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Recent Major Themes and Research Areas in the Study of Human-Environment Interaction in Prehistory

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ABSTRACT

We report a study in which we systematically reviewed the recent literature dealing with human-environment interaction in prehistory. We first identified the 165 most highly cited papers published between 2005 and 2015. We then identified the major research themes covered in the sample of papers and assessed whether the themes fall into clusters and/or vary greatly in popularity. Subsequently, we identified potentially important lacunae. Our review identified dozens of themes and four major clusters: 1) improving our reconstructions of past environments; 2) the impact of climate change on past human societies; 3) human adaptation to past environmental conditions; and 4) human impacts on past environments. We also identified several gaps that led us to make a number of suggestions for future work. One is to pay more attention to the epistemology of causality. A second is to take into account nonlinearity when considering causal relationships. A third is to study the impact of chronological uncertainty on analyses. Lastly, our review revealed that there are differences between the aspects of human-environment interaction in prehistory that interest scholars and those that interest policy-makers and the general public. This needs to be addressed for obvious reasons.

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Introduction

Over the last few decades most scientists and many policy-makers have become convinced that the current bout of anthropogenic climate change will pose major challenges for humans in many parts of the world. It is predicted that as the Earth warms, sea level will rise and changes in global atmospheric circulation will lead to increasingly severe weather in many regions (IPCC 2014b). These changes are forecast to disturb the ecological systems on which we depend, resulting in food shortages, mass migration, and increased conflict (IPCC 2014a).

Paralleling this growth in concern about global warming, there has been a marked increase in the amount of research on human-environment interaction in prehistory over the last few decades (Figure 1). The number of papers on the topic has risen from fewer than 10 per year before the 1970s to around 300 per year since 2010. This translates into an increase from less than 1% of the annual total of archaeological papers to almost 15%. The uptick in research began in earnest around 1990 and shows no sign of slowing down. In fact, it appears to be accelerating.

In the present paper, we report a study in which we reviewed the most influential journal articles dealing with human-environment interaction in prehistory

that were published between 2005 and 2015. The review had three goals. One was to identify the major themes represented in the sample of papers. Another was to determine whether the themes fall into clusters and/or vary greatly in popularity. The third goal was to spot potentially important lacunae with a view to paving the way for future research.

Methods

To ascertain which aspects of human-environment interaction in prehistory interested scholars from 2005 to 2015, we searched Web of Science (www.webofscience.com, accessed 2017–06). Our search included the keywords ‘climat*’ and ‘environment*’ – the asterisks acted as wildcards that captured different endings like ‘climat-e’ and ‘climat-ic’. These terms were searched within the title, abstract, author keywords, and keywords added by Thomson Reuters. We ignored post-2015 papers to control for instability in citation rates of newly published work.

We then created two lists of papers: 1) those from archaeology-specific journals and 2) those from interdisciplinary journals that publish research on human-environment interaction in prehistory. To create the first list, we limited our keyword search results to

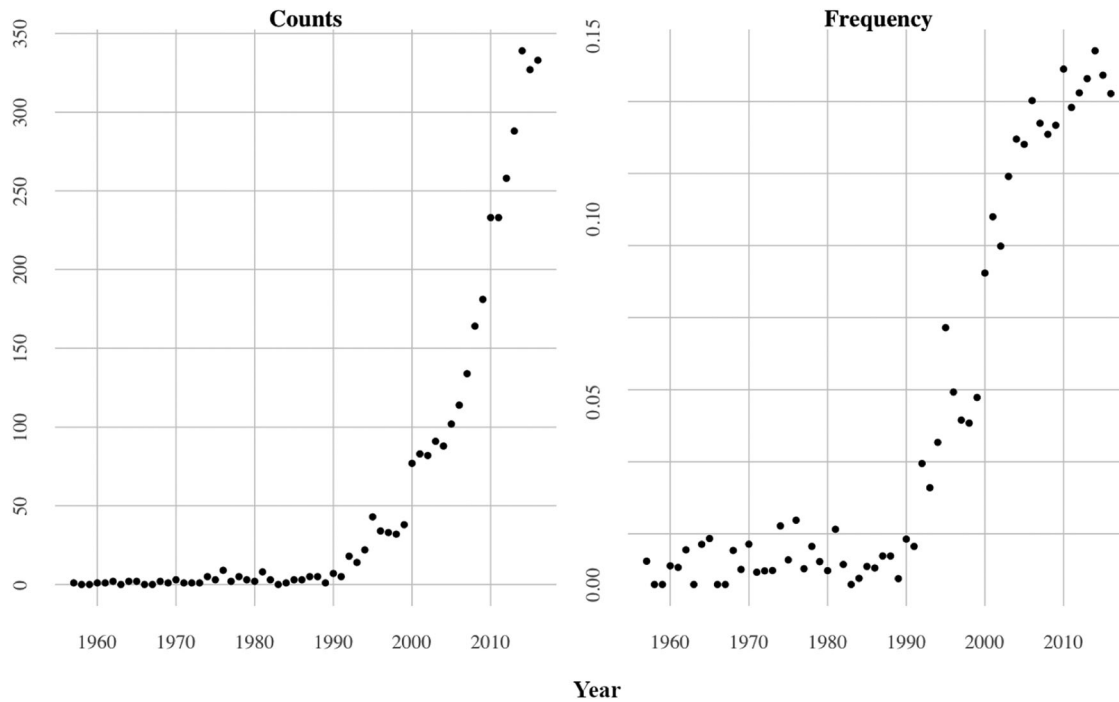


Figure 1. Publication trends in archaeological human-environment research. These data were collected from searches of the Web of Science database. See the Methods section for details.

papers in the Web of Science category ‘archaeology’, which includes top-ranked archaeological journals such as *Journal of Archaeological Science* and *Antiquity*, as well as less prominent ones. To create the second list, we manually added interdisciplinary journals like *Quaternary Science Reviews* and *Quaternary International* to the search pool. Table S1 gives the names of the journals from which the two lists of papers were drawn.

Next, we identified the ten most highly-cited papers for each year from the archaeological journal list and the five most highly-cited papers for each year from the interdisciplinary list. Our assumption was that the popularity of a given study – as indicated by its citation count – could be used as a proxy for the importance of the themes appearing in it. Sampling papers from each year allowed us to control for the increase in citation counts over time.

We sampled more archaeology papers than interdisciplinary ones in order to deal with the fact that while most research on human-environment interaction in prehistory is published in archaeology journals, papers from interdisciplinary journals tend to be cited far more often, presumably because the readerships of those journals are much larger. We reasoned that sampling twice as many archaeology papers as interdisciplinary papers per year would allow us to pick up the topics that have been of general scientific interest without missing too many of the topics that have only really interested archaeologists.

