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Trends in Ecology & Evolution

Opinion

Towards a science of archaeoecology

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We propose defining a field of research called 'archaeoecology' that examines the past ~60 000 years of interactions between humans and ecosystems to better understand the human place within them. Archaeoecology explicitly integrates questions, data, and approaches from archaeology and ecology, and coalesces recent and future studies that demonstrate the usefulness of integrating archaeological, environmental, and ecological data for understanding the past. Defining a subfield of archaeoecology, much as the related fields of environmental archaeology and palaeoecology have emerged as distinct areas of research, provides a clear intellectual context for helping us to understand the trajectory of human–ecosystem interactions in the past, during the present, and into the future.

Highlights

Ecology focuses on understanding the ecological and environmental context of extant and ancient ecosystems, yet often does not include humans explicitly.

Archaeology, with its focus on history and prehistory of humans, rarely studies the full ecological context of those systems.

Research deeply integrating archaeological and ecological data, questions, and approaches is on the rise.

We present the case for an emerging science of 'Archaeoecology', which provides an explicit framework for studying the structure, dynamics, and sustainability of past coupled natural–human systems.

Assessing the human place in ecosystems

> *That was not, in fact, rudimentary or isolated groups, but far-flung networks of societies, spanning diverse ecologies, with people, plants, animals, drugs, objects of value, songs and ideas moving between them in endlessly intricate ways.* David Graeber and David Wengrow ([1], see p. 516).

Although modern humans emerged in Africa ~300 000 years ago, their ability to significantly impact ecosystems (e.g., via extinctions and extirpations, or building large settlements) around the world has its roots in the late Pleistocene. Two intertwined trends intensified around 60 000 years ago: the increasing dispersal of *Homo sapiens* across the globe and the rapid development of technologies enabling humans to interact more effectively with new environments and the species they encountered. As humans spread to new places and their populations grew at local to global scales from the end of the Pleistocene throughout the Holocene, their impacts on ecosystems grew commensurately [2–4].

Archaeology has long examined the ways that humans impacted environments and how environments impacted societies in the past. These types of studies generally fall under the purview of environmental archaeology [5]. Yet, these realms of inquiry often do not take full advantage of ecological data and modeling on archaeological timescales, and instead focus on the abiotic environment (such as reconstructing past climate, see [6]) and, in some cases, one or a few non-human species (e.g., the '**Lagomorph Index**'; see Glossary [7]). These types of studies have been important for advancing our understanding of environmental effects and human impacts on key species. However, with advances in computational efficiency, ecological modeling and theory, statistics, and the digitization of archaeological reports, we can now pursue comprehensive and integrated studies of the archaeological past of ecosystems.

The question of how humans have interacted with ecosystems through deep time, both in terms of how they impact systems and how systems have shaped human culture and dynamics, is clearly a critical area of research as we confront pressing questions about the sustainability of current and

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future coupled natural–human systems (e.g., [8,9]). Increasingly there are calls for integration and synthesis in research on such questions [10–12]. Such research falls at the interstices of several major fields of study, particularly ecology, archaeology, and palaeoecology. Ecology is primarily concerned with the interactions of non-human organisms with their environments and other organisms in extant ecosystems, although more studies are beginning to explicitly include the human element [13]. Archaeology focuses on the study of human prehistory and history, and, while it often considers the abiotic environmental context and interactions with certain human-related taxa [14], it has less frequently focused on the full biotic ecological context. Palaeoecology focuses on reconstructing and analyzing past ecosystems that stretch deep into geological history [15].

Here, we propose the coalescence of approaches, methods, topics, and prior and future studies related to the archaeological past of ecosystems under the name archaeoecology, much as palaeoecology emerged at the intersection of palaeontology and ecology during the first half of the 20th century [16]. By combining modern ecological data, analysis, and modeling practices with archaeological data, questions, and approaches, we can better understand the trajectory of human–ecosystem interactions in deep time. While palaeoecology includes studies that extend into the Holocene (e.g., [17]) and environmental archaeology includes ecological approaches in some cases, the subdiscipline names reveal the lack of focus on archaeological (within palaeoecology) and ecological (within environmental archaeology) approaches, questions, and integration. While some ecologically oriented archaeological studies [14,18,19] have begun to grapple with understanding the human place in the broader systems in which they are embedded [20], 'environmental archaeology is more circumscribed, focusing on a single species typically represented by subfossil and archaeological evidence' ([21], see p. 3460).

