Archaeological Sites as Distributed Long-term Observing Networks of the Past (DONOP)

George Hambrecht [a], Cecilia Anderung [b], Seth Brewington [c], Andrew Dugmore [d], Ragnar Edvardsson [e], Francis Feeley [c], Kevin Gibbons [a], Ramona Harrison [f], Megan Hicks [c], Rowan Jackson [d], Guðbjörg Ásta Ólafsdóttir [e], Marcy Rockman [g], Konrad Smiarowski [c], Richard Streeter [h], Vicki Szabo [i], Thomas McGovern [c]

[a] Department of Anthropology, University of Maryland, College Park, MD 20742, USA
[b] Department of Ecology and Genetics, Uppsala University, 751 05 Uppsala, Sweden
[c] Department of Anthropology, Hunter College, City University of New York, New York, NY 10065, USA
[d] Institute of Geography and the Lived Environment, University of Edinburgh, Edinburgh EH8 9XP, Scotland, UK
[e] Research Centre of the Westfjords, University of Iceland, 400 Ísafjörður, Iceland
[f] Department of Archaeology, History, Cultural Studies, and Religion, University of Bergen, 5020 Bergen, Norway
[g] US National Park Service, Washington, DC 20372, USA
[h] Department of Geography and Sustainable Development, University of St. Andrews, St. Andrews KY16 9AL, Scotland, UK
[i] Department of History, Western Carolina University, Cullowhee, NC 28723, USA

Corresponding author:

George Hambrecht
University of Maryland
Department of Anthropology
0111 Woods Hall
4302 Chapel Lane
College Park, Maryland 20742
USA

ghambrec@umd.edu

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Abstract

Archaeological records provide a unique source of direct data on long-term human-environment interactions and samples of ecosystems affected by differing degrees of human impact. Distributed long-term datasets from archaeological sites provide a significant contribution to establish local, regional, and continental-scale environmental baselines and can be used to understand the implications of human decision-making and its impacts on the environment and the resources it provides for human use. Deeper temporal environmental baselines are essential for resource and environmental managers to restore biodiversity and build resilience in depleted ecosystems. Human actions are likely to have impacts that reorganize ecosystem structures by reducing diversity through processes such as niche construction. This makes data from archaeological sites key assets for the management of contemporary and future climate change scenarios because they combine information about human behavior, environmental baselines, and biological systems. Sites of this kind collectively form Distributed Long-term Observing Networks of the Past (DONOP), allowing human behavior and environmental impacts to be assessed over space and time. Behavioral perspectives are gained from direct evidence of human actions in response to environmental opportunities and change. Baseline perspectives are gained from data on species, landforms, and ecology over timescales that long predate our typically recent datasets that only record systems already disturbed by people. And biological perspectives can provide essential data for modern managers wanting to understand and utilize past diversity (i.e., trophic and/or genetic) as a way of revealing, and potentially correcting, weaknesses in our contemporary wild and domestic animal populations.

1. Introduction

Archaeological data is a vital but underutilized resource for environmental managers and policy makers. Archaeological sites are currently valued for preserving cultural heritage, tourism, and place-based education for sustainability, but they can also generate very large, well-documented collections of animal and human bone, shells, insects, and carbonized and waterlogged botanical materials that span thousands of years. Advances in stable isotope, ancient DNA (aDNA), and macrofossil analyses have improved the resolution of diverse organic samples, improving key archives for understanding long-term biogeographical change (Hofman et al., 2015), food web structure (Dunne et al., 2016), marine and terrestrial resource fluctuations (McKetchnie et al., 2014, Moss et al., 2016), and the long-term impacts of climate and human settlement on both individual species and whole ecosystems (Erlandson et al., 2008). Improved archaeological and palaeoecological datasets have significant relevance to contemporary researchers and resource managers who face the challenge of *shifting baselines syndrome* in which each successive generation of natural resource managers falsely identify their contemporary (and already heavily depleted) ecosystems as a pristine natural baseline (e.g., Jackson et al., 2001; Bolster et al., 2012). Identification of accurate environmental baselines has an essential relevance to major challenges of our time, including food security through overexploitation of marine and terrestrial ecosystems (Yletyinen et al., 2016), restoring biodiversity in heavily degraded environments, and the preservation of sustainable resource-use practices (Klein et al., 2007; Barthel et al., 2013). The relevance of long-term (century- to millennial-scale) perspectives offered by archaeologists and the natural sciences are recognized increasingly as key data sources for future sustainable resource use (Engelhard et al., 2015; Laparidou et al,. 2015). The authors of this article are generally operating in a time scale that encompasses the last millennium. Archaeology in the most general sense operates on two temporal scales. The last ten thousand years, meaning the period beginning with the Neolithic and the appearance of plant and animal domestication, and then the last two million years, meaning the period beginning with the emergence of our genus and the appearance of material culture. The authors belong to the first group. In each case the matching of millennial and century-scale to the lived experience of humans at the generational-scale is a central priority of archaeology.

