) further examined these data per sites and chronological periods, adding samples from sites located in the Downstream Area (Ajmana and Velesnica). Their results confirmed previous observations for the Mesolithic period, and indicated a fall in fertility at Lepenski Vir during the time of the Mesolithic-Neolithic contact, interpreted either in relation to an over-representation of adults due to their influx from outside or as an actual effect of changing and unstable conditions. In contrast, the grouped Neolithic sample indicate an increase in fertility (Lepenski Vir Early Middle Neolithic and Downstream Early Neolithic sites), consistent with the assumptions of the NDT. The new radiocarbon dates and the reassessment of chrono-cultural sequences has allowed us to re-assign individuals to different periods and to re-interpret these results. To limit the "squeezing effect" which may result from averaging data for numerous generations or for sites with different mortuary practices, we first inferred growth and birth rates from the juvenility index (the proportion of children aged 5-19 to the whole population; Bocquet-Appel 2002) calculated per sites' chronological phases and then per broader chrono-geographical groups (Table 1 and fig. 4)[2].

Reassessed growth and birth rates confirm that the Mesolithic population was rather stable and stationary (Table 1 and fig. 4). The particularly low growth rate inferred for the Early Mesolithic period could result from the habitual mobility patterns of foragers communities

[2] The age of children was reassessed based on dental development when possible or the length of long bones (de Becdelièvre *et al*. 2020a). We followed the procedure of MNI calculation developed by Jackes *et al.* (2008), just re-assessing the final accounts by-assigning individuals to different periods (using chronological information from Borić and Price 2013; Borić *et al.* 2014; Bonsall *et al*. 2015b; Stefanović 2016; Borić *et al*. 2018; data in de Becdelièvre *et al*. 2020a).

Phase - Sites	n 5-19	n 20+	$_{15}P_5$	Growth rate (95% confidence interval)	Birth rate (95% confidence interval)
Early Meso. Lep. Vir	3	14	0.17	0.001 (-0.009 – 0.01)	0.036 (0.03 – 0.04)
Early Meso. Padina	2	41	0.0046	-0.025 (-0.035 – -0.014)	0.014 (0.08 – 0.020)
Late Meso. - Trans. Vlasac	14	127	0.099	-0.01 (-0.02 – -0.001)	0.023 (-0.023 – -0.002)
Late Meso. - Trans. Haj. Vod.	5	40	0.1	-0.01 (-0.02 – 0.007)	0.025 (0.019 – 0.031)
Trans. Lep. Vir	12	62	0.16	-0.001 (-0.01 – 0.094)	0.034 (0.028 – 0.040)
Early-mid. Neo. Lep. Vir	11	36	0.23	0.009 (-0.0018 – 0.002)	0.046 (0.040 – 0.051)
Early Neo. Ajmana (Downstr.)	7	7	0.5	0.036 (0.025 – 0.047)	0.086 (0.080 – 0.092)
Early Neo. Velesn. (Downstr.)	3	5	0.375	0.025 (0.014 – 0.035)	0.068 (0.061 – 0.073)

Table 1. Growth and birth rates inferred from the juvenility index ($_{15}P_5$), computed using the proportions of individuals aged 5-19 years old and more than 20 years old, per sites and archaeological phases.



4. Growth rates and 95% confidence intervals inferred from the juvenility index ($_{15}p_5$) for the Mesolithic-Neolithic sites of the Gorges and comparison with Mesolithic (n=9) and Neolithic (n=91) European populations (data from Bocquet Appel 2001 and Downey *et al.* 2014). The cross refers to the growth rate value inferred for the Tranformational period of Lepenski Vir from house-floor-based Bayesian demographic methods (Porčić and Nikolić 2014).

using these locations as burials and/or residential sites, and to a biased representation of different age classes possibly caused by higher level of daily or seasonal mobility. Differential models of mobility and of territories occupations could indeed influence the representativeness of skeletal data either in relation to the place where the death occurred or because of associated mortuary practices, and one should keep in mind that the "squeezing" generational effect should be higher for long-term Mesolithic phases of occupation. These results also suggest that the apparent Late Mesolithic population increase reflected by the SCPD should rather be related to a change in the occupation patterns than to a demographic process internal to the population. Possible explanations include an increase in the number of localities used simultaneously for fishing activities, for instance, changes in the organization of subsistence and daily activities, changes in the territorial structuration and social organization perhaps related to an increased sedentism. Although excluded from these palaeodemographic indicators for methodological concerns, remains of numerous neonates have been recovered associated with adults in Late Mesolithic contexts[3] (Borić and Stefanović 2004; Stefanović and Borić 2008). An even higher number of neonates have been uncovered in the Transformational phase of Lepenski Vir below the house-floors[4], a cultural practice which points of the Anatolian and Southern Balkans Neolithic sphere (*ibidem*). Therefore, the deposition of these babies below the house-floors could reflect some modification of reproductive behavior and/or young children mortality rates which took place at the time of the first contacts with the Early Neolithic communities.

We did not find the drop in fertility observed by Jackes *et al.* (2008) for the Transformational period of occupation of Lepenski Vir: the growth and birth rates appear slightly higher than inferred for other Late Mesolithic-Transformational contexts, but still range in the lower part of European Mesolithic population variability (Table 1 and fig. 4). Thus, the important occurrence of neonates at Lepenski Vir might be related to their better preservation due to new mortuary rituals, and perhaps also to the site-specific symbolic nature. An increase in females' fertility and thus neonatal mortality could also produce such a pattern. Porčić and Nikolić (2015) recently estimated growth rate for the period of Transformations/Early Neolithic at the site of Lepenski Vir by combining the archaeological settlement evidence (data on house floor areas and stratigraphic information) and ethnoarchaeological information (floor area-to-household size, house-use life, hunter gatherer group size) with mathematical models of house accumulation and population growth within the Approximate Bayesian Computation framework. According to the authors, the initial population at Lepenski Vir must have been low, within the range of 5-20 people, while the final population size corresponds to ethnographically documented village size of people dependent on aquatic resources (30-40 people; estimated growth rate: ca 0.01-0.02; fig. 4). The growth rates estimated between skeletal data (-0.007-0.014) consistently overlap with house-floor inference (0.004–0.02). The slight difference between the estimated ranges might simply be related to the differential resolution and nature of these indicators: the growth rate calculated from skeletal data groupings should be tightly correlated to birth rates, and could be affected by mortuary practices (differential eligibility of some parts of the population to different burial places), whereas the growth rates based on archaeological stratigraphic information may be affected by alternate demographic or cultural factors, such as migrations or changes in the function or use of the houses.

While Jackes *et al.* (2008) pooled individuals from the sites of the Downstream Area (samples of Ajmana and Velesnica) with the Early-Middle Neolithic assemblage of Lepenski Vir, recent radiocarbon dates suggest that they might be earlier (Velesnica: ca 6,215-5,845 cal BC; Ajmana: 6075-5715 cal BC; Bonsall *et al.* 2015b). Palaeodemographic indicators reconstructed for these Early Neolithic sites located downstream suggest higher fertility and childhood mortality rates (Table 1 and fig. 4). Although these two samples are smaller in size (total number of individuals = 26), these different demographic parameters coincide with the notable cultural differences with the sites of the Inner Gorges, including funerary patterns (Stalio 1986; Vasić 2008). One cannot disregard the possibility that the inferred growth rate might be affected by specific mortuary practices for subadults. However, these results coincide with the broad differences observed between European Mesolithic and Neolithic demographic patterns (fig. 4) and fits with the results of the SCPD analyses of Mesolithic and Early Neolithic occupation in the Central Balkans (fig. 3). Because demographic models and mortuary practices may not be entirely unrelated, the differential birth and childhood mortality rates, as observed amongst European Mesolithic and Neolithic societies, may also influence the community idea about household and parenting, the social roles

[3] A proportion of 28 foetus and neonates for 127 Late Mesolithic – Transformational adults (mostly dated to the Late Mesolithic period – Borić and Stefanović 2004; Borić *et al.* 2014).

[4] A proportion of 41 neonates for 62 adults (Borić and Stefanović 2004; Stefanović 2016)

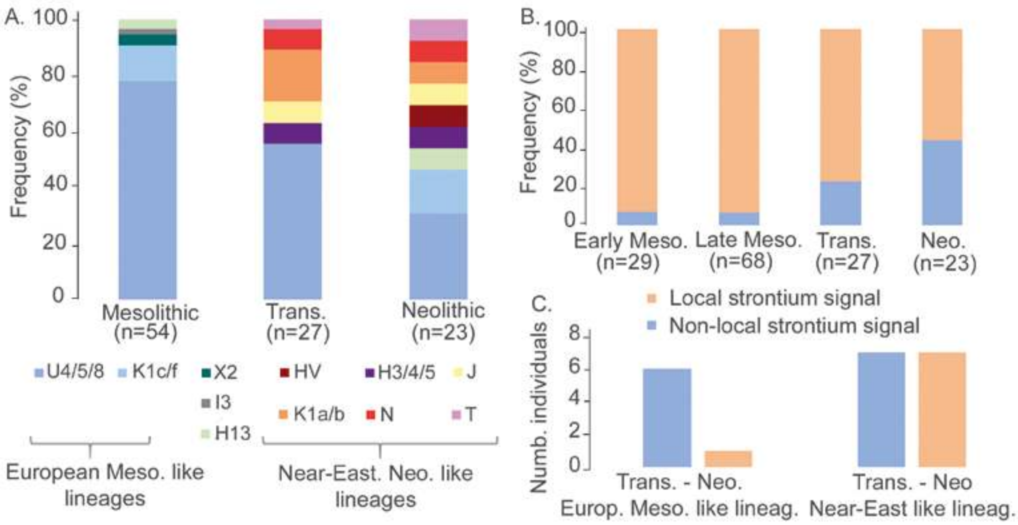
of the youngest amongst the community, and possibly their places amongst the deaths of the group. Thus, the peak in the Danube Gorges SCPD curve identified around 6,200-5,900 cal BC could be explained by the attractiveness of Lepenski Vir in the Inner Gorges and by the local presence of Early Neolithic communities with higher growth rates and probably different social organization. However, the growth rate inferred for the Transformational and Neolithic phases of Lepenski Vir (respective average ca -0.001 and 0.009) still range in the lower part of European Neolithic farmers' variability and coincides with the average value for European Mesolithic hunter-gatherers. As also suggested by the gradual drop noticed in the SCPD curve between 5,900-5,500 cal BC, the demography of local foragers may not have been sustained with the expansion of agro-pastoral populations of Pannonia and of the Central Balkans valleys, and the consequent marginalization of the Gorges.

3. Early Neolithic migrations, interactions, and admixture

Besides the changes in the population age structure, the osteoarcheological sample provided a direct opportunity to explore migrations and admixture issues and test Neolithic diffusion models. In the first studies conducted on the osteoanthropological assemblages from the Gorges, some authors observed a temporal trend towards gracilization interpreted as the effect of new dietary adaptations and/or of migrations (Mikić 1981; Menk and Nemeskéri 1989). Particularly, individuals buried at Downstream Area sites (Velesnica and Ajmana) display more gracility than most Mesolithic individuals buried at Inner Gorges' sites but are comparable to some individuals discovered in the Neolithic layers of Lepenski Vir (Živanović *et al.* 1986; Radosavljević-Krunić 1986). Roksandić formalized these observations further through a biodistance study of individuals buried at different sites of the Inner Gorges (Roksandić 2000). Her results indicate a local biological continuity in the region with a gradual temporal ordering and a more pronounced difference at the time of contact (Roksandić 2000). The chronological re-assessment of these results, as well as Principal Component Analyses additionally performed on a set of cranial measurements, have also shown that the Early Neolithic individuals buried in the Downstream Area range on the margin of the local Mesolithic-Neolithic distribution (de Becdelièvre *et al.* 2015).

The results of strontium radiogenic ($^{87}Sr/^{86}Sr$) and palaeogenetic (aDNA) studies have provided further insight into the causes for this morphological temporal variation pattern (Borić and Price 2013; Hofmanová 2017; Mathieson *et al.* 2018). Strontium radiogenic analyses have directly documented a dramatic increase in the number of individuals of non-local origin (first generation migrants), mostly females, buried in the Danube Gorges at two sites – Lepenski Vir (Inner Gorges) and Ajmana (Downstream Area) – during the period of Transformation-Early Neolithic, and during the Early/Middle Neolithic period (fig. 5B and C; Borić and Price 2013). Palaeogenomic studies have recently evidenced that an important proportion of individuals buried at Lepenski Vir during the Transformational and Neolithic phase belong to maternal clades which were found amongst Near Eastern and European individuals, but which were mostly absent amongst analyzed genetic sequences of European Mesolithic populations (fig. 5A; Hofmanová 2017; González-Fortes *et al.* 2017; Mathieson *et al.* 2018). Most individuals of non-local origins belong to Near-Eastern Neolithic-like maternal haplogroups. These observations have been confirmed on formal genetic distance analyses and additional Bayesian biostatistical analyses have also confirmed that a few individuals buried in the Gorges had an admixed European Mesolithic-like and Near-Eastern Neolithic-like ancestry (Hofmanová 2017; Mathieson *et al.* 2018). Foragers' interactions with Early Neolithic communities settled the downstream Wallachian plain and the southern Pannonian plain, and the presence of migrants descended from Anatolian Neolithic groups may thus explain the increased density of occupation observed in the Gorges ca 6,200-5,900 cal BC at the time of the flourishment of the Lepenski Vir culture.

Finally, the possibility that these interactions may have led to an increased pattern of social tension and inter-group conflicts has been explored through the examination of traumatic lesions on skeletal remains (fractures and projectiles injuries; Roksandić *et al.* 2006). The individuals who bear traces of wounds were mostly dated to the Late Mesolithic period (14 Late Mesolithic out of 16 individuals with traces of wounds), indicating that these traumas cannot have resulted from violent foragers/farmers oppositions but rather from sporadic episodes of interpersonal violence, maybe in relation to the increased density of occupation of the region during the first half of the 7th millennium BC.



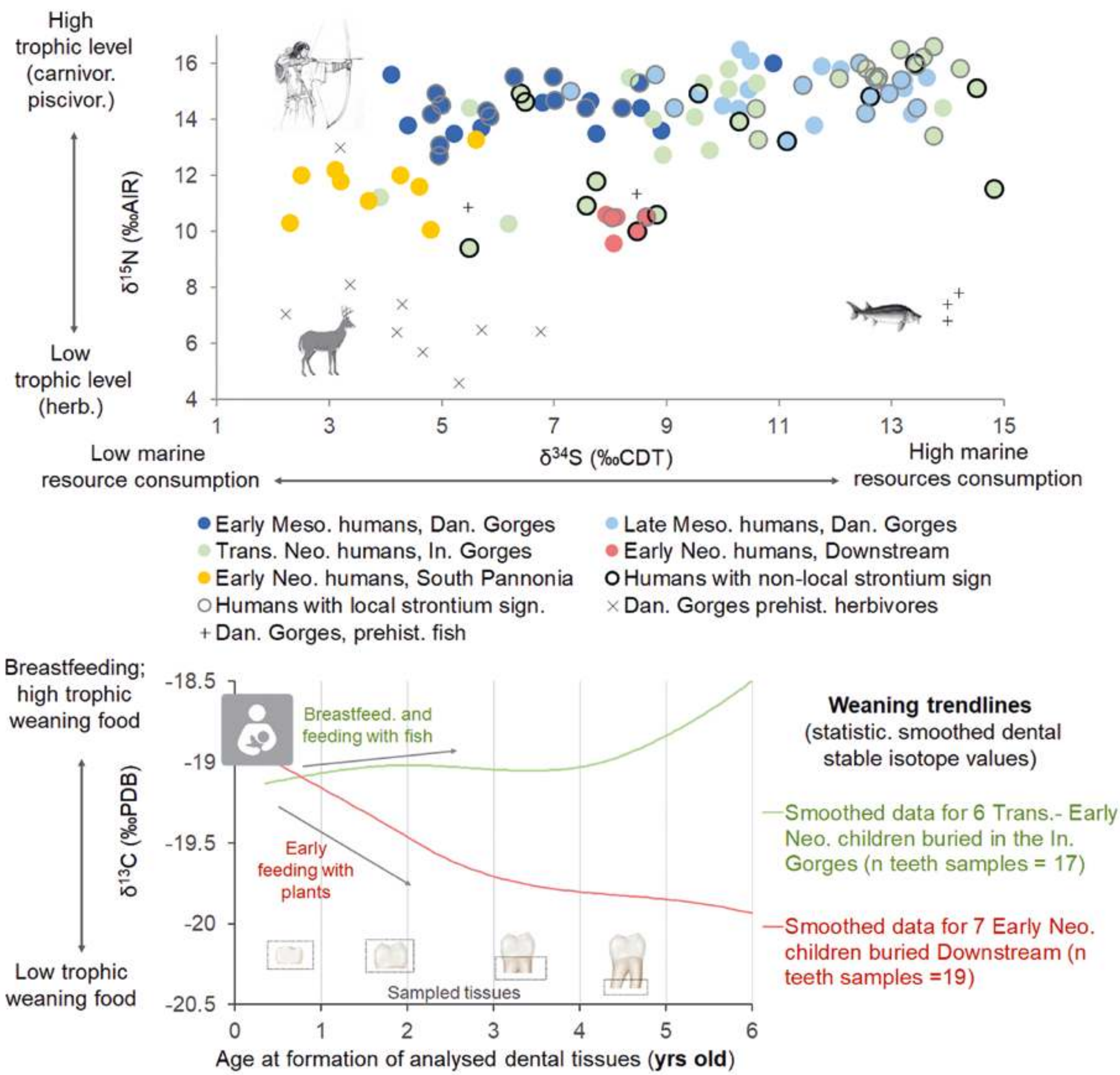
5. A: frequency of Danube Gorges prehistoric individuals from different mitochondrial haplotypes (from Hofmanová 2017; González-Fortes ***et al***. 2017; Mathieson ***et al***. 2018). B: frequency of Danube Gorges prehistoric individuals with a local or non-local strontium radiogenic signal (Borić and Price 2013); C: number of locals and non-locals assigned to U or non-U maternal lineages.

4. Behavioural interactions, adaptations and the mechanisms of the NDT

The information provided by numerous paleodietary studies and by the analyses of nutritional and physiological health markers conducted on the Mesolithic-Neolithic sample from the Danube Gorges provides the opportunity to consider the relationships between population dynamics and subsistence adaptations, and to examine locally some behavioral mechanisms beyond the NDT.

Stable isotopes studies have confirmed that fishing played a central role in the local ways of subsistence during the whole Mesolithic period (Jovanović *et al.* 2018). Various oral health studies have also suggested the greater consumption of protein-rich food, over carbohydrate-rich resources (low incidence of caries; high rates of dental calculus and high degree of teeth abrasion; e.g. Grga 1996; Radović and Stefanović 2013; Jovanović 2017). Some scholars have related the elevated rates of some skeletal markers of essential nutrients deficiencies to the possible presence of local aquatic food-borne parasitic infections (high frequency of porotic hyperostosis and presence of *cribra orbitalia* ; Meiklejohn and Zvelebil 1991; Jovanović 2017). More specifically, the observation of a shift up in δ^{34}S values suggests that anadromous fish should have become particularly important in the local subsistence after ca 7,000 cal BC, as a possible result of change in the availability of local species and/or in fishing strategies (fig. 6A; Jovanović *et al.* 2018; de Becdelièvre *et al.* 2020a). Therefore, we can suggest a relationship between the adaptation of subsistence strategies towards an intensified-specialized fishing and the intensified occupation reflected by the SCPD ca 7,000-6,500 cal BC, at the time when the earliest forms of trapezoidal buildings appear along the Danube. During warmer and better climate periods, a change in patterns of residential mobility amongst these semi-sedentary communities could have been associated with an intensified exploitation of local resources, the development of specialized fishing strategies, population agglomeration and increased density of occupation at some localities along the Gorges.