The term 'archaeoecology' is not entirely new; it has been used previously in a more limited way to suggest the use of palaeoecological approaches for systems in the archaeological past [20]. Archaeoecology is, and can be, much more than that, by encouraging the coalescence of approaches and questions from multiple fields, with archaeology, palaeontology, and ecology contributing significantly to the integrated study of past ecosystems. As an explicit area of inquiry, archaeoecology provides an intellectual home for a variety of related studies in recent years scattered across archaeology, ecology and evolution, environmental science, and earth sciences departments. Most importantly, archaeoecology shines a light on the many ways that the study of *H. sapiens* in ecosystems in the past can aid us in understanding the human place in ecosystems today and into the future.

What is new about archaeoecology?

Palaeoecology 'combines biological, geochemical and molecular information from natural archives to reconstruct ecological and evolutionary systems deep into the past' ([11], see p. 1; see also [22]). Its upper temporal limit typically corresponds to the Pleistocene megafauna extinctions, although some suggest its scope also encompasses the Holocene [11,15]. Palaeoecologists look for the incidentally preserved remains of past biota, including shale deposits [23], permafrost preserved ecosystems [24], bog contexts [25], and other fossilized or preserved remains. These traces of the past have been instrumental in helping to understand the climatic, evolutionary, and ecological trajectory of our planet. Palaeoecological studies have typically focused on species diversity, abundance, and distribution, community composition and dynamics, and extinction dynamics [22]. More recently, researchers have begun to reconstruct and analyze complex trophic networks of interacting species in the deep past [26–28].

By contrast, archaeology is concerned with studying intentionally deposited (e.g., **middens** and **tels**) and created remains (e.g., **artifacts**) plus incidentally preserved traces (e.g., pollen cores),

Glossary

Agent-based/individual-based models (ABM/IBM): computer models that model individual behavior (the agents/individuals) and their actions and interactions across space and through time.

Archaeobotany: study of plant remains in an archaeological site.

Artifact: object created or modified by humans in the past. These are purposefully created/modified by past humans, in contrast to an **ecofact**.

Ecofact/biofact: piece of material found at an archaeological site that has archaeological significance, such as a bone that was not modified by a past human but was moved to the site.

Environmental DNA (eDNA): DNA that is extracted from the environment that can provide information on past species that used the area.

Lagomorph Index: proportion of cottontail rabbits (*Sylvilagus*) to jackrabbits (*Lepus*) recovered from sites in the American Southwest, interpreted to indicate changes in the environment; if *Lepus* remains are proportionally higher than *Sylvilagus*, that may indicate drier and less forested ecosystems.

Metabolic scaling theory: theory based on first principles that describes how metabolism drives patterns and processes at all levels of biological organization.

Midden: trash deposit of domestic waste that includes artifacts and ecofacts associated with past human occupation.

Predator dampening: act of reducing predator species through hunting and intentional culling techniques.

Stratigraphic context (stratigraphy/strat): layer of depositional material over time. Strata show time sequences and, through the principle of superposition, older strata generally correlate with older archaeological periods.

Taphonomic process: weathering and transformation processes that impact biological remains after death and lead to the degraded state found in archaeological contexts.

Tel: hill or mound built up over the remnants of several lifetimes of occupation.

Traditional Ecological Knowledge (TEK): accumulation of knowledge and beliefs handed down over time through stories, song, and tradition, referring to local ecological interactions and the place of humans in them; can also be referred to as Indigenous Ecological which reflect signals of past human activity in an environmental context. For example, the archaeological record contains middens of trash deposited by humans in the past [29], which include fragments of animals and plants used by humans at different points in time, as elucidated by the practices of **zooarchaeology** and **archaeobotany** [30,31]. Middens and other intentionally deposited remains can be augmented by other forms of environmental and ecological reconstruction, including tree ring proxies for climate change [32], isotopic analyses of bones [33], and proteomics to understand past faunal composition [34]. The addition of methods for reconstructing past temperature [35], rainfall [6], flood episodes [36], and climatic shifts [37] via modern methods has enhanced understanding of the environmental context of past cultures.