Some of the search results included papers that refer to ‘environment’ but in a context other than human-environment interaction. Similarly, ‘climate’ is sometimes used to refer to abstract conditions rather than

the natural environment. Because of this we had to manually exclude papers that did not fit our criteria and select instead the next most highly-cited paper in the search results for the year in question.

Subsequently, we combined the papers from the two lists into a single sample of 165 papers. Publication details of the papers are given in the Table S2, along with their citation counts.

To analyse the sample, we turned to QSR International’s NVivo 12 qualitative data analysis software (www.qsrinternational.com/nvivo/). This programme allows text in PDF documents to be highlighted, tagged, and coded such that themes can be identified in a sample of documents.

The number of themes grew rapidly at first as we encountered new ones. It then levelled off as most papers could be coded by the existing themes. The themes are typically broad, referring to different variables involved in human-environment interaction in prehistory like ‘demography’, ‘diet’, or ‘climate change’. We stress that our research protocol was designed to identify popular themes, not necessarily new ones. Consequently, some of the themes we discuss in the next section were first investigated many years ago. Indeed, several of them have been the subject of study since archaeology emerged as an academic discipline.

Once the coding was complete, we created a table linking the papers and themes (see SI) and loaded it into R (R Core Team 2017). The table contains binary cells showing whether a theme X was present in paper Y. From the table, we were able to count the frequency of occurrence of each theme appearing in the sample.

We then used R to explore the patterns in the data by looking at theme prevalence and co-occurrence across the sample.

Themes

We identified a total of 73 themes related to human-environment interaction in prehistory in the sample. The top ten are listed in Table 1, along with the number of papers in which they occur (see Table S3 for the complete list).

In order of descending prominence, the top ten themes are 1) *Ecological Economics*, 2) *Climate Change*, 3) *Land Use*, 4) *Environmental Reconstruction*, 5) *Human Impact*, 6) *Agriculture*, 7) *Demography*, 8) *Landscape*, 9) *Evolution*, and 10) *Environmental Context* and *Migration* (tied). Here, we are using *Ecological Economics* to refer to causal links between environmental conditions and subsistence. *Climate Change* concerns the impact of rapid changes in climatic conditions. *Land Use* denotes the ways people used the landscape. *Environmental Reconstruction* pertains to the use of proxies for past environmental conditions. *Human Impact* alludes to the effect hominins had on the environment. *Agriculture* pertains to the adoption of agriculture or changes in agricultural practice. *Demography* refers to population size or population pressure. *Landscape* concerns distributions of sites or environmental interaction beyond individual sites. *Evolution* covers the use of evolutionary theory to

Table 1. Top Ten Themes, descriptions, and number of papers containing them.

Theme	Description	Count
Ecological Economics	Posited causal relationship implies a close connection between environmental conditions and basic subsistence	119
Climate Change	Rapid climate change events – e.g. The Younger Dryas, the Little Ice Age, etc. – or significant climatic variation	91
Land Use	How humans make use of the landscape, including ecology and modification	83
Environmental Reconstruction	Reconstructing or estimating past environmental or climatic conditions by proxy using palaeoenvironmental data	77
Human Impact	Human impact on the landscape or environment	59
Agriculture	Evidence of agriculture or the impact of agriculture or adaptation related to specific crop packages, and so on	54
Demography	Population size estimation	53
Landscape	Distributions of sites and site patterning or widespread evidence of occupation or impact beyond individual sites	53
Evolution	Applies evolutionary principles or explanations, including fitness and adaptation – could be biological or cultural	45
Environmental Context	Emphasizes the importance of context and differences in context regarding causality in the human-environment relationship and/or environmental reconstruction	40
Migration	Permanent human movement across a landscape	40

Note that “Environmental Context” and “Migration” are tied for tenth place.

explain genetic or cultural change in response to environmental change. Lastly, *Environmental Context* refers to the importance of accounting for differences in environmental conditions when interpreting palaeoenvironmental proxies, while *Migration* refers to the movement of people from one region to another.

To assess the relative prominence of themes in the sample, we plotted the frequencies of their occurrence in a bar chart (Figure 2). The distribution is close to exponential. The top ten themes are found in three to ten times more papers than the bottom 40 themes.

Co-Occurrences Among Themes

We ran a simple cluster analysis using an R function called *hclust* to determine whether themes co-occurred. The heatmap presented in Figure S1 (SI) summarises the result of this analysis – it is best viewed on a computer screen so that the row and column labels can be easily magnified. While there is a lot of variability and not much structure overall, two clusters stand out. One involves around 60 papers and eight themes. The other involves about 40 papers and six themes.

The themes in the first cluster are *Ecological Economics*, *Environmental Reconstruction*, *Climate Change*, *Landscape*, *Land Use*, *Agriculture*, *Human Impact*, and *Distinguishing Human and Environmental Impacts*. These themes appear in papers primarily focused on using proxy data to reconstruct past environmental conditions and interpreting temporal changes in those conditions at the landscape scale. Many of the papers describe attempts to identify human impacts on proxies in order to distinguish anthropogenic effects from natural ones and/or to improve understanding of the proxies and what they tell us about past environmental conditions. The majority of the papers are also concerned with changes in human land-use in response to environmental change or the ways in which human land-use altered environments. Most look at the impact of agricultural activity (e.g. Hoffmann, Lang, and Dikau 2008; Kuneš et al. 2015), but a few focus on the impact of hunter-gatherers (e.g. Surovell et al. 2009; O’Connell and Allen 2015). Several papers use pollen frequencies, plant remains, and/or charcoal concentrations to reconstruct past plant ecology with the aim of identifying anthropogenic impacts (e.g. Fyfe 2006; Lejju, Robertshaw, and Taylor 2006). The indicators include a reduction in the concentration of tree pollen, which is interpreted as evidence of deforestation, and a change in agricultural pollen frequencies, which is considered to be the result of a change in land use (e.g. Kennett et al. 2005; Nocete et al. 2005). A number of studies also involve soil variables such as total organic carbon content, magnetic susceptibility, and geochemical signatures (e.g. Simonneau et al. 2013; Wright et al. 2015). One study uses trace element analysis of shells to help identify heavy metal pollution from ancient

