Early domestication and farming: what should we know or do for a better understanding?

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ABSTRACT
This paper aims to identify a series of conceptual, strategic and technological challenges facing archaeozoology (and archaeobotany) in order to better understand when, where, how and why plant and animal domestication and farming developed during the last 12 000 years. Situated at the interface of human societies and their environment, this reflection is based on examples, some of them unpublished, and on many references to animal domestication and husbandry in Eurasia, especially in East Asia, Southwest Asia and Cyprus. From a conceptual point of view, the author calls for an integrative systemic approach within the structural framework of the anthroposystem – a metasystem grouping societies and their environments, namely, their biodiversity. In order to tackle the full complexity of the system, equal attention must be paid to the biological, evolutionary and ecological components, as well as to the anthropological dynamics of human societies including technical, social and cultural aspects. To facilitate such an approach, this paper proposes a series of dynamic lines of research in order to explore the numerous gaps in our understanding of the beginnings of domestication and of the Neolithic transition, covering both causal factors and the diverse strategies developed by past societies. It pays special attention to the increasingly varied and cutting-edge technologies that can be used within these research projects, specifically quantitative data processing and databasing, direct radiocarbon dating of the bioarchaeological remains, traditional or geometric morphometrics, paleogenetics and paleogenomics, and sequential analyses of stable isotope ratios. More generally speaking, this paper aims to contribute to the development of an emerging and very promising interdisciplinary field of research.

KEY WORDS
Domestication,
Neolithic transition,
archaeozoology,
archaeobotany,
Southwest Asia,
Cyprus,
China,
research strategy.

RÉSUMÉ

Les débuts de la domestication, de l'agriculture et de l'élevage : que devrions-nous savoir ou faire pour mieux comprendre ?

Cet article vise à identifier une série de défis conceptuels, stratégiques et technologiques que l'archéozoologie (et l'archéobotanique) devrait relever pour mieux comprendre quand, où, comment et pourquoi la domestication des plantes et des animaux, puis leur agriculture et leur élevage, se sont développés depuis 12 000 ans. Située à l'interface des sociétés humaines et de leur environnement, cette réflexion se nourrit de divers exemples, parfois inédits, et de travaux de la littérature concernant surtout la domestication et l'élevage des animaux en Eurasie, plus particulièrement en Extrême-Orient, en Asie du Sud-Ouest et à Chypre. Du point de vue des concepts, l'auteur plaide en faveur d'une approche systémique intégrative, inscrite dans le cadre structuraliste de l'anthroposystème, méta-système regroupant les sociétés et leur environnement, notamment sa biodiversité. Afin de prendre en compte toute la complexité de ce système et de ses dynamiques, il insiste sur la nécessité d'accorder une égale importance aux composantes relevant de la biologie évolutive et de l'écologie, et aux dynamiques anthropologiques propres aux sociétés humaines, notamment les aspects techniques, sociaux et culturels. Il propose une liste de directions de recherches prioritaires permettant, à différentes échelles d'espace et de temps, d'explorer les nombreux angles morts qui persistent dans notre compréhension des phénomènes de domestication et de transition néolithique, tant en ce qui concerne les facteurs de forçage que la grande diversité des stratégies développées par les sociétés. L'auteur accorde une attention particulière aux technologies de plus en plus variées et sophistiquées, susceptibles d'être mises au service de ces directions de recherche. Il insiste en particulier sur le traitement, la conservation et la mise à disposition des données quantitatives, sur les datations radiométriques directes des restes bioarchéologiques, sur la morphométrie traditionnelle et géométrique, sur la paléogénétique et la paléogénomique, et sur les analyses séquentielles des taux d'isotopes stables. D'un point de vue plus général, il tente de contribuer au développement de cet encore jeune mais très prometteur champ de recherche interdisciplinaire.

MOTS CLÉS
Domestication,
transition néolithique,
archéozoologie,
archéobotanique,
Asie du Sud-Ouest,
Chypre,
Chine,
stratégie de recherche.

INTRODUCTION[1]

The adoption of farming as a new way of life for a large part of humanity was a major step in its history. It also inaugurated an ever growing increase of human impact on the biosphere. This phenomenon, called the Neolithic transition, is rooted in the second half of the Late Glacial, around 14 000-12 000 years ago, and developed throughout the Holocene. It proceeded in a non linear manner with multiple local and global accelerations, as well as slowing down or even local failures or recurrences.

During the last 15 years, there have been considerable improvements in our archaeological knowledge concerning the development of farming, and the global and regional evolution of the climate during the last twenty millennia. Recent evidence has demonstrated that the connection between climatic change and farming emergence is not a simple and direct relationship of causality. Though climate continued to play an important role in the evolution of the biosphere during the Holocene, this period is mostly characterized by an increasing decoupling between climate fluctuations and the human socio-economic evolution (Vigne 2011a, 2012). It is evident that this new regime was not purely a geological or climatic phenomenon, but an anthropological and ecological one too, appearing as the result of the complex interplay between multiple natural and cultural factors, acting within socio-ecological systems.

This perspective provides a new framework for further investigations, and may allow us to better understand the reasons and mechanisms behind the many facets of the Neolithic transition. This article, based on a series of examples primarily from Europe and Asia, aims to fully explore this perspective in order to highlight the main questions that are still pending, to underline the main bottlenecks, and to formulate a series of recommendations for addressing the issues raised.

EARLY AND ONGOING DOMESTICATIONS

The earliest known animal domestication is that of the wolf, which seems to have occurred in the Old World around 17 000-15 000 years Before Present (calibrated: cal BP; Larson *et al.* 2012) without any apparent connection with the Neolithic transition, bar that it occurred just before humans began improving control of their food supply (Valentin 2008).

Later, around 14 000 cal BP, the Neolithic transition expanded to include more numerous regions, with plant and animal domestications being a primary component of this profound change of life. However, domesticates and new domestications also played a major role in a series of subsequent transitions, such as urbanization, birth of empires, industrialization and, more recently, globalisation. For example, 2010 could symbolize a major change in the history of humanity since this

1. This article is the slightly modified and augmented text of the plenary conference that I delivered on the 26th September 2014 during the 12th International Council for Archaeozoology, at San Rafael (Mendoza, Argentina).

was the year when fish surpassed beef in the global diet, as a consequence of the increasing fish domestication during the 1970s and 1980s (Earth Policy Institute 2013).

Though this paper deals mostly with early domestications, it needs to be stressed that domestication is an ongoing phenomenon which continues to play a major role in the history of humanity and the biosphere. The study of recent or modern domestications, together with experimental domestications conducted under conditions similar to the ones which prevailed in the last hunter-gatherer societies (see e.g., O'Reagan & Kitchener 2005; Cucchi *et al.* 2014), is a fantastic potential source of information for better understanding this diverse and complex phenomenon. This line of research is widely underexploited by archaeozoologists and archaeobotanists, and needs to be more intensively pursued.

A SOCIO-ECOLOGICAL APPROACH TO DOMESTICATION

Except in some rare situations, natural ecosystems no longer exist on the earth's surface (Dorst 1965; Millennium Ecosystem Assessment 2005). Aside from what could be called 'man-made ecosystems'[2], which are built or cultivated, there are numerous apparently 'natural ecosystems' which have, in fact, been deeply modified by human activities. For example, most of the so-called "natural" forests of Europe have been exploited throughout the centuries for wood, charcoal, fungi, hunting or feeding domestic animals.

Therefore, to restrict our scientific approaches to purely ecological or evolutionary biology analyses, or even anthropological analyses, would lead us to a partial or even mistaken view. We therefore need to base our research and reflections, under the heading of an 'anthroposystem' or an 'anthropo-ecosystem', within the framework of a metasystem composed of one or several 'natural' or 'man-made ecosystems', one (or several) human societies and their cultural characteristics, and the interactions between these natural and cultural components (Muxard *et al.* 2003; Pascal *et al.* 2005, 2006a, b; Vigne 2011a: fig. 4). Such a conceptual framework differs markedly from some of the domestication research that has fast developed during recent years, primarily based on evolutionary biology approaches (e.g., Zeder 2015), and sometimes producing too simplistic or questionable 'optimal foraging' or 'niche construction' approaches (Vigne 2011a; for additional discussions, see below: "Exploring the role of the technical system for food supply").

This proposed conceptual framework also has important methodological implications, as the two main components of the anthroposystem, the societies and the ecosystems, have entirely different structures. The characters, dynamics and resilience of the societies are, of course, directed by their biological and demographic characters, but also, and often primarily, by their socio-cultural characters and potentialities. They cannot be analysed using the concepts of ecology or reduced to models directly transposed from evolutionary biology. Socio-historical anthropology has elaborated many of concepts for this purpose (e.g., Mauss 1947; Lévi-Strauss 1958). Conversely, ecosystems and biodiversity dynamics are ruled by the laws of biology and ecology, and obviously cannot be studied using the concepts and methods of anthropology.

Within the framework of the anthroposystem, we have to be both anthropologist and ecologist, a difficult undertaking that can only be achieved by sound and well balanced collaborations between anthroplogists and ecologists. In addition, we must also reinvent the concepts, the intellectual tools and the methods for studying the interactions between humans and their environment. There is still a lot to do in the domain of socio-ecology.

Schematically, we can consider that the process of anthropisation resulted primarily in the stabilising of a series of 'man-modified' and 'man-made ecosystems', alongside 'natural ecosystems'. The first consequence was the initiation of a completely new environmental regime, characterized by both an increase in the diversity of the 'ecosystems', and a new ecological gradient that we call gradient of anthropisation. As a consequence of this new regime, some plant or animal species extended their distribution to the 'man-modified ecosystems' because their biological characteristics allowed them to colonize these new ecological niches. More generalist and adaptable species extended their domain to the 'man-made ecosystems'. A few species, such as mice and rats, were even able to take advantage of the most specialized 'man-made ecosystems' such as buildings, villages or cities. This produced a new system of ecological categories of plants and animals comprising several groups, called respectively (from a completely accepted anthropocentric point of view) anthropophobous taxa, anthropophilic taxa and weeds/commensal taxa, the last being divided into two sub-categories, strict and optional commensal (Vigne 2011a: fig. 3A, B). The second consequence of anthropisation is therefore an ecological redistribution of the species, along the gradient of anthropisation.

From an ecological point of view, domestication can be considered as the third component of anthropisation. Indeed, it brings new species into the circle of these new 'man-made' or 'man-modified ecosystems' as a consequence of both their ecological proximity to humans, and the intentionality of the latter, which then reinforces or even redirects the relationship (Vigne 2011a: fig. 3C). According to the degree of intentionality and its fluctuation through time, these relationships can evolve towards a deep integration of the animal population into human society, as with pets. On the contrary, it can also evolve towards a dissolving of the link between humans and the animal population, which can lead to feralisation. It should be noted that domestic animals can come from local ecosystems or from distant ones: taking Europe as an example, wild boar were locally domesticated (Larson *et al.* 2007) whereas cattle, sheep and goat lineages came from the Near East (Poplin 1979; Edwards *et al.* 2007).

From a socio-ecological perspective, the process of domestication can therefore be understood to be an intensification of the relationships between animals (or plants) and humans,

2. Strictly speaking, these are not true ecosystems, since their primary production is not recycled locally (Palka Santini & Palka 1997).

beyond the natural ecological relationships, due to human intentionality (Fig. 1). Admittedly, it is still difficult to be precise about what material manifestations of intentionality should be considered by archaeologists as evidence for the early stages of animal or plant domestication. However, from a theoretical point of view, intentionality can be clearly defined as the conception of a long term project, which characterizes humanity as well as the conscience of its proper imperfection and death (Manon 2015). In this definition, domestication by humans clearly differs from the fungi 'cultivation' or from aphid 'herding' that are practiced by social hymenoptera such as ants and termites. However, this unique capacity for multigenerational goal-oriented behaviour is not the only difference between ant and human domestication. The crucial point from an archaeological perspective is the development of specific knowledge, know-how and practices connected to domestication and their consequences, in terms of tools and machines (Mauss 1947). Only humans have invented sickles for harvesting cereals, sieves for milk processing, knifes for cutting meat and bits for controlling horses, as well as new social structures for cultivation or herding. Such conceptualizations and tools have been too often reduced to almost negligible by-products of domestication in recent approaches, mostly grounded in evolutionary biology. However, during the last 50 years, much anthropological research has demonstrated that they played a major role in the evolution of interactions between humans and their environment.

As recently discussed by several authors, the intensification in the relationship between humans and animals followed different pathways: such as commensalism (of which the cat is an excellent example), competition (of which the wolf is emblematic), predation (sheep or guanaco), direction (horses), taming (elephants) or experimenting (deer) (Zeder 2012; Larson & Burger 2013; Hulme-Beaman 2014). For each of these pathways, we can distinguish a series of intensification steps which are totally non-deterministic: a step can be skipped, or the progression does not necessarily reach the final step and stays static for several centuries or millennia at the initial stage or, because this trend can be reversed at any time, moves towards a less intensive step.