Knowledge in relation specifically to the rich ecological knowledge of indigenous peoples.

Zooarchaeology: study of the zoological remains in an archaeological site.

Building on aspects of palaeoecology and archaeology, archaeoecology is the branch of science that uses archaeological, ecological (biotic), and environmental (abiotic) records to recreate past complex ecosystems, including human roles, impacts, and dynamics (Figure 1), leveraging advances in statistical, computational, and theoretical analysis, and modeling of complex systems. Archaeoecology is driven by a central focus on the ecological contexts that humans in the past lived in, how those ecosystems changed over time both naturally and through direct and indirect human intervention, and how systems of the past led to the coupled natural–human systems we have today, with implications for the future. It does this by bringing together data, in **stratigraphical contexts,** on human-compiled materials and incidental environmental and ecological traces. Combined with the use of various computational approaches, such as **agent-based modeling (ABM)**, network structure analyses, and dynamical modeling, as well as theoretical

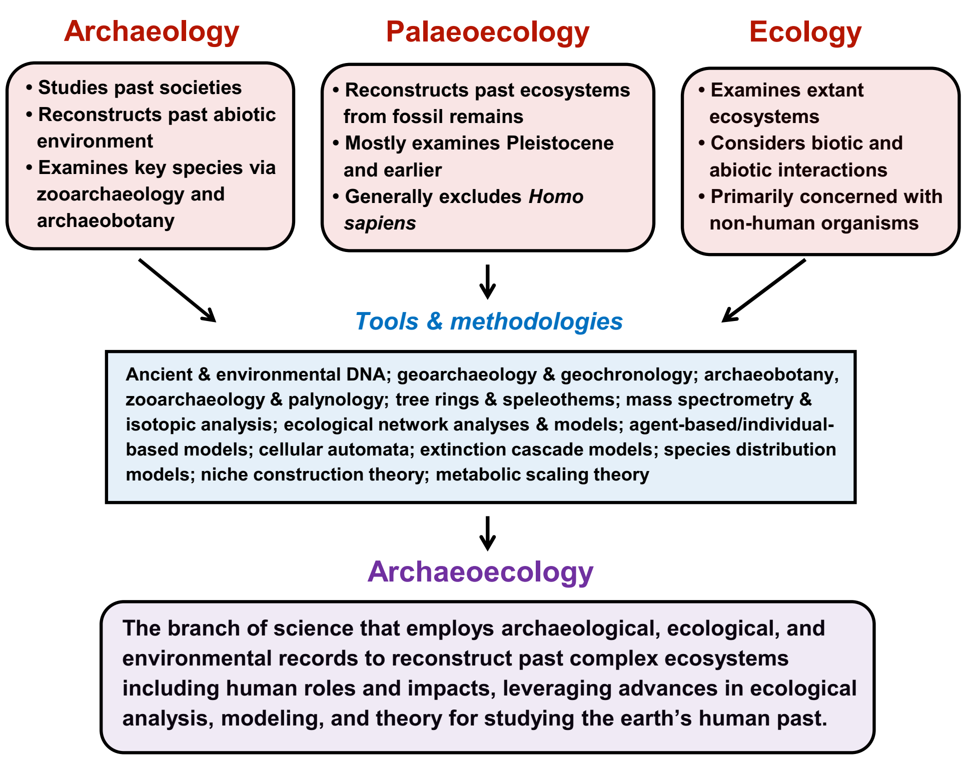

Figure 1. Archaeoecology emerges at the intersection of archaeology, palaeoecology, and ecology. Here, we show the main tenets of each of these fields. When these are brought together with diverse tools and methodologies, the research area of archaeoecology emerges.

frameworks, such as **metabolic scaling theory** [38] (but see [39]), archaeoecological approaches allow us to gain a more comprehensive understanding of ecosystems in the human past.