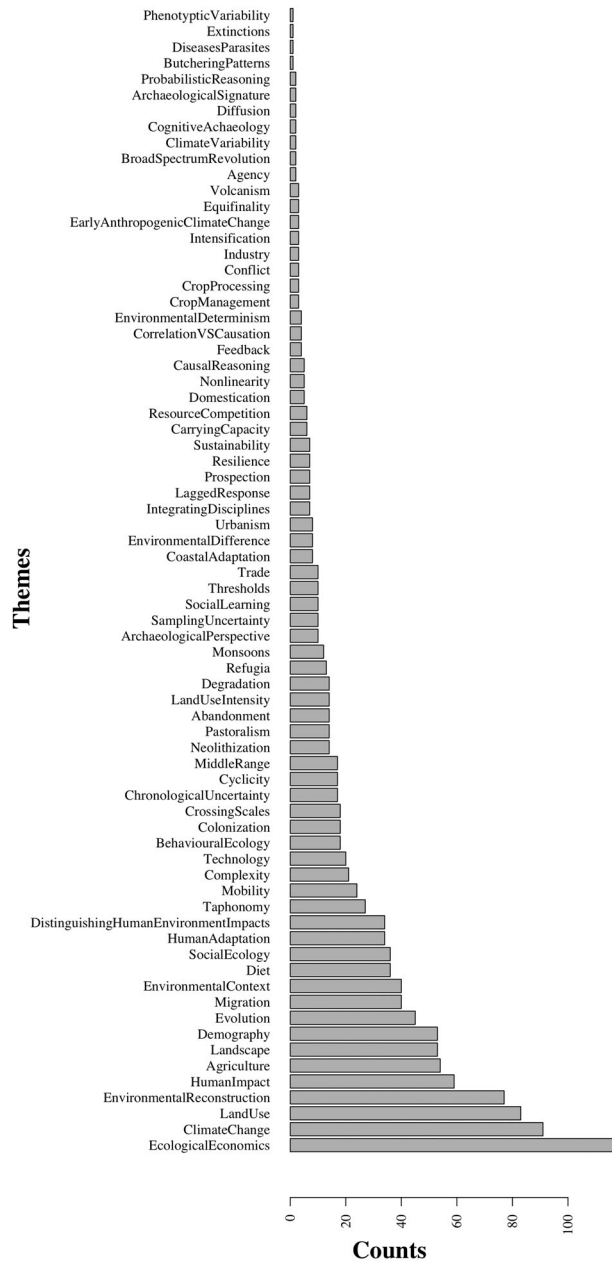


Figure 2. Frequency distribution of themes.

metallurgy (Nocete et al. 2005). Several of the papers employ simulated or experimental data to answer questions about the use of a particular proxy (e.g. Fyfe 2006; Fraser et al. 2013). In one theoretical paper, an author argues that researchers have overlooked the impact of hunter-gatherers on the landscape (Lightfoot et al. 2013). Taken together, the papers in this cluster show that there is great diversity in the proxies used to reconstruct past environmental conditions. They also highlight the need for caution when interpreting proxy records.

The six themes in the second theme-cluster are *Ecological Economics*, *Environmental Reconstruction*, and *Climate Change*, *Evolution*, *Colonization*, and *Migration*. The papers can be divided into two main groups. The first concerns hominin movement during the Pleistocene. Several papers focus on early hominin

dispersals into Eurasia and/or the subsequent migration of anatomically modern humans into the same regions, including interactions between modern humans and earlier hominins (e.g. Bar-Yosef and Belfer-Cohen 2013; Breeze et al. 2015). A number of other papers examine the dispersals of hominins into Sundaland and Sahul (e.g. Bird, Taylor, and Hunt 2005; O'Connell and Allen 2012). These are geographic regions corresponding to landmasses that were exposed by sea level reduction during the Last Glacial Maximum. Sundaland linked together the Malay Peninsula, and the islands of Borneo, Java, and Sumatra; Sahul was formed by Australia, New Guinea, Seram, and neighbouring islands. The Sundaland/Sahul dispersal papers explicitly address questions about migration routes and climate change. In most cases, the authors argue that climate change played a key role in the dispersal events.

The second group of papers includes ones that focus on migration and mobility during the Holocene. They include papers exploring the role of climate change and ecology in the spread of the Neolithic in Europe, and population movement involving Bronze Age societies in Europe and the Eastern Mediterranean (e.g. Berger and Guilaine 2009; McClatchie et al. 2014). There are also three papers that look at migration and/or mobility in mid-Holocene Meso- and South American societies (Craig et al. 2007; White, Price, and Longstaffe 2007; Knudson 2009). The papers in this group either attribute migration to climate change or explore the interaction between environmental variation and mobility in the archaeological record.

Conceptual Clusters of Themes

We also identified clusters of themes based on conceptual affinity. NVivo facilitates the identification of such clusters with its text-coding functions. As we explained earlier, the coding process involves highlighting text in a given paper and assigning a theme to that section of text. The theme can be new or one that has been previously identified in another paper. As sentences and paragraphs are coded, a list of themes grows and conceptual associations between themes begin to emerge. In NVivo, cognate themes can then be placed into folders or arranged hierarchically to reflect their conceptual affinity.

In this part of the study we identified three major groups of closely related themes. We will refer to these as *Human-Environment Dynamics*, *Environmental Reconstruction*, and *Epistemological Challenges*.

Human-Environment Dynamics

Themes in this group connect the environment to human behaviour. Typically, these connections consist of an environmental component and a mediating mechanism that links the environment to human impacts or responses. The environmental components that appear in the sample involve rapid climate change events, environmental variability, and regional differences in ecology.

In at least 45 papers, the authors investigate named climate change events, several of which have been identified in proxies from around the world. The earliest climate events in the sample comprise the late Pleistocene glaciations and de-glaciations – i.e. the Marine Isotope Stages (MIS). Several studies in the sample examine changes in the archaeological record dated to MIS 4-2, approximately 70,000-30,000 BP (e.g. Schmidt et al. 2012; Parton et al. 2015). Some of the papers focus on transitions between stages (e.g. Villa et al. 2010; Vogel-sang et al. 2010), while others examine single stages (e.g. Hunt, Gilbertson, and Rushworth 2007; Jacobs et al. 2008). MIS 3 and MIS 2 are the most commonly

investigated periods – the latter of course being the Last Glacial Maximum. There are also a few studies that look at periodic *Dansgaard-Oeschger* (D-O) events and periodic *Heinrich* events (e.g. Bradtmöller et al. 2012; Schmidt et al. 2012).