The nature and intensity of the biological modifications due to domestication depend upon various factors, including the biology of the considered species and the nature and intensity of the domestication process. Therefore, I propose to use the term domestic animal (or plant) only for organisms, populations, lineages or species which show biological modifications. This conception leaves open the possibility that a process of domestication is already raking place with respect to a still biologically unmodified animal or plant population, including with human intentionality. This situation has previously been postulated by archaeobotanists using the concept of 'predomestic' cultivation (Tanno & Willcox 2006; Willcox & Stordeur 2012). A situation that is much more frequent in the ethnological records than we suspected, and that we begin to encounter more and more frequently in archaeozoology (Vigne *et al.* 2009; Vigne 2011a). This concept of "cultural control" (Hecker 1982) also allows us to adapt our vocabulary with respect to the biological characters being considered, whether morphological, behavioural or genetic.

This differentiation, between the concept of domestication and that of the domestic animal, may appear to be rather artificial, but it is necessary as it has important methodological consequences. Indeed, it allows us to study separately the nature and intensity of the interaction between human and animal, characterized for example by age at death, and the biological modifications documented by morphometrics or genetics. The information which results from such an approach is obviously much richer, and enables us to be much more open to diverse situations, including that of the control of animals in the wild.

Using this conceptual and methodological framework, I will now try to provide more practical examples in order to address my initial question - what should we know or do for a better understanding of early domestication and farming? - using the four classical questions: where, when, how and why?

DETECTING, LOCATING AND DATING EARLY DOMESTICATIONS: CONTRIBUTING TO A CULTURES' HISTORY

When considering the earliest known domestications of plants and animals (see e.g., Diamond 2002), it is clear that they occurred independently in several regions of the world during the last 11 000 years. As this is a relatively short time in the history of the humanity, it suggests that the phenomenon was probably highly influenced, or even determined, by global factors such as climate or human demography. However, as they occurred individually at different times, in various environmental, demographic and cultural contexts, this implies a less deterministic and more stochastic process.

In order to better understand the roles of these two components in the emergence of animal domestication, and to analyse the interplay of determinism and stochasticity, we need first to intensify the ongoing effort for localising and dating. This would include not only the early biological modifications, but the initiation of the domestication processes as well, even those which did not produce any biological modifications. Therefore, the more archaeological excavations we undertake, the more detailed archaeozoological analyses we will have. This will increase our chances of understanding the diversity of situations and external factors which played a role in the dynamics of this phenomenon, and we may even be able to model their stochasticity. It is therefore imperative to develop shared databases, available in institutional frameworks, such as national museums, which will combine open access, sustainability and tight connections with research projects (e.g., Callou *et al.* 2011). We also need to pay close attention to the historical contextualisation, and to continue developing comparative approaches in order to contribute, by means of bioarchaeological approaches, to the definition of material cultures and the study of their interactions.

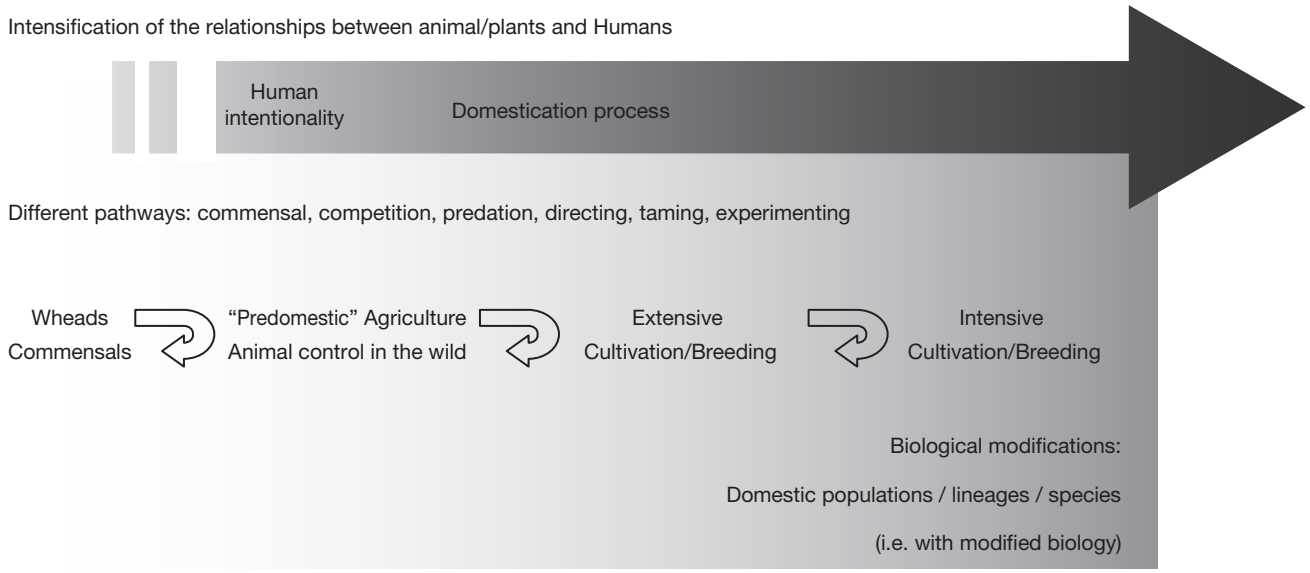

Fig. 1. — Schematic representation of the processes of domestication and of the belated consecutive emergence of the domestic populations, lineages or species (after Vigne 2011a, modified according to Zeder 2012, Larson & Burger 2013, and Hulme-Beaman 2014).

In order to illustrate this fundamental aspect of our contribution to prehistoric and historical anthropology, let us compare early animal domestications in Southwest and East Asia.

The earliest domestic mammals in Asia were dogs and cats. Dogs have been discovered throughout the Near and Middle East and in North China from around the same date, about 11 500 cal BP (Larson *et al.* 2012). Cats were transported to the island of Cyprus before 11 800 cal BP (Vigne *et al.* 2004, 2012; Vigne 2014), and the earliest in China, besides questionable evidence of cat commensalism or domestication in North China, date back to 5560-5280 cal BP (Bar-Oz *et al.* 2014; Hu *et al.* 2014).

The earliest sheep, goats, cattle and pigs found in Western Asia date from around 10 500 cal BP (Helmer *et al.* 2005; Peters *et al.* 2005; Hongo *et al.* 2009; Fig. 2). In China, in the Yellow River, pigs were domesticated independently from around 8600 cal BP (Flad *et al.* 2007; Cucchi *et al.* 2011). Following these initial domestications, the new domesticates and the early ideas of animal husbandry spread rapidly outside the southwestern Asian nuclear areas until they reached Europe in around 8700 cal BP, where local pigs were subsequently domesticated (Larson *et al.* 2007; Ottoni *et al.* 2013). Animal husbandry also spread to the Indus valley where the local aurochs were domesticated, giving birth to zebu cattle around 8000 cal BP (Meadow 1981). From the East Asia cradle, pig husbandry spread to the east and south, with the introgression of local lineages of Southeast Asian wild boar (Larson *et al.* 2005; Cucchi *et al.* 2008). Water buffalo were domesticated in North India (Yang *et al.* 2008). The western nucleus zone gave birth to the husbandry of sheep, goats and maybe cattle in Central Asia around 8000 cal BP (Dobney & Jacques 2010; Vigne & Debue in press), and in Africa from around 7000 cal BP (Linseele 2013).

How can this story, especially the comparison of the scenarios of the Neolithic transition in East and Southwest Asia (Fig. 3) contribute to the general cultural history of both areas?

In Southwest Asia, the Neolithic transition was successively composed of the sedentarisation of parts of the population, *c.* 14 000 cal BP (Belfer-Cohen & Bar-Yosef 2000; Bar-Yosef 2011), with the cultivation of annual plants such as cereals and legumes starting from *c.* 11 500 cal BP (Tanno & Willcox 2006; Willcox & Stordeur 2012), followed by animal domestication and the birth of husbandry between 10 500 and 9500 cal BP (Helmer *et al.* 2005; Peters *et al.* 2005; Vigne 2008, 2011a). Pottery only appeared after 9000 cal BP, with cities and the earliest writing dated to the 6th millennium cal BP (Huot 2004). In Eastern Asia, pottery first appeared around 20 000 or 17 000 cal BP (Boaretto *et al.* 2009). Then, in North China, between the Yellow and Yangtze Rivers, the sequence is almost the same as in the Near East: with sedentism beginning about 10 000/9000 cal BP (Cohen 2011), followed shortly after by the cultivation of rice, millet (Zhao 2011) and pig husbandry, *c.* 8600 cal BP (Cucchi *et al.* 2011); cities and writing developped only during the 5th and the 4th millennium BP, respectively (Elisseeff 2008).

Even though the scenario is more fragile for East Asia than for Southwest Asia, due to the smaller amount of reliable data (Bar-Yosef 2011), this comparison reveals important similarities in the successive stages of the two regions: sedentism, agriculture, husbandry, plus numerous other traits (see Bar-Yosef 2011). Apart from the much earlier appearance of pottery in China, which indicates, in my opinion, that pottery cannot be considered as a fundamental component of the Neolithic transition at a global scale, the comparison also reveals important differences in the duration and dates of the process: 4-5 millennia, from *c.* 14 000 to *c.* 9500 cal BP, in Southwest Asia vs 1-2 millennia, from *c.* 9500 to *c.* 8500 cal BP, in Northeast

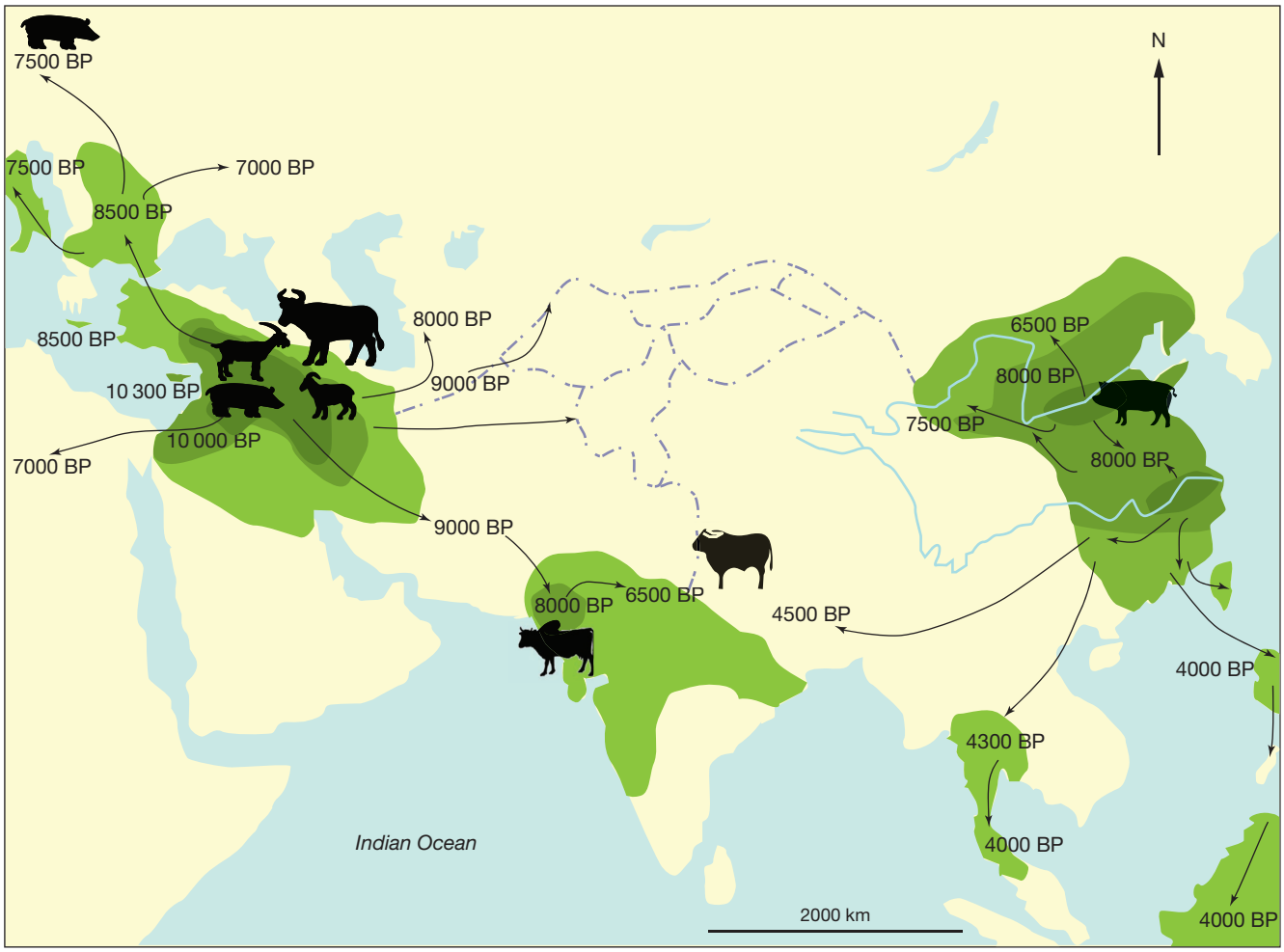

FIG. 2. — Location and dates of the earliest ungulate domestication in Asia (animal outlines), of the Neolithic routes of transportation (arrows), of the early domesticates and of the different steps of the early spread of husbandry starting from the nucleus zones (concentric degraded green patches); according to Meadow (1981), Helmer *et al.* (2005), Larson *et al.* (2005, 2007), Peters *et al.* (2005), Flad *et al.* (2007), Cucchi *et al.* (2008, 2011), Yang *et al.* (2008), Hongo *et al.* (2009), Dobney & Jacques (2010), Linseele (2013), and Vigne & Debue (in press).