Thus, archaeoecology represents a unique intersection of ecology, palaeoecology, and archaeology (Figure 1). Examples of archaeoecological research are already emerging, such as studies that move beyond recording the presence of plants and animals at archaeological sites to inferring, analyzing, and modeling the many complex interactions among taxa, including humans, in the past (e.g., [40]). Archaeoecology provides an explicit context for building, analyzing, and modeling ecosystems in the human past, thus encouraging the more detailed study of the interdependencies of human and non-human taxa in the past.

Examples of current methods in archaeoecology

Several of the methodological cornerstones of environmental archaeology are relevant for archaeoecology. Geoarchaeology enables the understanding of site formation processes (e.g., [41]). Archaeobotany, palynology, and zooarchaeology can help identify the animals and plants that humans brought back to a site, or arrived at a site without human intervention (e.g., via wind). Tree ring analysis [42] has also proven useful in reconstructing past climate signatures [43] and linking them to social signatures [32]. The more recent development of ancient DNA research has revolutionized how we understand ancient populations [44]. Augmenting these studies is the use of **environmental DNA (eDNA)**, which can be collected from sediments to examine past biodiversity [45]. Zooarchaeology by mass spectrometry (ZooMS) is enabling 'rapid taxonomic identification of large bone assemblages, cultural heritage objects, and other organic materials of animal origin' ([46], see p. 1). Complementing these, the study of carbon, nitrogen, and other stable isotopes provides a wealth of information on migration, feeding habits, and other aspects of ecology that could only be explored inferentially before [33] (Figure 2).

These and other approaches can be used to augment our understanding of past ecological networks in the form of, for example, food webs that include humans [40,47], human-mediated extinction cascade studies [48], and human-induced mutualistic networks. Mutualistic networks, from an archaeoecological perspective, hold the potential for understanding the historical roots of the current distribution of various taxa [49] and, thus, have implications for research on extant ecosystems. Of particular interest are the roles and impacts of humans within those systems [50], as well as the robustness and vulnerability of human and non-human populations to dynamics and perturbations at multiple spatial and temporal scales in the context of complex trophic interactions and other types of dependencies.

An important part of this endeavor includes working with '**traditional ecological knowledge**' **(TEK)** [51], knowledge of species, ecosystems, and environments passed down from prior generations. TEK allows humans to enhance critical ecosystem services through activities such as grassland promotion [52], fire ignition [53], seed dispersal [54], and **predator dampening** [55]. Many of these activities have a deep time component [56] and support the need for archaeoecological approaches to understand the human place in ecosystems.

Both social sciences and ecology use agent-based models, (known as **individual-based models** in ecology). These models can account for multiple interacting variables and can be used in conjunction with various types of archaeological and ecological data and inferences to analyze changing ecosystems over time [57,58]. Using these and other types of computational modeling to leverage the archaeological record to understand past ecosystems can also