Zooarchaeological studies have documented a continuity in the local ways of subsistence during the period of Transformations and the Neolithic; animal husbandry has indeed only been introduced after 6,000/5,900 cal BC in the Inner Gorges, where it likely remained subsidiary to fishing and hunting and played a minor role than at most surrounding Starčevo settlements (Bartosiewicz *et al.* 2001; Borić and Dimitrijević 2006). While crop remains have been found at numerous Early Neolithic sites of the Central Balkans, the documentation remains scarce concerning sites of the Gorges (Filipović *et al.* 2017; Jovanović *et al.* 2021). In accordance with the evidence for Early Neolithic migrations, the stable isotope analyses of Transformational – Neolithic individuals have



6. A: sulfur and nitrogen stable isotope ratios ($\delta^{34}S$, $\delta^{15}N$) for Mesolithic-Neolithic individuals from the Central Balkans (aged >10 years old) and prehistoric animals discovered in the Danube Gorges (data from Nehlich *et al.* 2009; Borić 2011; Jovanović *et al.* 2018; de Becdelièvre *et al.* 2020a). B: carbon stable isotope "weaning trendlines" for Transformational-Early Neolithic children from the Inner Gorges and the Downstream Area (smoothed $\delta^{13}C$ values obtained on several dental tissues using a Loess statistical procedure; adapted from de Becdelièvre *et al.* 2020a).

revealed a broadening of the local variability towards lower values, indicating that some individuals consumed substantially fewer aquatic resources (fig. 6A; Bonsall *et al.* 1997; Jovanović *et al.* 2018). While individuals buried at most sites of the Inner Gorges exhibit high $\delta^{15}N$ ratios in continuity with the previous period of occupations (high aquatic resources consumption), some buried at the central site of Lepenski Vir in the Inner Gorges display lower values, similar to all individuals buried in the Downstream Area (Ajmana and Velesnica) and to those discovered in other Starčevo contexts from the broader Central Balkan regions (fig. 6B; Jovanović *et al.* 2018; de Becdelièvre *et al.* 2020a). The individuals with lower $\delta^{15}N$ and $\delta^{34}S$ values whose strontium radiogenic signal was analyzed have been identified as first-generation migrants: they likely originated from communities with a mixed farming-foraging subsistence economy (de Becdelièvre *et al.* 2020b). In contrast, all their putative descendants – the individuals with a local strontium signature born in the region of the Gorges but belonging to a Near-Eastern Neolithic-like lineages – exhibit elevated stable isotope ratios, which confirm their adaptation to the local ways of subsistence (*ibidem*).

Intra-individual stable isotope analyses (the longitudinal analyses of different tissues formed between birth and teenage) have also shown significant differences in feeding strategies between the Mesolithic and Transformational children buried in the Inner Gorges and the Early Neolithic children buried downstream (fig. 6B). The later experienced a more abrupt transition to solid food and were supplemented with preparations made of lower trophic-level resources than the former whose weaning preparations likely contained aquatic resources (de Becdelièvre 2020a). The children buried at the downstream site of Ajmana are also the only one to display evidence of dental caries, only observed in the Gorges on a few Transformational-Early-Middle Neolithic adults discovered at Lepenski Vir and Ajmana (Jovanović *et al.* 2017; de Becdelièvre 2020a). With cereal-based weaning preparations (carbohydrate-rich food resources), deciduous teeth should have been particularly at risks for dental caries. Besides, although the occurrence of enamel hypoplasia, caused by events of physiological stress experienced during childhood, remains low in the Gorges throughout the Mesolithic-Neolithic sequence, a greater frequency of affected children has been observed at the Early Neolithic sample of Ajmana, downstream (*ibidem*). The skeletal examination of Early Neolithic discovered in the Broader Central Balkans and Southern Pannonian Plain has also revealed higher number of dental caries and of skeletal markers of nutritional deficiencies, confirming the pattern reported for several other Near-Eastern and European early farming communities (Jovanović 2017).

These results are in the line with some of the assumptions for the causes of the NDT, which posit that differences in terms of children feeding practices may contribute to the reported demographic differences between foragers and farmers (Bocquet-Appel 2008): the presence of potential new weaning strategies and technologies may have facilitated an earlier decrease in the intensity and the frequency of suckles and released the Neolithic mothers from the energetic burden of lactation, increasing fertility rates; in turn, these new feeding practices may not have been optimal for children oral and physiological health.

The analyses of anomalies on the annual deposits of cementum of Mesolithic and Neolithic individuals from the Danube Gorges and the broader Central Balkans region have also reported that Neolithic individuals experienced more frequent episode of stress during adulthood (Penezić *et al.* 2020). This tendency was statistically significant only for females which, combined with the fact that pregnancies are one of the major causes of stress layer formation in tooth cementum, might also be related to the Early Neolithic increased fertility in the region. In the trade-off with individual fitness (life-expectancy and well-being), it seems that the expansion of the farming niche dramatically favored populational fitness (reproductive success; Lambert 2009).

Conclusions: Neolithized foragers and Mesolithized farmers, an original case-study for palaeodemographic research

Demography plays a central role in all aspects of Anthropology, from the study of populating patterns and cultural transmission processes to the mechanisms of evolution and social adaptations. Research have shown that the onset of the farming system induced an unprecedented demographic growth, both triggering and stimulated by a sprawling geographic expansion, migrations, cultural transmission, and ecological adaptations. The archaeological complex of the Danube Gorges has provided a unique opportunity to reconstruct long-term trends in demographic fluctuations in the Central Balkans, a key region for our understanding of the Neolithization of Europe. Analyses of the radiocarbon dataset indicate an increase in the intensity of human occupation in the Gorges during the mid-7th millennium BC, which might be associated with a change in settlements patterns of occupation and a reduction of residential mobility. Interpreted in the light of stable isotope values and archaeozoological data, this intensified occupation of some localities may be related to an intensified exploitation of aquatic resources and the development of more specialized fishing strategies. This period of intense occupation was followed by an important decline (ca 6,400-6,200 cal BC), which coincides with the harsher conditions of the Hudson Bay Rapid Climate change, and perhaps with the departure of part of the local (semi-)sedentary population to more distant settlements.

The main increase in the intensity of occupation dates to the end of the 7th millennium BC and is concomitant with the arrival and demographic increase of the first farming communities in the broader Central Balkans, and the adoption of ceramics in the Gorges. Genetic analyses revealed that individuals genetically closer to Near-Eastern Neolithic communities were buried at Lepenski Vir near individuals genetically closer to European Mesolithic individuals. Also, there is genetic evidence for admixture. During this period Lepenski Vir may have been an attractive site for a broader population, and a central place for contacts, exchanges, and interactions between the foragers of the Gorges and the first agro-pastoralists settled in surrounding regions.

At the same time, bioanthropological and cultural material data suggest that the settlements located in the Downstream Area may have represented some Starčevo Neolithic cultural enclaves which may have played a role in the diffusion of Neolithic practices in the Inner Gorges. The growth rates inferred from the Transformational and Neolithic skeletal assemblages of Lepenski Vir are rather similar as data available for European Mesolithic population; in contrast, the demographic parameters inferred from the Early Neolithic osteo-archaeological assemblages of the Downstream Area are at the higher end of the prehistoric agricultural societies' variability. All individuals discovered in this area exhibit lower stable isotopes values than individual buried in the Inner Gorges. Children dental isotope analyses also demonstrated that their feeding strategies significantly differed, with higher rates of dental caries and greater frequency of enamel hypoplasia. It is possible that such different dietary behaviors may have differently affected some demographic parameters – females' fertility and children health – of the Danube Gorges foragers and of Central Balkans Early Neolithic communities.

After 5,900 cal BC, the intensity of human occupation in the Gorges gradually declined over the 6th millennium BC, at the time when the Early Neolithic demographic expansion in neighboring regions was likely fueled by the high fertility rates of the first agro-pastoralists. Further larger generations of migrants were discovered at Lepenski Vir and probably brought different socio-cultural Neolithic novelties. Yet, agro-pastoral activities remained rather subsidiary in the local ways of subsistence in comparison with fishing and hunting. The general pattern of health decline usually associated with the onset of the farming system is not documented in the region of the Danube Gorges: the important consumption of micro-nutrient and protein-rich food resources probably contributed to buffer the adverse effect of the Neolithic Transition, which contrasts with the situation observed at other Early Neolithic contexts of the Central Balkans where the greater occurrence of physiological and nutritional markers of stress could be a by-product of niche colonization, early farming practices, diet, and elevated fertility rates. At that time, it is possible that the environment of the Gorges was less suitable for the agropastoral practices of Starčevo people, and that the former foragers' way of living became increasingly forsaken by the appearing Neolithic social ethos.

The resolution of (bio-)archaeological information now available from the region of the Danube Gorges has shed lights on some local mechanisms of the NDT. The same relationships which have been observed between reduced residential mobility and intensified exploitation of local food resources amongst Near-Eastern Epipalaeolithic hunter-gatherers may have also sporadically caused similar increases in the size of some groups of European Mesolithic foragers, in the Gorges, the Dniepr, along the Atlantic, North, and Baltic seas coasts. Yet, as exemplified by the Late Mesolithic inhabitants of the Danube Gorges, it is possible that the extractive way-of-subsistence may have not be enough to sustain larger-size population of foragers for long period of time, and the comparison of the SCPD with paleoclimatic proxies suggests that the demography of these larger groups of sedentary foragers should have been quite dependent on climatic oscillations.

The population dynamics inferred at the onset of the agro-pastoral way of life in the Central Balkans is consistent with the predictions of the NDT, as there is evidence for Neolithic migrations followed by population growth which preceded a demographic decline. While the first contacts between foragers and first agro-pastoral communities should have contributed to stimulating population growth in areas populated by foragers, the presence of foragers may have also played a role in the rapid geographic expansion and adaptation of the Neolithic package in the region. Although there is evidence for greater proportions of admixture with foragers in the Central Balkans than in the regions previously populated by Early farmers, their biological contribution to future generations of Neolithic farmers remained limited, as observed in other regions of South-Eastern, Central and Western Europe. This situation likely contrasts with Northern and Eastern European regions where interactions may have lasted longer or where different aspects of the Neolithic were gradually adopted without significant demographic contribution from migrants.

Notable differences in terms of children feeding strategies between the Mesolithic – Neolithic foragers of the Inner Gorges and the Early Neolithic communities settled in the Downstream Area could have differently influenced some aspects of females' metabolism or reproductive development, as well as childhood health. Such differences in parenting strategies may have also contributed to the rapid Neolithic demographic expansion in the region. The analyses of children feeding practices amongst other transitional populations could allow further testing. In the Central Balkans, it is possible that local foragers' demographic behavior could not sustain high population density facing the explosive demography of the first agro-pastoral communities.

Conducting further research on the demographic dynamics during periods of subsistence transition may contribute to deepen our understanding of the mechanisms of human adaptability in relation with key events of niche construction and colonization. Far from saying "Farewell to palaeodemography" (Bocquet-Appel and Masset 1982), welcoming diverse bioarcheological and biomolecular approaches in paleodemographic studies has provided a wealth of comparable data that allows not only for reconstructing population dynamics, but also for exploring the causes and the consequences of historical demographic cycles, an essential knowledge to contemplate better paths towards sustainability in a connected and globalized world with billions of people.

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Ancient Greek colonization in retrospect: population projections from the birth of colonies

L'ancienne colonisation grecque en rétrospective : projections démographiques de la naissance des colonies

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Abstract: Greek colonization (8th-5th c. BC) was one of the most momentous demographic and socio-cultural events in ancient Europe, spreading people, goods, art, ideas, and lifestyles across the Mediterranean and the Black Sea. This paper evaluates the demographic developments that followed this historical process by applying classical methods of demographic projections (Preston *et al.* 2001). In this exploratory analysis, we use the Corinthian colony of Ambracia as a case study, estimating the most probable trajectories of population change throughout the three centuries. We developed numerous fixed demographic scenarios with the cohort component method and varying fertility, mortality, and migration levels. From these scenarios, we present the most likely ones following historical references and archaeological data.

Keywords: Greek colonisation, demographic projections, demographic scenarios, cohort component method, Ambracia

Résumé : *La colonisation grecque (VIII^e^-V^e^ s. av. J.-C.) a été un événement démographique et socioculturel de grande importance dans l'Europe ancienne. Ce phénomène a contribué au mouvement de la population et à la diffusion des biens, de l'art, des idées et des modes de vie à travers la Méditerranée et la mer Noire. Dans cet article, nous évaluons les développements démographiques de l'Antiquité classique qui ont suivi la colonisation grecque (VIII^e^-V^e^ s. avant Jésus-Christ) en appliquant les méthodes classiques de projections démographiques (Preston* et al. *2001). Dans cette analyse exploratoire, nous utilisons la colonie corinthienne d'Ambracie comme étude de cas, en estimant les trajectoires les plus probables de changement de taille de la population au cours de trois siècles. Nous avons développé de nombreux scénarios démographiques fixes avec la méthode des composantes des cohortes et des niveaux variables de fertilité, de mortalité et de migration. Nous présentons les plus probables des scénarios, conformément aux références historiques et aux données archéologiques.*

Mots clés : *colonisation grecque, projections démographiques, scénarios démographiques, méthode composantes des cohortes, Ambracie*

Introduction

Within the period of about four centuries (circa 8th-5th c. BC), population movements organized by Greek *poleis* of the Aegean islands, southern mainland Greece and Asia Minor caused significant changes in the population image of the ancient Mediterranean and the Black Sea. The establishment of overseas settlements by Greeks, referred to as Greek colonization, influenced the Hellenic and Roman world in antiquity and had a permanent imprint on European history (Graham 1999; Ridgway 1992; Boardman 1980).

The foundation of hundreds of new cities in distant areas, the interaction between settlers and a plethora of local populations, and the relatively short time in which many colonies evolved into major, cultural, commercial, and political centers, has turned Greek colonization into one of the most studied subjects in European ancient history and archaeology. Plenty of historical and archaeological studies describe the process of Greek overseas settlement (Graham 1999; Ridgway 1992; Boardman 1980; Grammenos and Petropoulos 2007; Tsetskhladze 2008). In many cases, Greeks founded numerous colonies in close spatial proximity to each other. For instance, the total count of Greek colonies in the area of the North Aegean, within a distance of about 400 km, exceeds one hundred, founded within the time span of three to four centuries (see Tiverios 2008).

The driving forces behind the Greek overseas expeditions, which started flowing from the Aegean around the 8th c. BC are still a subject of research and discussion among academic circles. A considerable number of theoretical outlines/scenarios/hypotheses for Greek colonization developed over the past century. Each one of these approaches focuses on a different aspect of Greek colonization, emphasing on some of its particular characteristics. Many such approaches analyze its socio-economic and political dimensions (e.g. Graham 1999; Ridgway 1992; Boardman 1980; Grammenos and Petropoulos 2007; Tsetskhladze 2008), while others highlight its demographic and population ecology conditions (Sallares 1991; Scheidel 2003). The latter approaches suggest that the overall population sizes of ancient Greek communities grew substantially over a few centuries. Furthermore, from the 8th c. BC onwards, ancient Greece was transformed from a world of villages to a world of towns (Morris 2006).

Despite the lengthy scholarly investigations, little is known today about the population history of Greek colonization. The number of bioarchaeological and palaeogenetic studies on the topic is still limited (see Zisis and Papageorgopoulou 2019 for a review), with only a small number of academic publications in the last decades (e.g. Keenleyside *et al.* 2006; Keenleyside 2008; Kyle *et al.* 2016). Moreover, the small, existing corpus of research mainly focuses on individual archaeological sites without framing or interpreting the results in a broader historical context. Also, written sources and archaeological data do not suffice for grasping a detailed image of how ancient cities grew in terms of demographics.

One hypothesis is that a substantial percentage of the total Greek population of 4th c. BC, up to 40 percent, lived outside the Greek homeland, either in colonies or overseas communities (Hansen 2006). Nevertheless, there is no clear image of how founding populations developed through time in colonial settings.

Consequently, an obvious research question arises about the population developments during this time. However, this is a complicated subject, which encompasses several problems. The first one is related to the population size of founders and the role of the demographic forces of population change (fertility, mortality, migration) during population growth. Other related questions are about the founding population structure and its development in time and the role of local populations in the formation of the demographic profile of these colonies.

To evaluate these demographic trends, we present a case study, the ancient city of Ambracia. We apply to this historical population the typical method of forward population projection in formal demography. Our procedure includes three steps:

1. The estimation of the founding population and the population size by age and sex at the beginning of the population projection;

2. The evaluation of the demographic components of fertility, mortality, and migration during these time points;

3. The application of the forward demographic projection method (Preston *et al.* 2001).

Population projections by age and sex are a way to estimate the size and structure in the future. Today, they are widely used by governments, international organizations, and academic institutions to plan and develop social, economic, and health policies, create public infrastructure, etc (Raftery *et al.* 2012). So far, this method has not been used to study ancient populations.

The cohort component method applied in this chapter is a discrete-time model of population dynamics based on mathematical functions compared to continuous-time models (Preston *et al.* 2001).

The method segments a population into different subgroups differently exposed to the likelihoods (risks) of fertility, mortality, and migration. Subsequently, the method computes the changes over time in each group separately, as it segregates the population into age and sex groups. Population characteristics are calculated at certain moments separated by time intervals that are usually the same length as the required age intervals. Then, the projection is carried out, one interval at a time (Preston *et al.* 2001).

This is the first effort to apply the cohort component method to ancient populations. The inverse methodology, i.e., backward population projections, has been applied to historical populations (e.g. Moreno-Almárcegui *et al.* 2016). The data used for backward projections vary over different studies, depending to their quality or even presence. Examples of such efforts are: the Webster *et al.* 1992 population estimates for Honduras (Paine *et al.* 1996) and the preserved population censuses, from which demographic projections move back in time, with fixed values for fertility, mortality, and migration (Moreno-Almárcegui *et al.* 2016).

Similarly, in our exploratory effort, we set fixed levels and scenarios of mortality, migration, and fertility trajectories but proceeding in the opposite direction of forward population projections. Several details of our methodology and its future applications are being discussed, testifying this method's applicability to palaeodemographic data.

Materials and Methods

The population setting

The ancient city of Ambracia is an exceptional example of a Greek colony with a wealth of historical information (fig. 1). The Corinthians founded Ambracia around 640 BC in the area known as Dryopis, near the river Arachthus. The city soon became economically prominent, with an impressive fleet. The colony's location was in the same geographic area as the contemporary city of Arta. The Corinthian *oekist* (term used for the founder of the colony), named Gorgos, was the son of Kypselos, the tyrant of Corinth (Gehrke and Wirbelauer 2004). Ambracia served as a member of the Hellenic League against Persia and participated in the Peloponnesian War, together with Corinth, as an ally of Sparta (Gehrke and Wirbelauer 2004). The city had an abrupt end, as it was devastated by the Romans during the 2nd c. BC.

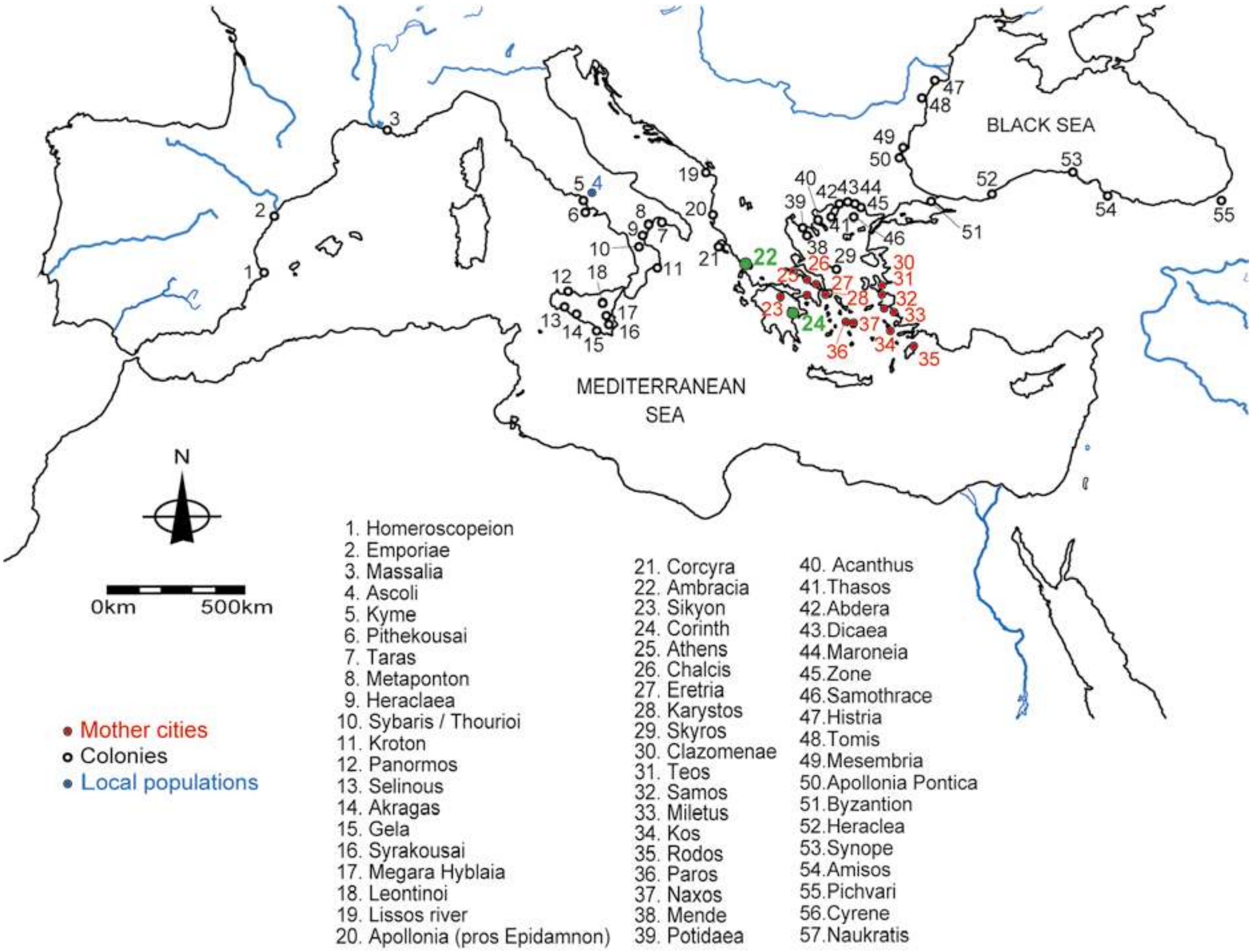
Estimation of the initial and final population sizes

The founding population

The initial number of founders is unknown. Herodotus (4.153) suggests that a typical number of settlers during the Greek colonization process would have been around 200 individuals. Such a suggestion cannot be easily dismissed because mother-cities frequently founded several colonies within a limited time frame. Keeping in mind that Greek cities in antiquity were of medium to small size, the question of population availability to sent to overseas settlements arises. If too many citizens participated in colonial endeavors, mother-cities would end up depopulated. However, there is no historical confirmation of such circumstances, except for the known case of Teos and Abdera, in which Abdera re-founded their mother-city, Teos (Graham 1992).