China. This confirms that global factors such as climate change can no longer be considered as the only common determinant factor for the Neolithic transition in these two areas (Fig. 3). In addition, neither of the Neolithic transitions in these two major areas actually corresponds to any of the major climate changes between 14 000 and 8000 cal BP (i.e. the Younger Dyras, the Holocene re-heating or the 8.2 kyrs cold event). The transition to farming therefore is probably due to several interplaying factors acting at a regional scale, such as demographic, technico-economic and socio-symbolic dynamics.

However, it is not clear if the Neolithic transition in North China was achieved around 8000 cal BP, since husbandry experienced further important changes during the following millennia with the beginning of cattle, sheep, goat, and even horse and camel husbandry (Flad *et al.* 2007). In this instance, locating and dating the first appearance of these taxa in North China is of the utmost importance.

As the wild ancestor of sheep and goats, the oriental mouflon (*Ovis orientalis* Gmelin, 1774) and the southwestern lineages of the bezoar goat (*Capra aegagrus* Erxleben, 1777; Naderi *et al.* 2008) were absent from the modern territory of China. Domestic sheep and goats must have been introduced there from lineages which were probably domesticated in Southwestern Asia about 10 500 cal BP. Unless one of the several ongoing international projects uncover an earlier date, the earliest known evidence of sheep (and goat?) in the Yellow River area dates to around 4500/4000 cal BP (Bashan and Mashang cultures; Flad *et al.* 2007). This is 6000 years after the first domestication in Southeast Anatolia (Peters *et al.* 2005) and 5000 years after the earliest evidence of domestic sheep and goats in Turkmenistan (Dobney & Jacques 2010). These dates provide evidence for the earliest unquestionable contact, though admittedly indirect, with the west 3000 years before the opening of the historical Silk Road.

Zhang *et al.* (2013) claimed to have found the earliest cattle management in Northeastern China based on a mandible with pathological tooth wear (oral stereotypy), dated to 10 756-10 565 cal BP and providing an unknown haplotypic signature (C group). This would mean that cattle domestication in China occurred earlier than millet, rice and pig do-

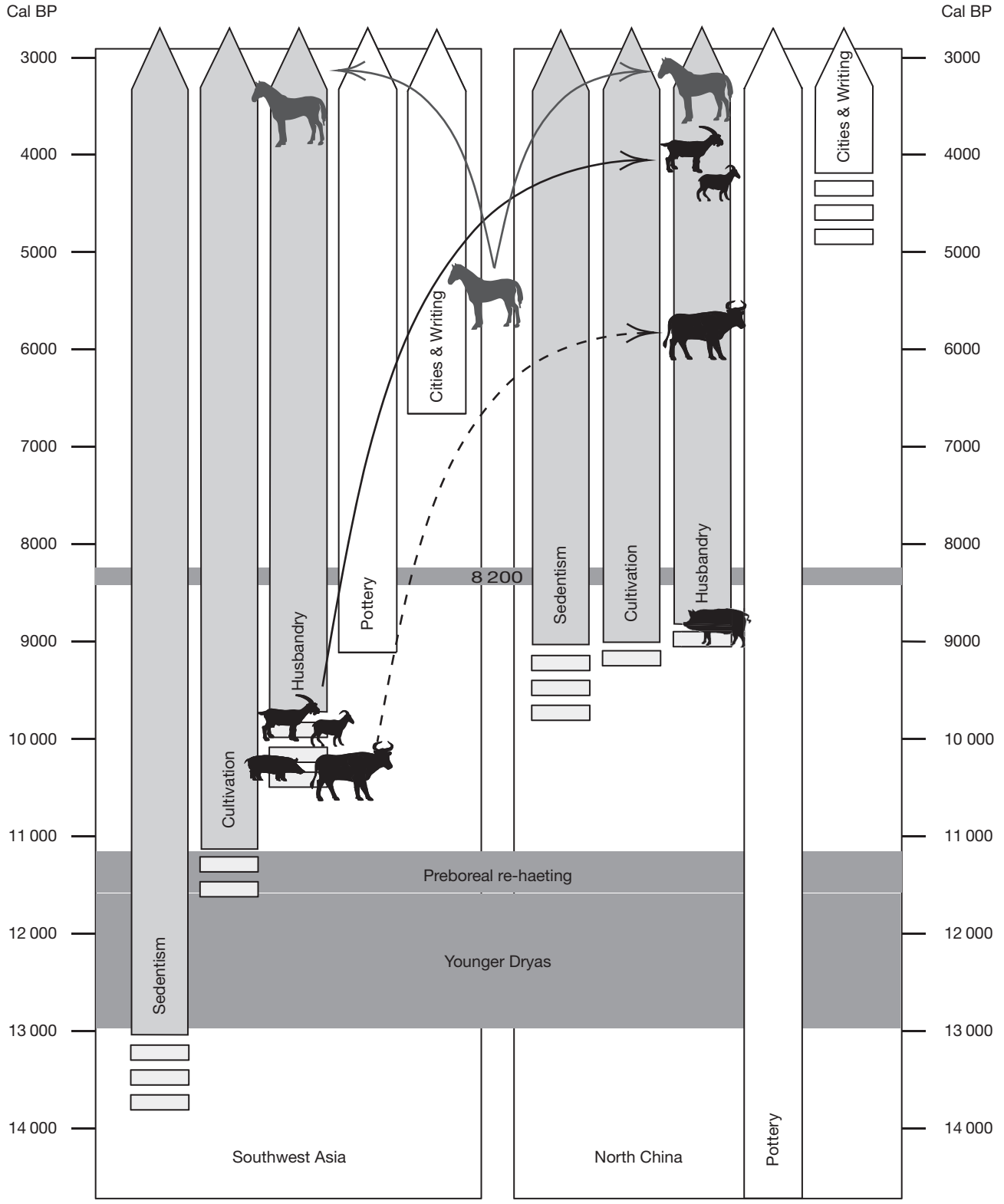

Fig. 3. — Comparison of the different components of the Neolithic transition in Southwest Asia and North China and their chronological succession, and the schematic representation of the origins of domestic pigs, sheep, goats, cattle and horse in the two regions, according to Vila (1998), Huot (2004), Helmer *et al.* (2005), Peters *et al.* (2005), Flad *et al.* (2007), Elisseeff (2008) Boaretto *et al.* (2009), Outram *et al.* 2009, Bar-Yosef (2011), Cohen (2011), Cucchi *et al.* (2011), Zhao (2011), and Willcox & Stordeur (2012).

mestication. At a time when most people were still mobile, and for which all previous finds have been attributed to wild aurochs (Flad *et al.* 2007). Not only is this claim rather unlikely, with reference to the archaeological context, but also extremely questionable since such pathological tooth wear can also be found in wild animals (Lv *et al.* 2014). This finding could be interpreted, therefore, as the first ancient DNA signature found for North China's early Holocene aurochs. In its present state, the data establishes the earliest evidence of domestic cattle in North China to the transition between the Early and Middle Neolithic (Beishouling/Lower Banpo), *c.* 6800 cal BP (Flad *et al.* 2007); however, this evidence is questionable and should be further investigated.

It can be stated though, without any doubt, that domestic cattle were reared in the Yellow River area starting around the late Yangshao, i.e. 500 cal BP, though we cannot be sure if this appearance resulted from a local domestication of the Chinese aurochs, or from the introduction of domestic cattle coming from the west. However, the late appearance of cattle, at least two millennia after millet, rice and pig domestication, as well as the haplotype of the modern East Asian cattle, similar to that of Southwest Asia (Maanen *et al.* 1998) and different from the C haplotype (Zhang *et al.* 2013) which should correspond to the Chinese aurochs, plea in favour of the hypothesis of an introduction from the west. This would mean that cattle would have been introduced to North China much earlier than sheep and goats and maybe through different routes and modalities.

The early history of the domestic horse in Asia follows a completely different scenario (Fig. 3). This species seems to have appeared at approximately the same time in Southwest and East Asia, during the Middle Bronze Age (4000-3600 cal BP; Vila 1998) and the Shang Dynasty (3500 cal BP; Flad *et al.* 2007), respectively, probably from North Central Asia where it was domesticated *c.* 5500 cal BP (Outram *et al.* 2009).

Altogether, these observations suggest early and complex interactions between Southwest and East Asia. They not only illustrate the utility, or even necessity, of contextualizing our archaeozoological results and the value of comparative approaches, but also demonstrate how the scenarios which are produced by archaeozoology can significantly contribute to cultural history.

UNDERSTANDING THE INITIAL STEPS OF THE DOMESTICATION PROCESS

Concerning the modalities of domestication, it is first necessary to explore in more detail the difficult but exciting question of the incipient domestication process, in which the biology of animals is still not visibly modified. Botanists lead the way in this domain, having already provided evidence for what they call a 'predomestic' agriculture: cultivated plants with no visible morphological modification, for cereals in the Near East, maize in the Americas and rice in China (Tanno & Willcox 2006; Willcox *et al.* 2007; Fuller *et al.* 2009; Zhao 2011). During these early stages, the seeds are still shed progressively down the ear during maturation, and their average size is the same as in the wild lineage. The domestic mutant appeared only some centuries later, characterized in cereals by a larger than average size, and by jagged scars resulting from indehiscent ears with spikelets that do not shatter, but separate when threshed. Even though the word 'predomestic' can be criticised because it is teleological, it conveniently formalizes an important stage of the early domestication process, at least for some annual plants.

Was there a similar 'predomestic' stage for animals? Several authors have already suggested early attempts to control wild gazelles or bezoar goats in Southwest Asia, long before the emergence of archaeologically visible modifications in the size and shape of the skeleton; based on the specialized exploitation of the species, and/or on age profiles loosely focused on certain age classes, especially subadults (Legge 1972; Hole 1996). It is, however, difficult to ensure that such patterns actually correspond to an incipient domestication, with an intentional control of demography or mobility of animals, rather than to a specialized hunting strategy. Besides, these two proposals have been reassessed by more recent analyses and characterized as mass hunting and cultural control, respectively (Legge & Rowley-Conwy 1987; Zeder & Hesse 2000).

Recent observations on the island of Cyprus shed new light regarding this issue, based on another archaeozoological argument: the transportation of animal populations out of their natural distribution area (Vigne *et al.* 2009). The small shelter of Aetokremnos is located at the south extremity of the island, on the Akrotiri headland, an offshore islet recently connected to the main Cypriot island by a double tombolo (Ammerman & Noller 2005). The sediment fillings in the shelter are composed of three layers (Fig. 4; Bunimovitz & Barkai 1996; Simmons 1988, 1999). The lowest one yielded two hundred thousand bones from dwarf hippopotami and elephants, which accumulated in the cavity at a time when it was nearly completely closed. They represent the undiversified endemic megafauna which lived in Cyprus during the Upper Pleistocene. A sterile layer of sand blown from the dunes, which covered the coastal plain at that time, suggests that the cavity then opened to become the shelter we know today (Ammerman & Noller 2005). The upper layer is an archaeological layer with hearths, Epipalaeolithic lithics, shellfish, and bird and fish bones (Simmons 1999), but apparently no hippo or elephant bones. During the period between these layers the latter probably became extinct, shortly before 12 500 cal BP, which is the date of this/these small archaeological occupation(s) (Zazzo *et al.* 2015).