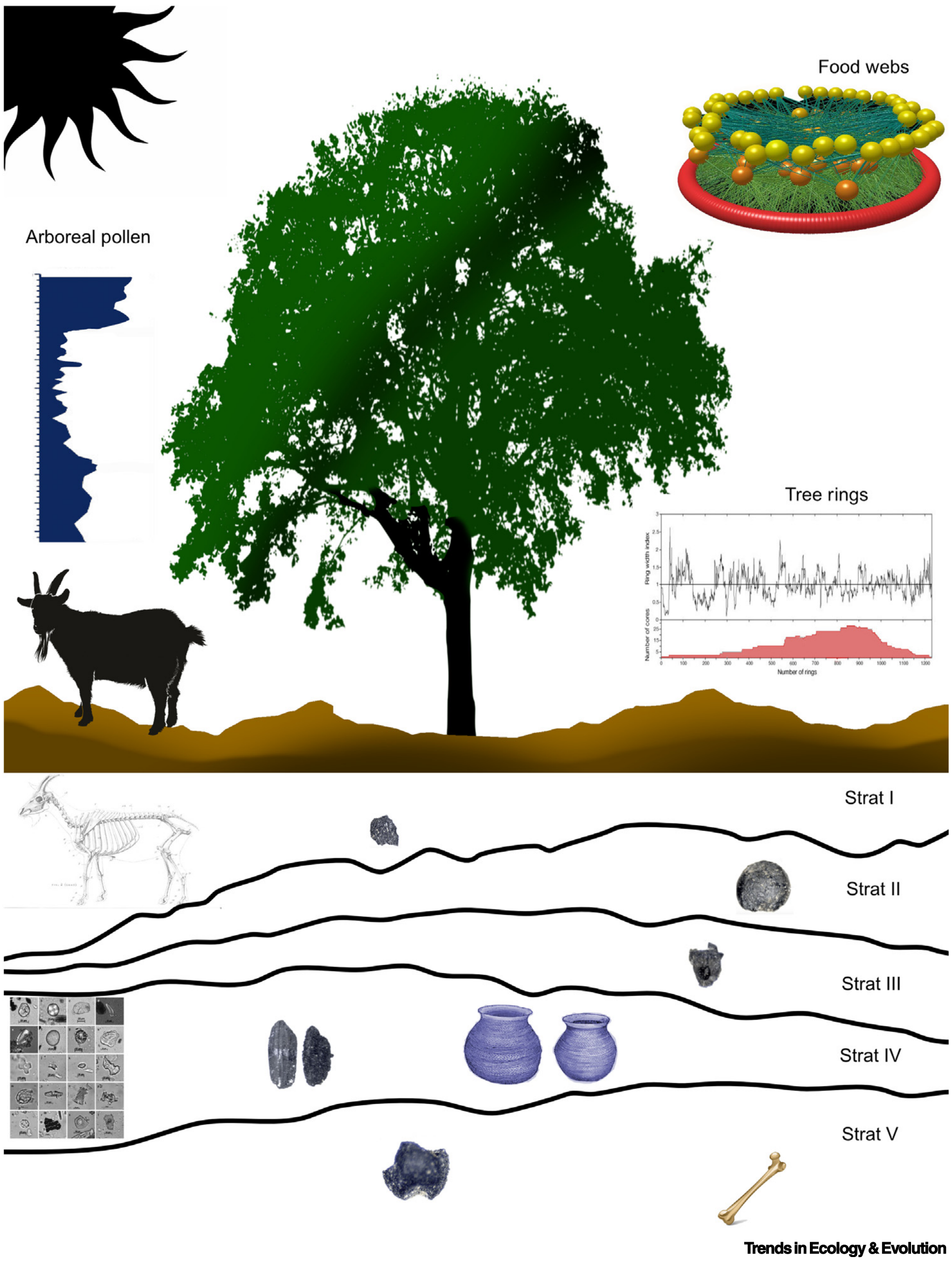

Figure 2. Archaeoecology can bring diverse data together to create a better understanding of the human place in ecosystems. Here, we show how classical environmental archaeology (e.g., palynology, dendrochronology, pottery analysis, and zooarchaeology) can be combined with modern ecological data (e.g., comparing zooarchaeology of a caprid to a modern goat) and *in silico* techniques (such as food web analysis and modeling). Taken together, information on extant plus archaeological ecosystems can enable a deeper understanding of ecological patterns and trends.

help calibrate our understanding of extant systems. The application of computational modeling and the weaving together of disparate data sets [59] differentiates archaeoecology and helps motivate analyses of past systems that incorporate both the biotic and abiotic contexts (Box 1).

Box 1. An opportunity for archaeoecology

Here, we discuss a long-term multidisciplinary environmental archaeology study that could provide the foundation for a fully developed archaeoecological study.