While many archaeologists have been aware of the potential of the growing global assemblage of well-dated, well-excavated sites with comprehensive archives of ecological material since the birth of our discipline, it can be challenging to communicate this potential to scientists from other disciplines engaged in global change research or to a wider public whose perceptions of archaeology are conditioned by images of Indiana Jones and Laura Croft. A challenge for archaeologists has been to shrug-off the perception of archaeology as an antiquarian pursuit focused on collecting high-value artifacts, rather than a science-based discipline that, among other pursuits, provides unique datasets for understanding long-term human interactions with changing environments. As highlighted in Kintigh and colleagues' (2014, pp. 6) *Grand Challenges for Archaeology*, "archaeological data and interpretations have entered political and public, as well as scholarly, debates on such topics as human response to climate change, the eradication of poverty, and the effects of urbanization and globalization on humanity." Communicating the relevance of archaeological data to practitioners, such as resource managers, using deep time perspectives illustrate not only the value of establishing environmental baselines and understanding ecosystem structures, but also supply narratives spanning multiple centuries to millennia of human resource-use and adaptation (Nelson et al., 2016; Spielmann et al., 2016).

At a 2013 meeting in Paris between the interim Future Earth management team (http://www.futureearth.org) and representatives of the Integrated History and Future of People on

Earth (IHOPE) group (http://www.ihopenet.org), the IHOPE presenters (Carole Crumley, Tom McGovern, Jago Cooper, Steven Hartman, Andy Dugmore) coined the phrase 'distributed observing network of the past' (DONOP) to communicate the value of archaeological sites for global change research (GCR), and adopt a vernacular more familiar to the wider scientific community and help argue the case for better inclusion of archaeologically-derived data sets into the Future Earth agenda. The DONOP concept resonates with the description of existing instrumental observation networks that monitor the current impacts of human activities on environmental change (Hari et al., 2016; Proença et al., 2016; Theobald, 2016; Marzeion et al., 2017). For examples, the Intergovernmental Panel on Climate Change (IPCC) occupies an authoritative position monitoring the impacts of climate change on biophysical systems and human societies. The International Oceanographic Commission (IOC) of UNESCO operates a Global Ocean Observation System (GOOS) to monitor global changes to ocean temperature, its ecosystems, and human communities reliant on the resources it provides. But long-term human processes have been largely absent from many major monitoring efforts reports despite being in a position to disseminate data relevant to GCR. This paper explores the relevance of DONOP with a specific focus on work carried out in the North Atlantic region.

Archaeological sites are a core aspect of DONOP as they have the ability to both show change through time as well as reveal local and regional dynamics. Ideally, the best DONOP sites would be those that have deep temporal range and are parts of networks of sites that can cover spatial scales from the local through the regional. Given the variety of sites and projects in the Archaeological community such data can be relevant from the scale of the household (i.e. how a particular individual settlement interacted with its local environment) to regional scales of varying size. The examples offered by this article show some of the spatial and temporal range of the application of DONOP.

2. Archaeological Sites as Distributed Long-term Observing Networks of the Past

Through the analysis of archaeological datasets, we have the potential to access long-term records of human interactions with natural systems at a wide variety of temporal and spatial scales and thus both reconstruct past environmental conditions and reveal the human dimensions of these processes. There is a rich record of research into the shifting relationship between culture, climate, and landscape change using archaeological data (Brown et al., 2012; Golding et al., 2015a; McGovern et al., 2007; Simpson et al., 2001a; Streeter et al., 2012; Thomson and Simpson, 2006). This effort has intensified as the key role of people within ecological systems and the wide spectrum of natural and anthropogenic environmental change have been recognized (Crumley, 2016). Alongside this, there have been major developments in the quantity and quality of paleoclimate reconstructions at multiple temporal and spatial scales that make possible effective connections to human systems. The increasing availability of sophisticated climate data sets whose scales match those of human societies and the human experience has made a profound difference to the ways in which we can understand interactions of people and environment (Hoggarth et al., 2016). The growing recognition in the scientific, global policy, and political arenas of anthropogenic climate change and the levels of extreme disruption that this will bring to contemporary societies have served as a final, and possibly most potent, influence on current research agendas and raising new questions that can only be answered with long-term perspectives of our interactions with the natural world (Anderson et al., 2013).

The development of refined, high-precision chronologies has played a key role in the translation of DONOP into a practical and very worthwhile reality. With tight chronological controls, such as those provided by AMS radiocarbon dating using a Bayesian framework, data from multiple sites can be combined with greater confidence. Thus, the extensive spatial distribution of archaeological sites, each with variable temporal continuity, can be transformed from a perceived weakness of DONOP to a real strength. Highly detailed but temporally-inconsistent records can be combined to chart the waxing and waning interactions of people and environment. An example of this is provided by the coastal middens that record long-term human exploitation of marine ecosystems. This data illustrates the reality of 'shifting baselines' and the chronic limitations of short observational timescales in fisheries management, as discussed in Bolster's (2014) *The Mortal Sea* (see also Jackson et al., 2001). There is a clear need for the effective integration of the *longue durée* with urgent issues of fisheries and marine resource management (Moss et al., 1990; Holm, 1995; Ogilvie and Jónsdóttir, 2000; Jackson et al., 2001; Perdikaris and McGovern, 2009). A major EU-funded initiative, the *Oceans Past* program (http://www.tcd.ie/history/opp), has begun to correct the effects of shifting baselines that can result in fundamentally flawed decision making with historical and archaeological data sets (Pinnegar and Engelhard, 2008).