In this Epipalaeolithic layer, one incisor and 17 phalanges or metapodials of wild boar, probably representing the remains of at least two hides, were discovered (Vigne *et al.* 2009). Compared to Near Eastern continental references, these bones were much smaller than the Younger Dryas wild boars, and the Early and Middle PPNB (Pre-Pottery Neolithic B) domestic suids, but were the same size as the small domestic Pottery Neolithic pigs. In order to test if they were, or were not, the result of recent contaminations, we radiocarbon dated them. We found degraded collagen in the

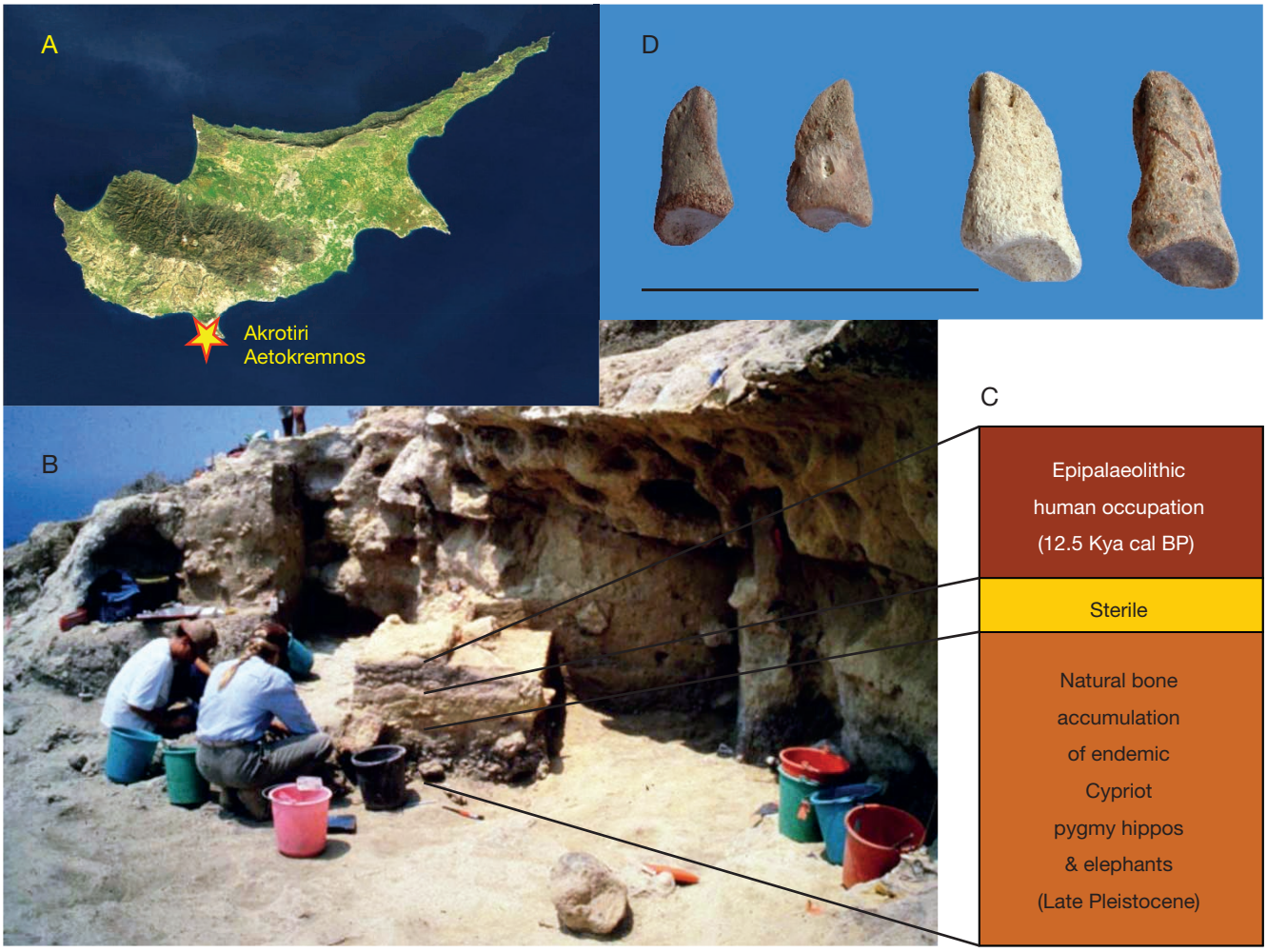

Fig. 4. — The Cypriot Aetokremnos shelter, where evidence of 'predomestic' control of wild boars has been discovered: **A**, location (Map: MODIS/MODLAND/ Decloîtres); **B**, view of the excavations (courtesy Allan Simmons); **C**, schematic interpretation of the fillings of the shelter; **D**, abaxial (left) and axial third phalanges of small sized wild boar found in the upper layer. Scale bar: 5 cm.

charred bones, which allowed dating to between 12 000 and 11 200 cal BP. Although the dating has probably been slightly rejuvenated by small quantities of more recent contaminant matter, this date corresponds rather well to the period of the Epipalaeolithic frequentation of the shelter. Until this point, no suid bones had ever been found in the rich paleontological records of Cyprus (Boekshotten & Sondaar 1972; Reese 1995). However, we can confirm for the first time that small wild boar were living on Cyprus at the end of the Late Glacial (before 12 500 BP), and that at least two hides were brought by mobile trapper-gatherers to the Akrotiri islet, then likely separated from the main Cyprus island by an arm of the sea.

How did these wild boar came to Cyprus? At the maximum of the last marine regression, Cyprus was separated from the continent by more than 70 km. Even though small islets could have played the role of stepping stones, the distances to be crossed by swimming are much too great for natural immigration (Vigne *et al.* 2014). There is a high probability that this immigration resulted from an intentional introduction of wild boar by humans, probably to restock the island with large game following the extinction of hippo and elephant. Shortly after their introduction, due to the available ecological niches, they spread rapidly across the island, quickly decreasing in size because of insularity (e.g., Raia & Meiri 2006).

The introduction of the wild boar to Cyprus before 12 500 cal BP, i.e. 4000 years before the first known evidence of morphological modifications in suids due to domestication (Peters *et al.* 2005), is clear evidence of control in the wild. This observation may strengthen the proposals for control in the wild which have been made in the Near East for goats (Hole 1996; Naderi *et al.* 2008) and boars (Redding *et al.* 1998), as well as in Africa for the Barbary sheep (*Ammotragus lervia* (Pallas, 1777); Di Lernia 1996, 2013), long before the appearance of early domesticates.

Though it is difficult to question such a phenomenon within the continental domain, it is crucial to understanding the initiation of the domestication processes, and why I suggest that we look intently at the small signs of intensification and exploitation of wild taxa. Significant increases in the proportion of one specific species through time and slight morphological change can only be revealed by sophisticated morphometric techniques (Helmer *et al.* 2005; Evin *et al.* 2013): as they allow

the beginning of the domestication process to be detected long before the earliest macroscopic biological modifications are visible. I also suggest looking at peripheral areas, such as islands or mountains areas, where the lower diversity in wild species makes the identification of such a phenomenon easier. The use of stable isotopes can also be useful for such research, especially in dating bones where the collagen is seriously degraded (e.g., Lösch *et al.* 2006). In other areas, we have also developed new techniques of direct dating, such as dating carbonates (Zazzo & Saliège 2011), or compact radiocarbon systems for small gas or solid samples (Wacker *et al.* 2010).

A RICH AND HEURISTIC DIVERSITY OF DOMESTICATION PROCESSES

The second important component of the domestication process that should also be investigated further is that of diversity. Much work has already been done in archaeobotany studying annual plants, such as cereals or legumes, which present strong syndromes of domestication and rarely return to the wild after a certain degree of development in their domestic lineage. But perennial plants such as figs, olive trees, date palms or vineyards show few domestication syndromes and can easily return to the wild, even after a long period of domestication (McKey *et al.* 2010a, b; Terral *et al.* 2010, 2012; Miller & Gross 2011; Meyer *et al.* 2012; Vigne & Terral 2013). These two models shed radically different lights on the exploitation system of plants by human societies and should be considered complementarily in each site or region.

In the same way, we can learn much from the comparative approaches of different species and different domestication pathways of animal domestication (Driscoll *et al.* 2009a; Zeder 2012; Larson & Burger 2013). Let's take the example of the process of cat domestication, the only wild ancestor of which is the Southwest Asian and North African subspecies of wildcat (*Felis silvestris lybica* Forster, 1780; Driscoll *et al.* 2007). In 2004 a complete skeleton of a morphologically wild cat was found in a human burial at the site Shillourokambos, Cyprus, dated to between 9500 and 9000 cal BP (Vigne *et al.* 2004; Vigne & Guilaine 2004). This cat, having no native ancestors in Cyprus, must have been introduced to the island before that date, indicating that wild cats were controlled. There is also evidence that at least some cats had a special status within the human society of this village, either as a status symbol, a pet or purely as a symbolic representation. It is therefore clear, even though the earliest domestic cats are those in Mesopotamia 4 millennia later (Vila 1998) and in Egypt 5 millennia later (Van Neer *et al.* 2014), that the process of domestication had already begun during the 10th millennium BP somewhere in the Levant, an area with which the inhabitants of the Cypriot site were connected. This also means that biological modifications to the domestic lineage of cats appeared very slowly.

Since this discovery, further information has accumulated, which both modifies and clarifies this process (Fig. 5; Vigne 2014). On the one hand, it has been evidenced that after the extinction of the native endemic hippo fauna, some time before 12 500 BP, and the introduction of the wild boar which was hunted or controlled in the wild on the island during the 12-11th millennia, dogs were also introduced to the island. It was also evidenced that cats were actually present in the earliest phases of occupation of the Pre-Pottery Neolithic village at Shillourokambos, around 10 300 cal BP (Vigne 2011b, 2013; Vigne *et al.* 2011a). Recent excavations conducted in the village of Klimonas, where a 10 m wide semi embedded communal building was discovered, revealed that cats were introduced to the island even earlier, around 10 800 cal BP (Vigne *et al.* 2012), before the introduction of domestic ungulates and more than 1500 years before the burial of Shillourokambos (Vigne *et al.* 2014). This is also the time when we find the earliest evidence for the introduction of cereals (emmer, *T. monococcoides*) from the continent, and of the development of 'predomestic' cultivation in Cyprus (Vigne *et al.* 2012).

Using this information, we can suggest the following process (Driscoll *et al.* 2009b; Vigne 2014). The accumulation of cereals in early Neolithic villages created a new commensal niche and attracted a lot of mice (Tchernov 1993; Cucchi *et al.* 2012); there is abundant evidence of this from the continent, and in the Cypriot village of Klimonas as well. The abundance of small commensal mammals attracted small carnivores, with cats becoming commensal as a result of a natural intensification of their relationship with humans. The fact that humans probably noticed that cats were useful for reducing pests, and so brought them to Cyprus, is clear evidence of human intentionality. This intentionality strengthened the relationship which evolved from a commensalism to a domestication process. The presence of one of these cats in a burial appears purely as an epiphenomenon, though deeply rooted within the process of early agriculture.

It seems that similar parallel processes of wild cat species 'commensalisation' developed independently in Egypt (Malek 1993; Van Neer *et al.* 2014) and as previously mentioned in China (Hu *et al.* 2014), though evidence from the latter is questionable (Bar-Oz *et al.* 2014).

The scenario of cat domestication should encourage us to look more deeply at the interplay between the intensification of ecological relationships, which has sometimes been improperly called 'self-domestication', and the intentionality of humans which characterizes the domestication process (see above).

In the heuristic story of the early introduction of mammals to Cyprus, we also found that the Persian fallow deer (*Dama dama mesopotamica* (Brooke, 1875)) was introduced to the island, together with domestic ungulates, at the beginning of the 9th millennium. It was immediately released in the wild and hunted throughout the Neolithic in Cyprus (Vigne 2011c; Vigne *et al.* in press); which suggests that somewhere on the continent, during the early 9th millennium, people were experimenting with the control of wild deer. As already suggested by Zeuner (1963), and numerous authors after him, there is much work to be done to understand how people experimented with domesticating different species of plants and animals in order to find the best candidates for long-term domestication.