There is also a significant limitation in the traveling/colonizing capabilities of people in the ancient world. Before the invention of the trireme, and its general use from the 5th c. BC onwards, the most commonly used type of ship, for all nautical purposes, was the penteconter (50 rowers in its crew), which could not carry more than 120 persons (Casson 1986). The relatively limited space of ancient sea vessels to carry passengers, together with the financial cost of shipbuilding, is an additional factor supporting that the founding populations of Greek colonies did not exceed a few hundred individuals, in most cases. However, it is possible that the colonies' settlement was a continuous process on behalf of mother-cities, which lasted for a long time.

For these reasons, we hypothesized that the initial population must have been somewhere between 100 and 400 individuals. Moreover, we hypothesized that this population must have been structured with age groups below the age of 40, considering the elevated mortality in ancient times (see text below). We applied several sex ratios for every age group to create many scenarios for the founding population in the forward population projections. The influence of the initial population size in projection results will be discussed in the results section.



1. Selected ancient Greek colonies and mother-cities. Corinth and Ambracia are labeled in green dots.

The population at the end of the projection (mid-4th c. BC)

For the final population size of Ambracia, we used the estimation of Hansen 2006 for the mid-4th c. BC. This estimation is based on habitation quarters, houses, the size of a typical Greek household (which was about 4-5 persons), and published archaeological landscape surveys for ancient Greece. Specifically, Hansen considers that approximately 150 people inhabited each hectare within a walled city. Moreover, Hansen suggests that only half of the intramural area was inhabited for each city, while the rest of the space was available, for example, for roads and public buildings. However, such an estimation could be conservative toward a low population density. Our hesitation to accept Hansen's estimation without further critical though is because similar population densities have been suggested for older periods, such as the Neolithic (Bocquet-Appel and Bar-Yosef 2008), when population sizes could have been even smaller. Despite the aforementioned limitation, we have chosen to follow Hansen for the time being.

According to this approach, the intramural space of Ambracia covered 130 ha in the mid-4th c. BC. Hansen 2006 assumes that only half of this space was occupied for residential purposes. Therefore, 65 ha x 150 persons per ha give a population of 9,750 inhabitants in the urban center, which corresponds to the Greek colony, and will be used as the end population of our projections.

Mortality, fertility, and migration trajectories between the founding time and the mid-4th century BC

Mortality

There are no direct estimations of mortality levels for ancient Ambracia. Although the osteological sample excavated from the two cemeteries of Ambracia exceeds 600 individuals between the archaic period and the arrival of the Romans, the anthropological study of this material is still ongoing at the Laboratory of Physical Anthropology at Democritus University of Thrace and unpublished.

However, we know that since the Neolithic Demographic Transition, a high-pressure demographic regime was initiated, probably with high birth and mortality rates (Bocquet-Appel and Bar-Yosef 2008). The development of sedentism and the intensification of agriculture have been connected with increases in infectious diseases and nutritional deficiencies, particularly affecting infants, children, and older adults (Armelagos *et al.* 1991). The increase of population density (Bocquet-Appel 2011) and the appearance of urbanization (Dyson 2011) developed favorable circumstances for the spread of pathogens and the rise in mortality rates in urban environments later on (MacFarlane Burnet *et al.* 1972; some examples for classical Greece can be found in Papagrigorakis *et al.* 2006 and for a discussion see Shapiro *et al.* 2006).

These findings are in accordance with the epidemiological theory proposed by Omran (1971); and despite the criticism of his view (see McKeown 2009), which suggests that the pre-industrial societies, and consequently the ancient world, lived in the age of pestilence and famine when a high mortality regime dominated, and the mean life expectancy ranged between 20 and 40 years. At the same time, according to the classical theory of demographic transition (Galor 2012), pre-industrial societies had high levels of both fertility and mortality - not forgetting, of course, the high variability existing among ancient populations (Morley 2011).

Thus, mortality rates in Greek antiquity were most likely high compared with today's standards. But, how high exactly? Lawrence Angel produced rather pessimistic estimations about life expectancy at birth in ancient Greece, based on scanty, fragmentary, and spatially limited osteological remains, and thus not representative (Angel 1969; Angel 1947), which -for males- would not exceed 25 years for the period around 650-350 BC (Sallares 1991). However, such extremely high mortality levels can only be understood in mortality crisis contexts, such as the advent of the black death in European history (see Shipman 2014).

Therefore, life expectancy at birth in ancient Greece may need to be revised somewhat upwards, in line with what Angel proposed, perhaps to the upper twenties or low thirties (Woods 2007) - but such estimations still appear to be rather pessimistic.

A more optimistic approach was followed in this procedure. Life expectancy at birth (e^0) was set to cyclically fluctuate during each century between 30 and 40 years for both males and females. This approach is more compatible with the historical data, indicating the prosperity of the ancient cities and their developmental course (Morris 2006).

For each projection period, the hypothesized levels of life expectancy at birth were used as the basis for the evaluation of age-specific mortality rates and probabilities with the method of linear extrapolation (Rowland 2003). To do so, we selected the Coale *et al.* 1983 empirical model life tables, population West, level 4, as our standard age mortality pattern. We chose these life tables because of their potential suitability to fit the mortality regime in ancient Greece (these model life tables were also used by Hansen 2006). All the other model life tables from the Coale *et al.* 2013 database were used during the projection, but they gave similar results to the West level 4 model life table. Therefore, we chose to present only the aforementioned.

Fertility

As suggested in the previous paragraphs, fertility in the ancient world is expected to be high. One possible explanation for this is that the ancient populations were in a natural fertility state, i.e., they did not use fertility control methods, such as extended breastfeeding, plant use, newborn sex-selection, medical intervention. (Henry 1961). However, even with control methods, relevant total fertility rates (TFRs) among populations can vary, ranging from about 3.5 to 10 live births per woman (Hirschman 1994; Wood 2017). Within this framework, Hansen suggested that a woman living in ancient Greece would give birth to five or six live-born children on average (Hansen 2006).

However, suppose we accept such fertility rates as standard. In that case, we ignore the possible diversity of the ancient Greek populations and the probable different fertility trajectories that might have occurred in the past. We must not forget that fertility, as a social phenomenon, is characterized by small inertia, being subject to several socio-economic, historical, and political parameters, especially when the population is living in a Malthusian regime, which governs both mortality and fertility rates (Malthus 1872).

In fact, the elucidation of fertility rates in ancient Greek societies is one of the major goals of this analysis. Since fertility is a fundamental life-history trait with a significant contribution to population growth, we tested many different fertility rates. Specifically, for each founding population, we created scenarios with unchanged TFRs (2,3,4,5,6,7) throughout the three centuries and with TFRs changing with time. The combinations of changing TFRs that were tested are 2-3-4, 4-5-6, and 5-6-7. According to TFRs, the variability in the projected populations was remarkable. These results' diversity led us to choose only possible scenarios and discard the others.

Migration

In half of the scenarios, a zero-migration balance was applied. The reason for that is primarily to test the contribution of fertility rates to the overall population growth and decipher the role of mortality in demographic processes.

In the scenarios with positive migration balance, we chose to give the net migration inflows a unimodal shape with an augmented cohort of 20-24 years of age for both sexes. This is because we assumed that young people would be more likely to join a newly founded colonial site – given that new opportunities would be abundant there. This is why migratory inflows were set to gradually increase during each century's timespan and start over at their initial size at the beginning of each new century.

Thus, the annual net migration changed over time in our models. This trend was repeated every 100 years. At the beginning of each century, some migrants were set to join the colony. In models with a settling population of 100 individuals, five migrants joined the colony during the first year. When the settling population was 200 or above, ten migrants joined the colony the first year. Migration numbers followed a cyclical pattern. By the end of each century, migratory flows reached 50 individuals, when the settling population was 100, and 100 individuals for larger settling populations. Since the actual annual migration flows are unknown, we used a rather conservative positive migration balance, which includes variations and seemed to suit our model scenarios.

Whoever entered the city's population contributed positively to the migration balance of our models, even when belonging to local tribes. Greek colonies, in general, must have been more of a center of attraction for people outside the founding population (locals, individuals from the mother-city, or other Greek cities) than cities that expended migratory outflows, at least during the first centuries of their existence. Therefore, a positive migration balance was always considered.

The application of the forward demographic projection method

In the forward cohort component method, both the overall size of a population and its structure by age and sex at a given future time (t_1) equal with the initial population (at time t_0) plus births and migratory inflows, minus deaths and migratory outflows. The estimates are calculated separately for every sub-group. Each cohort includes five-year age groups for males and females, separately. The same five-year range also applies to each population projection.

According to this method, the population is distributed into different sub-groups, experiencing the "risk" of fertility, mortality, and migration. The calculations are made for each sub-group separately. The time interval for each projection is usually the same as the age-group interval. For each projection interval, three steps are followed, as described in Preston *et al.* 2001, where the mathematical formulas and several details of the cohort component analysis can be found.

Every possible combination of variability in the demographic components was tested.

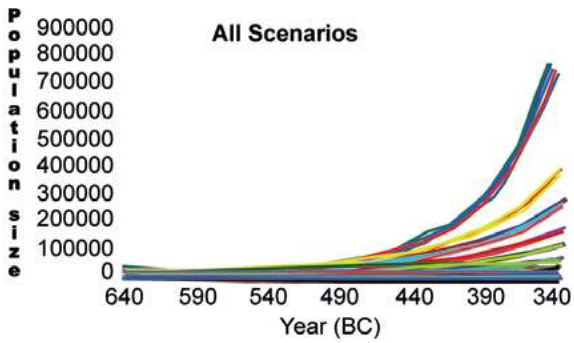
Results

According to the values given to the components of demographic change, each population model developed differently. The final projected populations ended up with a range between a few hundred individuals to nearly 800,000 (fig. 2). Fertility and migration contributed positively and enhanced the overall variability of the estimated population sizes, considering that the same mortality trajectories were applied in all scenarios.

In our results, a kind of exponential population growth is suggested. On the one hand, this has to do with the selected trajectories of fertility, mortality, and migration.

On the other hand, the growth may represent a possible population expansion. We should not forget that there are cases of historical populations, such as Egypt (Whittaker 1970), where exponential population growth occurred over long periods because of the availability of natural resources. However, exponential population growth is not always the case for historical populations, and the shortcomings of our method will be discussed below.

We present the four most plausible scenarios: All scenarios begin with a small base population of a few hundred individuals and reach a size close to 10,000 (Table 1). All population pyramids that accompany the projected scenarios define a young population structure with high fertility and mortality. The inclusion of a positive migration balance in scenarios 3 and 4 differentiates the shape of population pyramids slightly compared to scenarios 1 and 2, calculated with zero migration.



2. Illustration of all the projected demographic scenarios of five initial settling groups, ranging from 100 to 400 individuals.

	Initial population (640 BC)	Total fertility rate (TFR)	Mortality rates	Migration	Final population (340 BC)
Scenario 1	100	6-7	30-40 years	zero	9,054
Scenario 2	200	5-6-7	30-40 years	zero	9,577
Scenario 3	100	4	30-40 years	positive	9,829
Scenario 4	200	2-3-4	30-40 years	positive	10,568

Table 1. Demographic parameters summary of the scenarios 1-4.

Scenario 1 (fig. 3)

The founding population is 100 individuals, ranging between five and 49 years. This population is distributed unevenly between the age groups and increases the population size between 20-24 and 25-29. Because it is exceedingly difficult to hypothesize how older adults participated in the migration, age groups become smaller towards the end of the pyramid.

According to this scenario, the total fertility rate (TFR) is six children per woman, except for the final 15 years, when it increased to seven. Migration is zero. Life expectancy at birth for both sexes is around 30 years at the beginning of each century and increases gradually to 40 years by the end of each century. The final projected population in the year 340 BC is 9,054 individuals.

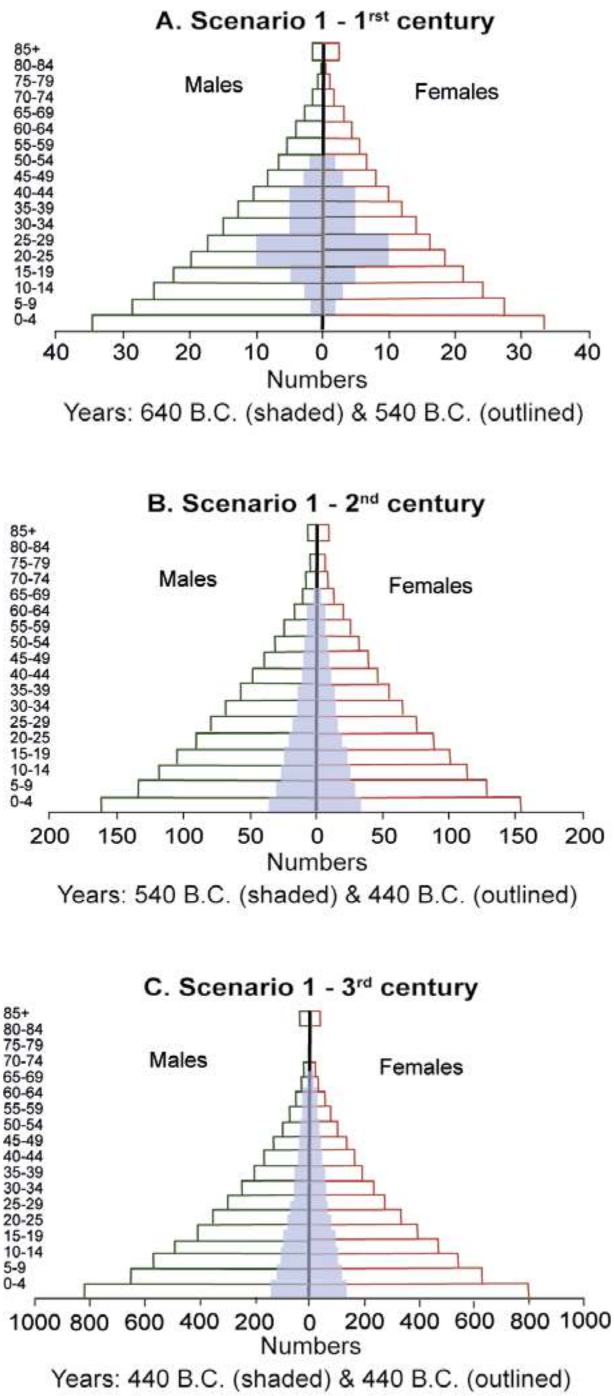
Thus, the population of Ambracia will develop to the desired population size only if fertility rates were very high under the assumption of zero migration and considering the selected mortality levels. If mortality were higher, then fertility rates would have to be even higher.

In such circumstances, Hansen's estimations of five to six live-born children per woman are somewhat pessimistic. Nevertheless, this is an unrealistic scenario because the hypothesis of a closed population cannot be satisfied in actual circumstances.

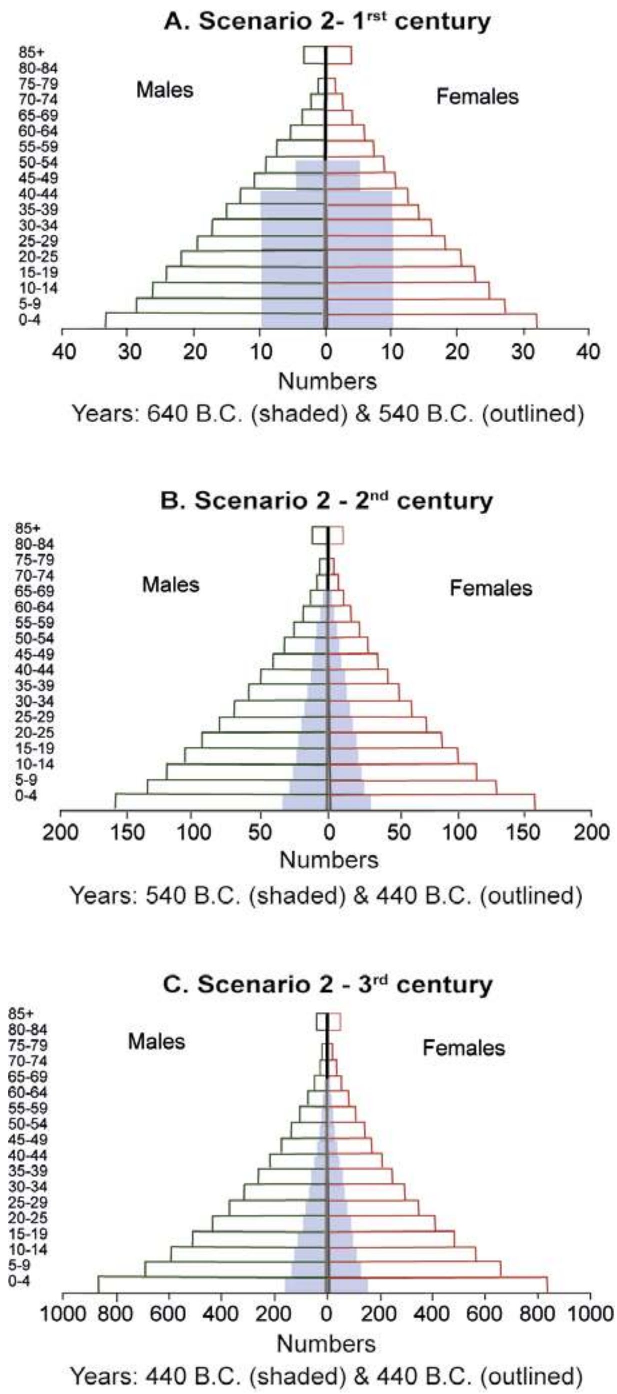
Scenario 2 (fig. 4)

In the second scenario, we have doubled the initial population to 200 individuals. Even if the age distribution does not affect significantly the projections, as it happens with all the scenarios tested, in the analysis, we included ten males and ten females for all age groups until the age of 44. In the age groups 45-49 and 50-54 there are five males and five females respectively. The TFR is five for the first 95 years of the projection, six for the next 180 years, and seven for the last 15 years. Migration is zero. The final projected population in the year 340 BC is 9,577 individuals.

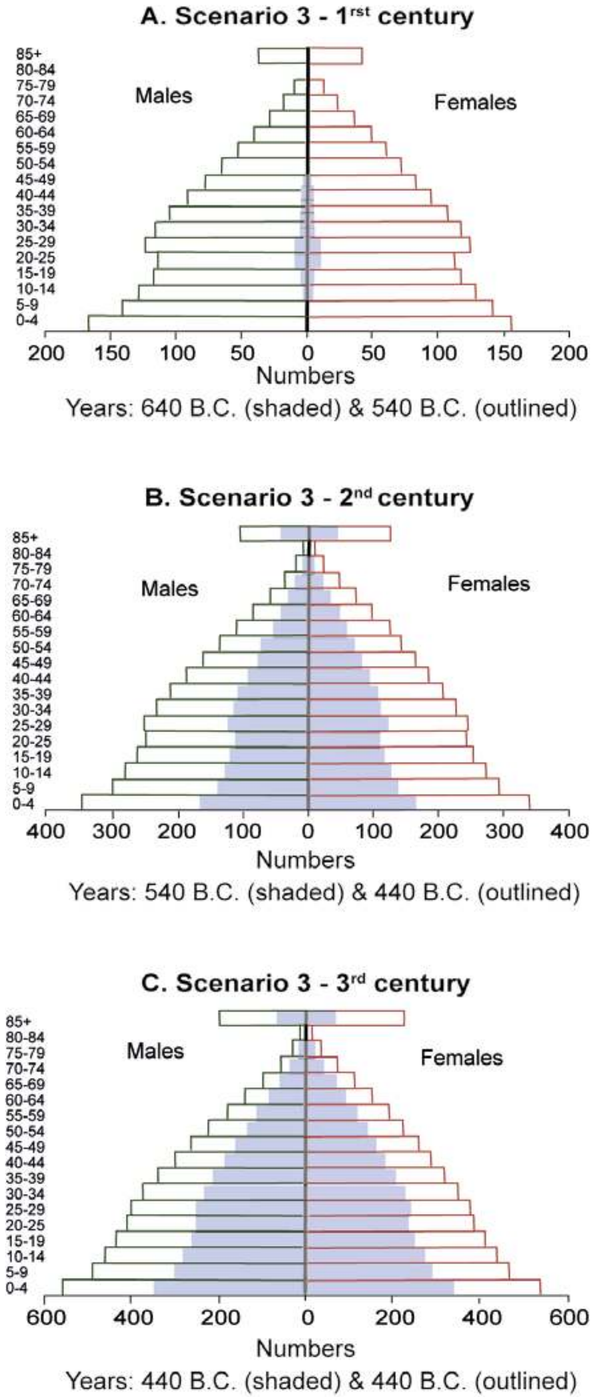
In this scenario, we also need very high levels of fertility, which are again above Hansen's estimations.