Archaeological DONOP are our best (and for many regions and periods of time our only realistic) source of information on the resilience of past cultures to natural hazards. Past cultures provide a vast range of human interactions with different climatic and ecological conditions (Cooper and Sheets, 2012). Contrasting outcomes illustrate the consequences of different social organizations, alternative adaptive strategies, and contrasting approaches to resource use, sustainability, and building resilience. Though the past cannot be used as a direct analogue to explain how present and future populations will deal with external environmental threats, it does offer us significant opportunities to better understand processes of social interactions with environmental change and to generate both data and new theory that can contribute to a wide spectrum of managerial issues raised by contemporary anthropogenic climate change.

Distributed long-term observing networks have been (and can be) used to emphasize the anthropogenic dimensions of data sourced from archaeological sites because the record is created by people and extracted from the lived environment (Crumley, 2015). By aggregating *in situ* evidence of human impacts on their local environments – through extirpation of local resources and engineering of cultural landscapes (Smith, 2007) – to the regional and continental scale, DONOP assimilate comparative interactions between humans and their environments with chronological controls.

Firstly, the physical assemblages have been deposited as a direct result of human actions. They will have specific biases created by diverse ways in which the environment has been sampled and contrasts that reflect the beliefs, values, and knowledge of different social groups. As such, DONOP provide comparative data reflecting different human behaviors. Secondly, DONOP data is sourced from an environmental context that has been directly impacted and in many cases directly formed through human actions. Whether the sample is from a wild species that is subject to human predation or from an ecosystem that is shaped by the interaction of human actions, ecosystem dynamics, Earth surface processes, and climate, this type of data holds information about both natural *and* human processes.

Humans selectively sample the surrounding ecology and they collect specimens (consciously and unconsciously) from across trophic webs, landscapes, and seascapes. Then, given favorable post-depositional conditions, these samples are preserved in one place – the archaeological site. Wherever (and whenever) humans and our ancestors have lived, and when conditions allow for survival and preservation, it is possible to find these sites. Some DONOP records are scattered and of limited duration but can be linked together to create a coherent regional picture of change through the rigorous application of both relative and absolute dating. If these sites accumulate long-term records they can produce very deep cultural layers and thus large accumulations of material for analysis. Very high temporal resolutions can be achieved within such contexts due to the wide range of dating methods that can be applied to both organic (e.g., dendrochronology or radiocarbon dating within a Bayesian framework) and inorganic artifacts (e.g., ceramic seriation). In turn, these datasets contain the signatures of environmental, climatic, and cultural dynamics (Figure 1). Additionally, archaeological survey and environmental analysis of landscapes dotted with small, ephemeral sites can reveal patterns in the timing and nature of past landscape occupations, ecosystem impacts and resource usage that are important for understanding complex processes such as colonization, adaptation and abandonment (e.g., Altschul and Rankin 2008) and engaging with other *grand challenge* agendas for research that have relevance for contemporary debates (Kintigh et al., 2014; Jackson et al., in review). All of these optimal conditions are dependent on a wide set of variables that span from the effectiveness