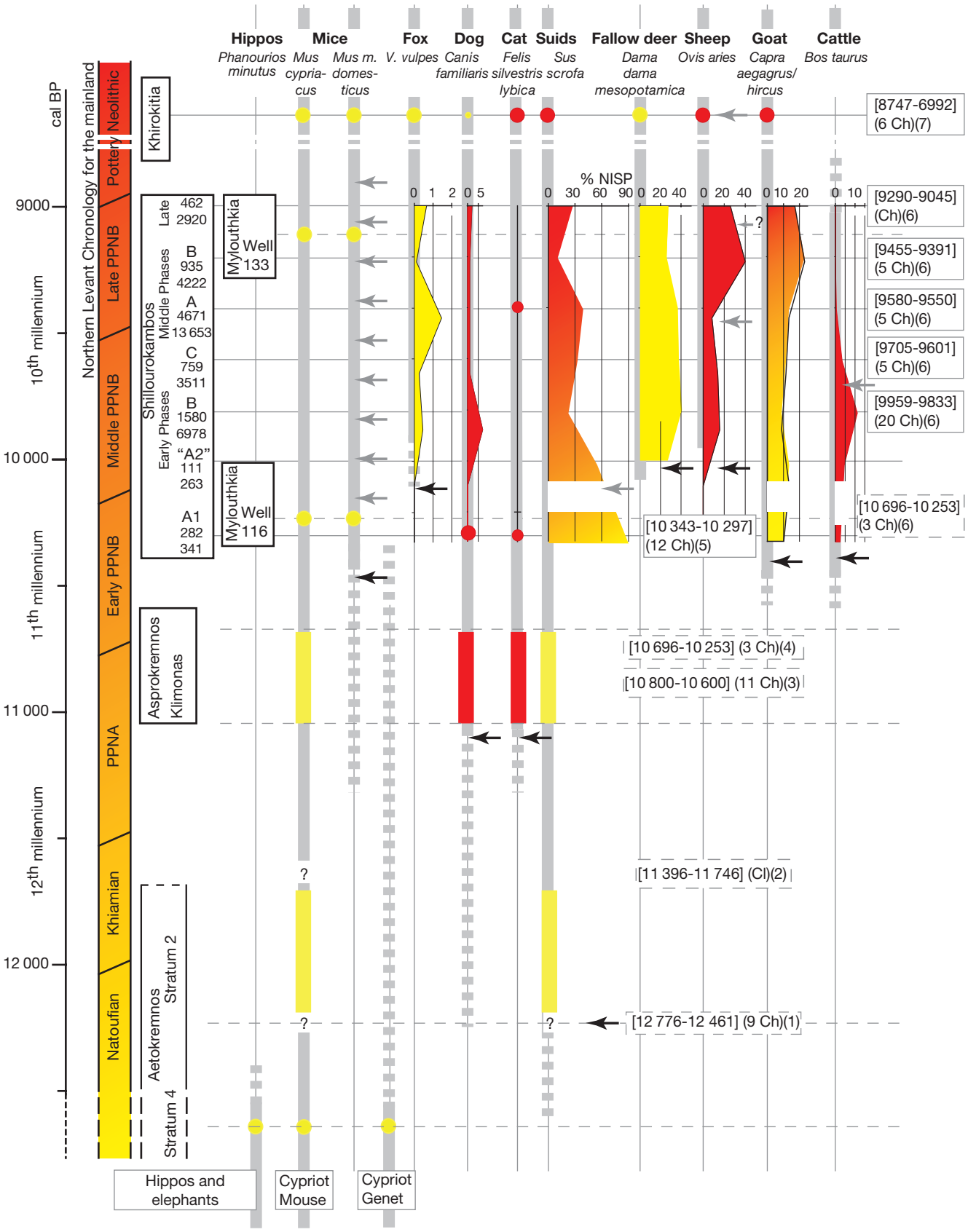

FIG. 5. — Evolution of large mammals on Cyprus during the neolithisation, with particular focus on the data from Shillourokambos (adapted from Vigne et al. 2014). Abbreviations: **NISP**, number of identified specimens of animal bones; **PPNA**, Pre-Pottery Neolithic A; **PPNB**, Pre-pottery Neolithic B.

PROMISING CUTTING EDGE TECHNIQUES TO BE EXPLORED, ADAPTED AND DEVELOPED

New techniques open new perspectives

Detecting these attempts at domestication is a difficult task because their bioarchaeological signatures are as tenuous as those of incipient domestication. Up until now we simply didn't have the adequate techniques for investigating the very subtle biological changes which might have been provoked by these early processes in the animals themselves. However, today these can be tracked through paleoepigenetic approaches; which recently have become accessible through the bio-informatic processing of the paleogenomic data (Orlando & Willerslev 2014), through stress markers such as linear enamel hypoplasias (e.g., Dobney *et al.* 2004; Balasse *et al.* 2010; Upex *et al.* 2012) or through the investigation of barely detectable morphological modifications. These technological improvements, not only makes it possible to explore new questions, but also to stimulate new reflections, enabling us to modify our own concepts and models.

Geometric morphometrics (GMM)

The classical morphometric techniques are still highly effective and will continue to stay popular as they are easy to process, we benefit from excellent international standards (Von den Driesch 1976) and we have an ever growing measurement dataset. However, they are not powerful enough to allow us to detect these small putative morphological differences, due to three main limitations. Firstly, classical morphometrics takes into account a limited number of characters for each anatomical part (i.e from 2-3 to 5-7 standards linear measurements between two points); therefore the shape of the measured biological organ is reduced to less than ten (and often no more than four) points, which fails to provide an adequate representation of the complexity of the biological shape and its subtle variations. Secondly, the information provided is subject to severe degradation because the geometrical relationships between the different measurements taken on the same specimen are not preserved. This precludes the three, and often the two, dimensional complexity of the bone/tooth's shape being considered. Thirdly, depending on the measurement, the two points which delimitate each of the linear measurements are not necessarily anatomically homologous. As a consequence, even if the measurement standards after von den Driesh (1976) are more or less universally adopted, specimens are not always measured in exactly the same way between investigators. Therefore, comparisons are biased by these subtle, yet crucial, methodological fluctuations which obscure the small putative morphological variations due to incipient domestication.

In addition, we need to acknowledge that the quantitative data from traditional osteometric measurements are partly determined by the genetics of the species (which influences the shape more than the size), and partly by their environmental conditions (which influences the size more than the shape). It is, therefore, impossible to know what the relative contribution of these two factors is, and difficult, or even impossible, to discuss the environmental or genetic significance of classical osteological results. One way to improve this consists of using geometric morphometrics (GMM; Cucchi *et al.* 2015). This method and its different technical approaches (landmarks, outlines, sliding semi-landmarks, 3D surface) have been elaborated by several biologists and biomath specialists (Bookstein 1989, 1991; Rohlf & Slice 1990; Rohlf & Marcus 1993; Goodall 1995; Marcus *et al.* 1996). In the domain of bioarchaeology, it was first applied to botanical material during the 1990's (Terral & Arnold-Simard 1996; Terral 2002) for differentiating wild from irrigated olive trees based on the anatomy of the wood and on the outline of the shape of the stones, and describing the diversity of the lineages of vineyard, plum or barley, based on the shape of the pips, cores or seeds (Terral *et al.* 2010; Burger *et al.* 2011; Ros *et al.* 2014). In archaeozoology (Cucchi *et al.* 2015), it enabled the identification of the first introduced house mouse (*Mus musculus domesticus* Schwarz and Schwarz, 1943) to Cyprus, as early as the beginning of the PPNB (Pre-Pottery Neolithic B; Cucchi *et al.* 2002, 2006); to ascribe a new present-day mouse species on the island using archaezoological, modern morphometric and genetic evidence (Cucchi *et al.* 2006), and to address the question of the mobility of horses and of the Magdalenian hunters in France during the Late Glacial (Bignon *et al.* 2005). During the last five years, the technique has rapidly gained popularity with its application to the question of the arrival of the house mouse to the Western Mediterranean during the Iron Age (Valenzuela-Lamas *et al.* 2011), the early domestication of pigs in China (Cucchi *et al.* 2008) and their diffusion to Southwest Asia (Cucchi *et al.* 2011), the complex story of pigs in Europe during the Neolithic and the Bronze Age (Evin *et al.* 2013, 2014a, b; Krause-Kyora *et al.* 2013; Ottoni *et al.* 2013) and the differentiation of horse lineages based on their molars (Seetah *et al.* 2014). This technique has been applied to great effect in biology for more than 30 years now, and is therefore not surprising that the study of archaeological bones and teeth (or seeds), which are biological items, can greatly benefit from it.

Improving traditional morphometric techniques in parallel with GMM

GMM should be used to complement (Evin *et al.* 2014c) rather than replace traditional morphometric techniques because the latter are easier to apply, and benefit from large datasets accumulated by bioarchaeologists over the last fifty years. In addition, these traditional techniques have also made important progress during the last few years, due to the refinement of mathematical and statistical processing. For example, we know that using logarithms of the measurements, rather than the measurements themselves, greatly increases the linearity of the relations between the variables and the homogeneity of the variances, and therefore improves the quality of the comparisons between them (Bookstein 1991). Several simple protocols can also assist in drawing more information from the traditional morphometric datasets.

As with GMM, traditional morphometric techniques allow the two components of form, size and shape, to be studied separately (Bookstein 1991). This is highly important as

distinct information can be gained from each component when analysed individually: the genetic aspects, which mainly determine the shape; and the environmental factors (including domestication) which mostly influence the size. It also enables discussion of the allometries, due to age or size, which can be estimated through analysis of the correlation between size and shape. This is a straightforward procedure based on traditional linear osteometric measurements, established during the last fifty years, using calculations proposed by Jolicoeur (1959) and Mosiman (1970). In brief, isometric size is represented by the distances between the projections of different measurements on the regression line, the latter being the longer axis of the ellipse of distribution of the measurements (Fig. 6A). For each of the specimens, numbered 1 to i, the isometric size (ISi) is estimated by the sum of values of the measurements (V, or of the logarithms of them, logV) obtained for this specimen for the n variables, divided by the number of variables ($IS_i = (\Sigma_{(1,n)} \log V) / n$). The shape index, also called Log Shape Ratio (LSR), is represented by the residues of the regression, that is to say, the distances between the specimens when they are projected on the smaller axis of the ellipse of the scatter diagram. The latter is perpendicular to the longer axis. For each specimen, from i_1 to i_n, and for each of the variables, 1 to n, the LSR is estimated by extraction of the isometric size by subtracting the isometic size (IS_i) from the logarithm of the value of the measurement: $LSR_{i,n} = \log V_{1,n} - IS_{1,i}$. Because the smaller and the longer axis of the ellipse are perpendicular to each other, the LSR are theoretically independent from the isometric size, except in the case of allometries. These shape indexes can be analysed using classical tools such as MANOVA, Principal Component Analyses (PCA), Canonical and Discriminant Analyses. The analysis of correlation between the isometric size and the coordinates of the shape indexes on the PCA, allows the size allometries to be studied.

For example, Mosiman's protocol has been applied to the four linear metric measurements of suid tali (*Sus scrofa* ssp.) from the Cypriot sites of Klimonas (PPNA, *c.* 10 800 cal BP; Vigne *et al.* 2012) and Shillourokambos (PPNB, 10 400-9000 cal BP; Guilaine *et al.* 2011). The study aimed to establish if, in spite of a significant size decrease between the two sites (Vigne 2011d), the suids belonged to the same autochthonous Cypriot lineage, or if this size decrease was accompanied by a shape modification which resulted from the introduction of another lineage from the near mainland. Mosiman's protocol (Fig. 6B) confirmed that the mean isometric size did not differ between Klimonas and the early phases of Shillourokambos (permutation t test, p= 0.24), but that it significantly decreased between the middle phases of occupation of the latter, starting from 11 500 cal BP, and its later phases (ANOVA, p= 0.004). This size decrease probably results from the intensification of cultural control during that period, which is visible through other lines of evidence (Vigne 2011d). The principal component analyses of the LSR and the associated MANOVA, however, show no significant change in the shape of the astragali during the two millennia covered by the two sites. This argues against the introduction of new suid lineages to Shillourokambos around 9500 cal BP, but in favour of the local domestication of the autochthonous small Cypriot wild boar, introduced to the island 2000 years previously (see above: section "Understanding the initial steps of the domestication process"; Vigne *et al.* 2009). Of course, this proposal has still to be confirmed by ongoing analyses of other parts of the skeleton, through both traditional and geometric morphometric techniques.

Another issue that could be easily resolved with simple calculations based on traditional measurements is the comparison between different samples coming from dimorphic species. In such cases, the decrease or increase of size can only result from the modifications of the sex ratio (Zeder 2005). The only reliable technique is to compare separately males with males and females with females, which is possible using the Gaussian mixture analyses (Everitt & Hand 1981; Monchot & Léchelle 2002; Vigne 2011c; Vigne *et al.* in press). If the models are well supported by an appropriate Akaike Information Criterion (Hammer *et al.* 2001), this calculation can provide the mean measurement, the variance and the proportion for each sex (Fig. 7A), and allows not only size but also sex-ratios to be discussed.

This technique allowed Helmer *et al.* (2005) to provide evidence for the early domestication of cattle in the Near East, based purely on a reduction of sexual dimorphism, one of the earliest morphological modifications in domestication (Arbuckle 2005). It also allowed a process of local domestication of feral goats in Cyprus to be revealed (Vigne 2013; Vigne *et al.* 2015). The mixture analyses of the metric data indicated that the early goats on Shillourokambos were smaller than contemporary wild goats (Fig. 7B). This suggests that the goats which had been introduced from the mainland were already domesticated. Subsequently, the female goats were not subjected to any significant modification during the occupation of Shillourokambos, except a size decrease after the Middle A phase. The males' size also decreased at the very end of the chronological sequence, to such a proportion that the sexual dimorphism also decreased.

During the late phases, a new type of horncore appeared closer in morphology to the domestic than to the *aegagrus* type. The sex-ratio of adults did not vary from the 50/50 range during the early phases (Fig. 7C). During the Middle A period, the proportion of males decreased to less than 50 % in some cases, and at the end, the proportion of adult females was significantly dominant. The sex ratio decrease shows that the domestication process of the local goat began during the Middle phase, and explains the subsequent decrease of size and sexual dimorphism. We can conclude, therefore, that the goats were released into the wild shortly after their introduction, were hunted between 10 400 to 9500 cal BP, and then re-domesticated by the Shillourokambos villagers.