The papers that examine these major climate change events – the transitions between MISs, D-O events, and Heinrich events – are primarily concerned with settlement patterns, mobility, hominin expansion out of Africa, changes in stone tool technology, and/or changes in diet. It is also worth noting that many of the papers that discuss these climate change events include the theme *Evolution* and, so, explain human-environment interaction in terms of explicitly evolutionary hypotheses.

The more recent climate change events discussed in the sample of papers occurred during the Pleistocene-Holocene transition and later in the Holocene. The earliest is the Bølling-Allerød, a period of significant global warming that occurred ~14,700-12,700 BP (Weaver et al. 2003). In Southwest Asia, this period is known for what Flannery (1969) called the ‘Broad Spectrum Revolution’, an increase in diet breadth that has been claimed to have spurred the development of agriculture (Stiner 2001; Rosen and Rivera-Collazo 2012). Two papers in the review sample address the possible association between the Bølling-Allerød and the Broad Spectrum Revolution (Maher, Banning, and Chazan 2011; Morgan 2015).

Another event called the Laacher-See eruption – a massive volcanic eruption in Germany – is discussed in some of the papers (e.g. Riede 2008; Riede and Edinborough 2012). While not a climate change itself *per se*, the Laacher-See eruption is thought to have altered the environmental conditions in Germany around 12,900 BP, leading to regional cooling and damage to plant communities with knock-on effects for the rest of the food chain. In the papers in question, it is argued that these changes caused severe disruption among human societies, including emigration, social network fragmentation, and the loss of bow-and-arrow technology.

The next event is the Younger Dryas, which occurred around 12,700-11,700 BP. The Younger Dryas is characterised by a rapid return to glacially cold temperatures after the warmer Bølling-Allerød in the Northern Hemisphere – changes that occurred within the span of a decade (Alley 2000). This climate event is discussed by eight papers, all of which refer to its impact as potentially stressful, possibly having led to reduced diet breadth, population contraction, or adaptive changes (e.g. Migowski et al. 2006; Yi et al. 2013).

The so-called 8.2 ka Event appears in six papers (Brooks 2006; Hoffmann, Lang, and Dikau 2008; Maher, Banning, and Chazan 2011; Bocquet-Appel et al. 2012; Simonneau et al. 2013; Kuneš et al. 2015). As the name suggests, the event is dated to around 8,200 BP and appears to have been severe and

widespread, affecting much of Europe and possibly Southwest Asia (Simmons 2010; Wicks and Mithen 2014; Akkermans et al. 2015). It was as a period of abrupt cooling that has often been argued to be responsible for a series of site abandonments and reductions in socio-cultural complexity in Southwest Asia and the eastern Mediterranean (e.g. Simmons 2010). However, some of the papers suggest that the impact of the 8.2 ka Event could have been different in different places. For example, Maher, Banning, and Chazan (2011) conclude that it does not coincide with any significant changes in the archaeological record of Southwest Asia.

A few thousand years after the 8.2 Event there was another period of rapid cooling. This is often called the 4.2 ka Event. Several papers refer to this event and, like the previous 8.2 ka Event, it is generally characterised as having had a largely negative impact on human societies (e.g. Arz, Lamy, and Pätzold 2006; Kuneš et al. 2015).

The final named event dealt with in the sample of papers is the Little Ice Age, which began around 1200 CE and lasted perhaps until the mid-nineteenth century. Dozens of papers in the sample refer to this event and its impact on societies from around the globe, including those of Great Zimbabwe, Medieval Ireland, and the Yucatan peninsula during the post-Classic period (e.g. Brooks 2006; Guyard et al. 2007). In most of these studies, the authors refer to increased aridity during the Little Ice Age and posit that it had negative consequences for a given society and/or that people responded with intensification/expansion of agriculture.

In addition to the named climate changes, many papers in the sample examine low-magnitude unnamed climate changes, climatic oscillations, and/or environmental variation. Some of these papers compare fluctuations in a proxy, such pollen frequencies, to changes in the archaeological record (e.g. Fuchs 2007; Langgut, Finkelstein, and Litt 2013). Typically, they investigate regional climate changes during the Holocene on a smaller spatial scale than the papers that examine named events – e.g. climate change in early-mid Holocene Turkana basin (Wright et al. 2015), or mid-Holocene Ireland (Whitehouse et al. 2014; Wright et al. 2015). The unnamed climate changes were less severe than the named ones and involved mostly oscillations between wet and dry conditions, as reflected by fluctuations in flora, fauna, and/or lake levels. A few papers investigate the impact of El-Niño Southern Oscillation (ENSO) on past societies (e.g. Knudson 2009; Mooney et al. 2011). While ENSO is a named phenomenon, it involves quasi-stable oscillations of low magnitude relative to the named events, and so can be thought of as variation rather than rapid, directional climate change.

In the review sample, climate change and/or environmental conditions are linked to human

behaviour via putative mediating mechanisms. Some of the papers draw causal arrows from environmental change (or variation) to the impacts of those changes (or variations) on humans, while others draw the arrow in the other direction, positing anthropogenic causes for observed environmental changes.

Two primary types of mediating mechanism are discussed – economics and culture. In 119 of the papers, the authors link environmental conditions directly to human subsistence and other resources – i.e. to economics. One common mechanism involves cultivation and animal domestication. Needless to say, environmental conditions impact plant growth, and most authors agree that changes in the productivity of crops would have affected farming societies in some meaningful way (e.g. Kaplan, Krumhardt, and Zimmermann 2009; Whitehouse et al. 2014). Some authors look at the role of climate change in the adoption of cultivation in a given region (e.g. Tallavaara, Pesonen, and Oinonen 2010; Warinner, Garcia, and Tuross 2013), while others examine how population size was affected by environmentally-driven changes in crop productivity (e.g. Eitel et al. 2005; Langgut, Finkelstein, and Litt 2013). Still others investigate the impact of cultivation on past environments (e.g. Kennett et al. 2005; Fraser et al. 2011). Several papers in the sample also investigate the process of animal domestication, including its impact on animal populations and plant ecology (e.g. Pearson et al. 2007; Gifford-Gonzalez and Hanotte 2011).