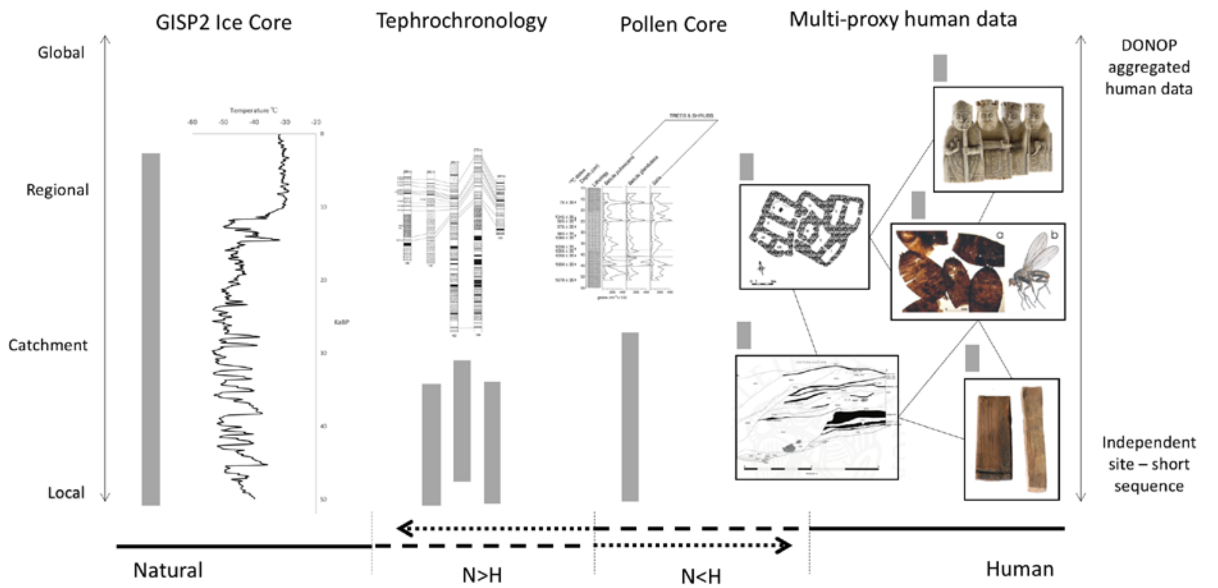

Figure 1- Observation records of natural and human processes in the past. DONOP is the aggregation of short sequences within the archaeological and environmental record to build a multidimensional record of human-environmental interaction and modification. Greenland Ice Sheet Project 2 (GISP2) data provides a local-to-regional scale proxy record of climate, storm and sea ice conditions, but provides no direct evidence of influence on human processes in the past (Dugmore et al., 2007). In regions with significant volcanic activity, such as Iceland, human impact on the environment and vegetation change can be measured using the tephra profile as a chronological control (Streeter and Dugmore, 2013). At the individual settlement scale, excavation data (for example: diet, artifacts, and architecture) can be aggregated to form regional and even continental-scale networks of subsistence, trade, and environmental modification.

of the excavation strategy and methods, the local environmental conditions and the potential for organic remains to survive in situ until excavation, and the availability of continuous and deep chronological control. Yet such assemblages do exist and their number and spatial and temporal resolution are increasing.

There is a growing body of work focusing on archaeological data as a proxy for the complex relationships between cause, response, and outcome in human ecodynamics (Hegmon et al., 2008; Dugmore et al., 2013; Vésteinsson et al., 2014; Boivin et al., 2016; d'Alpoim Guedes et al., 2016). DONOP provide detailed records of these completed long-term human ecodynamics experiments of the past and the range of outcomes stemming from different pathways taken by past cultures in the face of environmental change (Diamond and Robinson, 2010; Hegmon et al., 2014). They can serve as examples of alternative choices and the pathways they create, and these case studies can be used to assess contemporary ideas of how to build resilience and reduce vulnerability in the face of both environmental and social stresses. They can provide both inspiration and warnings.

The ideal of deep temporal and broad spatial data that is at the core of DONOP aligns it, and reveals a debt to, attempts to conceptually break down the borders between the ideas of nature and culture (Chakrabarty, 2009). For example the concepts of coupled natural and human systems (CNH) and socio-environmental systems (SES) both inspire much of the following scholarship (Zeder et al., 2014). When examined over the longue durée, the myriad interconnections between human and natural systems becomes clearer and the idea of static and pristine ecosystems that host humans but that see no anthropogenic impact becomes much harder to support. The history of the impact of humans, and other organisms, on landscapes continues to be pushed deeper in time through archaeological work. The dynamics behind these impacts is being revealed as more nuanced and increasingly complex. Niche Construction Theory is perhaps the best expression of these relationships and is relevant to all the projects presented in this article (Boivin et al., 2016; Sullivan et al., 2017; Zeder, 2016).

The utility of DONOP sites and the data they contain for contemporary global change research can be explored from three perspectives: those that are 1) concerned with human behaviors, 2) related to shifting baselines, and 3) addressing biology. The *behavioral perspective* examines human action within intertwined social and natural systems. The *shifting baselines perspective* emphasizes the contrasting implications of baseline data for species, landforms, and ecology set before industrial expansion, commercial-scale resource exploitation, the ‘great acceleration' and other trends representing significant human impacts on their environments – all in stark contrast to the typical temporally shallow modern data currently in use (Pinnegar and Engelhard, 2008; Steffen et al., 2015a, 2015b). Finally, the *biology perspective* seeks to understand and utilize past diversity (i.e., trophic and/or genetic) as recovered through archaeological remains in order to develop tools and datasets that can be used to better manage contemporary wild and domestic animal populations (Hofman et al., 2015; Boivin et al., 2016; Zeder, 2015, 2016).

In the following section, we evaluate archaeological sites as DONOP within the conceptual frameworks of human behavior, shifting baselines, and biological systems. We argue that archaeological sites contain valuable, and at times unique, data that have the potential to provide solutions to problems in the present and future. For this reason, there is a need to view and value archaeological sites as 'observable networks' that capture the resourcefulness of the past for understanding the impacts of human populations on their environments, establish accurate environmental baselines, and learn from human adaptation to climate change over century-to-millennial timescales. Furthermore, given the current and increasing threats to archaeological sites from anthropogenic climate change, there is a pressing need to act quickly and decisively to collect critical archives before they are lost forever (Dawson, 2015; Hambrecht and Rockman, 2017).