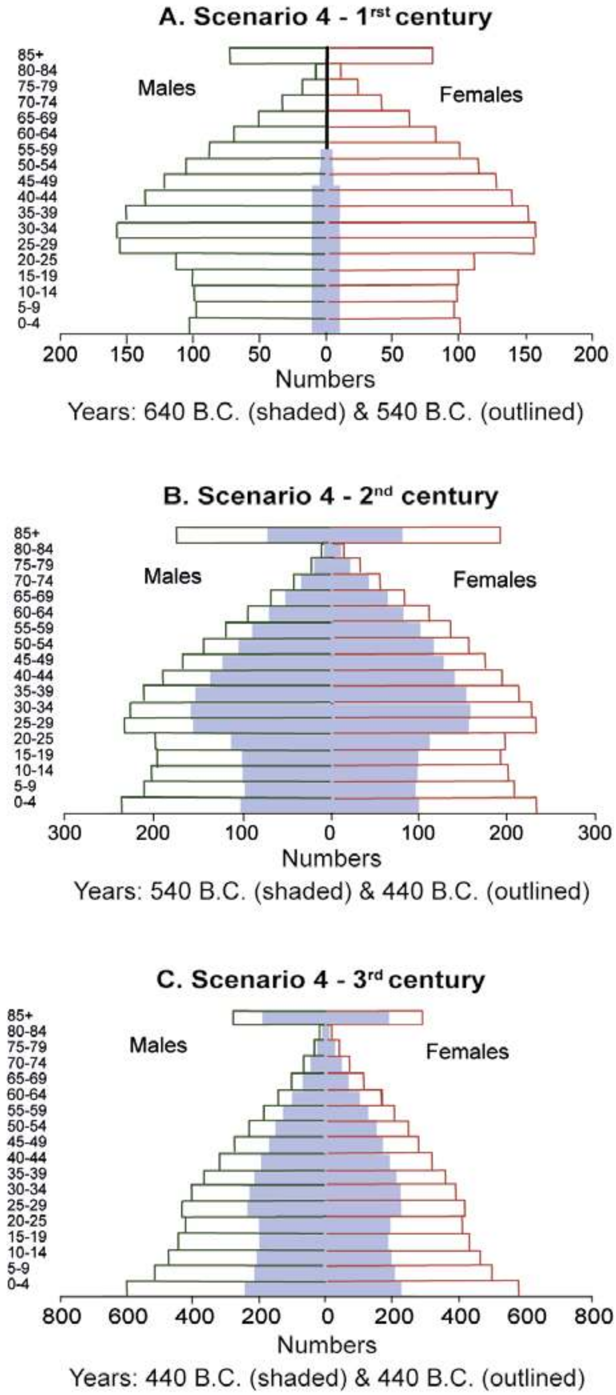
3. Ambracia - Population Pyramid by Age & Sex for scenario 1. A: 1rst c.; B: 2nd c.; C: 3rd c.



4. Ambracia - Population Pyramid by Age & Sex for scenario 2. A: 1rst c.; B: 2nd c.; C: 3rd c.



5. Ambracia - Population Pyramid by Age & Sex for scenario 3. A: 1rst c.; B: 2nd c.; C: 3rd c.



6. Ambracia - Population Pyramid by Age & Sex for scenario 4. A: 1rst c.; B: 2nd c.; C: 3rd c.

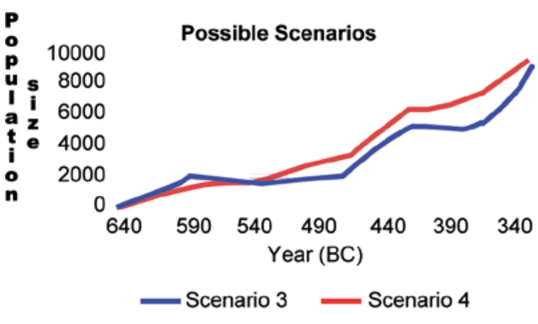
Scenarios one and two are impossible to adapt to real-world circumstances. We present them to demonstrate the levels of total fertility rates needed for the desired Ambracia's population size to be reached in the mid-4th c. BC, under specific assumptions for migration and mortality.

Scenario 3 (fig. 5)

In the third scenario, the initial population is set at 100 individuals, and its age distribution the same as in scenario one. In this scenario, the population is open to migration. The annual net migration is positive and starts with five persons in the first five years of each century. Then, it gradually rises to 47 by the end of each century. The total fertility rate (TFR) is four children per woman throughout the projection to reach a total population of 9,829 individuals at the end of the process. Thus, fertility is somewhat lower than Hansen's estimations.

Scenario 4 (fig. 6)

In the fourth scenario, we doubled the initial population to 200 settlers. The age distribution of the base population is the same as scenario two. The desired population size is reached with moderate total fertility rates (TFRs=2,3,4), increasing by one unit every century. The annual net migration is positive and starts with ten persons for the first five years of each century, rising to 95 for the last five years of each century. The final population in the year 340 BC is 10,568 individuals.



7. Population trajectories of scenarios 3 and 4. Scenario 3 begins with 100 settlers, and scenario 4 with 200 settlers.

After the population projections, the population sizes according to scenarios three and four are illustrated in Figure 7. We can see that similar results can spring from different demographic scenarios. In both cases, fertility rates were estimated to be lower than Hansen's estimation. However, these scenarios are only two of the possible solutions given in a variety of fertility, mortality, and migration trajectories that may have occurred in the past. This is why we need to extend this approach to consider the possible diversity of the demographic components trajectories through time in antiquity.

Conclusion

Palaeodemography complements biological anthropology to shed light on population processes, for which osteological samples do not suffice, either because of their poor representativeness or because of the difficulty for correctly estimating skeletal age at death (Wood *et al.* 1992; Konigsberg and Frankenberg 1992). So far, palaeodemographic research has followed different methodological approaches to address these difficulties (see Bocquet-Appel and Bar-Yosef 2008; Séguy and Buchet 2013; Wood 1998; Hoppa and Vaupel 2008). Bocquet-Appel and Masset (1982) emphasized all the issues to consider for a palaeodemographic analysis in their classic paper.

The cohort component forward projection method, in addition to its suitability for demographic predictions and its wide use in current research, has another fundamental advantage. The method can show how the conditions of an existing population age structure may influence future population growth – a phenomenon referred to as 'population momentum.' In other words, population growth depends not only on current fertility and mortality levels but also on the population age structure, which, in turn, is a legacy of past fertility and mortality (Preston *et al.* 2001).

Our research topic was the historical process of Greek colonization and how it changed the demographic history of ancient Greece. Historical demographers (Morris 2006; Scheidel 2003; Sallares 1991) have previously suggested that the ancient Greek population grew substantially between the 8th and 4th c. BC – a period that covers precisely the period of Greek colonization. The reasons for this suggested growth include a favorable natural environment and improved agricultural methods.

Using the ancient city of Ambracia, a colony of Corinth, we tested numerous demographic scenarios with varying levels of fertility, mortality, and migration as a case study. We used fixed values for all three variables and combined them in forward population projections. Although we concluded in favor of some possible scenarios, among a vast majority of unsuitable ones, other scenarios, which did not appear in our analysis, are still probable.

The final populations may vary greatly depending on the influence of each component of demographic change or their combination– beginning only a little over a hundred individuals and reaching up to almost 800,000.

In our projections, life expectancy at birth increases with each century but decreases again at the beginning of the next century. This cyclical pattern, repeated three times in each projection, serves as a demographic 'safety' mechanism for possible periods of population stress, known to be frequent in historical times. We do not hypothesize a steady increase in life expectancy at birth over time because human communities during antiquity are broadly put into the 'Age of pestilence and famine' category (Omran 1971), with a relatively low average life duration.

We were particularly interested in fertility in our analysis. First, because we consider fertility to be a key component in ancient population dynamics. Second, we wanted to explore fertility's specific role in the presumed population growth during the time that followed the foundation of Greek colonies.

We suggest that the initial group of settlers who arrived at the area from Corinth was close to 100 and 200 individuals in size. The fertility rates in the colony were somewhere between two to four children on average for each woman.

We consider scenarios three and four as highly likely to have occurred in reality, following principles of modern demography and the information given by ancient historians and the archaeological data. We suggest that in antiquity, and specifically, during the development of Greek overseas colonies, a typical family would have had 2-4 children who should have survived into adulthood. Although we are not aware of family sizes in ancient Greece, and given that our estimations are close to reality, we could agree with Hansen 2006, who argued that, on average, each woman must have given birth to five or six live-born children, out of which only two or three would come to age and procreate.

We are aware that our approach has some limitations. First, the population projection method is a long-term approach. In our case, the method is applied to an environment with unknown historical circumstances, including the availability of natural resources and the specific political landscape. Moreover, the typical population projections' methods have a deterministic character. They try to assign a specific value to the demographic measures calculated (e.g. population size and structure).

Besides the numerous methodological issues that have been addressed, there are a few other historical ones. For example, there is the sex ratio of the first settlers and the role of the local populations in the demographic and socio-economic development of Greek colonies. It is often argued that the groups of first settlers arriving with ships to new lands consisted mainly of young males. However, there is no consensus regarding this view, as females and children could have been part of naval, overseas expeditions (e.g. Petropoulos 2005). Nevertheless, a typical ship's crew consisted mainly of male rowers - and long-distance rowing would be difficult for most women and children.

The nuclei of settlers must have attracted local individuals and perhaps local women. However, there is only little archaeological evidence supporting the presence of local women in Greek colonies. An example of such archaeological markers in colonial cemeteries is the fibulae found in graves in Magna Graecia (Coldstream 1993). Since there is currently no definite answer to this question by anthropological data, we constructed our projection scenarios with equal numbers of males and females in the base populations. Consequently, either Greek colonists came with their spouses from the mother-city or married local women. These women were included in our initial population structures, even though we cannot be sure of their place of origin.

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4. Epistemology of a discipline, from biological anthropology to paleodemography

Thoughts on some manuscripts by Jean-Pierre Bocquet-Appel

Réflexions à propos de quelques manuscrits de Jean-Pierre Bocquet-Appel

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Abstract: Some of Jean-Pierre Bocquet-Appel's publications among the least cited in GoogleScholar are mentioned here, seeking to explain the reasons for their small international audience and showing how they shed light on some aspect of the scientific career path of their author.

Keywords: publication strategy, anthropometry, fecondity, path analysis, wombling

Résumé : *Quelques publications de Jean-Pierre Bocquet-Appel parmi celles qui sont le moins citées dans GoogleScholar sont évoquées ici, en cherchant à expliquer les raisons de leur faible audience internationale et en montrant en quoi elles éclairent le parcours scientifique de leur auteur.*

Mots-clés : *stratégie de publication, anthropométrie, fertilité, analyse des pistes, wombling*

Jean-Pierre Bocquet-Appel's (JPBA) publications have, for the most part, achieved a significant readership. According to Google Scholar, the most cited article is undoubtedly "*Farewell to paleodemography*" (Bocquet-Appel and Masset 1982), with 661 citations[1]. Of all his publications tracked via Google Scholar, the average citation is around 56, with 34% of publications cited less than ten times. As with any career, the publication strategy depends on various linguistic, institutional, or financial constraints, which inevitably leads to a certain proportion of seldom or never cited publications. This rather dry statistic obviously reveals nothing about the intrinsic quality or interest of such publications. They are often the result of original work carried out on the fringe of the researcher's dominant themes and may have been the subject of publications, often mediocrely edited in obscure journals or poorly promoted by the authors themselves. Some works fade away with time, quickly eclipsed by more visible, better published, or more relevant novelties. Is this wretched fate always deserved? Do such neglected works deserve further attention or are they merely the froth of 'real' science that dissipates over time?

To illustrate these introductory remarks, I propose to review some of JPBA's publications to highlight those that have not had the chance to acquire the readership they undoubtedly deserved. Were these works really irrelevant or too technical, or only published in inadequate journals? Or are they just an indicator of future work promised to gain a better audience by choosing a better publishing strategy? There are many explanations, as illustrated by the following examples.

Consider the article on "*Estimation de la stature de la classe féodale d'après les armures du XVI^e^ s.*[2]". This original work proposes to compensate for the lack of information on the elites' stature of the time by measuring their heavy protective equipment. Despite its novelty, this article, published in "*Ethnologie française*," a journal that claims to be a "reference in French-speaking social science," is cited only twice. The first time, briefly, in a book by C. Theureau on the skeleton's anthropology of the Saint Pierre-le-Puellier cemetery (Theureau 1985). The second citation is included in an article published six years after JPBA's in the "*Zeitschrift für Morphologie und*

[1] As of 26/11/2019

[2] Estimating the stature of the feudal class from 16th c. armor

Anthropologie" (Wurm 1985). The author uses the same methodology advocated by JPBA, this time applying it to the German Empire's soldiers in the 16th and 17th centuries, JPBA data published in the "*Ethnologie française*" are abundantly reproduced and compared with those collected in Germany. Although this German publication is a testimony to the creativity of JPBA's idea, it does not seem to have been followed up. Was it because the choice to publish his initial article in a French journal was an inappropriate one? Or should we judge that the initial idea of inferring the stature of 16th c. elites by the size of their armor, while both original and compelling, proved to be too anecdotal to have a future rich in citations?

Another example is given by the article published more than 30 years ago, in collaboration with the author of this note (Darlu and Bocquet-Appel 1987). Its ambition was to infer the degree of kinship between two people based only on anthropometric data measured on the skeleton or the living. At the time, JPBA had just published his dissertation and then his book on the biological variation of the Portuguese population in the 19th c. (Bocquet-Appel and Xavier de Morais 1987), in which anthropometric measurements on skeletons featured prominently, while at the same time being exploited by multivariate methods and so-called distance analysis, which were very fashionable in the 1980s. For my part, as his coauthor, I was interested in Bayesian methods of kinship distance based on genetic data such as blood groups (Darlu and Cavalli-Sforza 1985)[3]. This potential synergy gave rise to this collaborative work, in which anthropometric measurements, reduced to their independent components after multivariate analysis, were integrated into a Bayesian model for expressing the degrees of relationship. Simulations were used to verify the effectiveness of the method. Published in the *Bulletins et Mémoires de la Société d'Anthropologie de Paris*, with quite a few typos, this article was cited only once, probably unread, in a dissertation by Charisse Carver (Carver 2015) for a PhD from the University of Arizona. The citation came only as evidence of the historical interest of French physical anthropologists in kinship research in the 1960s.

Despite the interest of this Bayesian inference method, which was almost the only one at the time able to propose such a diagnosis of kinship based on physical measurements, it did not have the impact it could have had. Was the journal inadequate? The authors' obvious lack of commitment to promoting this work in a publication with better visibility is probably the first reason. This paucity of citation can probably also be explained by the fact that this approach would, at the turn of the 1990s, quickly become totally obsolete with the arrival of DNA. Skeletal DNA sampling and identical-by-descent DNA length comparisons (Huff *et al.* 2011) would prove to be a much better method of determining kinship, to the extent that such kinship diagnostics are now being marketed by various commercial companies, which will not be advertised here.

A third example is also instructive. JPBA and Lucienne Jakobi published their first article on the transmission of fertility, in French, in the journal *Population* (Bocquet-Appel and Jakobi 1993a). This article is based on genealogical data collected by Lucienne Jakobi in the village of Arthez-d'Asson (Pyrénées-Atlantiques) from the 18th to the beginning of the 20th c. JPBA applied the methods of path analysis widely used at the time in the field of epidemiological genetics (Li 1975). Although published in a good journal, this article has only been cited once in a general article on "*Biologie et histoire de la population*[4]" by Guy Brunet, in the *Annales de démographie historique* (Brunet 2004). In the article, Brunet refers to Bocquet Appel and Jakobi to illustrate "the impossibility of demonstrating whether there is a heritability of fertility" in a discussion raising the unrealistic nature of a simplistic dichotomy between biology and culture. The same year, a similar article was published by the same authors in the Annals of Human Biology (Bocquet-Appel and Jakobi 1993b). This one is cited 14 times! However, three of these 14 articles are authored by the same Michael Murphy (e.g. Murphy 2007), who does not fail to insert this reference, and not the one from Population, when he compares the heritability values he estimated and those reported by JPBA. This example shows how preferable it is to favor English-language journals over French-language ones. Yet, the French INED journal *Population* has a very good international audience and (now) has an English version.

Let us now examine JPBA and Bacro's article published in 1994 in the excellent journal *Systematic Biology* (Bocquet-Appel and Bacro 1994). They present a generalization of the Wombling model developed by Womble (Womble 1951) and Barbujani and colleagues (Barbujani *et al.* 1989). The article describes abrupt changes in a variable's value in geographical space, such as an allelic frequency or a name, or a continuous variable such as stature

[3] The reader will appreciate how the author surreptitiously takes advantage of this short note to hope to inflate his work' citation count, currently stuck at three, despite the second author's fame and the journal's high quality where it was published!

[4] Biology and Population History.

or fecundity. The generalization proposed by JPBA considers several variables simultaneously while also factoring in the correlations that may link the variables together. This rather technical article seems to have been a real success since it is cited 45 times, although much less than the "*Farewell to paleodemography*," no doubt because it is both more technical and above all because it is not controversial, which, as is well known, generates a multitude of citations. However, what about the specifics of these 45 citations? The vast majority of the citations are included in the articles only to point out the existence of Wombling's methods, citing the three 'classic' authors on the subject (Womble, Barbujani, Oden), to which JPBA reference has now been added to form a quartet regularly cited as essential references for these statistical methods applied to geography. The various authors include these four citations mainly to demonstrate that their own methodological developments are far more innovative than those proposed by the former... Furthermore, very few citations mention the implementation of this generalized Wombling method. In fact, these citations are only those proposed by JPBA or Bacro themselves (Bocquet-Appel *et al.* 2002 ; Balabdaoui *et al.* 2001; Bocquet-Appel and Jakobi 1997), except for one (Darlu 2004), which was poorly used. In other words, JPBA has found the ability and the energy to make substantial improvements to the "Wombling" method and to write a complex program (in Fortran) to apply it to various types of data. Unfortunately, almost no one has ever used it except himself, Bacro, and Darlu through publications that are themselves seldom cited. If JPBA is rightly included in the history of Wombling, it is only for having made a brief incursion into it, which did not produce as many results as it could have. No doubt attracted by other themes dear to him, such as palaeodemography and settlement histories, JPBA thus abandoned this fine foray into the field of spatial description without having brought it to fruition.

These few examples illustrate the atypical and evolving career of JPBA, with its varying publication strategies, which can lead, depending on the situation, to excellent articles in small minor journals and more opportunistic articles in wide-readership journals. These forgotten publications, erased by time, scarcely cited or cited by convention, thus reveal other facets of JPBA's talent than those manifested by his successful articles. All of his work, both large and small, is a beautiful illustration of the fluctuating complexity of a scientific trajectory when guided by creative imagination and scientific rigor.

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From craniometry to paleogenetics
De la craniométrie à la paléogénétique

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Abstract: French physical anthropology has persisted, longer than other countries, in measuring skulls and defining "races." This tradition, developed in the 19th c. by *the Société d'anthropologie de Paris* and Paul Broca, continued until the 1980s with the work of Henri Victor Vallois and his school. The latter maintained ambiguous relations with the German physical anthropologists linked to Nazism, which continued after the Second World War and led to the awarding of the Broca Medal to the German anthropologist Ilse Schwidetzky in 1980. Jean-Pierre Bocquet-Appel has written a critical but relatively isolated critique of the role and work of Victor Henri Vallois. Although French physical anthropology abandoned craniometry to become "biological" from the 1980s onwards, we can nevertheless find in some current paleogenetic works, irrespective of their interest, the temptation to confuse biology and culture once again.