Developing palaeo-genetics and genomics in close conjunction with archaeology

Five years ago we were just beginning to understand how genetic modifications could help explain the domestication process, yet there were still huge gaps in our knowledge. The

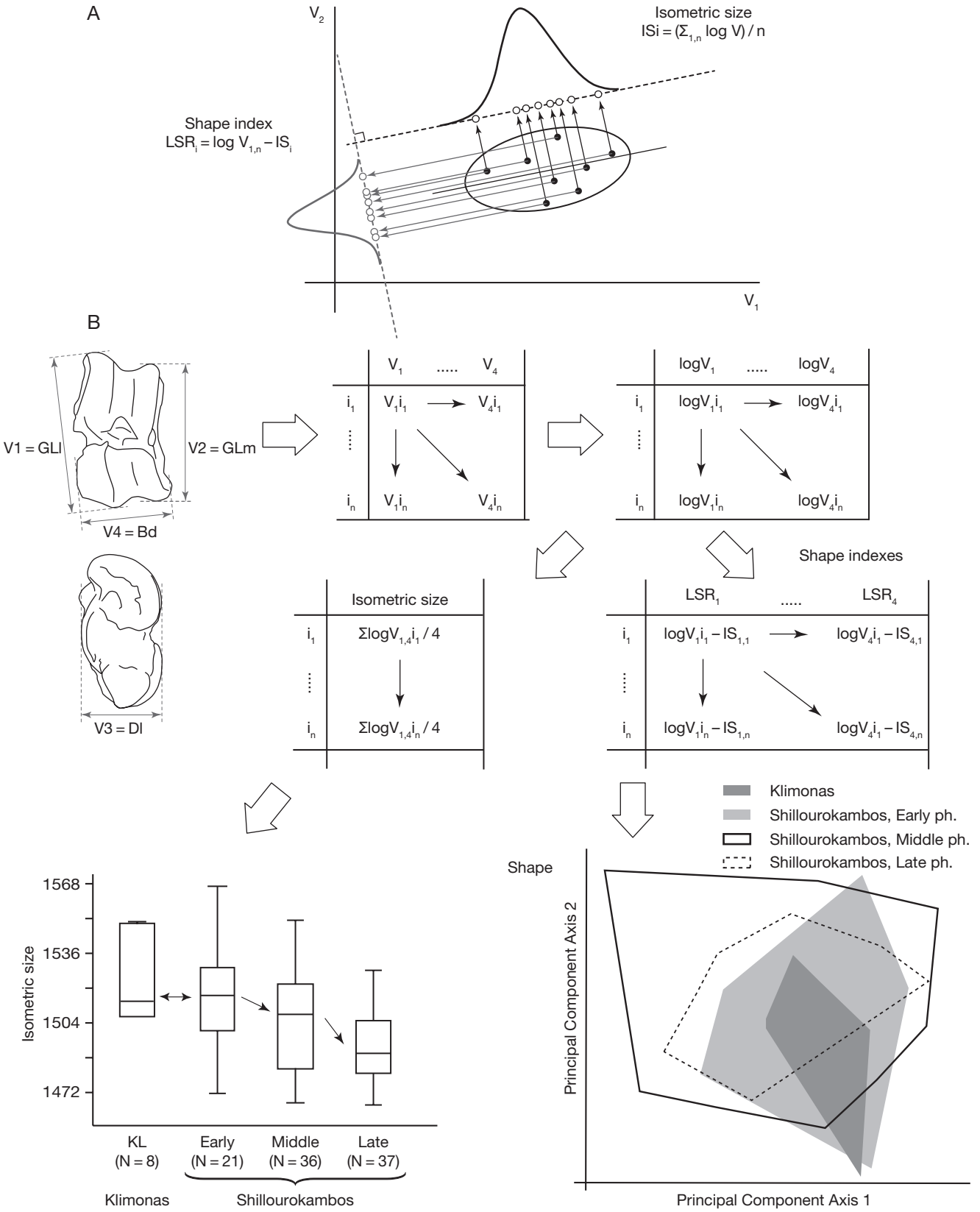

FIG. 6. — Processing the traditional morphometric measurements for studying separately the two components of the form, i.e. isometric size and shape (Mosiman's protocole): **A**, geometric representation of the independency of shape and isometric size; **B**, example based on the measurement of four variables (V1 to V4) on the talus of the PPNA (Pre-Pottery Neolithic A) and PPNB (Pre-Pottery Neolithic B) Cypriot suids (*Sus scrofa* ssp.) at the sites of Klimonas and Shillourokambos. Isometric size analyses confirm a size decrease tendency which is probably due to the intensification of the cultural control during the occupation of Shillourokambos. Conversely, the analyses of the Log Shape Ratios (LSR, i.e. shape analyses) evidences no change all along the two millennia sequence, suggesting local domestication of the autochthonous small wild boar. Abbreviations: **KL**, Klimonas; **N**, number of specimens of animal bones studied.

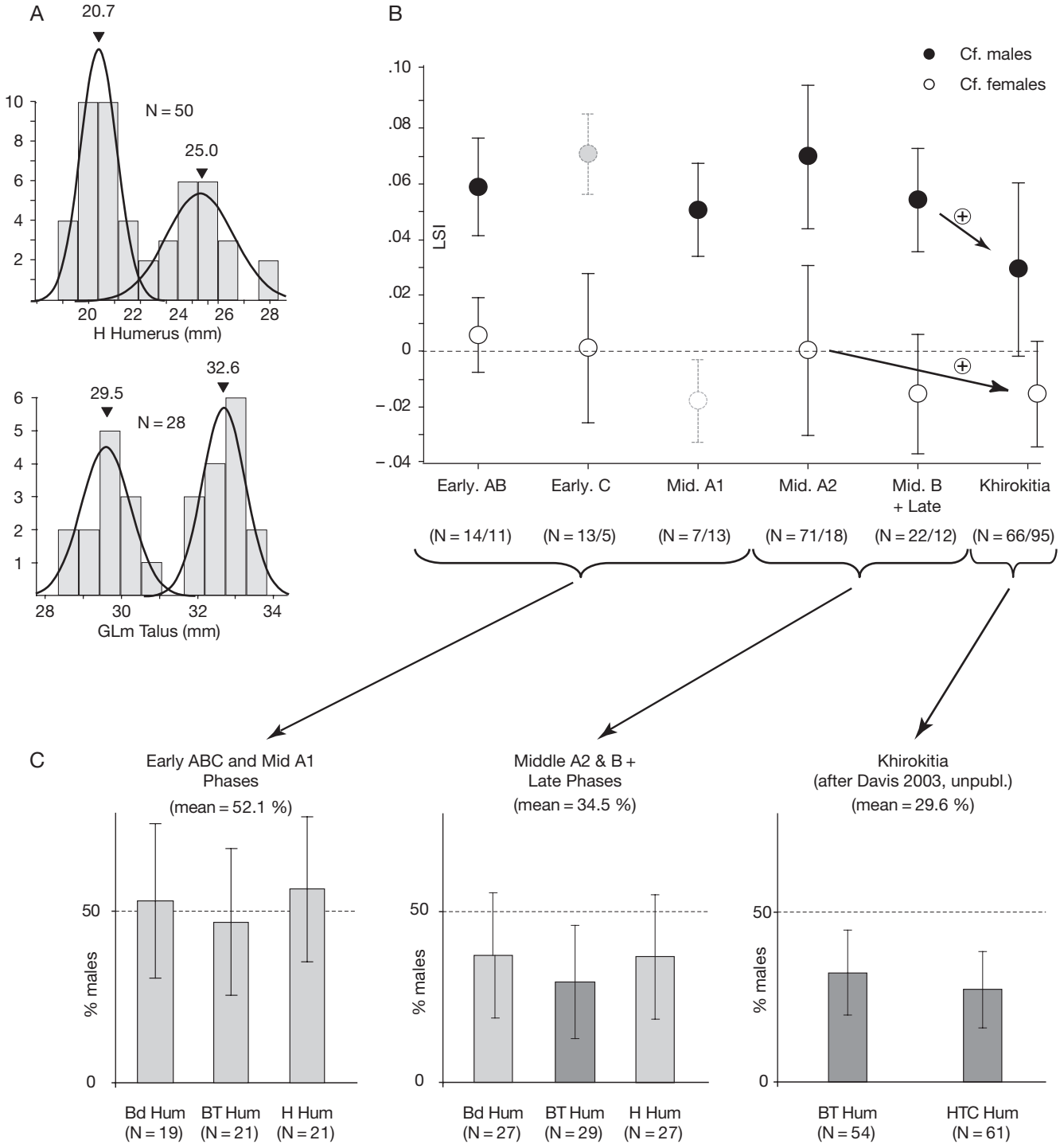

Fig. 7. — The process of re-domestication of the feral goat at Shillourokambos, adapted from Vigne *et al.* (in press): **A**, histograms of distribution of the densities and mixture analyses for two measurements (according to the standards of von den Driesch 1976), one for the humerus and one for the talus, as examples of the protocol which has been used for estimating the sex ratio and the separate mean and standard deviation for males and females; **B**, evolution of the average size (expressed by the Log Size Index, LSI) of males and females (separated by mixture analyses) over the different phases of occupation of the village of Shillourokambos (Early AB to Mid. B + Late) and at Khirokitia; **grey dots** correspond to small samples; **arrows and (+)** indicates the statistically significant differences; significant size decreases due to domestication appear at the end of the sequences, *c.* 9500-8500 cal BP; **C**, evolution of the goat sex ratio over three successive phases of the PPN's (Pre-Pottery Neolithic) evolution in Shillourokambos and Khirokitia, according to the mixture analyses of different measurements of the humerus distal part (Bd, BT, H, HTC according to von den Driesch 1976, and Davis pers. obs.) of adult goats; the vertical segments delimitate the standard deviation of the mean; light grey columns indicate no statistically significant differences between the sex ratio estimate and 50 %; conversely, dark grey columns indicate significant differences. The sex ratio is well balanced during the early step, but tends to decrease below 50 % (i.e. less adult males than females) during the middle phase. It is significantly biased toward adult females during the most recent phase. Together with the size decrease, this unbalanced sex ratio advocates for the local domestication of goats. Abbreviations: **Bd**,braedth of the distal end; **BT**, breadth of the trochlea; **H**, heigth of the medial edge of the trochlea; **HTC**, minimal height of the trochlea groove; **N**, number of specimens of animal bones studied.

genetic pattern of modern populations allowed the production of exciting scenarios, but those scenarios could not be validated without paleogenetic data (e.g., Naderi *et al.* 2008; Larson *et al.* 2012). The poor preservation of DNA in archaeological bones from certain regions reduced dramatically the possibility for investigating early domestication (Bollongino & Vigne 2008; Bollongino *et al.* 2008). Yet, ancient DNA did allow us to trace the origins of the European Neolithic cattle (Edwards *et al.* 2007; Tresset *et al.* 2009; Lenstra *et al.* 2014; Scheu *et al.* 2015) and pigs (Larson *et al.* 2007; Ottoni *et al.* 2013; Evin *et al.* 2014a), but unfortunately, paleogenetics gave little information about the biological processes involved in their domestication.

However, since then, huge advancements have been made especially due to the development of numerous population modelling techniques and of the rise of the 'next-generation of sequencing technologies' (e.g., Dijk *et al.* 2014). These allow the risks of contamination to be better controlled, and occasionally for DNA to be extracted from severely degraded bones. This revolution opens up a new era for palaeogenomics. It allows us, for example, to pinpoint to about 80, the number of females which produced the modern lineages of cattle (Bollongino *et al.* 2012). It also created the possibility to reconstruct the coat colours for mammoths, horses, pigs and dogs (Römpler *et al.* 2006, Ludwig *et al.* 2009; Krause-Kyora *et al.* 2013; Ollivier *et al.* 2013), which are important phylogeographic markers.

No doubt shortly, we will be able to pinpoint the modification of the digestive enzymes of dogs as an adaptation to a starch-rich diet (Axelsson *et al.* 2013) and the appearance of their bark or floppy ears, the curled tail of pigs and the milk release reflex of cows (Balasse 2003). We are even able to access the paleoepigenetic patterns (Orlando & Willerslev 2014) which should have been impacted by small environmental modifications during the first steps of the domestication processes, and have probably played a major role in the expression of the 'domestication genes'.

It is, of course, crucial for osteoarchaeologists to follow this development in close collaboration with molecular biologists and modelling specialists. However, moving towards a purely biological approach, with little consideration of the archaeological contexts and of major issues within archaeology, must be avoided at all cost. Though the evidence needs to be studied by molecular biologists, these ancient molecules are artefacts in exactly the same way as are stone and metal tools, pottery, plant parts and bones (see Vigne & Darlu 2008).

Stable isotopes as powerful markers of early control or domestication

Even before any morphological changes have taken place, early cultural control or incipient domestication processes entail modifications in the animals' ways of life such as a reduction in their mobility, or a transfer to a different environment and consecutive change in their diet. The relative proportion of the stable isotopes of oxygen, carbon, nitrogen or strontium which are recorded in the collagen or in the apatite of archaeological teeth or bones, are beginning to shed new light on these phenomena (for a review, see Balasse 2015). For example, the increase of the $\delta^{15}N$ in suids due to the consumption of agricultural refuse and even human excreta, allowed the detection of their early intensification in Japan and in Southeast Anatolia (Matsui *et al.* 2005; Lösch *et al.* 2006).