The other causal route from environmental to economic conditions involves hunting and gathering. Some authors discuss the impact of hunting on prey populations (e.g. Milner, Barrett, and Welsh 2007; Steele and Klein 2008) while others look at the impact of changes in ecological productivity on hunter-gatherer population size or mobility (e.g. Madsen et al. 2006; Britton et al. 2009). Many of these papers specifically discuss the distinctive role of environmental refugia in the evolution and dispersal of hominins (e.g. Banks et al. 2008; Jennings et al. 2015). This topic is so prominent in the sample that we treated it a distinct theme (*Refugia*). Still other papers examine the impact that prehistoric hunter-gatherers had on plant ecology and the landscape (e.g. Hunt, Gilbertson, and Rushworth 2007; Lightfoot et al. 2013). Dozens of papers focus on dietary evidence of hunting such as isotopes from human skeletal remains and faunal remains (e.g. Hu, Ambrose, and Wang 2006; Shahack-Gross and Finkelstein 2008). Many of these papers also include an evolutionary perspective, i.e. they interpret economic changes as human adaptive responses to environmental change (e.g. Chase 2010; Buchanan, O'Brien, and Collard 2014). Unsurprisingly, the papers tend to focus on the Pleistocene and early Holocene when most human societies subsisted on hunting and gathering (e.g. Tryon et al. 2012; Kyriacou et al. 2015).

In 36 of the papers, authors link environmental conditions to social and cultural traits rather than directly to diet or economics. Several papers, for example, discuss the association between environmental carrying capacity, population size, and the transmission and maintenance of cultural traits via social learning (e.g. Banks et al. 2008; Clark 2011). Some cultural traits are technological and linked to subsistence, as in the case of the loss bow-and-arrow technology in the Bromme Culture (Riede 2008). Others, however, cannot be directly linked to food procurement. Bevan and Conolly (2009), for instance, examine the relationship between landscape variation and distributions of different types of pottery on the Greek island of Antikythera. In another example, Nocete et al. (2005) investigate past heavy metal pollution from mining and metallurgy in Italy. Some authors point out that cultural preferences can frustrate our attempts to understand past human-environment interaction, such as the effect of beer consumption on location-informative isotopes in the Andes (Knudson 2009), or the effect of cultural preferences on travel pathways in Minoan Crete (Siart, Eitel, and Panagiotopoulos 2008). A few other authors compare putative economic and cultural mechanisms, but come down strongly in favour of the latter as an explanation for a given change in the archaeological record (e.g. Eriksson et al. 2008; Huffman 2009).

Environmental Reconstruction

The second conceptual theme-group involves environmental reconstruction. In 77 of the papers, the authors attempt to interpret one or more palaeoenvironmental proxy records with the aim of reconstructing past ecological or climatic conditions for a given region and time period. The proxies and methods vary, including remote sensing (e.g. Challis 2006), dietary isotopes (e.g. Hu, Ambrose, and Wang 2006), environmental isotopes (e.g. Warinner, Garcia, and Tuross 2013), pollen series (e.g. Sadori et al. 2010), sedimentology (e.g. Eitel et al. 2005), and frequency distributions of animal taxa (e.g. Cuenca-Bescós et al. 2009). Some authors report a review of pre-existing environmental data, while others interpret their own data. By far the most common approach to environmental reconstruction involves pollen and sedimentological sequences from wetland sediment cores, dated with radiocarbon or optically stimulated luminescence techniques. Often the focal sequence is divided into different periods and the environmental or climatic conditions of each period are then interpreted, creating a narrative of environmental or climatic change over time (e.g. Simonneau et al. 2013; Goiran et al. 2014).

A pair of related themes highlight the challenges scholars face when attempting to reconstruct past environments. One of these is *Distinguishing Human*

and Environmental Impacts, which appears in at least 34 papers. Frequently, humans have a sizable impact on the environment, causing measurable changes in the proxies used to reconstruct past conditions. Consequently, it can be difficult to determine whether a change in a proxy, such as a change in the frequency of the pollen of a particular species, should be attributed to fluctuating climatic conditions or human impacts. Several authors make this point. Butzer (2005), for example, notes that human activities such as agriculture often lead to erosion, making it challenging to determine whether evidence for past erosion in Greece was caused by shifting rainfall patterns and temperature or by agricultural activity. In another example, Hunt, Gilbertson, and Rushworth (2007) posit that early modern humans living in Malaysian Borneo intentionally set fires to manage the edges of forest ecosystems, improving the resource richness of such areas but also changing the fire history of the region recorded in charcoal records of local sediment cores. In a third example, Milner, Barrett, and Welsh (2007) point out that temperature changes rather than human predation might have slowed the growth of marine animal shells, leading to smaller average shell sizes in middens. The message is clearly that we can mistakenly suspect climate change produced an observed pattern in a given proxy when anthropogenic activity was actually responsible, and *vice versa*.

The other theme that highlighted the challenges of environmental reconstruction is the *Importance of Environmental Context*. This theme appeared in at least 40 papers. Bevan and Conolly (2009), for example, present a geostatistical regression method designed specifically to address heterogeneity in landscape variables because, as they point out, the relationships between environmental variables and artifact data are not necessarily constant throughout a given landscape. Langgut, Finkelstein, and Litt (2013) make a similar point about human responses to rainfall variation. They note that a precipitation change of 100 mm might have no effect on people in one region but might be devastating for those living in another region. Several other authors argue that heterogeneity in natural environmental isotope ratios can confound reconstructions. For instance, in the process of studying isotopes and past mobility, Buzon, Simonetti, and Creaser (2007) discovered that the Nile Valley in Egypt contains a mosaic of natural isotope signatures, making it difficult to draw conclusions about the isotope values measured in human remains. Along similar lines, Tafuri et al. (2006) point out that different areas in the Sahara have the same heavy isotope signatures, meaning that people might have migrated without the migration impacting the isotopes we recover from their remains. Overall, the papers that discuss the importance of environmental context highlight the fact that environments in the past were as varied as

they are today and that our reconstructions can be confounded by that variability.

Epistemological Challenges

The last theme-group comprises themes that explore epistemological challenges pertaining to human-environment interaction research. In order of descending prominence, the top three themes that constitute this group are *Taphonomy*, *Crossing Scales*, and *Middle-Range Theory*.

At least 27 papers contain extended discussions about taphonomic issues – i.e. depositional and post-depositional processes that affect the preservation of palaeoenvironmental and archaeological material (Bar-Yosef and Belfer-Cohen 2013; Rink et al. 2013). The point of this theme is that, as archaeologists have long been aware, depositional and post-depositional processes affect the preservation and recovery of the evidence used to infer past environmental conditions, which in turn affects our interpretation of human-environment interaction.