Keywords: physical anthropology, biological anthropology, Jean-Pierre Bocquet-Appel, craniometry, racism, Paul Broca, Henri Vallois, paleogenetics, DNA

Résumé : *L'anthropologie physique française s'est obstinée, plus longtemps que d'autres pays, dans la mesure des crânes et la définition de « races ». Cette tradition développée au XIX^e^ s. par la Société d'anthropologie de Paris et Paul Broca, s'est poursuivie jusque dans les années 1980 avec les travaux de Henri Victor Vallois et de son école. Ce dernier a entretenu avec les anthropologues physiques allemands liés au nazisme des rapports ambigus, qui se sont poursuivis après la seconde guerre mondiale, et ont abouti à la remise en 1980 de la médaille Broca à l'anthropologue allemande Ilse Schwidetzky. On doit à Jean-Pierre Bocquet-Appel un examen critique, mais resté relativement isolé, du rôle et des travaux de Victor Henri Vallois. Si l'anthropologie physique française a abandonné la craniométrie pour devenir « biologique » à partir des années 1980, on peut cependant trouver dans certains travaux actuels de paléogénétique, quel qu'en soit l'intérêt, la tentation de confondre à nouveau biologie et culture.*

Mots-clés : *anthropologie physique, anthropologie biologique, Jean-Pierre Bocquet-Appel, crâniométrie, racisme, Paul Broca, Henri Vallois, paléogénétique, ADN*

Although I had the opportunity to collaborate closely in recent years with Jean-Pierre Bocquet-Appel, a long-standing friend, on demographic models suitable for explaining the Neolithic transition (see Dubouloz, *this volume*), I will report here on an earlier aspect of his work. Besides, this aspect is coherent with the professional commitments of Jean-Pierre Bocquet-Appel's early years, mindful as he was to the proper operation of his discipline. This is actually the critical and historiographic study that he produced in the years 1980-1990 on the characteristics of the French physical anthropology, specifically of Henri Victor Vallois' school, to which we owe a particular longevity of the "raciological" definitions in France via the multiplication of measurements. This study is not trivial because, to my knowledge, no other study has come from within French physical anthropology to date.

An anthropological review

During the 18th c., following the example of other emerging sciences and their classifications, naturalists also attempted to classify humans, which in turn implied that the Bible had gradually lost its legitimacy. Didn't all humans descend from Adam (and Eve) via Noah and his three sons?

For the Swedish Protestant Carl von Linnaeus (1707-1778), physician to the royal family, to classify humans in his *Systema naturae*, admittedly following Aristotle, in his group of primates, thus named because it was the "first" among all other animals, was almost sacrilegious.

In his masterwork, published from 1735 in several successive editions, Linnaeus divided *homo sapiens* into four subcategories, *Europaeus albus*, "ingenious, inventive"; *Americanus rubesceus*, "swarthy, irascible"; *Asiaticus luridus*, "proud, miserly... yellowish, melancholic"; *Afer niger*, "cunning, lazy, careless... black, phlegmatic" - borrowing both the popular classifications of skin colors and Aristotle's typology of the four humors. Moreover, Linnaeus adds a fifth category, *homo monstruosus*, grouping together dwarfs and presumed giants, the Sami of northern Europe (formerly called Lapps) and the Bushmen (Sans and Khoikhoi) of southern Africa.

Further "progress" was made by Johann-Friedrich Blumenbach, professor at Göttingen, with his *De generis humani varietate nativa* in 1775. We owe him the term "Caucasian," still used by the American police, to define the "white race" (although the same police put in a separate class the "Latinos"), because, writes Blumenbach: "*It is in the vicinity [of the Caucasus] that the most beautiful race of men, the Georgian race, is found, and if it is possible to assign a cradle to the human race, all physiological reasons concur in placing it there [...]. Finally, the skin of the Georgians is white, and this color still seems to belong primitively to the human race, but it degenerates easily into a blackish color*" (Poliakov 1987: 197).

Finally, in a non-exhaustive list, we must mention another Swede, Anders Retzius, inventor since 1842 of the "cephalic index," which measures the ratio between the length and the width of the skull, seen from above. This index can distinguish between "long" or "dolichocephalic" heads if the length is, on average, more than three-quarters of the width, and "short" or "brachycephalic" heads if it does not exceed it by more than one eighth. Retzius' work was combined with the "facial angle" of the Dutchman Peter Campen, supposed to measure intelligence according to its slant, which allowed the Englishman Charles Pritchard to distinguish between "orthognaths,"with a straight face, and "prognaths," whose face moved forward "in a snout" (Regarding these anthropological origins, see in particular Poliakov 1987; Blanckaert 1981, 1989; Sarga, 2003; Guiral and Temine 1977; Reynaud Paligot 2006; Demoule 2017: 109-160; Kremer-Marietti 1984; Lauriere 2015; Irvin Painter 2019).

The scientific study of human races

During the second half of the 19th c., societies and schools of anthropology were founded and organized on these "scientific" bases. One of the first was the *Société d'Anthropologie de Paris,* founded in 1859 by physician Paul Broca. This was a fertile anthropological year since it was also the year in which English geologists authenticated Boucher de Perthes' Paleolithic discoveries in the gravel quarries of the Somme valley and the year Charles Darwin published *The origin of species*.

As everyone knows, Paul Broca was by no means just anyone, since we owe him, since 1861, the identification of our "Broca's area," the area of the brain that allows us to speak and whose lesion can cause "Broca's aphasia." Son of a physician, Broca founded this society with many physicians, and by combining physical anthropology, ethnology, and prehistory, three disciplines that would gradually become autonomous in the following decades. More precisely, the society defined itself in its statutes as its primary goal: "the scientific study of human races." For this purpose, measurements were multiplied, and Broca himself invented or developed all sorts of measuring instruments, such as the craniograph, craniophore, cranioscope, craniostat, endograph, stereograph, pachymeter, orbistat, goniometer, sphenoidal hook or Turkish hook, optical probe or tropometer. He even went so far as to go and dig up some sixty skulls in a Spanish Basque cemetery at night to complete his collection and investigate the supposed characteristics of the Basques.

However, the "scientific" program is unambiguous. As Broca writes: "*A more or less white skin, a smooth hair, an orthognathic face are the most ordinary prerogative of the highest peoples in the human series [...]. Never a people with black skin, woolly hair and a prognathic face could spontaneously rise to civilization*" (Broca 1866: 280, 295; on Broca and the Anthropological Society, see in particular Blanckaert 1981, 1989; Blanckaert *et al.* 1989; Sarga 2003; Guiral and Temine 1977; Reynaud Paligot 2006; Demoule 2017: 122-160). Nevertheless, these freethinking physicians, firmly opposed to the biblical monogenetic vision, are not strictly reactionary. They thought that, unlike other forms of colonialism, France's colonialism had a duty to help peoples disadvantaged by nature and race to move up the ladder of civilization.

The end of "races"?

However, French anthropologists soon encountered many difficulties. The first one was about France: was there a French race? The sensitive evidence pleaded against it, and they attempted, at first, to rally to an older position, the one proposed in 1829 by William Edwards, founder of the Ethnological Society of Paris: there would have been originally two "Gallic races" which would have mixed later, the "Kimris," tall, blond and dolichocephalic in the north, and the "Galls," short, brown and brachycephalic in the south.

Nevertheless, if the races can mix, what happens to the notion of race? The second problem was that of the origin of the Indo-Europeans, or "Aryans," which was the subject of many societal debates, faithfully reproduced in the Bulletin: were they brown or, on the contrary, blond, and where did they come from, and finally (Broca's position) was it only the language that spread, without migrations? There was never any consensus. Finally, and most importantly, Darwin's ideas, at first firmly rejected, slowly became accepted. In this case, if species never stopped evolving, there were no more "races" in a world in perpetual change. In fact, the more measurements (up to 5,000 on a single skull) and measuring instruments were produced, the fewer boundaries and distinctions between "races" could be established.

Paul Topinard, one of Broca's principal heirs, drew the radical conclusion: "*Race does not exist in the human species, [...] it is a product of our imagination and not a raw, palpable reality. ...] Men seem to present only individual variations*" (Topinard 1891: 4, 39). In other countries, the position was not much different. Contemporary German anthropologists, who had generally been more discrete than their French colleagues about "races," joined them in these new criticisms, such as the Berlin anthropology professor Felix von Luschan, who stated: "*All attempts to divide mankind into artificial groups based on skin color, length or breadth of the skull, or type of hair, etc., have been totally misguided [...], future attempts of this kind [...] will increasingly prove to be a fruitless pastime*" (Luschan (von) 1922: 13; Massin 1993: 212-213). Similarly, in the United States, the work of the ethnologist Franz Boas showed that the skull's shape, especially in the case of immigrants' descendants, could change with the environment (Boas 1911).

Thus, the craniometric version of "scientific racism" (Barkan 1992) was gradually fading. However, this was of little consequence for cultural racism and anti-Semitism in European populations or populations of European origin, nor for institutional racism and anti-Semitism, with apartheid in the United States, South Africa, and many European colonies, and soon, as Nazism would tragically show, for institutional racism.

However, even within scientific racism, the desire to proclaim the inequality of human beings led to the development of new methods. Thus, in the United Kingdom, the school of Francis Galton developed, with statistical force, the I.Q. tests - invented in 1912 by the German psychologist Wilhelm Stern following the work of Alfred Binet in France to detect children in academic difficulty - which explicitly allowed, and still allows, to justify social inequalities. The success of the American bestseller by psychologist Richard Herrnstein and political scientist Charles Murray: *The bell curve: intelligence and class structure in American life*, published in 1994 and justifying "racial" inequalities between "whites" and "blacks," was a striking confirmation.

Similarly, in Germany, the relatively early development of genetics in the interwar period also served as a powerful means of exclusion, notably with another bestseller, one co-authored by three staunch supporters of the Third Reich, the biologist Eugen Fischer, the plant biologist Erwin Baur, and the racial hygienist Fritz Lenz, *Menschliche erblichkeitslehre und rassenhygiene* ("Human heredity and racial hygiene"), constantly republished from 1921 onwards. A study by Fischer in 1912 had already outlawed interracial marriage in the

German colony in West Africa (today's Namibia) when the Herreros were being subjected to genocide.

Nevertheless, craniometry continued to be used for the "Aryanity" passports issued in Germany (and soon also in Vichy France) by eminent anthropologists, who could either sentenced to death or not those who were forced to apply for such passports. One example is Ilse Schwidetzky (to be discussed later), assistant to Baron Egon von Eickstedt, who directed the Institute of Anthropology in Breslau (present-day Wroclaw, Poland). After the war, the institute was transferred to Mainz, and she became its director. In a self-justifying history of German anthropology, she claimed that their institute had always refused to issue racial certificates. Unfortunately, the historian Benoît Massin found some, signed by her, in the archives of the institute (Spiegel-Rösing and Schwidetzky 1982; Massin 1999: 42 and note 105).

A French history

Surprisingly, what Jean-Pierre Bocquet-Appel was precisely working on, and in my opinion, which still does not have a complete historical explanation, is that France was one of the rare countries where craniometry and raciology continued to be practiced with fervor by scientists, not only throughout the interwar period but until the early 1980s. Admittedly, the importance of the French colonial empire and the colonized populations to be managed, then governed by various forms of apartheid, may be one explanation, but probably not the only one, for this intellectual sluggishness (Reynaud Paligot 2006, 2007; Lauriere 2015).

Nevertheless, there was already a very skeptical scientific lineage, as we have already seen with Paul Topinard. The prehistorian and protohistorian Joseph Déchelette, the leading, contemporary specialist of these periods, stated in 1914, in his founding *Manual*, about races and anthropology: "*Instead of a small number of clearly defined forms that can be grouped within the framework of a simple classification, we encounter multiple types with numerous varieties. Also, despite the persevering efforts of the specialists, the theories relating to the origin and the distribution of the old European races, theories numerous and often confused, provide to the primitive history of humanity only too problematic data. The general conclusions of anthropologists do not exactly agree on many points with the observations of archaeology. One raised on both sides, on weak bases, many ingenious doctrines, but ephemeral*" (Déchelette 1927: vol. 1, p. 482).

Although Déchelette's death in October 1914 near the Chemin des Dames deprived French prehistory of a critical perspective, this attitude continued among several anthropologists, as Jean-Pierre Bocquet-Appel has well documented, such as Henri Neuville, Jacques Millot, and the rector Étienne Patte, whom Vichy revoked (Neuville 1933; Patte 1938a, 1938b; Lester and Millot 1939; see Bocquet-Appel 1988, 1989). In contrast, there were raciologists, if not racists and anti-Semites, such as René Martial, Georges Montandon, and the Nobel Prize winner for medicine Alexis Carrel. All three were active collaborators under Vichy - Montandon himself, having issued "racial" certificates. We could also quote the veterinarian Emmanuel Leclainche, president of the Academy of Sciences, who quipped in 1937 about "races": "*It is understood that, for scientists, there are no longer any human races. But, unfortunately, or fortunately, there are not just scientists on earth. The mass of ignorant people persists in believing that there are still whites, blacks, and yellows and that they can be recognized without too much difficulty*" (Leclainche 1937: 1279; quoted in Bocquet-Appel 1989: 31).

Between these two positions, the less committed craniometric line of Henri Victor Vallois thrived. This is because Valois reigned over French anthropology for half a century by being successively or simultaneously, professor at the *Muséum national d'histoire naturelle*, director of the *Musée de l'Homme*, director of the *Institut d'paléontologie humaine*, director of the *Laboratoire d'Anthropologie* at the *École Pratique des Hautes Études*, editor of the journal *L'Anthropologie* and secretary general of the *Société d'anthropologie*, director of the *Institut de Paléontologie humaine*, director of the Anthropology laboratory of the *École Pratique des Hautes études*, editor in chief of the review *L'Anthropologie* and general secretary of the *Société d'Anthropologie de Paris* (during thirty years, from 1939 till 1969). Under a civil guise, he nevertheless maintained excellent relations with the German anthropology of the time, notably in his reviews of *L'Anthropologie*.

Vallois and National Socialist Anthropology

In 1936, reporting on a book by Egon von Eickstedt, *Rassenkunde und rassengeschichte der menschheit* ("Raciology and racial history of mankind"), Valois endorsed its worldview as follows: "*Adopting the idea of the inequality of the races, not only anatomical but also psychological, the author concludes by declaring that a rigorous racial selection is the only way to oppose the annihilation of our civilization*" (Eickstedt 1934; Vallois 1936a: 429). In this book, Baron von Eickstedt wrote, among other things: "*Race, blood, and land are more important than parliamentary work*" (Eickstedt 1934: 889)[1].

Similarly, regarding another work by the same author, he wonders: "*Thus, concludes M. von Eickstedt, racial psychology has risen to the level of a true science, [...] no one, in Germany at least, questions its importance. Will all anthropologists share this conclusion? We fear not. The premature generalizations of the authors [...] have harmed this science, at least in the minds of many. To rehabilitate itself, it would need numerous researches, made without a spirit of partiality, and by deductive rather than inductive methods*" (Eickstedt 1936 in Vallois 1936a: 427-429).

Commenting on a craniometric study of the Austrian anthropologist Rosa Koller on the Jewish population of Constantinople, Valois stated: "*These skeletal dispositions would be correlative to the development of certain facial muscles; they would therefore be related to the mimicry so characteristic of a large number of European Israelites*" (Vallois 1936b; Schnapp 1980: 26). Finally, in his obituary of the racist ideologist Georges Vacher de Lapouge, Valois laments: "*An observant and industrious spirit, M. Vacher de Lapouge certainly deserved better than the oblivion to which he was relegated. The excessiveness of the theories that he developed, the overly categorical way he exposed his 'laws' [...], probably explain the vacuum created around his research. There are, however, exact aspects of his work, and it would be unfair to forget them*" (Vallois 1936c) - "exact aspects" that Valois is careful not to specify.

The Vichy government did not forget Paul Rivet in its wave of dismissals. He was the progressive director of the Musée de l'Homme, where a strong resistance network was set up and dismantled. Vallois was a candidate against Millot, whom the Museum's professors supported. The Minister of Education, Jérôme Carcopino, author of the law excluding Jews from education and a law making archaeological excavations subject to authorization, chose Vallois, advised notably by the Abbé Breuil (Bocquet-Appel 1989: 31). This episode was omitted from the obituary that appeared at his death in *L'Anthropologie* in 1982 and from the special issue of the *Bulletins et Mémoires de la Société d'Anthropologie de Paris* that was devoted to him the same year.

After World War II

In practice, Vallois continued his career peacefully after the war, and his 1944 *Que sais-je?* on *Human Races* was constantly republished (Vallois 1944). Vallois distinguished 27 "races," grouped into four large groups, including the "primitive races," which included the Australian aborigines and the Veddas of Sri Lanka. He continued his reviews in *L'Anthropologie*, publishing in 1960 a laudatory review of Baron Otmar von Verschuer's anthropology textbook, in which he regretted, already on the defensive: "*We know that certain biologists, who have acquired a justified reputation in their own field, and then, late in life, have become interested in anthropology, have, with all the ardor of neophytes, declared that this science should be radically transformed: all the work accomplished for more than a century by hundreds of anthropologists, who have studied the characters of which genetics is unknown and who have tried to establish classifications from them, must be discarded. Only known genetic traits should be considered. Some professional anthropologists thought they had to echo this solemn ex-communication*" (Verschuer 1959; Vallois 1960: 343-344; quoted in Bocquet-Appel 1988: 42) - Ottmar von Verschuer, then Mengele's superior, who wrote in 1942 in the *Völkischer Beobachter*, the organ of the Nazi party: "*The unique racial danger posed by the Jews has found, through the policy of the National Socialist, a definitive settlement*" (Müller-Hill 1989 [1984]: 48).

Vallois' students, such as Denise Ferembach or Raymond Riquet, were pursuing the same approach anyway. For instance, Raymond Riquet, a professor at the University of Bordeaux, who died in 1983, defined all sorts of "prehistoric races" from a sample of about 700 skulls, distinguishing, for example, "Neolithic invaders," including the "corded race," which "*corresponds to the Hinkelstein type of Schliz, to the type II of Reche, to the dolichocephalic form of East Germany of Scheidt and the type I of Ulrich. [...] This race corresponds to large and very dolichocephalic subjects.... The origin of this type is unknown but can be sought on the side of the Black Sea steppes if the Corded Ceramics actually originated in these same regions, as is generally supposed. It can also be assumed that this race is indigenous. With the Brünn race, it forms the essential components of the present Nordic*" (Riquet 1951: 205-206). Hence, biology and culture are also mixed as they often were, the Corded Ceramics often passing for having been the principal vehicle of the dispersion of the Indo-European languages. Perhaps more grievous are the racialist views that Riquet dispensed in his contribution to the *Manuel d'anthropologie physique* published by the CNRS in 1986 (Ferembach *et al.* 1986, chapter 27).

The 1980 clash

Regarding Denise Ferembach, who passed away in 1994, she was another student of Vallois who succeeded him from 1970 to 1982 as secretary-general of the *Société*

[1] « *Rasse, Blut und Boden sind wichtiger als parlamentarische Tageserfolge*. »

d'anthropologie. Ferembach was specialized in the study of Mesolithic and Neolithic skulls of the Mediterranean area. She was responsible for the decision to award the Broca Prize to the German anthropologist Ilse Schwidetzky, mentioned above, under the auspices of the CNRS, during the symposium organized for the centenary of Paul Broca's death in June 1980.

Because of their proximity, the two craniometric traditions, the German and the French, the Vallois version, now explicitly met. Several researchers, including the archaeologist Alain Schnapp, who had already worked on Nazi archaeology and its perception in France, including in anthropology, decided to intervene. Jean-Pierre Bocquet-Appel was their relay among anthropologists but preferred to remain anonymous at the time, so intense was the pressure from the community. Jean-Pierre Bocquet-Appel had a militant past, having worked voluntarily in factories, and was sympathetic with the Syndicat national des chercheurs scientifiques (SNCS). Therefore, these researchers forced the entrance to the amphitheater, previously promised to them but finally denied at the last moment, during the tribute session to Ilse Schwidetzky on June 18, 1980. They were allowed to speak briefly on the subject, even though the president of the CNRS, the biologist Charles Thibaut, reminded Alain Schnapp that he was "*too young to have suffered racial persecution,*" while other, less polite, congressmen commented, according to the testimonies, that *"the Nazis killed fewer Jews than is claimed: there are still many left*" (Jacquard and Schwidetzky 1981).