An example of using archaeological data to advance dynamic understanding of ancient ecosystems can be found in work looking at the settlement of Cyprus at the end of the Mesolithic (~11 000 BP [60]). The Neolithic settlers who came to Cyprus brought with them several nondomesticated animals and plants, including fox (*Vulpes vulpes indutus)*, deer (*Dama dama*), pistachios (*Pistacia vera*), flax (*Linum* sp.), and figs (*Ficus carica*), to alter the Cyprian ecosystem to meet their needs [49,60,61]. These were supplemented with domestic einkorn (*Triticum monococcum*) and barley (*Hordeum vulgare*), as well as domesticated pigs (*Sus scrofa*), sheep (*Ovis* sp.), goat (*Capra* sp.), and cattle (*Bos* sp.). The impacts that these early settlers had on the ecosystem are still felt today, predicated on a landscape that was substantially transformed by humans starting ~10 000 years ago.

Assembling this narrative required different lines of archaeological, environmental, and ecological evidence [60]. First, archaeologists needed to describe the ecosystem prior to the arrival of the Neolithic settlers, requiring excavations that provided data on the baseline, prehuman system. From those data, archaeologists were able to infer the arrival of various noncultivated plants and animals that appear endemic to Cyprus today but were likely brought from the mainland. The coincidence of their arrival with the arrival of early migrants is highly suggestive of intentional niche construction. The same applies to nondomesticated foxes and deer, which were likely introduced [49]. Were scientists to describe and model the 'natural' state of Cyprus without humans by removing only humans and their direct domesticates (wheat, barley, and domesticated animals), the ecosystem they describe would be an anthropogenic one merely without humans and a few closely associated taxa.

To move this work beyond a nuanced environmental archaeological exploration and into the realm of archaeoecology would require the next step of ecological analysis and modeling. Methods, such as species distribution models and food web approaches, could make use of the detailed data documenting changes in flora and fauna compiled by Zeder and colleagues as the foundation for extending the ecological scope and depth of their research [60]. For example, species distribution models could be used to examine ancient community composition and how that has changed over time [48]. Furthermore, because it is well established that species introductions can have cascading effects in ecological networks [62], the use of network approaches in the Cyprus case study would help elucidate how and why Neolithic introductions changed the structure of the baseline ecosystem.

These and other methods can support development of quantitative understanding of how the modern Cyprian ecosystem emerged from direct and indirect effects of human introductions of species and other ecological impacts through time. An archaeoecological approach was used, for example, by Crabtree *et al.* [55], who looked at how 20th century removal of the Martu Aboriginal people from the Western Desert of Australia resulted in local extinctions of taxa and simplification of the ecological network, with implications for ecosystem resilience. This demonstrates another benefit of this type of framework: the potential for better forecasting and prediction. With regard to Cyprus and other cases, archaeoecological investigations of how humans altered, and were shaped by, ecosystems across deep time can be used to explore implications for the future sustainability of anthropogenically modified landscapes, given scenarios such as changing climate, land-use intensification, and species extinctions.

Challenges and opportunities for creating a science of archaeoecology

While there have been many years of archaeological, ecological, and palaeoecological research, different training pathways, methods, goals, and questions of those research areas influence the collection and analysis of data, which in turn inhibits researchers' ability to, or interest in, working together. Siloed categories of research have unintentionally led to disciplinary fragmentation and isolation. For example, while many archaeological departments would benefit from inclusion of palaeoecological training, it is mostly seen in the context of palaeoanthropology, if at all [21]. Identifying archaeoecology as an explicit area of inquiry enhances the opportunity for research at the interstices of the relevant fields, motivates the development of novel data sets and methods, leads to new opportunities for cross-collaborative funding, and provides training and networking communities for interested researchers, and a reason for scientists with different types of domain expertise to learn each other's languages and frameworks.

A second challenge in pursuing a science of archaeoecology lies in the accessibility of data. Too often, older archaeological excavations have data published in physical site reports, which cannot be accessed easily. Even when they are accessible, it is extremely time-consuming for subsequent researchers to compile and curate such data. The advent of central archaeological repositories, such as the Digital Archaeological Record (tDAR) [63], reduces the need to dig through decentralized reports and facilitates cross-system analyses of past human societies. The Paleobiology Database also has many records relevant for archaeoecological research. For example, currently, of more than 225 000 collections, almost 3000 are returned when the time interval 'Holocene' is searched. However, the uploading, vetting, and integration of such centralized data are still time-consuming. Nevertheless, as more data are compiled and put into central repositories (including many repositories of ecological and environmental data) in accessible and consistent formats, more studies of an archaeoecological nature will be possible.