The theme *Crossing Scales* appears in at least 18 papers (e.g. Meltzer and Holliday 2010; Trauth et al. 2010). It refers to discussions of how causal relationships can vary across spatiotemporal scales. For example, Edwards et al. (2015) discuss the complexity of the relationship between frequencies of pollen at the spatial scale of the individual site and frequencies of pollen-producing plant species at the scale of the region. In another example, Eriksson et al. (2008) discuss the potential for isotope studies involving human remains to reveal relationships between individual- and population-scale changes in diet. Lastly, Gamble, Gowlett, and Dunbar (2011) argue that meaningful explanations for the large brain of humans have to ‘work at all levels’ (pg. 117) accounting for both short-term cultural processes and long-term biological processes. The main point of this theme is that both human and environmental processes can look markedly different at different spatiotemporal scales, possibly requiring different causal explanations. Thus, different scales need to be considered simultaneously to fully explain human-environment interaction in prehistory.

The last prominent theme in this theme-group, *Middle-Range Theory*, appears in at least 16 papers in the sample (e.g. Lyman 2005; Marguerie and Hunot 2007). Here, Binford’s (Binford 1977) term Middle Range Theory is used to describe any extensive or prominent discussion of the linkage between physical evidence and human behaviour, particularly cases in which authors theorise about the uncertainty involved in inferring behaviour from archaeological and/or environmental data. For example, Fyfe (2006) argues that pollen frequencies are indicative of past human land-use because changes in land-use would lead to changes in vegetation. Along similar lines, Hallmann

et al. (2009) contend that micro-growth lines on shellfish remains from archaeological sites can be used to identify patterns of procurement by humans, including seasonality and even time of day. In another example, Harvey and Fuller (2005) contend that patterns in phytolith assemblages may be indicative of plant processing at a given site in spite of an absence of pollen or other macrobotanical evidence, which implies that phytolith evidence may be useful for interpreting past human behaviour. As these three examples illustrate, several authors in the sample of papers thought it necessary to carefully consider the link between patterns in material remains and the human behaviour that led to them – i.e. middle-range theory. This theme is important because uncertainty in our inferences about human behaviour obviously affects our assessments of human-environment interaction in the distant past.

There were several other themes we identified that fit in this theme-group but occur much less frequently. Significantly, what we consider to be a crucial theme – *Causal Reasoning* – only appears in five papers. We distilled three main points about causal reasoning from these papers. One is that a good causal explanation requires a mechanism. According to Maher, Banning, and Chazan (2011), Middleton (2012), and Meltzer and Holliday (2010), making a causal argument requires a logical connection between a given archaeological change and a particular episode of climate change. The second point is that temporal precedence is required to make causal claims – i.e. linking archaeological changes to climate change requires that any perceived changes in a climatic record must precede the archaeological changes in time. Maher, Banning, and Chazan (2011) make this point by demonstrating that many published claims about climate-driven sociopolitical upheaval in the Near East cannot be supported because the putatively causal climate events occurred after the onset of the changes observed in the archaeological record. The last point is that the study of human-environment interaction in prehistory is limited by our inability to manipulate causal conditions – this point is closely related to the adage that correlation does not necessarily imply causation. Bocquet-Appel et al. (2012) make this point in their study of the environmental determinants of the expansion of agriculture across Europe during the Neolithic. In their discussion, they argue that is difficult to determine whether a given terrain type, like rugged mountains, actually affected the rate of expansion because the alternate condition involving the same society in a different terrain type is not available for comparison. Consequently, they suggest, determining causality in human-environment interaction in prehistory can be very challenging, requiring carefully thought out analyses and large samples.

Other themes belong to this theme-group, too, but they occur even less frequently than *Causal Reasoning*.

For example, themes like *Archaeological Signature* (i.e. the sensitivity of archaeological proxies to environmental change), *Correlation VS Causation*, *Environmental Determinism*, and *Equifinality* all refer to epistemological challenges, but each are represented in only one to three papers.

Discussion

The literature review reported here indicates that over the last decade or so the study of human-environment interaction in prehistory has focused heavily on four main topics. One is improving reconstructions of past environmental conditions. A large number of studies have focused on developing new ways of obtaining information about past environments using a variety of different proxies. Many authors have sought to improve understanding by publishing new datasets, such as pollen cores or reference isotope measurements. Some have contributed by drawing attention to new methods, such as statistical techniques or computer simulations. Still others have raised our awareness of analytical confounders or additional complexity, like the problems caused by spatial heterogeneity or equifinality in environmental proxies. The papers we examined make it clear that a major source of complexity for archaeological human-environment interaction research is distinguishing between climatologically-driven and human-driven changes to the environment. Accurately reconstructing past environmental conditions, including determining where and when humans were a primary driver for environmental change, is crucial for understanding human-environment interaction in prehistory.

The second major topic is the impact of climate change on hominin evolution and dispersal. While most of the papers in question looked at spatiotemporal variability in environmental conditions, like gradual changes in climatic conditions or variation in landscape traits, at least a third were concerned with rapid climate changes. The most prominent rapid climate changes were the transitions between Marine Isotope Stages, the Younger Dryas, Bond Events like the well-known 8.2 and 4.2 ka cold events, and the Little Ice Age. Most of these rapid changes appear to have occurred over decades and had wide-ranging effects on continental or hemispheric scales. The concern with these events in the literature probably should not be surprising considering that discussions about the current bout of climate change often stress that its effects will be catastrophic (Stocker et al. 2014). It seems only natural for archaeologists to ask whether climate change affected past hominins in a similar manner.

While we are not surprised by the focus on the impacts of climate change, we are a little surprised by the way in which those impacts are conceptualised. In more than three quarters of the papers climate change is posited to have affected the availability of

resources, especially food. We find this surprising because both environmental and economic determinism have been criticised frequently in the archaeological literature over the last few decades. We expected the criticisms to have resulted in a stronger focus on the role of culture and ideology in human-environment interaction in prehistory. Evidently, though, the current consensus among archaeologists is that economics was the main pathway by which past humans were affected by climate change. We find it hard to disagree.

The third major topic highlighted by the review is adaptation to environmental conditions. More than half of the papers indicated that prehistoric humans adapted to conditions, either by changing their subsistence practices, moving to new locations, developing new technology, or changing the way they used their landscapes. Interestingly, most of the research either describes human-environment interaction in neutral terms or emphasizes human adaptability. We were not anticipating this. Given the popularity of collapse narratives like those detailed in Diamond's (2005) best-selling book 'Collapse: How Societies Choose to Fail or Succeed', we expected more papers to focus on the potentially dire consequences of climate change or human impact. Our impression of the literature prior to conducting the review was also biased toward collapse phenomena because of several well-known, highly cited academic papers on famous collapse events including the collapse of the Classic Maya and the Late Bronze Age collapses in the Near East (e.g. Drake 2012; Kaniewski et al. 2013). However, in reality only 21 of the 165 papers in the sample – i.e. just ~13% – discussed collapse at all, a theme we labelled *Complexity* to avoid too narrow a focus on the decline of large hierarchical societies at the expense of smaller scale cases involving regional cultural and/or economic fragmentation (e.g. Kennett et al. 2005; Middleton 2012). Within this group, only a handful focused primarily on collapse as a topic (e.g. Hodell, Brenner, and Curtis 2005; Langgut, Finkelstein, and Litt 2013).