The French anthropologists in charge of the Société at the time defended Ilse Schwidetzky. They spoke to Yvonne Rebeyrol, the journalist from the newspaper *Le Monde* specializing in archaeology and paleontology, author of several scientific works, and usually very well informed. She became their spokesperson, mentioning "troublemakers," more precisely that *"a few people, mostly young and not anthropologists, disrupted the beginning of the session*" (Rebeyrol 1980), and relating the exculpatory testimonies of several foreign anthropologists, such as the Hungarian Andor Thoma, the Romanian Olga Necrasov, the Pole Andrzej Wiercinski and the Czech Jan Jelinek. The fact that all of them came from Eastern Europe is also explained by the fact that traditional craniometric physical anthropology had continued to flourish there, exempted from the crimes of Nazism under communist regimes, in contrast to Western Europe and West Germany in particular.

An explanatory press conference was held by the "troublemakers" four days later, in which Albert Jacquard, Jacques Le Goff, Emmanuel Leroy-Ladurie, Léon Poliakov, Maurice Godelier, and Albert Ducros participated. The geneticist Albert Jacquard relayed the affair in the *Bulletin de l'Association française des anthropologues* (quite distinct from the *Société d'Anthropologie de Paris*), which also published a response from Ilse Schwidetzky, justifying any racist writing while reaffirming the scientific reality of "races," and adding that, as a mother of three children with a husband killed in the war, it had been impossible for her to manifest her opposition to the regime - something that Albert Jacquard willingly acknowledged.

However, as Jacquard pointed out: "*It is not possible to present as exemplary the scientific career of an anthropologist who participated in the definition of the Nazi' politics of race' [...]. The strict duty of the involved scientists, that is to say of anthropologists regardless of their specialty, is to proclaim that the theories developed by the Nazis, and currently taken up by the nostalgics of this regime, are in total contradiction with the results of their discipline [...]. The progress of biology, and in particular of genetics, has shown that the first proposal does not conform to reality: the interactions between human groups have been such that classification according to the content of the genetic heritage could only be arbitrary and meaningless: the concept of race is not scientifically operational.*" Jacquard called for a debate in the CNRS journal, the *Courrier du CNRS*, since the institution was the inviting power of the colloquium (Jacquard and Schwidetzky 1981; Schnapp 1981).

From "physical" to ... "biological"

The debate never occurred in this format, but the Paris Anthropological Society was nonetheless shaken, even though, in her annual "moral report," Denise Ferembach, the general secretary, regretted these "deplorable incidents," which "fortunately, hardly affected the course of the colloquium" (Ferembach 1980: 351.). However, when Vallois died the following year, the Société felt forced to organize a special session on "ethical problems in physical anthropology." During this session, according to Denise Ferembach's moral report for that year, "*the responsibility of the anthropologist, the emotional context surrounding the notion of race, a concept that cannot be abandoned, the exploitation of scientific works for ideological purposes, diverting them from their real meaning, leading to unwarranted attacks on anthropology, were addressed in turn while considering how anthropologists should react against the attacks made on our discipline*" (Ferembach 1981: 474).

However, the situation gradually changed during the 1980s. In addition to Vallois' death in 1982 and despite a very pared-down obituary, the management team of the Anthropological Society changed. Denise Ferembach gave up her position as Secretary-General that same year in favor of Jean Dastugue, a surgeon by training and essentially specialized in paleopathology rather than in "racial" definitions, and then by Jean-Jacques Hublin in 1990. In effect, "racial" classifications were abandoned with the gradual disappearance of the Vallois school. Some researchers had already turned to other issues, notably genetics, blood groups, or demography, such as Jean-Pierre Bocquet-Appel, while the term "physical anthropology" was definitively replaced by "biological anthropology."

Nevertheless, at this stage, three points should be emphasized. The first is that the scientific notion of "race" had been abandoned in most Western countries, and Vallois's France was like a strange, out-of-touch island of resistance. France's colonial past does not explain everything. In Belgium, with a similar heavy past, a researcher like Jean Hiernaux could declare in his 1968 thesis, after a very detailed statistical comparison of a hundred or so African populations: "*No population fulfills the condition [...] of minimum distance from any other to be classified in the same taxonomic rank as a constellation. Consequently, the reduction of the diversity of African populations to a limited number of taxa, as all proposed racial classifications do, presents a high number of logical contradictions*" (Hiernaux 1968, quoted in Ducros 1992: 129; see also Hiernaux 1978 and his contribution in Ferembach *et al.* 1986). Only when genetics finally penetrated French anthropology could fixist racial classifications be officially abandoned in favor of network structures consistent with reality (Langaney 1988; Langaney *et al.* 1992).

The second aspect is that Jean-Pierre Bocquet-Appel is, to my knowledge, the only (biological) anthropologist to have done a precise critical work on the history of his discipline, however carefully, given the pressures of the community at the time. However, he tackled Vallois's biography and intellectual affinities in his article for the journal Gradhiva almost ten years later (Bocquet-Appel 1989). Furthermore, although Jean-Pierre Bocquet-Appel had dared to record an interview with Vallois three months before his death at 91 years old, he did not publish it until fifteen years later, while acknowledging that he had not always been sufficiently critical of Vallois's autobiographical account in this interview (Bocquet-Appel 1996a, 1996b). Jean-Pierre Bocquet-Appel also told me how the interview was broadcasted at a meeting of the Anthropological Society under extreme tension. Consequently, without any transition, reflection, or explanation, we have moved from "physical" anthropology to "biological" anthropology. English-speaking researchers continue to use the term "physical" anthropology to distinguish it from "cultural" anthropology, both of which, along with prehistory, are usually grouped in the "Department of Anthropology." Alternatively, when we refer to "physical anthropology," we will identify it with the archaeological excavation of burials, i.e., their meticulous recording, later named "archaeothanatology" (See, for example, Duday and Masset 1987; Guy and Richier 2012). Besides, there is sometimes an attempt to rewrite history, such as the Wikipedia entry on the *Société d'Anthropologie de Paris*, created by an anonymous contributor in August 2008. The entry states that its "aim is to study the natural history of Man, that is to say, the origin and biological diversity of the human species," without mentioning the original statutes mentioned above, which more precisely claimed "the scientific study of human races."

The third aspect is the paradoxical ambiguity that continues to surround the term "race." Albert Ducros already emphasized this ambiguity in 1992 when he concluded a historiographical article with the following words: "*But we must also admit that forty years of discussion have not removed the ambiguities, contradictions and conservatism among the professionals themselves*" (Ducros 1992: 137). Indeed, the fact that not all humans are alike is a truism, even if they are increasingly mixed and not including the effects of the environment. These differences demonstrate long histories, if not long prehistories. These differences are not just about external features but also about reactions to various illnesses, various foods (milk assimilation or not in adulthood), and various medications.

"Race," beyond racism, is still a category considered operational by the police in some countries. In fact, the preamble to the constitution of October 27, 1946, which is part of the current constitutional body, states in its article 1: "*the French people reaffirm that every human being, without distinction of race, religion or creed, possesses inalienable and sacred rights*." Debates have occurred and continue: if "race" does not exist, why include it in the founding texts? But at the same time, how can racism be prosecuted and condemned without mentioning "race"? The motion for the May 16th, 2013 bill, passed by the National Assembly, proclaimed in its Article 1: *The French Republic condemns racism, anti-Semitism and xenophobia. It does not recognize the existence of any so-called "race."* The bill replaced the word "race" with "alleged race" in several legislative texts, but was never adopted. However, the law of January 17th, 2017 "on equality and citizenship" at least replaces the term "race" with "alleged race" in the penal code. Meanwhile, the word race still appears in the constitution.

Lately, "race" has been taken literally, if not turned on its head, by traditional victims of racism, mostly of sub-Saharan origin, who speak of "racialized," "racialism," and "white privilege," whether in the United States with the "Black Lives Matter" movement, or more simply in Europe and France (Thuram 2020; Irvin Painter 2019).

Genetics and culture

This ambiguity is not limited to common sense. In fact, the remarkable growth of paleogenetics over the last decade, of which a lot is still to be expected, sometimes results in simplifying interpretations reminiscent of the early days of the Paris Anthropological Society. Furthermore, we should mention that paleogenetics started in France with some delay compared to Germany, the United States, or Denmark. One of the reasons for this delay was undoubtedly the defensive fallback on "funerary archaeology" after the departure from craniometric anthropology, but also a certain reluctance from the CNRS, not to mention the rivalries between laboratories.

Nevertheless, after the pioneering work of the German laboratory of the Swedish geneticist Svante Pääbo, this discipline developed considerably in the laboratories of Harvard, Jena, London, and Copenhagen and, at the end of the 2010s, was spread to the general public through several popular educational books (Reich 2019; Krause 2019; Heyer 2020; Orlando 2021). Although paleogenetics is well represented in France at the Musée de l'Homme, at the Institut Jacques Monod in Paris, or the universities of Bordeaux and Toulouse, relatively ambitious programs have only been developed very recently due to a lack of support (Brunel *et al.* 2020).

However, some laboratories' results, notably those of Havard, directed by David Reich (now in Germany) and of the Max-Planck Institute of Jena (with Wolfgang Haak and Johannes Krause), have occasionally been inclined to draw broad arrows on maps and to reconstruct "massive migrations" through space, supported by a small number of archaeologists (such as Kristian Kristiansen in Denmark). This was particularly true of the two collective 2015 papers from Jena and Copenhagen, respectively, claiming to have recovered the route of the supposed original Indo-European people, who would have spread the Indo-European languages in Europe, following Marija Gimbutas (Haak *et al.* 2015; Allentoft *et al.* 2015).

Eventually, the bloody path of the "most violent people in history" was identified since they supposedly spread the genetic group (haplogroup of the Y chromosome) called R1a in part of Europe. In reality, the story seems a bit more complex, especially since genetic studies of current European populations show that there is little difference in the genetic component between those speaking Indo-European languages and those speaking languages of other linguistic groups (Basques, Hungarians, Estonians) (Haak *et al.* 2015: Figure 3). Moreover, the supposed violence of this "mass migration" is not based on any archaeologically proven massacre (Demoule 2019). Finally, the preferential spread of a genetic group may as well be explained by a particular matrimonial system and reproductive advantage over the centuries, rather than by a violent invasion, as studies of recent as well as ancient populations have evidenced (Heyer *et al.* 2012, 2015; Zeng *et al.* 2018).

Studies on the Bell Beaker phenomenon have been equally striking. The Bell Beaker is the extension of a cultural entity characterized by its funerary rites and its inverted bell-shaped cups (hence the name) over a part of western and central Europe in the third millennium but in discontinuous patches. Yet analyses show that, despite this homogeneity in material culture, the populations linked to this phenomenon in the northern half of Europe are genetically quite different from those in the continent's southwest (Olalde *et al.* 2018, 2019; Olalde and Posth 2020). If there were any doubt before, there is no correspondence now between biology and culture. Far more complex historical phenomena of crossbreeding and permanent mixing are thus rather worth considering, admittedly at the price of far more elaborate and complex research, which some archaeologists are beginning to propose, after an initial sense of dismay (Furholt 2019; Hansen 2019). The situation will probably take some time to stabilize before we can work on genuinely interdisciplinary programs. Especially since, given the sums involved (a single complete genome of a single individual can cost up to 60,000 euros, even if this figure is gradually decreasing), the competition between laboratories leads to hasty conclusions and the most spectacular announcements possible. In fact, ideological hijackings were not long in coming, especially on the side of the extreme right[2]. Likewise, several anonymous contributors to the online encyclopedia Wikipedia have decided to include genetics everywhere in the sections dealing with ancient or even recent societies and civilizations[3].

[2] See, for example, the special issue of the far-right journal New School, entitled "Paleogenetics of Indo-Europeans," No. 68, 2018.

[3] See, for example, the numerous contributions of a certain Thontep

For one Anthropology, with an A?

Therefore, reducing cultural anthropology to biological anthropology has been the subject of regular, albeit varied, attempts for at least a century and a half, depending on the scientific state of the art - with the frequent attempt to justify social inequalities by biological inequalities in the background. Conversely, productively articulating these two disciplines was the agenda of researchers as diverse as Sigmund Freud, Paul Rivet - the latter with the conception of the Musée de l'Homme - or André Leroi-Gourhan (Joulian 2015; see also the journal *Technique & Culture*). However, setbacks were constant. For instance, the creation of the current *Quai Branly* Museum was cut off from the *Musée de l'Homme* for purely short-term, political reasons (*cf.* Dupaigne 2006). Likewise, the separation of the human and social sciences of the CNRS into two distinct institutes, the National Institute of Human and Social Sciences (INSHS) on the one hand, and the National Institute of Ecology and the Environment (INEE) on the other, was again because of immediate expediency.

Consequently, following this overview intended to emphasize the critical role, albeit somewhat isolated, that Jean-Pierre Bocquet-Appel played in the critical historiography of biological anthropology, it is worthwhile to remember the conclusions of a collective text published in 2017 in *L'Homme*, and co-authored by Jean-Pierre Bocquet-Appel, Bernard Formoso and Charles Stépanoff: *"Reinstating the reference to the biological, technical, mental and social evolution of humans would reinforce the epistemological coherence of the combination of biological anthropology - ethnology - prehistory. A general anthropology university curriculum, integrating the three disciplines in all the places where they already exist, should be promoted*[4].

Finally, the authors referred to Claude Lévi-Strauss' authority, who claimed in 1950: "*an anthropology, that is to say, a system of interpretation that simultaneously accounts for the physical, physiological, psychic and sociological aspects of all behaviors*" (Bocquet-Appel *et al.* 2017: 240-241; Levi-Strauss 1950: 25)[5].

[4] « *Réintégrer la référence à l'évolution biologique, technique, mentale et sociale des humains renforcerait la cohérence épistémologique de l'association anthropologie biologique – ethnologie – préhistoire. Un enseignement universitaire d'anthropologie générale, intégrant les trois disciplines dans tous les lieux où les unes et les autres existent déjà, devrait être promu.* »

[5] « *une anthropologie, c'est-à-dire un système d'interprétation rendant simultanément compte des aspects physique, physiologique, psychique et sociologique de toutes les conduites.* »

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Jean-Pierre Bocquet-Appel and the interdisciplinary dialogue

Jean-Pierre Bocquet-Appel et le dialogue interdisciplinaire

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Abstract: In 2014, while the mandate of the previous National Council of Universities for anthropology (2011-2015) was coming to an end, Jean-Pierre Bocquet-Appel, who sat on it, expressed the wish that Council members discuss the future of the association of social anthropology-ethnology, biological anthropology and prehistory collegially. In his view, such an association was becoming meaningless due to the increasingly divergent construction of knowledge in these different disciplinary fields. With Jean-Pierre and Charles Stépanoff of the *Laboratoire d'Anthropologie sociale*, we created a working group to assess the evolution of these partnerships and identify several avenues for renewing the interdisciplinary dialogue. This paper summarizes the content of this joint reflection which led to the publication of an Op-Ed article in *L'Homme*, the flagship journal of social anthropology in France.

Keywords: anthropology, biological anthropology, social anthropology, prehistory, epistemology

Résumé : En 2014, alors que s'achevait le mandat du précédent conseil CNU 20^e^ section (2011-2015), Jean-Pierre Bocquet-Appel qui y siégeait avait formulé le souhait que les membres du Conseil discutent collégialement du devenir de l'association de l'anthropologie sociale-ethnologie, de l'anthropologie biologique et de la préhistoire, tant cette association lui paraissait de moins en moins évidente, compte tenu de l'évolution de la construction des savoirs dans ces différents champs disciplinaires. Avec Jean-Pierre et Charles Stépanoff du Laboratoire d'Anthropologie Sociale*, nous avions alors constitué un groupe de travail pour dresser le bilan de l'évolution de ces partenariats et dégager un certain nombre de pistes afin de renouer le dialogue interdisciplinaire. La présente contribution restitue la teneur de ces échanges, ceux-ci ayant abouti à la publication d'une tribune dans* L'Homme*, la principale revue d'anthropologie sociale française.*

Mots-clefs : anthropologie, anthropologie biologique, anthropologie sociale, préhistoire, épistémologie

Introduction

In February 2015, when the mandate of the previous National Council of Universities 20th section (2011-2015) was coming to an end, Jean-Pierre Bocquet-Appel, who sat on it, had expressed the wish that the Council members discuss the future of the association of social anthropology-ethnology, biological anthropology, and prehistory collegially, as this association seemed to be increasingly less clear. Remarkably, Jean-Pierre was frequently assigned social anthropologists' applications during these four years due to insufficient candidates for qualification and promotion in biological anthropology. While he always produced quality reports, the epistemology and the evaluation criteria of his field of study made him deeply uncomfortable when he had to assess the research objects and the careers of social anthropologists. Accustomed as Jean-Pierre was to formulating questions within the long time frame of evolution, he sometimes found it challenging to grasp the meaning and relevance of the very localized problems reduced to the short time frame of contemporary social phenomena studied by social anthropologists. Having built his objects of study based on statistical or mathematical models that were sparing of words, Jean-Pierre found it difficult to take seriously the talkative, highly textualized models to which researchers in the humanities and social sciences mostly resorted. This interpretative rationale, often supported by the theoretical crutches provided by fashionable philosophers and sometimes disconnected from evidence-based requirements, rightly seemed to lack rigor. Jean-Pierre was accustomed to well-defined transdisciplinary collaborations with related or complementary epistemic traditions (prehistory in particular). He found it difficult to reconcile the increasingly frequent forays of social anthropologists into territories distant from their disciplinary field, often resulting in hazardous propositions. Finally, Jean-Pierre was used to publishing his work in high-profile international journals and did not understand that many social anthropologists build their careers on publications in non-referenced journals. According to the data provided by the CNRS, there are nearly 2000 journals in social sciences and humanities in France, 800 of which are published regularly. He was the only member of the commission to put forward the bibliometric H index in his evaluations.

The other representatives of biological anthropology (Anna Degioanni and Estelle Herrscher) shared to some extent the doubts about the future of the institutional partnership between the three disciplines of the 20th section of the CNU that Jean-Pierre had expressed on the commission at the time.

We decided with Jean-Pierre and Charles Stépanoff, a colleague from the *Laboratoire d'Anthropologie Sociale*, to create a working group to produce an "assessment and perspective" type of document that could serve as a starting point for discussion within the CNU during the last session of the term, without pretending to solve the problem of the interdisciplinary ties' distortion by the magic of a small committee discussion. The purpose of this text was twofold: to identify the factors at the origin of epistemic distancing and to identify some paths for renewing the interdisciplinary dialogue. Subsequently, we elaborated on this text through several correspondence and meetings. Following Jean-Pierre suggestion, we published this article in 2017 in *L'Homme,* a generalist journal where he had once published. The column was entitled "*For a general anthropology. Crisis and renewal of the scientific and institutional partnership of biological anthropology, social anthropology and prehistory*"[1]. Borrowing an editorial format from the journal Current Anthropology, the Op-Ed was supplemented by comments produced by colleagues chosen by the journal's editorial board, Maurice Bloch, professor of social anthropology at LSE, and Philippe Boissinot, archaeologist and director of studies at EHESS[2]. The purpose of this paper is to summarize the assessment we produced, the proposals we presented and the comments that this forum has generated.

Assessment

We started from the observation that although prehistory, biological anthropology and social anthropology now produce their knowledge in a largely separate manner, this has not always been the case. Moreover, it became clear that this evolution of interdisciplinary links was quite characteristic of the French context and was far less valid for English-speaking countries, particularly the USA. First, we must remember that at the beginning of the development of the Humanities in France and until the 1960s, the three disciplines were part of common academic structures. This was the case at the *Musée de l'Homme*, where the Institute of Ethnology, in accordance with the "Total Man" project that Marcel Mauss (1950

[1] Jean-Pierre Bocquet-Appel, Bernard Formoso and Charles Stépanoff, « Pour une anthropologie générale. Crise et renouveau du partenariat scientifique et institutionnel de l'anthropologie biologique, l'anthropologie sociale et la préhistoire », *L'Homme*, n° 223-224, 2017/3, pp. 221-246.

[2] Philippe Boissinot, « Sur l'anthropologie générale aujourd'hui. Commentaires d'un archéologue », *L'Homme*, n° 223-224, 2017/3, pp. 247-260. Maurice Bloch, « Bearing the other anthropological disciplines in mind », *L'Homme*, n° 223-224, 2017/3, pp. 261-264.

[1924]: 285) had formulated by defining anthropology as "*the combined sciences that consider man as a living, conscious, and sociable being*[3]", offered a curriculum that integrated courses in prehistoric ethnology and physical anthropology.

This interdisciplinary collaboration was at the time characterized by an explicit complementarity. On the one hand, the anthropologists of the Durkheimian school, including Marcel Mauss, took as their premise the existence of social invariants that applied to all humans. On the other hand, according to Jean-Pierre, anthropological biologists started, and still start, from the biological similarities shared by the different primate species, while still questioning the presence of fundamental social regularities also observed in the great apes (i.e. gift-giving, prevention of incest). Jean-Pierre added that one of the aims of prehistory is precisely to discover when and how such regularities could emerge in the past and how, according to their degree of elaboration, they can provide markers for tracing the long evolutionary process that links the great ape's fossils to the species *Homo sapiens sapiens*.