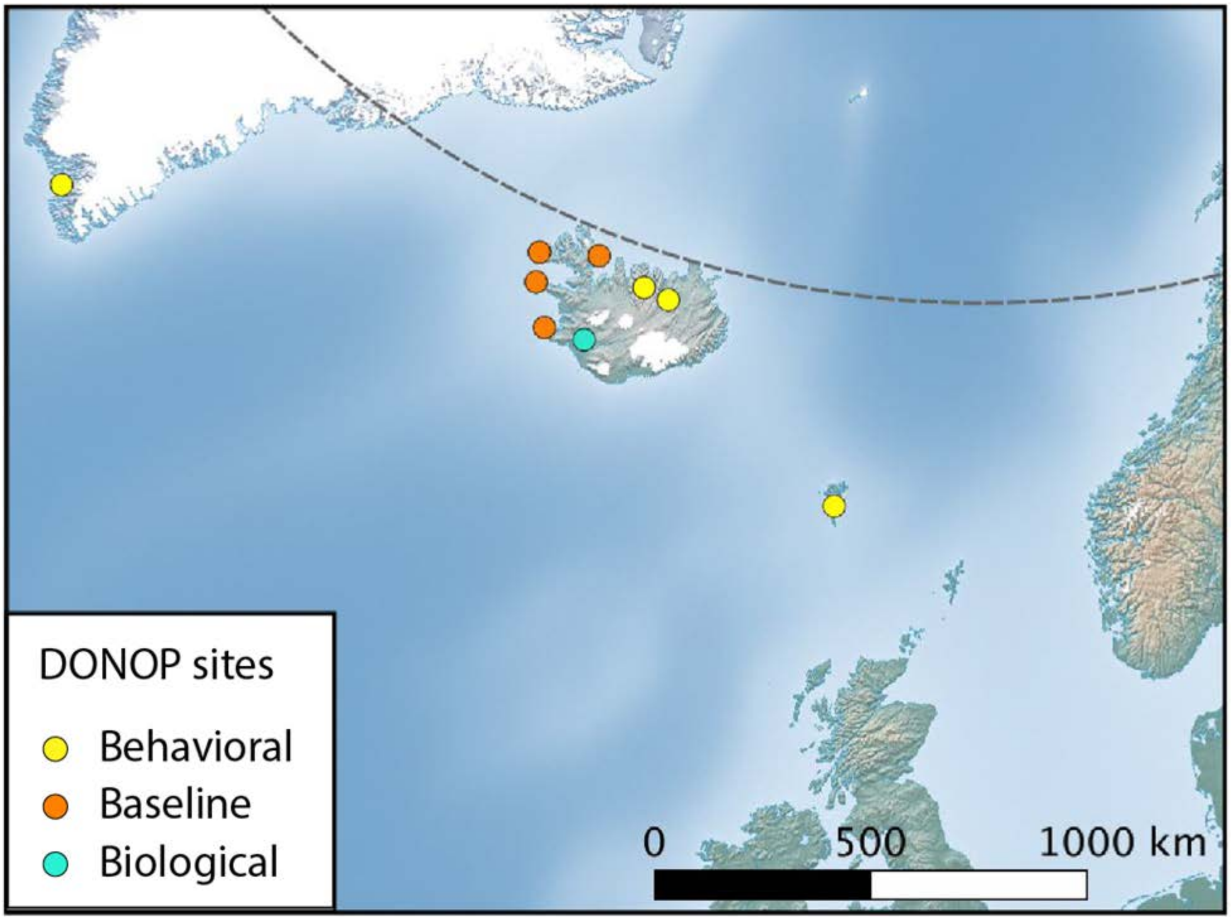

Figure 2. A map of the eastern North Atlantic region showing the locations of sites in the Faroe Islands, Iceland, and Greenland that are discussed in this article.

2.1 Human Behavior and DONOP

Over the last thirty years, research in the North Atlantic by the North Atlantic Biocultural Organization (NABO, http://www.nabohome.org) has, in part, been focused on comparing datasets from separate geographical areas towards understanding the contrasting fates of Norse medieval communities in the Faroe Islands, Iceland, and Norse Greenland (Figure 2; see Nelson et al., 2016). These settlements were established by Scandinavians over several centuries, starting with: the Faroes (ca. 860 CE), Iceland (ca. 870 CE), and Greenland (ca. 985 CE). These three areas were settled by people of a shared cultural and biological heritage (Jesch, 2015). Yet the paths chosen by these communities and their long-term fates contrast starkly. The Faroes survived centuries of relative economic isolation, limited natural resources, and numerous socio-political challenges, enduring to this day as a small but resilient nation (Brewington, 2015). Despite environmental, economic, and epidemiological challenges, Iceland was able to transform its economy, and has since become a highly-developed society with among the highest living standards and health care in the world (Karlsson, 2000). The Norse settlement in Greenland, by contrast, came to an end in the late fifteenth century. The contrasting fates of Iceland and Greenland have come to be discussed in popular discourses around ideas of 'collapse' (Diamond, 2005) and remain active subjects for international interdisciplinary research (Dugmore et al., 2012, 2013; Streeter et al., 2012; Nelson et al., 2016).