The paucity of collapse literature in our highly-cited sample is also interesting because the IPCC included archaeological cases of collapse in their last assessment report (IPCC 2014a). The IPCC has a mandate to provide policy-makers with evidence for the impacts and risks of climate change, so their interest in archaeological work on societal collapse due to environmental factors makes sense. But our review raises the possibility that they might have a skewed view of the significance of collapse in long-term human-environment interaction. Given the importance of the IPCC for setting international policy regarding climate change and our response(s) to it, there would seem to be a fairly urgent need to explore this apparent disconnect.

The last major topic we identified in the review sample is human impact on past environments. In 59 of the papers, authors looked directly at how we can

identify the effects of human activity on the environment. Most of these studies involved pollen and sediment cores and the authors argued that certain pollen taxa frequencies or sediment patterns are signals of past human landscape change, primarily caused by agricultural activities. The most obvious indicator of human activity in a pollen core is the presence of crop pollen or the pollen of weedy taxa known to coexist with crops. In sediment cores, the most common indicator is increased sedimentation rates, caused by clear cutting vegetation that would otherwise trap sediments. In some studies, authors describe landscape degradation that reduced productivity. However, only a few studies explicitly refer to degraded landscapes (e.g. Marguerie and Hunot 2007; Edwards et al. 2015), suggesting that most archaeologists have simply been looking for evidence of human presence, a more neutral view. Still, considering that almost a third of the review sample included some discussion of human impacts, it is clear that archaeologists have been concerned lately with how human activity impacted the environment in the past, and what those impacts might have meant for a given society. This interest seems likely to be at least partly a reflection of modern concerns about anthropogenic climatic and environmental change – an inference supported by papers that posit anthropogenic climate change began much earlier than the industrial revolution (Ruddiman et al. 2008; Kaplan, Krumhardt, and Zimmermann 2009) and papers in which authors explicitly argue that archaeology is important for understanding modern human-environment interaction, a theme we labelled *Archaeological Perspective* (e.g. Riehl, Bryson, and Pustovoytov 2008; Campbell and Braje 2015). That said, past human impacts are also a genuinely important part of past human-environment interaction, as the recent research shows.

The patterns we identified in our review lead us to several recommendations for future research. One area that needs more attention, we think, is causality. Most of the papers in the review sample deal with causality in some way, usually in the sense that the authors are making causal claims about past human-environment interaction. But, only a handful of the papers address the epistemology of causality head-on (Maher, Banning, and Chazan 2011; Mooney et al. 2011; Bocquet-Appel et al. 2012; Middleton 2012; Morgan 2015). The paucity of explicit work on causality is a problem because identifying and understanding causal relationships requires that we know what we are looking for and how to find it. Crucially, we need to explicitly define what we mean by causation and what sort of evidence we might demand to see in order to accept a causal claim. Thus, researchers ought to devote more attention to theorising about how we make causal claims, and how causality might operate in human-environment interaction.

Methodological work in allied disciplines could serve as a jumping-off point for future archaeological research on identifying causality. For example, a recent paper by Ferraro, Sanchirico, and Smith (*in press*) explores some of the challenges involved in understanding causality when human and natural systems contain feedback. Coupled human and natural systems – ‘CHANS’ in Ferraro et al.’s terminology – are challenging to assess because changes in a given natural system prompts changes in the relevant human system, which in turn produce further changes in the natural system, and so on. This coupling creates a unique challenge for causal research because it is difficult to isolate the impact of an external cause – e.g. climate change – from the feedback between human and natural systems. To explore this problem, Ferraro, Sanchirico, and Smith (*in press*) use a computer simulation, an approach that could be useful for human-environment causal research in archaeology. They also advocate the use of structural equation models (SEMs), which are statistical models that explicitly describe hypothetical or known relations between observed and unobserved variables. SEMs are commonly used in social science research (MacCallum and Austin 2000), and have been employed in causality research as well (Pearl 1998). However, to the best of our knowledge, they have not been used in relation to the problem of identifying causality in prehistoric human-environment interaction. Other methodological and theoretical avenues to explore include Granger Causality (Granger 1980; Detto et al. 2012), Dynamical Systems Theory (Sugihara et al. 2012), and Causal (Bayesian) Network Analysis (Pearl 1988, 2009).

We think archaeologists could also benefit from drawing on philosophical work on causality to arrive at a clear definition for causal relationships that can be operationalised in human-environment interaction research. For example, Pearl (2009) describes causality as a special kind of relationship between events or processes. Importantly, it has characteristics that distinguish it from other kinds of relationship. One is *directionality*, meaning that causes produce effects and not the other way around. Another is that causality requires *temporal precedence*, which means that causes must occur before effects. The last is that *interventions* – i.e. manipulating causes – will alter effects, so changing or removing a cause will change or remove an effect. Whether we use this definition or another, we certainly need a clear understanding of what is meant by the term ‘causality’ in order to advance research on human-environment interaction in prehistory.

Another area in need of additional attention, in our view, is nonlinearity in causal relationships. Climatologists are acutely aware that the Earth’s climate is a complex system that includes nonlinear cause-and-effect relationships – a small change in the Earth’s orbital parameters can have enormous climatological

consequences, for example (Cronin, 2010). Some archaeologists have also investigated nonlinearity in cultural and environmental phenomena (e.g. van der Leeuw and McGlade 1997; Kohler and van der Leeuw 2007). However, only five of the papers in the review sample mention nonlinearity explicitly in either climate or cultural effects (Butzer 2005; Basell 2008; Trauth et al. 2010; Winterhalder et al. 2010; Middleton 2012). A few others look at tipping points, thresholds, and feedback, but only in a cursory, qualitative way (e.g. Ejarque et al. 2010; Ur 2010). The paucity of mentions of non-linearity and lack of concrete evidence for it suggests either that archaeologists think human-environment relationships in prehistory were usually linear, or that we have yet to recognise the nonlinearity inherent in those relationships. We strongly suspect the latter is the case.