This shared synergy was sustained during the two decades following the Second World War by André Leroi-Gourhan, who was at the same time an ethnologist, a prehistorian, and skilled in paleontology. Appointed deputy director of the *Musée de l'Homme* in 1946, he created the *Centre de formation à la recherche ethnologique*, the CFRE, which until 1962 was the only structure for ethnological research training in France. The teaching program of the CFRE combined courses in ethnology, technology, physical anthropology, and excavation internships. Later, appointed to the chair of ethnology at the Sorbonne, Leroi-Gourhan would pass on to several generations of students the taste for this total science of Man initially formulated by Mauss. It was also under Leroi-Gourhan impetus that the three disciplines were grouped in the same section of the National Committee of the CNRS in the 1960s.

A first gap in this multidisciplinary structure was opened in 1962 when Claude Lévi-Strauss created a *Centre d'initiation à la recherche en anthropologie sociale*[4] at the EPHE 6th section, in direct competition with the *Musée de l'Homme* CFRE. Philippe Descola attests to this (Descola and Charbonnier 2014) if the training proposed by Leroi-Gourhan, with a technical focus, was an extension of archaeology, the one offered by Lévi-Strauss emphasized the study of social organization and its symbolic dimensions.

[3] « *Total des sciences qui considèrent l'homme comme un être vivant, conscient et sociable.* »

[4] Center for the Initiation of Research in Social Anthropology.

According to our analysis, the fracture between the three disciplines was fully achieved in the 1970s due to several converging institutional and epistemological factors. The institutional factors were the closing of the CFRE in 1969, which in turn set up the 6th section of the EPHE as the primary training center for social anthropology. In 1975, when the 6th section of the EPHE became autonomous with the creation of the EHESS, the division between humans' social and biological dimensions was confirmed. The universities followed suit. Today there is no longer a generalist training program in France that integrates prehistory and biological anthropology with ethnology, as there used to be at the Institute of Ethnology and then at the CFRE. Of the eight bachelor's degrees in "human sciences, anthropology and ethnology" currently offered in France, only one, Paris-Nanterre, combines courses in social anthropology and prehistory, and no French institution of higher education offers courses that combine biological and social anthropology. Similarly, at the CNRS, the "Anthropology, Prehistory, and Ethnology" section split up in 1992, with social anthropologists forming a separate section, while prehistorians, anthropological biologists and biogeographers are distributed between sections 31 and 32 of the INSHS. To interpret such a development, we suggested an increase in the complexity of the techniques required, particularly in the areas of prehistory and biological anthropology, which demand advanced skills in genetics, morphometry, geochemistry, or physics. We also considered the fragmentation of research structures into multiple laboratories and units as a result of increasing specialization within our disciplines and from the CNRS general policy.

Jean-Pierre compiled some interesting statistics based on an exhaustive analysis of anthropology programs offered in the United States. They showed that on the other side of the Atlantic and unlike the French example, the interdisciplinary link remained strong since 77% of the 112 departments surveyed offered undergraduate and graduate programs combining biological and cultural anthropology. Among them, almost 40% combined these two disciplines with archaeology. Also, I compared four major journals, namely *American Anthropologist*, *Current Anthropology*, JRAI, and *L'Homme*, according to the disciplinary fields of the articles they had published between 1961 and 1989. This enlightening comparison showed that 54% of the articles published during this period in *Current Anthropology* were in the field of biological anthropology or prehistory, 34% in JRAI, 18% in *American Anthropologist* and only 1.2% in *L'Homme*.

These statistics reveal differences between the United States and France, essentially for epistemological reasons.

The first is the influence that structuralism had on French anthropology in the 1960s and 1980s. For example, Lévi-Strauss developed all his anthropological project in the direction of the social structures, the acts of language and the symbolic elaborations which distinguish humanity in the animal kingdom. Thus, the structuralists were incited to build their objects of study based on the dualist predicate nature/culture. If the Durkheimian school remained anchored in an evolutionary interpretation grid by seeking to identify social laws of universal scope from the study of populations that they described as "primitive," in the 1950s, French social anthropologists broke with this approach, including Marxists who discussed Engels' theory of the five stages critically. Only a small number of authors continue to consider evolutionary stages and will question the processes of transition from one to the other (for ex., Alain Testart) or will be interested in hominization and the processes of formation of human technocultural complexes, following the example of Frédéric Joulian at the EHESS. However, their work is mainly echoed by prehistorians and anthropological biologists.

In contrast, in the United States, the relationship between anthropology's biological and cultural sides has never ceased. The program that Franz Boas outlined for the discipline at the turn of the 20th c. persisted. Boas defined anthropology as a branch of biology as well as a branch of the cognitive sciences and considered the problem of human evolution to be its ultimate goal. In the 1950s and 1960s, at the same time that French anthropologists were turning away from the concept of evolution, their American counterparts were producing several paradigms to theorize the notion. The movement was initiated by Julian Steward's multilinear theory (1955) and Leslie White's energy stages theory (1959), complemented by Richard Lee and Irven DeVore's 1966 hunter-gatherer symposium. Since then, American anthropologists and prehistorians continue to produce in close collaboration essays on the evolution of human societies.

Another epistemological reason that we isolated in the column of *L'Homme* is the narrowing of some thematic bridges. Consequently, the study of material culture and techniques was confined to the margins of the discipline from the 1970s onwards, despite the dynamism of the "Techniques and Cultures" group. However, this was one of the main fields of cross-disciplinary research between social anthropology, archaeology and prehistory. The collaboration between these three disciplines has also suffered from a decline in research dedicated to hunter-gatherers due to the residual nature of this subsistence mode and the attraction of the younger generations for subjects supposedly better anchored in modernity. With this decline in hunter-gatherers' interest, issues such as the emergence of politics, gift-giving and the prohibition of incest disappeared using the observation of primates and great apes as a comparative basis. However, hunter-gatherer bands are the human groups that anthropological biologists and prehistorians consider to be the closest to early humans. Once again, an essential interface between the three disciplines is lost.

Finally, the last ground for separation stems from the transformations specific to social anthropology since the 1990s. The understanding of societies in their different dimensions corresponds increasingly less to the intermediate aims of the discipline. Thus, in the last CNRS CRCN entrance exam, only 8% of the candidates set the study of the sociocultural logic of a human group as their objective. Following a general trend, the other candidates focused their research on institutions, phenomena, social, artistic, or religious movements constructed in an inter or transcultural context. Consequently, the analysis of cultural features gave way to approaches that were more sociological in nature. Depending on the researcher's orientation, social anthropology tends to dissolve into sociology, human geography, political science, or art history. The corollary is a blurring of disciplinary lines that prehistory and biological anthropology are not subjected to because of scientific habits based on teamwork and a greater outreach of their publications to the international community, limiting the risks of individual deviation.

Perspectives

Despite these deep divides, in the last part of our article, we reported on the research directions currently taking shape, suggesting that the interdisciplinary connection is not completely broken and could even be given new life. These new orientations are essentially the result of a radical critique of the interpretative scheme based on the nature/culture opposition initiated in the 1980s by the work of Marylin Strathern (1980) and continued since then by authors such as Bruno Latour (1991), Tim Ingold (2000) or Philippe Descola (2005). This challenge to the great division between the natural sciences, which would be responsible for studying the physical facts that bring us closer to other species, and the social sciences, which would be responsible for studying what gives humans their specificity, has opened the way to new approaches and explanatory models that link the biological and the social.

Jean-Pierre highlighted the work on the foundations of human sociality by Enfield and Levinson (2006), as well as the phylogenetic analysis of behaviour in human and non-human primates with regard to killing coalitions (Kelly 2005), cooperation (Tomasello 2009) or kinship (Chapais 2008), among others. Jean-Pierre also pointed out research currently exploring verbal and non-verbal communication in humans, which makes interesting connections with animal gestures and rituals, in particular those of Jean-Marie Schaeffer (2010). Together with Charles Stépanoff, we noted the emergence of new methodological approaches such as etho-ethnography or multi-species ethnography and, on the theoretical level, the production of new models that consider culture-gene coevolution (Lumsden and Wilson 1981), the construction of an ecological-cultural niche (Richerson and Boyd 2005) or biosocial futures (Ingold and Palsson 2013).

We also recognized that the domestication of plants and animals is a field of research in full revival thanks to the dialogues emerging, notably through the organization of colloquia, between archaeozoology, paleobotany, genetics, biochemistry, ethology and social anthropology. This renewal is particularly promising since the interconnections between biological and cultural processes are robust and visible in the case of domestication.

Charles Stépanoff, a specialist in Siberian populations, noted a renewed interest in hunter-gatherer societies as evidenced by the success of the 11th Conference on Hunting and Gathering Societies held in Vienna in 2015. He noted that the renewals triggered by the ontological turn have placed hunter-gatherer animism at the center of theoretical debates concerning the relationship between humans and non-humans and the role of humans in their environment.

The architects of the new research areas I have just mentioned have in common that they reinvest the conceptual framework of evolution while at the same time purging it of its deterministic undertones. They are in line with the proponents of the niche construction paradigm, which proposes dynamic, non-linear interpretation patterns that complexify the neo-Darwinian model. Jean-Pierre explained that these researchers revealed that organisms do not only adapt to selective environmental pressure but that they transform it by creating eco-cultural niches, and in so doing, they co-direct their evolution. In his view, eco-cultural niche theory opens the door to rich dialogues between disciplines insofar as the theory is already applied in evolutionary biology, prehistory and is beginning to be debated in social anthropology (Bloch 2016).

Conclusion

Building on the promising developments that I have just presented, we appealed in the essay's conclusion to all our colleagues to revive the project of general anthropology that was pursued by the founding fathers or the great masters. Although the increasing specialization of our disciplinary fields and the quest for new objects is legitimate, as André Leroi-Gourhan wrote in 1952 (1952: 511): "*Whatever the desire for autonomy that may drive the specialist, the values of the general views that are the reason for any research on man remains in direct function of the interdependence of disciplines.*"[5] From this perspective, there is much to be expected from renewed perspectives that consider the technical or epistemological advances of related disciplines on fundamental subjects such as kinship, body techniques, communication, cooperation, religions, the imaginary, diet or domestication.

Postscript

To conclude this paper, I would like to briefly summarize the comments that Philippe Boissinot and Maurice Bloch offered. Boissinot regretted that we had not integrated linguistics and history, two essential related sciences for archaeologists, into our reflection. He also challenged the fact that archaeological science could be reduced to the study of material culture, insofar as artifacts always refer to ideas and intentions that the discipline aims to decipher. In addition, he considered that the opposition nature/culture remained relevant for prehistorians because it allowed them to dissociate during excavations the processes that are related to the biophysical environment from those that are related to the action of man. Finally, Boissinot did not think that evolution was a central question in prehistory because it mainly concerns the Paleolithic.

Maurice Bloch pointed out that in the United States, the partitioning of disciplines was also a reality, despite the apparent unity of anthropology departments' structuring. Taking the opposite view of our proposals, Bloch considered that a tight combination of the three disciplines would be harmful to research because it would lock them into an epistemological bind. He claimed to have learned more from his collaborations

[5] « *Quel que soit le désir d'autonomie qui puisse animer le spécialiste, les valeurs des vues générales qui sont la raison de toute recherche sur l'homme reste en fonction directe de l'interdépendance des disciplines* ».

with neuroscientists than from advances in biological anthropology. However, Bloch considered it absolutely necessary to foster interdisciplinary dialogue so that social anthropologists, nourished by biological anthropology and prehistory contributions, could reframe their theories within a broader understanding of the human species.

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From the Teaching Unit "*Hommes et Milieux*[1]" to the "General Anthropology" seminar: Jean-Pierre Bocquet-Appel's commitment to teaching at the *École Pratique des Hautes Études*[2] (2008-2016)

De l'UE « Hommes et Milieux » au séminaire d'Anthropologie générale : l'engagement de Jean-Pierre Bocquet-Appel dans l'enseignement à l'École Pratique des Hautes Études (2008-2016)

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Abstract: Jean-Pierre Bocquet-Appel was elected Director of Studies at the *École Pratique des Hautes Études (EPHE)* in 2008, with the position of Director of Studies in Demographic Anthropology in the 3rd section of the *École*. As soon as he was elected, he joined the *Laboratoire de Paléoanthropologie* (directed by Henri Duday), which became the *Laboratoire Broca* in 2011. Committed to his scientific responsibilities (two-terms member of the EPHE Scientific Council), JPBA was also active in teaching at the EPHE until his retirement in 2016. His professorship enabled him to enthusiastically transmit his vision of biological anthropology to the EPHE students and auditors. From 2010 to 2015, he was the creator and head of the "*Hommes et Milieux"* teaching unit of the EPHE Master's degree in Biology, Health, and Environment. With Charles Stépanoff, member of the EPHE 5th section and the *Laboratoire d'Anthropologie Sociale*, he was the driving force behind the EPHE General Anthropology seminar's construction set up at the Sorbonne and the *Collège de France* in collaboration with the EHESS[3]. These two courses enabled many students to enrich their knowledge of demographic anthropology and spatial demography and discover the Neolithic or agricultural demographic transition concepts, dear to Jean-Pierre Bocquet-Appel.

Keywords: EPHE, biological anthropology, demographic anthropology, ecological niche, paleodemography

Résumé : *Jean-Pierre Bocquet-Appel a été élu Directeur d'Études cumulant à l'École Pratique des Hautes Études en 2008, titulaire de la Direction d'Études en Anthropologie démographique en 3e section de l'École. Il a rejoint dès son élection le Laboratoire de Paléoanthropologie (dirigé par Henri Duday) redevenu Laboratoire Broca en 2011. Engagé dans les responsabilités scientifiques (deux mandats de membre du Conseil Scientifique de l'EPHE), il a été aussi actif dans les enseignements de l'EPHE jusqu'à sa retraite en 2016. Sa fonction professorale à l'École Pratique lui a permis de transmettre avec enthousiasme aux étudiants et auditeurs de l'EPHE sa vision de l'anthropologie biologique. Il a été de 2010 à 2015 le créateur et le responsable de l'Unité d'Enseignement « Hommes et Milieux » du Master Biologie Santé et Environnement de l'EPHE. Avec Charles Stépanoff, membre de la Ve section de l'École et du Laboratoire d'Anthropologie Sociale, il a été le moteur de la construction du séminaire d'Anthropologie générale de l'EPHE, mis en place à la Sorbonne et au Collège de France en collaboration avec l'EHESS. Ces deux enseignements ont ainsi permis à de nombreux étudiants d'enrichir leurs connaissances sur l'anthropologie démographique et la démographie spatiale et de découvrir les concepts de transition démographique néolithique ou agricole, chers à Jean-Pierre Bocquet-Appel.*

Mots-clés : *EPHE, anthropologie biologique, anthropologie démographique, niche écologique, paléodémographie*

[1] Humans and Environments.

[2] Practical School for Advanced Studies.

[3] *École des Hautes Etudes en Sciences Sociales*/School for Advanced Studies in the Social Sciences.

The *École Pratique des Hautes Études*, alpha and omega of Jean-Pierre Bocquet-Appel's career

Jean-Pierre Bocquet-Appel had a strong link with the *Ecole Pratique des Hautes Etudes* (EPHE), mainly at the beginning and at the end of his scientific career, a kind of alpha and omega in his research and teaching career in biological anthropology.

Jean-Pierre's career at the *Ecole Pratique des Hautes Etudes* began in 1969 when he enrolled in a diploma under Annette Laming-Emperaire, Director of Studies in the 6th section, chair of South American prehistoric anthropology. He received his EPHE diploma in 1974, and with this academic passport allowing him to register for a doctorate, he approached Denise Ferembach, who had just been appointed to the 3rd section (Life and Earth Sciences) as director of the "Broca laboratory."The 6th section splitting from the EPHE in 1975 to become autonomous under the name of *Ecole des Hautes Etudes en Sciences Sociales* (EHESS), Jean-Pierre Bocquet-Appel completed his Ph.D. in historical anthropology under the joint direction of Denise Ferembach and Jean-Marie Pesez, a medieval archaeologist, a thesis he defended in 1977 entitled "Paleo-demographic perspectives." However, as soon as he received his Ph.D., Jean-Pierre joined the EPHE in Denise Ferembach's laboratory of biological anthropology with the title of "Preparator", a position he held until 1981 when hired by the CNRS[4] Section 33, where he spent most of his career while remaining devoted to young researchers' training in biological anthropology.

In 2008, Jean-Pierre renewed his link with the EPHE through the creation of a Department in Demographic Anthropology (status of Director of Studies) by Henri Duday in the EPHE paleoanthropology laboratory (the legacy of the Broca laboratory). Elected to this position by the 3rd section assembly, JPBA will actively participate in the EPHE life by being an elected member of its Scientific Council during two successive mandates from 2010 to 2016, when he retired from the CNRS.

During this period, within the framework of the section assembly and his elective functions on the establishment scientific council, of which he was a devoted and active participant, JPBA left his mark on the minds of all the members of these bodies. They remember his interventions, which were both pertinent and sharp, sometimes incisive but courteous and always hitting the mark. He readily evoked his attachment to the EPHE history, of which he had lived a part of before the reform of the statutes: "*I would like to say that I entered as a preparator in the 3rd section of the Ephe, in 1978, at the time when its administration was located under the roof of the Sorbonne. It made for a funny School, when we entered this strange little room, coming from the big staircase of the Sorbonne, because of the curvature of the slopes of the roof*[5]" (JPBA, email dated March 11, 2016). "*I remind you that I began my scientific career at the École 38 years ago, as a young doctor in anthropology, with the title -- which may seem old-fashioned today -- of Preparator, at the Laboratoire d'Anthropologie biologique, then directed by Mrs. Denise Ferembach. The dean of the 3rd section was then Paul Fraisse. Then I pursued a career at the CNRS*[6]" (JPBA, email dated October 20, 2016).

This status of preparator, of which he was so proud, was that of the EPHE pioneers, notably within the Natural Sciences Section, the assistant in charge of the practical help of the directors and the practical work of the students, it was that of Broca's young students, Ernest Hamy, Paul Topinard, and Léonce Manouvrier, who became great names in Anthropology. Moreover, this EPHE anthropology laboratory in which JPBA carried out his duties was the Broca laboratory founded by the Master of the discipline in 1868, rich with its historical archives, which Denise Ferembach inherited as director in 1973.

As a participant of the EPHE history, Jean-Pierre never stopped fighting to defend its identity, which he feared would disappear amid major federating projects. First, the EPHE's membership in the HéSAM (*Hautes Etudes, Sorbonne, Arts et Métiers*) community of institutions, then the eventful departure for the PSL (*Paris Sciences Lettres*) Idex, seemed to JPBA to carry structural risks.

Moreover, JPBA was particularly concerned about the request of certain SVT section[7] members to change the

4 *Centre National de la Recherche Scientifique*/National Center for Scientific Research.

5 *« Je voudrais dire que je suis rentré comme Préparateur à la 3e section de l'Ephe, en 1978, à l'époque où son administration était localisée sous les toits de la Sorbonne. Cela faisait une drôle d'École, quand on rentrait dans ce local un peu bizarre, venant du grand escalier de la Sorbonne, à cause de la courbure des pentes du toit. »*

6 *« Je rappelle que j'ai commencé ma carrière scientifique à l'École il y a 38 ans, jeune docteur en anthropologie, avec le titre -- qui peut sembler vieillot aujourd'hui -- de Préparateur, au Laboratoire d'Anthropologie biologique, alors dirigé par Mme Denise Ferembach. Le doyen de la 3e section était alors Paul Fraisse. Puis j'ai poursuivi une carrière au Cnrs. »*

7 *Section des Sciences de la Vie et de la Terre* / Life and Earth Sciences section.

status of the Affiliated Director of Studies (DEcu[8]), which was his status, towards a temporary and not permanent recruitment status: "*While the School is committed to a second Idex project, I would like to say a few words, ultimately, about the identity of the EPHE within PSL. [...]. In this second PSL Idex project, after the first one which failed and for which, to my knowledge and which is a pity, there was no critical assessment from the point of view of the EPHE, it will become challenging to maintain the identity of the School, what we would now call its DNA, what essentially distinguishes the EPHE from the University or the EPST. In this DNA, in addition to their diploma, there is the status of* "Affiliated Director of Studies" *(DEcu), which allows for a mix of institutional backgrounds by promoting a kind of research university. This status also gives the DEcu more freedom of speech, as their advancement does not depend on internal politics. [...] From the beginning, the School was composed of many DEcu, even if they did not bear this title. The present attempt by some of the DEs of the SVT section to abolish this status is, on the one hand, a splintering position of the (historical) GA of the School and, on the other hand, would transform the SVT section into its own, simple, university department. This would deeply compromise, in my opinion, the global identity of the EPHE, of course of its SVT section, but also of its two other sections."* (JPBA, email dated October 20, 2016)[9].