Especially efficient are sequential analyses of stable isotope ratios in tooth enamel or dentine, the growth of which covers a significant period of the life of animals (hypsodont teeth). As the variation in stable isotope ratios is recorded along the tooth as it grows, that variation can be sampled systematically by analysing small quantities of collagen or bioapatite sequentially sampled along the crown (Fig. 8; Balasse *et al.* 1999; Balasse 2002). This technique has not only been successfully applied to the molars of caprines and cattle, but also to other teeth and species, such as the incisors, tusks and molars of suids (Frémondeau *et al.* 2012); it can also be used for equids or camelids as well.

This technique makes it possible not only to detect changes due to early domestication, but also to investigate early herding practices such as foddering (Ervynck *et al.* 2007; Balasse *et al.* 2009, 2012a), early weaning (Balasse & Tresset 2002) or changes in the birth season (Blaise & Balasse 2011; Balasse *et al.* 2012b). Early calf weaning is intrinsically connected with sophisticated practices for milk exploitation (Vigne & Helmer 2007), as is the staggering of birth seasons during the year to increase milk availability (Towers *et al.* 2011; Balasse *et al.* 2012a). Sequential stable isotope analysis has demonstrated that shortly after they were first settled on the Orkney islands (north Scotland; 5500 cal BP), sheep adapted to the extreme climatic conditions by feeding on seaweed during the winter when grass was unavailable (Balasse *et al.* 2009; Balasse & Tresset 2009). Joint age profiles and sequential stable isotope analyses on the Romanian site of Burduşani (6400-6200 cal BP), revealed that milk was exploited by delaying the slaughter of calves until the end of the cow's lactation, and that the herd was managed in different ways according to age (Gillis *et al.* 2013).

Stable isotopes, especially their sequential analyses, represent a fantastic opportunity for analyzing past herding techniques and practices (Henton *et al.* 2011; Gillis *et al.* 2013), including their regional diversity and evolution through time, and subsequent adaptation to social, climatic or environmental change. It is imperative that the analysis of stable isotopes play an increasing role in research, as this analytical approach is key to understanding the complex interactions between humans and their environments (Vigne 1998). Their study also places archaeozoology at the forefront of reconstructing scenarios to help meet modern challenges in sustainable development.

LOOKING FOR THE CAUSES OF DOMESTICATION AND FARMING

A multifactorial and systemic approach

Concerning the causes of domestication and farming, the general tendency of researchers has long been, implicitly

or not, to try to identify a prime mover that produced a 'snowball effect' (Vigne 2008). Climate change and social dynamics both having been considered as good candidates (Braidwood 1960; Testart 1998; Cauvin 2000). But the new systemic perspective, developed in the introduction of this paper, precludes any simple cause-effect relation between the different components of the anthroposystem. As is usual for complex phenomena, we have to reflect within the framework of a multifactorial system, with a series of positive feedbacks between its different components. Such a conception allows all kind of trajectories to be envisaged, including inversions of trajectory in which people returned to a more hunter-gatherer way of life. The main factors involved in these complex interactions are demography, climate and social, and technical and cognitive factors.

Investigating the role of climate

The Cypriot village of Shillourokambos was occupied for more than one millennium, during the Neolithic transition (Guilaine *et al.* 2011). Osteoarchaeological estimations of the proportion of herding, with reference to hunting, during this period reveal a complex and unstable trajectory, which returned to an increase in hunting during the Early C phase, around 9500-9400 cal BP (Fig. 9; Vigne *et al.* 2011b). During these phases, we recorded evidence of flock failure or even collapse, in the form of drastic and rapid reductions of both body size and relative frequency of sheep (Vigne *et al.* 2015). Was this connected to climatic degradation? If we compare the global climate temperature variations (according to Stuiver *et al.* 1995) with the evolution of food production, we find no connection. However, this is not conclusive, because we know nothing about the local climate fluctuations or their environmental consequences. Without this local or regional data, of which information is scarce for this period, including in South Cyprus, we will not be able to assess correctly the role of climate during this time.

Demography as a forcing factor

Outside of Africa, Homo sapiens was an invasive species. Their successive waves of invasion resulted in a non linear but constant increase in human populations (e.g., Biraben 2003). Recent paleodemographic investigations, based on the relative proportions of age of death across large datasets of human burials, have shown that the Neolithic transition was connected with a strong signal of demographic increase due to the rise of fertility in Europe, the Near East and North America (Bocquet-Appel 2002, 2011; Bocquet-Appel & Naji 2006; Guerrero *et al.* 2008; see also Gignoux *et al.* 2011, for a population genetic approach). This discovery represents a significant improvement in understanding the Neolithic transition, though it is still not clear if it was a cause or a consequence of the Neolithic diet transition (Vigne 2008), as these events clearly occurred at separately (Fig. 10). Neither appears to be directly connected with climatic change, except that they both occurred during the more stable and temperate Holocene period, but they still must be taken into consideration within the deterministic factors of the Neolithic transition.

Fig. 8. — Medial view of a right upper third molar of a Late Neolithic sheep of Orkneys (Skara Brae; first half of the 3rd millennium cal BC). The enamel of the anterior lobe has been sequentially sampled by drilling, in order to analyze the variations of the oxygen and carbon stable isotopes ratios during the period of mineralisation of the tooth. Scale bar: 1 cm (Photo by M. Balasse).

If we truly want to assess the role of demography, we need to look within the continental or macro-regional scale, to the local scale itself. However, as age at death data are generally not numerous enough to document demographic fluctuations through time on the same late Pre-Neolithic and early Neolithic sites, we need to use other less stable demographic proxies.

On the Cyprus PPNB site of Shillourokambos, where 5000 m² has been excavated (Guilaine *et al.* 2011), we postulate that the number of identified specimens of animal bones (NISP) can offer a rough demographic proxy. It is interesting to observe that there is no significant temporal association between the NISP fluctuations and the crisis of the Early C phase with its consecutive decline of animal food production, with reference to hunting (Fig. 9). This crisis clearly does not result from a significant demographic increase, which would have created disequilibrium between the population size and the animal food supply. Conversely, we can observe that the NISP substantially increased between the early and middle phases of the village occupation, in parallel with the increased development in animal food production, and in fact, it appears that the former slightly preceded the latter. This would suggest a positive feedback loop between these two variables: an increase in the number of villagers stimulating the development of stock rearing, and reciprocally.

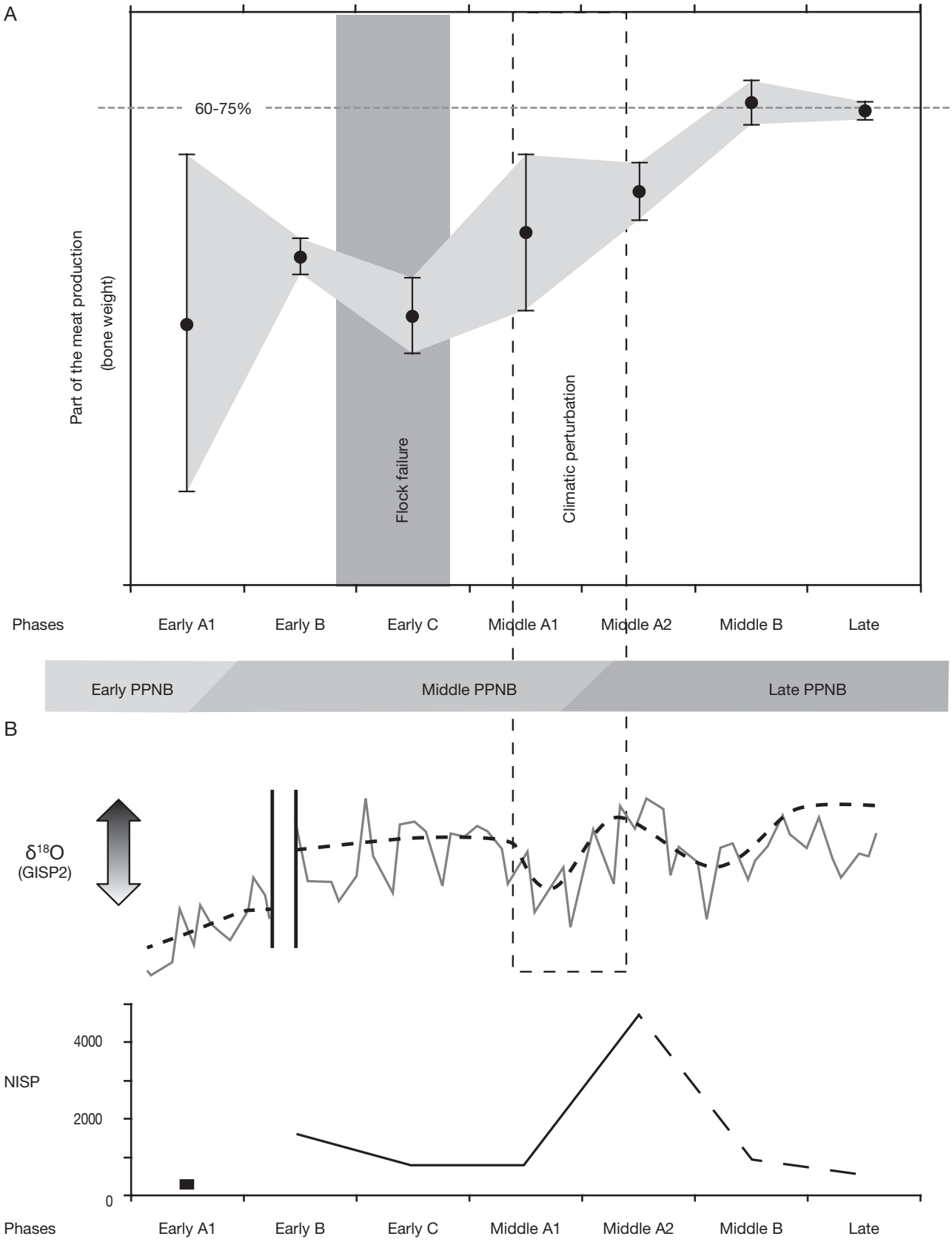

FIG. 9. — **A**, Evolution of meat production through the chronological phases of Shillourokambos (Cyprus; Vigne *et al.* 2011b) in comparison with the global climatic fluctuations, as evidenced by the rate of ^{18}O in the GISP2 record (Stuiver *et al.* 1995); **B**, Demography of the village, estimated by the number of identified specimens of animal bones (NISP, for an excavated surface of 5000 m²; the dotted line indicates low reliability due to much smaller archaeozoological datasets). Bone weight percentages are not exact estimates of meat procurement. Only the relative variations between the different phases can be taken into consideration in this diagram, which is why ordinates are not graduated. Abbreviation: **PPNB**, Pre-Pottery Neolithic B.

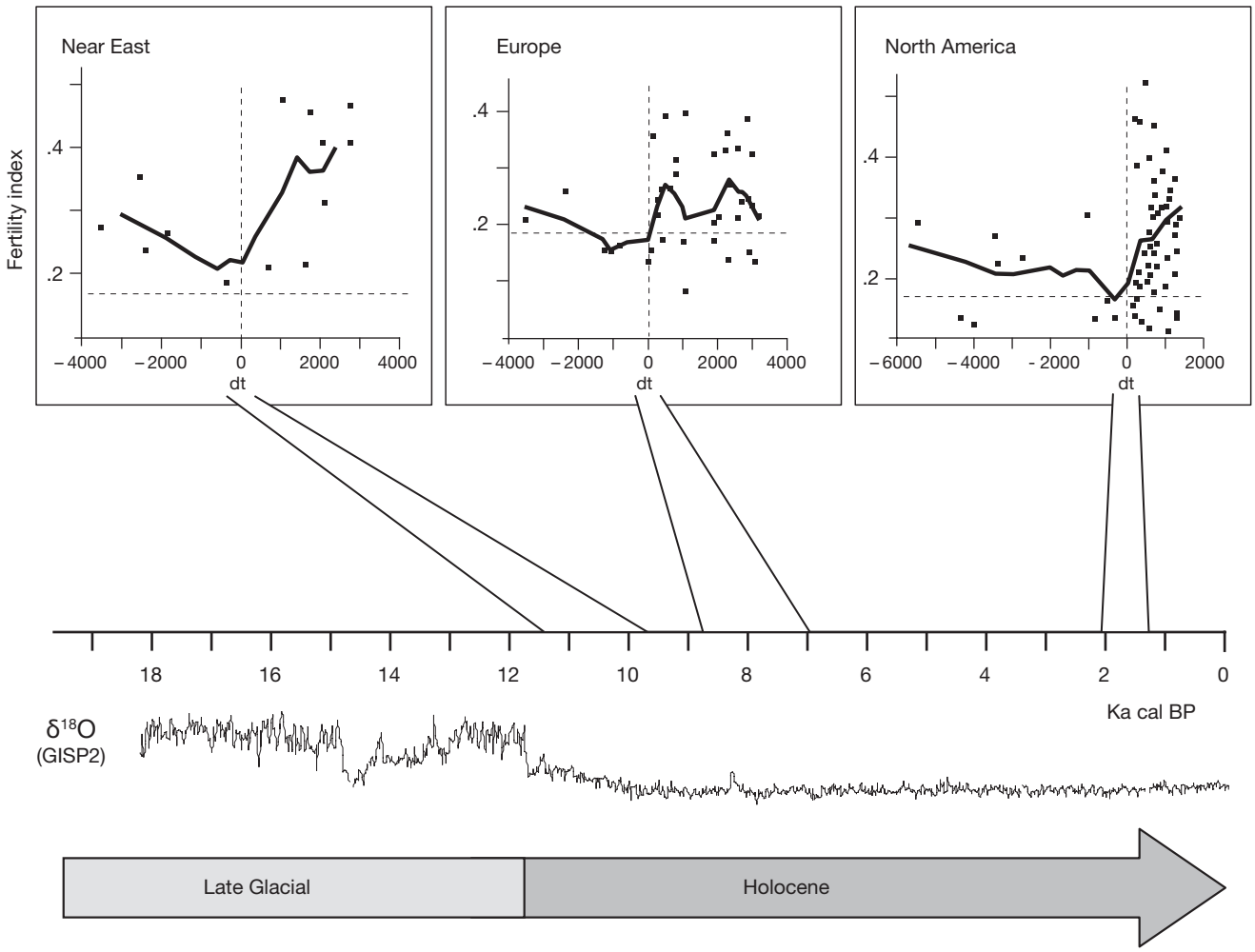

Fig. 10. — Evolution of the demography before and after the Neolithic transition (dt=0) in the Near East (Guerrero *et al.* 2007), in Europe (Bocquet-Appel 2002) and in North America (Bocquet-Appel & Naji 2006), estimated by the fertility index. The demographic transition occured at different times during the Holocene, unconnected to any major climate change (referenced by the global temperature fluctuations at the bottom of the graphic), estimated by the ratio of the 18 stable isotope of oxygen in the GISP2 ice core (adapted from Stuiver *et al.* 1995).