Viewing these cases through the lens of DONOP distills the research down to a series of narratives that have important implications for current debates. First, the simple 'collapse' narrative of why societies choose to fail through maladaptation is too simplistic and actively misleading for these cases (Dugmore et al., 2009, 2012). DONOP-based long-term perspectives of the Scandinavian communities of the Atlantic islands in general, and Iceland and Greenland in particular, provide specific examples of human behavior that was environmentally-nuanced, adaptive, and sustainable over multi-century time scales. This creates a picture that is far more disturbing than the simple collapse thesis because it shows that societies may undertake entirely rational, adaptive strategies in the face of unprecedented challenges and yet still undergo painful transformational changes (Butzer, 2012; Dugmore et al., 2012).

The example of Norse Greenland, which has often been used as a parable of human inaction in the face of increasingly hazardous climates to the point of self-extinction, offers a complex and bleak message (Diamond, 2005). A combination of new data acquisitions, reinterpretation of established knowledge, and a somewhat different philosophical approach to the question of collapse has revealed a society that was, in fact, flexible and adaptive in the face of changing climates (Dugmore et al., 2012). Within the first generation of settlement in the late tenth and early eleventh centuries CE, the Norse Greenlanders adjusted their diet to fit the seasonal availability of local resources: fishing ceased and the large-scale exploitation of migrating seals began (Ogilvie et al., 2009; Arneborg et al., 2012). The Norse went on to create an effective economic network for communal provisioning and international trade (i.e., walrus ivory). Provisioning networks consisted of imported domesticated species (sheep, goats, cattle, horses, and pigs) supplemented with a broad set of wild resources (seals, caribou, seabirds, small mammals, and some berries and herbs). Zooarchaeological and stable isotope data from DONOP show that native caribou and non-migratory seal populations were managed sustainably over multiple centuries (Arneborg et al., 2012; Dugmore et al., 2012; Ascough et al., 2014) . Organization of economic networks emerged from the twelfth century, integrating domestic subsistence systems with wild resource cycles, such as the spring harp seal migration, late-summer bird collections, and walrus hunting (Ogilvie et al., 2009; Frei et al., 2015). In the mid-to-late thirteenth century, further adjustment of lifeways and diet towards a deeper exploitation of marine mammals in response to unprecedented climate change can be seen in the zooarchaeological record as well as in stable isotope analysis of human burials (Arneborg et al., 2012). The poignant and rather grim conclusion to this is that even with adaptive flexibility and, in some cases, sustainable management systems, the Scandinavian settlement of Greenland still failed. This was not a collapse due to simple maladaptation but change driven by a variety of factors: spatial, climatic, demographic, social, political, and economic (Dugmore et al., 2012). While a full explanation of the current understanding of the nature of the

Greenland Norse collapse is outside of the remit of this article, a recent assessment of the North Atlantic by Nelson and colleagues (2016) offers a good summary of current research.

On a more successful note, DONOP records of archaeofauna from the Mývatn region in the north of Iceland documents a millennial-scale case of successful, community-level management of migratory waterfowl beginning at first settlement (*Landnám*) and continuing to the present day (McGovern et al., 2006; Hicks et al., 2016). Today, there is an annual collection of eggs from nesting migratory waterfowl that does not adversely impact these species (Guðmundsson, 1979). Nesting waterfowl are monitored and protected; only a few eggs per nest are taken and adults are rarely hunted (Beck, 2013). Looking further back in time, the restricted collection of waterfowl eggs is documented in mid-nineteenth century written records, such as diaries, journals, and visitors accounts. Using DONOP we can create even longer time perspectives; some terrestrial (non-waterfowl) bird hunting has happened alongside waterfowl conservation and egg utilization since the Viking age; archaeofaunal assemblages are rich in waterfowl eggshells while bones were mostly from ptarmigan (grouse), a non-aquatic terrestrial species (McGovern et al., 2006, 2007). This suggests that a community-level avian management system produced a valuable crop of eggs while maintaining adult waterfowl populations. This management strategy was not only useful in conserving waterfowl populations over the long term: there is also historical and archaeological evidence that careful use of wild resources helped Mývatn inhabitants buffer themselves against starvation during hard times caused by climate change (McGovern et al., 2013).

Successful long-term resource management is also evident from DONOP records in the Faroe Islands, where zooarchaeological (Brewington and McGovern, 2008; Brewington, 2011, 2014) and documentary (Baldwin 1994, 2005) evidence suggests that local seabird colonies have been sustainably exploited for over a millennium. As in Mývatn, fowling in the Faroes has long been carefully controlled by local communities (Nørrevang, 1986; Baldwin, 2005). This community-level management regime employs a sophisticated body of local ecological knowledge to gauge the relative vulnerability of individual bird species and nesting areas on a year-by-year basis. Faroese resource managers (traditionally, landowners) are thus able to determine sustainable harvest limits for birds and eggs each season (Williamson, 1970, pp. 153–156; Nørrevang, 1986). Also of critical importance for the success of the system has been the ability to effectively monitor and manage nesting sites, protecting this sensitive resource both from overexploitation by people and from destructive domesticates such as pigs (Brewington et al., 2015).