The defense of teaching in biological anthropology at the EPHE, from the teaching unit "*Hommes et Milieux*" to the "General Anthropology" seminar

Jean-Pierre's sincere interest in the teaching of his discipline and the training of young researchers was expressed through his involvement in Section 20 of the *Conseil National des Universités*, of which he was an elected member from 2011 to 2015 as well as through his EPHE functions. During the four years as a preparator in the Broca laboratory, JPBA contributed to communicating his passion for the discipline to the students attending the laboratory of Juvisy-sur-Orge. Then, after a period devoted to research initiated at the time of his hiring in the CNRS, he returned to university training by leading a paleodemography seminar at the EHESS from 2004 to 2008. However, at the EPHE, JPBA was able to take responsibility for teaching as Director of Studies. Thus, JPBA created within the EPHE master's degree in Biology, Health and Environment the teaching unit "Humans and Environments" that he has led for five academic years, from 2011 to 2015.

As a recent recruit at the EPHE, I had the chance to participate in this teaching unit (TU) since its creation, and it was the first course that I gave at the beginning of the 2011 academic year in my new institution. At the time of the TU termination in 2015, which was not of JPBA's choosing because he wished to maintain it under my direction upon his retirement, but which was imposed on him without consultation, he reminded me of its history in an email dated April 7, 2015: "*When I joined the School (2008), Henri [Duday] and I were considering a kind of seminar combining his skills (archaeo-thanatology as he says) paleopathology, paleodemography, and the colonization of the Planet. We thus considered a cross-disciplinary approach with colleagues of the archaeological and ancient history section (I do not remember the number...). Despite two meetings, this did not lead to a joint seminar [...] I, therefore, tried to maintain Biological Anthropology, given the configuration of SVT, with H&M [Hommes et Milieux]. It seems that you have been able to recognize the difficulty of raising the discipline's flag in the context of the heterogeneous SVT section. [...]*[10] *"*Indeed, faced with the same challenges, I had chosen to defend biological anthropology from the perspective of the interactions between humans and their pathogens, which Jean-Pierre found amusing when he told me that I was hiding anthropology behind germs.

This "Humans and Environments" course was designed to maintain biological anthropology within our EPHE section by referring to the CNRS Section 31 title in

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8 Directeur d'études cumulant.

9 « *Alors que l'École est engagée dans un second projet d'Idex, je me permets de dire quelques mots, in fine, sur l'identité de l'EPHE dans PSL.* […]. *Dans ce second projet d'Idex PSL, après le premier qui échoua et dont il n'y a pas eu de bilan critique du point de vue de l'École, à ma connaissance et ce qui est dommage, il va devenir difficile de maintenir l'identité de l'École, ce qu'on appellerait maintenant son ADN, ce qui la distingue essentiellement de l'Université ou des EPST.* […] *Dans cet ADN, à côté de son diplôme, figure le statut de DE cumulant (DEcu), qui permet de mélanger les origines institutionnelles en favorisant une sorte d'université de recherche. Ce statut rend aussi plus libre la parole des DEcu, car leur avancement ne dépend pas d'enjeux internes. Dès l'origine l'École était composée de nombreux DEcu, même s'ils ne portaient pas ce titre. La tentative actuelle d'une partie des DE de la section SVT de faire abolir ce statut est, d'une part, une position scissionniste de l'AG consubstantielle (historique) de l'École et, d'autre part, transformerait la section SVT en simple département universitaire dans son style. Ceci altérerait profondément, à mon sens, l'identité globale de l'EPHE, bien sûr de sa section SVT, mais aussi de ses deux autres.* »

10 « *Quand je suis rentré à l'École (2008), Henri* [Duday] *et moi-même envisagions une sorte de séminaire couplant ses compétences (archéo-thanatologie comme il le dit lui-même) la paléopathologie, la paléodémographie, et la colonisation de la Planète. Nous avons donc envisagé une transversalité avec des collègues de la section archéologique et histoire ancienne (je ne sais plus le numéro...). Malgré deux réunions, cela n'a pas débouché sur un séminaire commun; […] J'ai donc essayé de maintenir l'Anthropologie biologique, étant donné la configuration de SVT, avec H&M* [Hommes et Milieux]. *Il me semble que tu as pu te rendre compte toi-même de la difficulté de sortir le drapeau de la discipline, dans le contexte de la section SVT, hétérogène. […]* »

charge of our discipline. JPBA managed the program and coordinated the teaching team, which was mainly composed of EPHE professors from different fields, whom he had sensitized to our discipline, such as Hélène Blanchoud (Associate Professor EPHE, specialist in aquatic ecotoxicology), Laurence Mathieu (Associate Professor EPHE, specialist in environmental and health microbiology), Maria Fernanda Sanchez-Goñi (Director of Studies EPHE, specialist in paleoclimatology and marine paleoenvironment), Thierry Wirth (Director of studies EPHE, specialist in microbial evolution and population genomics), and myself. JPBA was also able to rely on CNRS researchers' participation from his unit, specialists in human evolution such as Sandrine Prat and Christine Verna. He had traced the outline of the course around the question of the colonization of the Earth by the *Homo* genus: "*The main objective of the course is to provide students with the spatio-temporal benchmarks of paleoanthropology and archaeology, and the application of demographic, ecology, and population genetics concepts and models to the problem of the global Earth colonization by the humans' metapopulation over the past 2.8 million years.*"[11] Moreover, JPBA had defined the essential questions: "*Why are we the only animal whose natural geographic distribution is global? What is/are the cause(s) of the initial human dispersal/migration leading to global colonization? Is there a coincidence between technological innovation and the first colonization?*"[12].

As a fervent defender of the ecological niches notion, JPBA had made it the common thread of his teachings, adopted by the course guest speakers: *"The colonization of the Earth was that of the main ecological niches, as one moves towards the poles, from the forested intertropical savannah to the cold steppe, through hot and cold deserts, tropical forests, mountains, and islands. When, by whom, and with what cultural devices were these ecological niches conquered?"*[13] The evolution of human demography, shaped by the concept of the Agricultural Demographic Transition of which he was the author, was also at the center of this teaching: "*The massive increase in population density, originating with the agricultural demographic transition in many parts of the Earth during the Holocene, has led to an anthropization of natural ecological niches, producing the construction of a specifically human artificial niche, where an ever-increasing proportion of humans is detached from any action directly related to food production. Moreover, this Agricultural Demographic Transition probably coincided with the emergence of zoonoses, linked to domestication.*"[14] The presentation of this course concluded as follows: "*By 2050, the average prediction of the number of inhabitants on Earth is 9 billion, against six today, that is, one more China and one more India, the two most populous countries in the world. According to the criteria of population biology, has man become an invasive species?*"

These questions were developed in the program, of which a general outline can be presented here:

I- First out-of-Africa

- The impact of macro climatic constraints (exogenous) on mammalian metapopulations (example of the extinction of Neanderthals)

MF Sanchez Goni

- Biocultural and paleoecological data of the first representatives of the genus *Homo* and the *Paranthropus* in Africa. Which actors? Which ecological niches?

S. Prat et C. Verna

II- The continental blocks: the high latitudes of Eurasia, Australia, the Americas, and Oceania.

- The colonization of the main ecological niches and their tempo.

JP. Bocquet-Appel, S. Prat, C. Verna

- The main population-resource demographic models.

JP. Bocquet-Appel

- Human migrations from the geneticist's point of view

Thierry Wirth

11 « *Le cours a pour principal objectif de fournir aux étudiants les repères spatio-temporels de la paléoanthropologie et de l'archéologie, et la mise en application des concepts et des modèles démographiques, d'écologie et de génétique des populations à la problématique de la colonisation globale de la Terre par la métapopulation des hommes, depuis 2,8 millions d'années.* »

12 « *Pourquoi sommes-nous le seul animal dont la distribution géographique naturelle soit mondiale ? Quelle(s) est/sont la/les cause(s) de la dispersion/migration humaine initiale provoquant la colonisation mondiale ? Y-a-t-il une coïncidence entre innovation technologique et la première colonisation ?* »

13 « *La colonisation de la Terre fût celle des principales niches écologiques, quand on se dirige vers les pôles, de la savane intertropicale arborée à la steppe froide, en passant par les déserts chauds et froids, la forêt tropicale, les montagnes et les iles. Quand, par qui, et avec quels appareils culturels ces niches écologiques furent-elles conquises ?* »

14 « *L'augmentation massive de la densité de la population, née avec la Transition démographique agricole en plusieurs points de la Terre au cours de l'Holocène, a amené à une anthropisation des niches écologiques naturelles, produisant la construction d'une niche artificielle proprement humaine, où une proportion toujours croissante d'êtres humains est détachée de toute action liée directement à la production de nourriture. En outre, cette Transition Démographique Agricole a vraisemblablement coïncidé avec l'émergence de zoonoses, liées à la domestication.* »

III- From the colonization of natural ecological niches until the Holocene to the construction of the Anthropocene's artificial niche.

• The consequences of the anthropization of environments.

Hélène Blanchoud

• Human-Environment interactions and human health.

Laurence Matthieu

• Epidemiological transitions, from the Pleistocene to the Anthropocene.

Olivier Dutour

This cross-disciplinary course, which lasts about thirty hours, has trained about fifty students over the course of its existence, with very positive feedback on the course content, providing a real insight into the chronological depth of the key current environmental issues. However, the programmed restructuring of the "Environment" course teachings in the Biology Health Environment Master was more geared towards specialized teachings, and this course was considered too generalist in a curriculum with a professional purpose. Jean-Pierre had tried advocating for the place of his teaching in the EPHE's "Environment" course with one of the coordinators on April 7, 2015, in an exchange that I was cc'd on, putting forward his conception of the Environment:

> "*The theme of H&M is not so much the Environment per se, as the construction of the niche of Humans since 2.8 MA and their biogeographic structuring, despite the natural environment, since we are reaching the Anthropocene, that is, an era essentially formed by the fallout of human activities and the artificialization of the world.*[15]"07/04/2015, 13:41 (correspondence on the position of the TU in the Environment theme lectures).
>
> "*The word Environments, understood literally, as data, was misleading; it was the changing environment (modified/created by humans) to which this TU refers.*[16]"07/04/2015, 18:13 (correspondence on the position of the TU in the Environment theme lectures),
>
> "*As I am mainly interested in humans' evolutionary trajectory, the interest of the Environment theme was to illustrate that this environment was becoming more and more a human construction and that there is practically no longer a natural ecosystem (species in equilibrium with others). H[*umans*] are not a species like the others in the ecosystem. (Humans) tend to steer it (*the environment*) since 2.8 ma, for its own purpose. I will not develop. So H&M was not conceived as H(umans) present in the natural ecosystem, but its Environment as a niche construction started long ago.*[17]"07/04/2015, 18:42 (continued from correspondence): in response to "Man is one of the elements of the Ecosystem."

Two days later, recognizing that the restructuring of the Environment course would be done without him, he wrote:

> "*Re: Fwd: Re: Restructuring of environmental education*
> *Jean-Pierre Bocquet-Appel jean-pierre.bocquet-appel@cnrs.fr*
> *Thu 09/04/2015 10:46*
> *TO: xy@ephe.sorbonne.fr*
> *Cc: Olivier Dutour Olivier.Dutour@ephe.sorbonne.fr*
>
> *Hello,*
> *My perspective is the evolution of man (humans) and the construction of his niche (and the significant influence of this construction on those of other species, including pathogens) since 2.8 ma (determining his biological structuring, with the global colonization of the planet), but not from the point of view of men disturbing a kind of virginal, ideal environment, such as it existed before the humans. Aquatic Ecology is a part affected and modified by the construction of the niche. In short, my theme is humans and not the Environment, which does not exist without humans. Anyway, this TU doesn't seem to fit anymore in this new context focused on "Environmental technician/engineer" (i.e., in fact, also niche builder...).*
> *Never mind, I'll look elsewhere.*
> *Best wishes,*
> *jpba*[18]"

[15] « *L'axe de H&M n'est pas tant l'Environnement en soi, que la construction de la niche des Hommes depuis 2.8 MA et leur structuration biogéographique, en dépit de l'environnement naturel, puisque nous arrivons à l'Anthropocène, cad une ère constituée essentiellement par les retombées des activités humaines et l'artificialisation du monde.* »

[16] « *Le mot Milieux, pris au premier degré, comme une donnée, était trompeur ; c'était le milieu en évolution (modifié/créé par les humains) auquel cette UE fait référence.* »

[17] « *Pour moi, qui suis principalement intéressé par la trajectoire évolutive des humains, l'intérêt de l'axe Environnement était de montrer que cet environnement devenait de plus en plus une construction humaine et qu'il n'y a pratiquement plus d'écosystème naturel (des espèces à l'équilibre avec les autres). L'H n'est pas une espèce comme les autres dans l'écosystème. Il tend à l'orienter depuis 2.8 ma, pour sa finalité propre. Ne vais pas développer. Donc H&M n'était pas conçu comme l'H présent dans l'écosystème naturel, mais ses Milieux comme une construction de niche entamée depuis longtemps.* »

[18] *Bonjour,*
Ma perspective s'inscrit dans l'évolution de l'homme (des humains) et la construction de sa niche (et l'influence majeure de cette construction sur celles des autres espèces, incluant les pathogènes) depuis 2.8 ma (déterminant sa structuration biologique, avec la colonisation globale de la planète), mais pas du pt de vue des hommes perturbant une sorte d'environnement virginal, idéel, tel qu'il existait avant les humains. L'Ecologie aquatique est un morceau impacté et modifié par la construction de niche. Bref, mon axe ce sont les humains et pas l'Environnement, dont la question n'existe pas sans les humains. Bon, cette UE ne semble plus à sa place dans ce nouveau contexte axé sur "technicien/ingénieur en Environnement" (c a d, en fait, aussi constructeur de niche...).
Tant pis, je vais me renseigner ailleurs.
Bien à vous,
jpba »

Since then, no doubt disappointed at losing a place in the curriculum that he had legitimately earned and that he wished to maintain after he departed from the School, Jean-Pierre had worked on setting up his major project in the new context of the *Paris Sciences Lettres Idex*: the creation of a General Anthropology program in Paris. He had outlined his intent during his tenure at the CNU[19] section 20 between 2011 and 2015, initiating active discussions with two ethnologist colleagues, Bernard Formoso and Charles Stépanoff. This collaboration resulted in a joint article published in 2017[20] in the journal *L'Homme*, a leading journal in social anthropology, and entitled: "For a General Anthropology: Crisis and Renewal of the Scientific and Institutional Partnership of Biological Anthropology, Social Anthropology, and Prehistory." Under this triple signature, the authors concluded as follows:

> "*Reintegrating the reference to the biological, technical, mental, and social evolution of humans would reinforce the epistemological coherence of the combination of biological anthropology - ethnology - prehistory. A university curriculum of general anthropology, integrating the three disciplines in all the places where they already exist, should be promoted [...].*[21]"

This context is how the PSL University General Anthropology Seminar carried by the EPHE, EHESS, and ENS opened in 2017. Having become emeritus in October 2016, Jean-Pierre Bocquet-Appel was not one of the academic bearers. However, he gave what was undoubtedly his last major lecture on March 9, 2017, in the *Collège de France*, entitled "Agricultural demographic transitions during the Holocene and the emergence of the main regulatory ideologies on a global scale," a seminar in which he related the emergence of agriculture, the agricultural demographic transition, and the emergence of the main religions.

Today, we must hope that JPBA's broad conception of training in the discipline of biological anthropology, which is probably the only one that can save the field from the current generalized trend of knowledge fragmentation, will take root in our communities and our national academic institutions. However, JPBA will be sorely missed in the accomplishment of what he called the "anthropological project."

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[19] *Conseil National des Universités*/National Council of Universities.

[20] Bocquet-Appel *et al.* 2017, Bocquet-Appel J.P., Formoso B., Stépanoff C., Pour une anthropologie générale, *L'Homme*, 2017/3 n° 223-224, 2017, p. 221-246.

[21] « *Réintégrer la référence à l'évolution biologique, technique, mentale et sociale des humains renforcerait la cohérence épistémologique de l'association anthropologie biologique – ethnologie – préhistoire. Un enseignement universitaire d'anthropologie générale, intégrant les trois disciplines dans tous les lieux où les unes et les autres existent déjà, devrait être promu* […]. »

Bibliography of Jean-Pierre Bocquet-Appel

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In this section, we wanted to collect the list of Jean-Pierre Bocquet-Appel's publications. We present his written production since 1976, to which we must add two unpublished university manuscripts, a post-graduate thesis and a doctoral dissertation[1]:

Bocquet-Appel 1977, BOCQUET-APPEL J.-P., *Perspectives paléodémographiques*, Thèse de 3e cycle, Anthropologie historique, École des Hautes Études en Sciences Sociales, Paris, 1977, 206 p.

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[1] Before 1984 and the introduction of the New Regime thesis, a short thesis, known as a postgraduate thesis, was followed by a longer and more substantial thesis, known as a state thesis.

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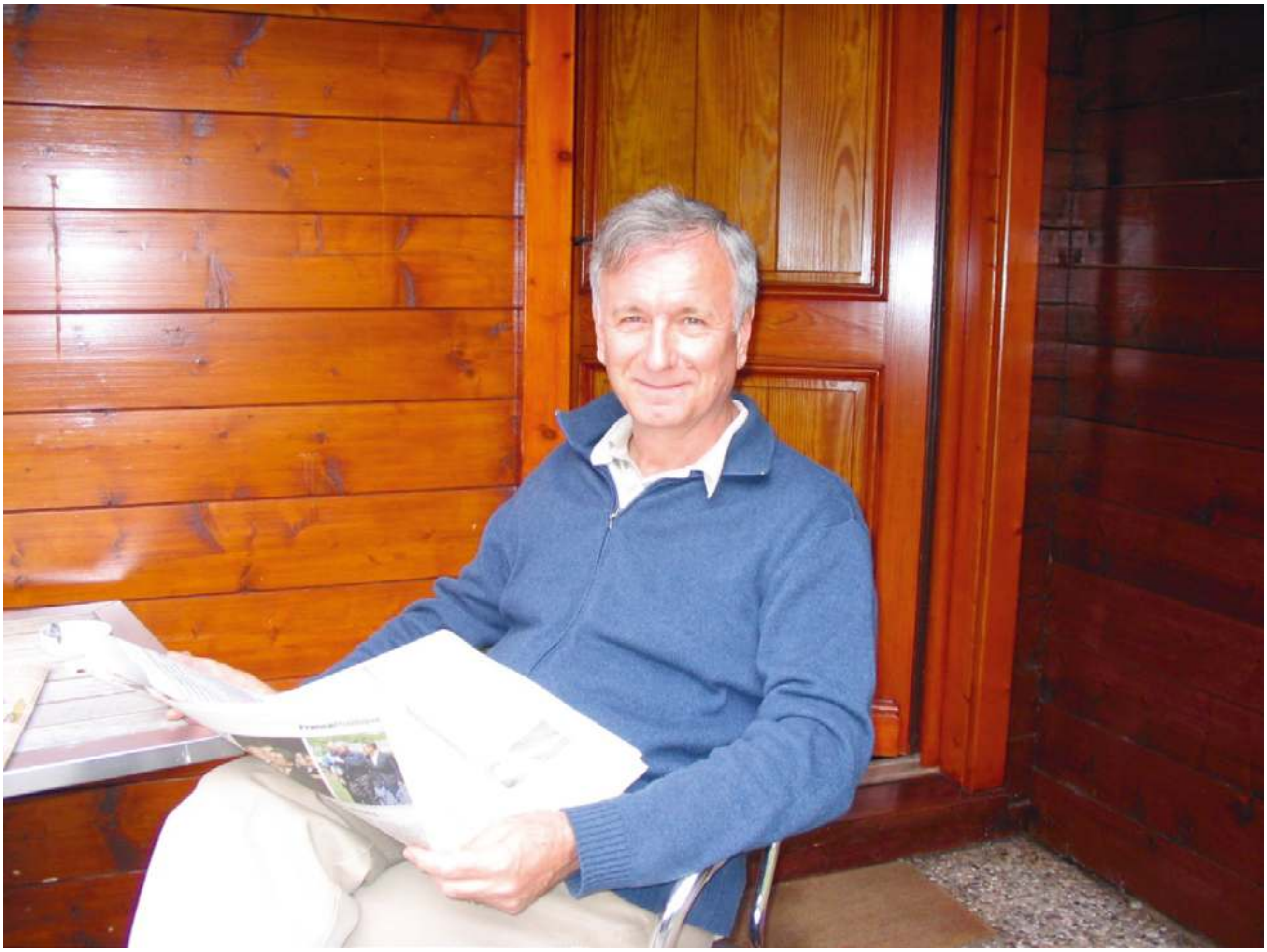

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