Exploring the role of the technical system for food supply

It is also necessary to have a complete overview of the technical system (Vigne 1998), not only in order to understand how the system of exploitation of animals interacts with the other components of the general system, but also to have a better assessment of the technical skills of the last hunters who invented plant and animal domestication.

For example, it is striking to see that in the Near East, the meat supply from hunting continued to dominate that of husbandry for more than 10 centuries after the appearance of early domesticates (Vigne & Helmer 2007; Vigne 2008). In fact, domestic meat only became the main component of the meat supply at the transition between the Middle and Late PPNB, *c.* 9500 cal BP. Why did it take so long? And what was the role of early domestic animals in human society if not to primarily produce meat? To address these questions, we need to consider and test various technical and social hypotheses:

– Seasonality was a major factor of the Late Glacial and Early Holocene (McCorriston & Hole 1991; Munro 2003; Gourichon 2004; Gourichon & Helmer 2008). So could domesticates have been primarily exploited to provide a complementary supply of meat during periods when game was less abundant, less productive, and more difficult to hunt? Or when hunting began adversely affecting the regeneration of wild populations? In order to precisely assess the role of early domesticates in relation to seasonal supply and its seasonal complementarities (i.e. hunting, trapping and fishing), osteological and stable isotope seasonal evidence for both wild and domestic species needs to be developed especially for the early stages of domestication, prior to the beginning of husbandry (or cultivation).

– Was milk one of the reasons for domesticating ruminants? As it cannot be collected from wild animals, milk availability is tightly connected to the domestication of ruminants and common sense dictates to F. Poplin (1980, 2012) that this must have started at the beginning of the Neolithic. The long held belief was that it was initiated in Europe, North Africa and the Near East during the 'Secondary Products Revolution' (7-6th millennia BP; Sherratt 1981, 1997; Greenfield

1988), although a better term would be 'Second Neolithic Revolution'. However, a series of ongoing research projects are currently addressing this issue, with a good deal of evidence for early Neolithic milk exploitation in Europe, Africa and the Near East having already been collected. Analyses has been based on the culling profiles of caprines and bovids (Helmer *et al.* 2007; Vigne & Helmer 2007; Gillis 2012; Gillis *et al.* 2014), coupled with the sequential analyses of stable isotopes (Balasse & Tresset 2002; Gillis *et al.* 2013), and on the lipid residues from pottery vessels (Evershed *et al.* 2008; Dunne *et al.* 2012). Although cheese making has already been evidenced in East Poland during the 8th millennium cal BP (Salque *et al.* 2012a, b), we still need much more information about the relative importance of milk in the early Neolithic diet, the regional economy, and the various milk production techniques during the Neolithic. It seems out of the question that the exploitation of cattle and caprine milk was not part of the subsistence strategy of Neolithic societies as they began to spread into Europe and North Africa. For the Near East, the earliest evidence for milk exploitation comes from the 9th millennium BP in Anatolia (Evershed *et al.* 2008) and from the 10th millennium BP (Middle PPNB) in the Levant and Cyprus (Helmer *et al.* 2007; Vigne *et al.* 2011a, in press). However, there is no evidence, to date, for the period between 10 500 and 9500 cal BP, which is precisely the time when the PPNB societies actually had domestic ruminants, yet ate mainly game. It is therefore necessary to concentrate our efforts on this precise region and period, possibly by looking at the lipid residue from the stone vessels: pottery did not appear in the Near East before 9000 cal BP in this area (see above: section "Detecting, locating and dating early domestications: contributing to a cultures' history"). The question of the role of milk exploitation in the motivation of early domestications can also be asked for all the other ante-mortem products[3] such as load carrying, which has recently been documented as early as 10 000 cal BP (Middle PPNB; Helmer & Gourichon 2008), as well as traction and hair.

– During the last hunter-gatherer complex societies, for which there is evidence of a rich socio-symbolic life (e.g., Helmer *et al.* 2004), was prestige a strong reason for owning domestic animals, namely large ones such as cattle? Sadly, what little evidence we have to answer this is disputable. The only clear evidence we have comes from Neolithic representations of animals and animal burials, interred with and without human bodies. However, such representations of burials only indicate a complex interaction with the animal, but not necessarily prestige. To fully investigate this issue, which is relevant for all periods though primarily the beginning of domestication, we need a large and well documented dataset, which still needs to be developped.

– Were early domestic ungulates principally used as auxiliaries of agriculture? As previously mentioned, in the Near East, 'predomestic' agriculture began shortly before the end of the 12th millennium cal BP and developed during the PPNA, when villager societies were still basing their food supply on hunting wild or partially controlled ungulates, with domestic ungulates only appearing in the middle of the next millennium. Some of the domestication processes, such as that of the wild boar, could have been generated by the attraction that cultivation and its refuses exerted on the wild animals living around the villages (Ervinck *et al.* 2001; Redding 2005). In these situations, it appears that at least some wild game were becoming natural recyclers of cultivation waste; a role which continued during the following centuries, with the intensification of the domestication process. In parallel, by harvesting the cultivated surfaces, the early cultivators created a new type of ecosystem, characterized by a negative balance of mass and energy as the harvested biomass was not recycled locally. This necessarily generated a rapid decrease of fertility in the cultivated areas, an issue which was probably solved in several ways, including bringing early domestic ungulates onto the fields after the harvest season in order to take advantage of their manure. Using these two perspectives, early domesticates could be considered, at least partly, as auxiliaries of agriculture. What important contributions these animals made to the earliest Neolithic economies, and to what degree early villagers developed specific practices around these issues, are important questions which need to be addressed and documented: e.g., with stable isotope approaches (see above: section "Improving traditional morphometric techniques in parallel with GMM") or metagenomics.

Paying special attention to the social and symbolic dimensions of early domestications

Social anthropology has taught us that all techniques are tightly bound with a socio-symbolic life (Levi-Strauss 1958; Leroi-Gourhan 1964; Lemonnier 1986). Our materialistic, ethnocentric point of view pushes us too frequently to interpret the archaeological results in terms of optimisation of return (e.g., 'optimal foraging' theory; e.g., Stiner 2001). The complexity and partial unpredictability of social functioning and trajectories cannot be understood with simplistic or mechanistic models, more or less directly transposed from evolutionary biology. The concept of the "cultural[4] niche construction" (Smith 2012) is better adapted for integrating the numerous biological, environmental and cultural dimensions of the phenomenon (Sterelny & Watkins 2015), provided it does not lead us to allocate a secondary role to the social dynamics and their consequences on the techniques and practices, as is sometimes the case (Zeder 2015). This is all the more important as the latter are directly connected to the most abundant part of the archaeological documentation. Of course, the social value of the relationship between humans and animals, or plants, is rarely accessible through the archaeo(zoo)logical records; and the impact of the modification of the techno-economic role of animals or plants on the human societies themselves are also often out of reach for archaeologists. However, this is precisely the reason why we need to pay extra attention to

3. This term is more correct than 'secondary product' for the reasons discussed in Vigne & Helmer (2007).

4. ' Cultural' is more relevant than 'human' as it may lead to a perception of our species being restricted to its biological components.

the representations of animals/plants of all kinds, and to their presence in human burials or sanctuaries, even though these manifestations are difficult to interpret.

CONCLUSION

This paper has emphasized a series of conceptual, research and technological priorities for better understanding early domestication and farming.

From a conceptual point of view, we recommend:

– That we base our work within an anthroposystem conceptual framework; which allows equal attention to be paid to both the socio-anthropology and the evolutionary biology concepts and functions. Such a conceptual position will stimulate improvement in the interdisciplinary intellectual toolkit, and promote collaborations which will allow us to provide an account of the complex issues involved in the domestication phenomenon.

– That we fully include in our reflections, the technical, cognitive and socio-symbolic dimensions of domestication. Admittedly, this makes our job much more complex than if we merely restrict conceptual frameworks to the main ecological or biological trends, as some popular theories directly derived from the evolutionary biology sometimes tend to do. However, disregarding, or even reducing, these dimensions would lead to dead-ends as it is these very dimensions that make the specificity of domestication by humans so unique and complex.

In addition, numerous lines of research should be developed:

– There is an urgent need to weave collaborations between all scientific communities working on the past and on the ongoing domestication processes, as well as to experiment with domestication processes and their biological effects under conditions as similar as possible to the ones of the Pre-Neolithic early domestications.

– It is also necessary to clearly distinguish the concept of domestication (in terms of biological modification in the targeted animal/plant) from that of the domestic animal, and adapt methodological strategies and techniques for each of these two distinct issues.

– We should intensify the ongoing efforts for locating and dating not only the early biological modifications due to domestication, or the first occurrence of domesticates in different regions of the world, but also the incipient domestication processes. Amongst other things, we should look more intently at the small signs of intensification and exploitation of wild taxa by the last hunter-gatherers societies, in order to detect possible controls of wild species which could have initiated early domestication processes.

– We need to pay major attention to the historical contexts and to continue to develop comparative approaches in order to maintain strong connections with, and to efficiently contribute to, the cultural history.

– We must develop research, especially in a heuristic context, in peripheral areas (e.g., islands or mountain regions) with less complexity which may allow us to easily detect important phenomena.

– We need to accept that one of the main challenges for the near future consists in trying to assess the respective role of the intensification of ecological relationships and of the intentionality of humans in these different processes and pathways of domestication, including the attempts of domestication/cynegetisation which might not have resulted in stable domestication (e.g., deer);

– We need to decipher the respective roles of the main forcing factors (climate, environment, human demography) in the development of the Neolithic transition across different geographic scales (local to continental), using a high density of environmental data.

– We have also to assess the role and values of early domesticates for the last hunters and early farmers, not only in terms of direct food supply, but also with reference to their seasonal distribution, their ante-mortem products (milk, hair), some of their particular technico-economic utilisations (traction, carriage, manure) or social uses (prestige, religion). Each of these domains should be explored with adapted bioarchaeological and archaeological techniques and research strategies, based on large reference datasets.

In parallel, we have to improve our technological tool-kit by constructing shared, dynamic and sustainable databases in tight connection with research projects:

By developing new techniques for the direct dating of small or degraded samples of organic matter in the bioarchaeological specimens.

By more frequently using geometric morphometrics and improving the necessary traditional morphometric techniques (e.g., to detect early slight morphological modifications resulting from incipient domestication).

By active participation in the fast development of paleogenetics and paleogenomics, in order to maintain strong connections with the archaeological context and issues.

By developing stable isotope ratio analyses, particularly sequential analyses, which allows the life history of early domesticates to be reconstructed, enabling the detection of early cultural controls and the exploration of the rise of control and husbandry techniques.

One of the main challenges for our community is to continue improving techniques and standards in order to construct shared databases with new and better quality information from bones, teeth and shells, whilst working closely with the archaeological excavators on whom we depend for the abundance and quality of our primary data.

Though deeply rooted in archaeology, and in spite of their high potential in the domain of ecological and evolutionary sciences, archaeozoology and archaeobotany are still classed as young sciences. For the study of domestication, as well as the other big questions that we are aiming to address, we must construct our own concepts, standards and issues, within the boundaries of many different disciplinary domains. But, provided we were confident in the outstanding research that we can achieve, and of the necessity of keeping our minds open to the fantastic complexity of the systems that we are dealing with, it looks set to be a long but stimulating journey.

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