In terms of behavior, DONOP from the North Atlantic can be used to draw two key lessons relevant to the present and future: sustainable millennial-scale management of natural resources is an attainable goal and adaptability in the short- or even medium-term is no guarantee of long-term survival.

2.2 Shifting Baselines and DONOP

Shifting baseline syndrome is a concept that describes situations in which communities formulate natural resource management decisions on ideas about primal or pristine natural resource populations that are inaccurate (Pauly, 1995; Pinnegar and Engelhard, 2008). Given that decisions about the management of natural resources can often be based on a 'baseline' standard that is constructed around an idea of a minimally exploited population, then the assumptions behind this baseline are very important. This can be a problem in conservation and resource management if the baselines used to define sustainable exploitation of populations are based on inaccurate, misleading data such as that from flawed human memory or temporally shallow data sets (Papworth et al., 2009). Recent discussions of fishery management in the North Atlantic have a distinct relevance to DONOP. The problem centers on what datasets people are using to define a sustainable fish population. Pauly (1995) and others have described a phenomenon where fishermen and fisheries managers use a combination of their own memory of the early days of their fishing careers and catch data with a shallow time depth as baselines for what a sustainable fish population should be. This concern runs deeper into environmental movements, the media, and scientific works about rewilding (Monbiot, 2013). A specific example of this is described by Bolster and colleagues (2012) in which they argue that the North Atlantic fisheries, especially cod fisheries, have seen significant human impacts on fish populations from at least the early nineteenth century. Yet consistent catch data on North Atlantic Cod (*Gadus morhua*) in the North Atlantic has only been consistently collected since the beginning of the twentieth century (Bolster et al., 2012). Thus, many of the assumptions about what baseline cod populations and catch levels should be are based on populations that were already significantly impacted by human exploitation. This situation can lead to a misperception of the level of human impacts on a natural resource that can lead to much higher levels of stress on these populations than anticipated. Zooarchaeology (the analysis of animal remains sourced from archaeological sites) can help clarify if this is in fact a problem, especially when it utilizes recent advances in the analysis of aDNA and stable isotopes of animal remains. Though there has been significant and innovative research on shifting baselines in the North Atlantic that focuses on past ecological conditions and past landforms, this article, in the interest of brevity, will discuss examples that are addressing the species level of analysis (i.e., Dugmore et al., 2000; Simpson et al., 2001; Dugmore and Newton, 2012; Streeter and Dugmore, 2013, 2014; Golding et al., 2015).

In 2012, Atlantic cod (*Gadus morhua*) was ranked by the Food and Agriculture Organization of the Union Nations (2014) as the 11th-most fished species in the world. In addition to being an important contemporary marine resource, this species was also crucial in both the medieval and early modern European colonial expansions. It was, and continues to be, a key species for both subsistence and the economic well-being of communities across the Atlantic from Maine to Norway.

The DONOP data represented by fish bones found in middens (refuse deposits from which archaeologists often excavate organic remains) across the North Atlantic region have long been of interest to zooarchaeologists focusing on the origins of the trade in dried cod and the onset of intensified non-subsistence fishing in North West Europe (Barrett et al., 2004). Zooarchaeological analysis charting the changing patterns of fish utilization has produced data crucial to understanding Atlantic cod's transformation from a subsistence good to an internationally traded commodity (Perdikaris, 1999; Perdikaris et al., 2007). Stable isotope analysis of fish bones is now revealing what regional populations of Atlantic cod are represented in the archaeological record (Orton et al., 2014).

CodStory is a current project that examines demographic and ecological data of Atlantic cod derived from archaeological excavations of DONOP fishing sites (Ólafsdóttir et al., 2014). In 2011, a pilot project began to investigate the feasibility of using Atlantic cod vertebrae to examine the historical genetic structure of Atlantic cod populations, and showed that this work is both feasible and rewarding. DNA was successfully extracted from fish bones and the cytochrome B gene sequenced from a time series of zooarchaeological samples in western Iceland dated from 1500-1910 CE. Further analysis of the genetic variation indicates a sharp decline in effective population size of Atlantic cod in the fifteenth century, and further population size fluctuations coinciding with recorded temperature changes (Ólafsdóttir et al., 2014). Although the concomitant loss of genetic variation in the sixteenth century does suggest a severe bottleneck, estimates of the genetic structure of Atlantic cod may be complicated by shifts in population structure distribution and changes in feeding migrations that occur as the cod seek favorable temperatures and feeding grounds because the Icelandic cod stock comprises both migratory and coastal elements (Hovgård and Buch, 1990; Rose, 1993; Vilhjálmsson, 1997; Pampoulie et al., 2006). To test these ideas, the *CodStory* project has continued by producing higher resolution genetic data, stable isotopes assays, and shape analysis and growth reconstruction based on otolith increments. The otolith analysis indicates a shift in the abundance of migratory and coastal Atlantic cod populations in the historical catch and suggests that growth conditions for the two Atlantic cod ecotypes changed in the early modern period (Ólafsdóttir et al. 2017). Together, these results signal a disruption in the North Atlantic marine ecosystem coinciding with a temperature minimum in the North Atlantic. Using archaeological samples, the *CodStory* project is generating paleodemographic data on one of the most important maritime resources of the North Atlantic while also investigating the effects of changing climate on these fish populations at a high temporal resolution.