A third area that needs considerably more attention, we believe, is the impact of chronological uncertainty on the analyses we carry out to investigate human-environment interaction in the distant past. While a considerable amount of work has been done to improve the accuracy and precision of calibrated radiocarbon dates and age-depth models (e.g. Blaauw 2010; Blaauw and Christen 2011; Trachsel and Telford 2017; Hamilton and Krus 2018), the effect of chronological uncertainty on 'downstream' statistical analyses has not been sufficiently explored. End-users of new modelling approaches still rely heavily on point-estimates for dates and pay little attention to the uncertainties around those estimates. In a previous study, we found that chronological uncertainty can significantly distort the results of archaeological data-based research on human-environment interaction (Carleton, Campbell, and Collard 2014). In another study, we discovered that such uncertainty has the potential to severely undermine statistical methods that are commonly used to identify cyclical phenomena in archaeological and palaeoenvironmental records (Carleton, Campbell, and Collard 2018). Both findings involved analyses based on Bayesian age-depth models, which highlights the fact that improved age-depth models alone are insufficient. Other scholars have also pointed out the problems with chronological uncertainty, particularly radiocarbon dating uncertainty and its effect on palaeoenvironmental time series (e.g. Telford, Heegaard, and Birks 2004; Mudelsee 2014), but only a few papers in the review sample paid any attention to chronological uncertainty (e.g. O'Connell and Allen 2015; Thomas 2015). This is a problem because the vast majority of papers make causal claims – or at least speculate about causal relationships – based on palaeoenvironmental and archaeological data that are affected by chronological uncertainty. Consequently, we think that awareness needs to be raised among scholars that chronological uncertainty can greatly complicate research on human-environment interaction, even if new age-

depth models are employed. A determined effort needs to be made to explore the various ways in which chronological uncertainty can affect our analyses, and to explore possible ways of overcoming the challenges it poses.

Several avenues are worth exploring in this regard. Most obviously, we need to evaluate the robustness of common statistical methods given data with varying kinds and degrees of chronological uncertainty. In our recent work, we found that an established method for identifying cycles in palaeoclimate time-series can be expected to yield false positive findings around 90% of the time when the relevant records are dated with calibrated radiocarbon dates. This finding is obviously concerning and suggests that other methods may be susceptible to chronological uncertainty. So, research should focus on testing statistical tools given simulated and real palaeoenvironmental and archaeological records. The primary goal should be estimating false positive/negative rates – i.e. statistical power analysis. Another useful undertaking involves re-evaluating findings in the published academic literature. With sizable error rates, it is possible – indeed, highly probable – that many published findings used to support causal claims about archaeological human-environment interaction are in fact false. Consequently, it is important to identify those false findings by re-analyzing the published data – research similar to one of our aforementioned studies (Carleton, Campbell, and Collard 2014). Lastly, we need a better toolkit. While identifying the problems caused by chronological uncertainty and exploring their scope is crucial, the next obvious step is to fix the problems – i.e. to build a better toolkit. This research will require close collaboration with statisticians and mathematicians to devise quantitative methods that properly account for the idiosyncrasies of archaeological and palaeoenvironmental data. We think this step is pivotal since the ultimate goal of understanding archaeological human-environment interaction will be impossible to achieve without appropriate scientific tools.

The last research area in need of additional work involves investigating the differences between the scholarly research and its use outside of academic archaeology. As we noted, the IPCC's last assessment report includes archaeological case studies of societies that may have collapsed in part because of climate change – e.g. the Classic Maya and Chaco Canyon Anasazi. The degree to which climate change drives collapse is, not surprisingly, heavily debated among archaeologists (e.g. Tainter 2008; McAnany and Yoffee 2010). More importantly, though, our review found that overwhelmingly the most highly-cited research has focused on human adaptability rather than collapse. So, it is possible that important policy organisations and the general public have a skewed impression of the state of knowledge about past human-environment

interaction. It is, however, also possible that academic archaeologists are not responding adequately to external demand. If the public and high-level policy organisations like the IPCC are mostly interested in what happens to human societies during and after climatic disasters, then we are missing an opportunity to address questions of immediate and substantial significance. Thus, we think that more research needs to be conducted on the potential gap, or gaps, between professional academic interest in past human-environment interaction and what people outside the field want to know. If, as many scholars have argued, archaeologists should take part in public discussions and contribute to policy regarding present-day climate change, then we should probably start by assessing and improving the lines of communication between academic archaeologists and other groups.

Conclusions

While archaeologists have long worked on human-environment interaction in prehistory, interest in the topic has risen rapidly in the last few decades and it is now one of the most prominent areas of archaeological research. Not surprisingly given the speed with which the relevant academic literature is growing, keeping track of research patterns and identifying important lacunae has become challenging. With this in mind, we conducted a systematic review of high-profile archaeological human-environment studies published between 2005 and 2015. We had three goals for the review. One was to identify the major themes represented in the sample of papers. Another was to determine whether the themes fall into clusters and/or vary greatly in popularity. The third of the review was to identify potentially important lacunae with a view to paving the way for future research.

We identified dozens of major themes and grouped them into four main areas. The first was improving our reconstructions of past environments. Archaeologists have spent a lot of time trying to improve understanding of the proxies used to estimate past environmental conditions. In particular, research has focused on identifying challenges in distinguishing anthropogenic environmental changes from natural ones in a given proxy. The second area was the impact of climate change on human societies. Unsurprisingly, much of the recent highly-cited research has been concerned with climate change and its impact on past societies. The third area was human adaptation to environmental changes and conditions. Many authors viewed human responses to climate change as adaptations in the evolutionary sense. Many also explicitly emphasized human adaptability, or resilience, in the face of climate change or environmental variability. The last main area was human impact. In contrast to the previous two areas, a substantial number of studies investigated the human-

environment relationship from the environmental side. Clearly, there is an interest in humanity's past environmental footprint with an emphasis on understanding the long-term effects of human activity on the human-environment relationship.

Our review led us to several recommendations for future work. While there are of course a plethora of potential avenues for future research, we think a few ought to be explored with some urgency. One is our understanding of causality in past human-environment interaction. Another is identifying nonlinearity in past human-environment relationships. A third is the impact of chronological uncertainty on our models of past human-environment interaction. The last is exploring possible misalignments between the interests of archaeologists and non-archaeologists. Like a number of scholars have already argued, archaeologists are in a unique position to study long-term human-environment interaction and we should be helping to educate the public and inform policy discussions. With an exponentially expanding literature, however, achieving that goal will require some strategic thinking. We hope this review will help in that regard.

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