A third challenge lies in the gathering of new data. To enable a broad understanding of the human place in past ecosystems, archaeological excavations can anticipate the need for ecological data [64]. While projects may not be focused primarily on ecology, the relatively small investment in sampling for pollen cores, baseline environmental signatures, and other types of ecological data can dramatically advance future understanding of ecosystems of the human past.

A fourth challenge lies in understanding the chronologies of archaeological data and the fragmentary nature of the archaeological record, a similar problem faced by palaeontologists. Deposition is not constant between regions or even within a single archaeological site. Therefore, working with experts who understand the depositional contexts of the region being studied is critical for creating comparable chronologies. Additionally, **taphonomic processes** can also impact the quality of the data recovered, and current advances from palaeoecology [65] can be very helpful when thinking about the archaeoecological context. In addition, ecological models regularly make use of fragmentary data, for example, by bootstrapping or aggregation of data so that different data sets have similar resolution.

A fifth challenge for archaeoecology lies in mismatches across archaeology, ecology, and palaeoecology between researchers' expectations for data availability and resolution as well as methodological literacy. As with DNA studies, any new scientific approach will appear highly promising, and researchers unused to the inherent limitations to novel approaches may have outsized and incorrect expectations for what those approaches can provide to their research program. Keeping expectations well matched to the technique at hand can enable better discovery through those methods. Just as there are domain experts, methodological experts should be consulted as researchers primarily trained as archaeologists, ecologists, or palaeoecologists embrace new approaches for archaeoecological inquiry.

Even with these challenges, opportunities abound. Using new methodological approaches for archaeoecological analysis and modeling of archival and other data provides new ways to answer both new and old questions about ecosystems of the human past. Furthermore, as more sites are analyzed, digitized, and archived, archaeoecologists can identify commonalities and differences across different societies and how they relate to their ecological, environmental, and cultural contexts, enabling deeper understanding of the place of humans in ecosystems across space and time. Finally, archaeoecology can provide a useful bridge between palaeoecological and ecological studies, helping to leverage our understanding of the past at different timescales and at critical points in human history as a means of enhancing and transforming our understanding of the trajectory of extant and future ecosystems [66,67].

Concluding remarks and future perspectives

The impacts of humans on ecosystems for the past ~60 000 years deserve more explicit and nuanced study that achieves both depth and breadth within and across systems. As subsistence-

Outstanding questions

How have humans shaped ecosystems and ecosystems shaped humans over the past 60 000 years? To fully examine this question, modeling humans as part of ecosystems in archaeological time is essential. While palaeoecology can help us to understand ecosystems in deep time, archaeoecology can help us to understand the ways humans embed themselves in ecosystems.

To what extent are modern landscapes the product of prior human use? The archaeoecological approach we suggest can help disentangle the extent that landscapes were impacted by humans and how human interventions led to the ecosystems we see today. Quantitative methodologies and the coalescence of several approaches can help us to understand the trajectory of human–ecosystem interactions.

based societies are lost to urbanization and the critical ecological functions of humans are abandoned [68], it is essential that we understand the deep and ever more entangled trajectory of human–ecosystem interactions. The emerging coalescence of parts of ecology, archaeology, and palaeoecology deserves its own identity as 'archaeoecology', which will support a more integrated and comprehensive understanding of the ways in which environments, ecosystems, and humans have coevolved since the Pleistocene (see Outstanding questions).

The ability to mine the archaeoecological record for examples of past experiments in sustainability can aid the better assessment of modern challenges [66,67], such as the extinctions and community restructurings happening as a result of climate change and other anthropogenic forces. Knowing when and where human effects have helped augment ecosystems, contributed to their unravelling, or had neutral roles in the past can help scientists and policy-makers make better recommendations for ecosystem resilience in the face of multidimensional change now and in the future. Thus, archaeoecology can be an explicit and key partner in addressing the challenges of the Anthropocene.

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Declaration of interests

None declared by authors.

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