It is also possible to use DONOP archaeological data coupled with aDNA analysis to understand the distribution of marine mammal populations before the commercial and industrial exploitation of the Arctic oceans with potentially major implications for historical biogeography, modern conservation biology, and marine management. A pilot project, completed in 2014, included 35 presumed marine mammal specimens from archaeological sites in Iceland, Greenland, and the Faroes; six samples gave positive results for aDNA. Four specimens were identified to the species level, including one blue whale (*Balaenoptera musculus*, AK-CESP-001), two fin whales (*Balaenoptera physalis*, UJF-CESP-003 and HRH-CESP-002) and one harbour porpoise

(*Phocoena phocoena*, SGN.103-CESP-507). Two additional specimens (UJF-CESP-001 and UJF-CESP-008) were identified as being species of right whales, but were not isolated to unique species beyond *Eubalena* spp. In order to further test how universal the primers were, DNA extracted from a 13,000 year old bowhead whale bone was included, and two samples from the Swedish Museum of Natural History, one bone sample previously identified as being a humpback whale and a sample from a sperm whale tooth. The primers managed to amplify DNA confirming the species (Anderung et al., 2014). The successful results of this pilot project mean that marine mammal bone from DONOP sites, which can be difficult for zooarchaeologists to identify morphologically, can now be identified, providing a window into species distributions in past seascapes. Future work will also use methods such as protein analysis, ZooMS, which is proving to be cheaper and often more useful under a variety of different taphonomic circumstances than aDNA analysis (Buckley, 2018).

Due in part to the success of this pilot project, a three year NSF-funded project (*Assessing the Distribution and Variability of Marine Mammals through Archaeology, Ancient DNA, and History in the North Atlantic* – NSF award #1503714 – PI Dr. Vicki Szabo) commenced in 2016. This has explanded analysis to approximately 300 archaeological samples of whale, seal, and walrus bones across the Norse North Atlantic. Species-level identification of DONOP archaeological material will allow deeper historical access into the premodern Arctic, Subarctic, and North Atlantic societies' impacts on marine mammals, adding to recent groundbreaking studies of pre-modern North Atlantic walrus exploitation and biogeographies (McLeod et al., 2014; Frei et al., 2015). Norse economies, hunting or scavenging strategies, commercial uses of marine mammals, and subsistence will be reassessed. aDNA analysis will allow insights into genetic diversity and drift, possibly paleodemographic data, identification of now-lost or endangered species in certain regions, and provide historical depth to the management of species under threat today.

These projects are pushing baseline data of key natural species back into the last millennium. In both cases they are focusing on species that have seen predation by humans, at varying levels of intensity since the Neolithic period. Each one is focusing on the medieval to early modern transition and attempting to build demographic data that could radically alter current ideas of what a ‘normal’ or sustainable population is and of the historical spatial ranges of these species.

2.3 Biological Records and DONOP

Analysis of aDNA has revolutionized our understanding of the history of our species as well as that of our commensals and domesticates (Magee et al., 2014; Orlando, 2015; Scheu et al., 2015; Zeder, 2015). aDNA analysis from DONOP sites can also directly contribute to understanding the results of modern day breeding programs; revealing vulnerabilities and suggesting improvements (Fahrenkrug et al., 2010). Finally, aDNA, with the advent of gene editing technology, has the potential to become a source for past genetic variation that could be reintroduced into modern domestic animal populations, allowing us to restore some of the variability lost to modern industrial breeding programs.

A collaboration between the University of Maryland Zooarchaeology Laboratory, Recombinetics LLC, and the aDNA Laboratory of the Catholic University of the Sacred Heart in Piacenza, Italy is aligning the interests of the historical sciences with those of present-day animal sciences. This project is beginning with an initial investigation focusing on aDNA analysis of cattle bones from archaeological sites in Iceland. This will produce DNA sequence-based data that sheds light on the interactions between humans, domestic animals, and a variety of exogenous forces such as climate change, epidemics, trade, and ideology. In addition, the sequence data provides an orthogonal element to the genetic record of livestock that shed insight into decoding the genomes of contemporary domestic animals. The discovery of unique genetic variation from the past could, for example, represent lost genetic variants effecting a wide spectrum of phenotypes. Bioinformatic analyses will attempt to isolate unique genetic variants underlying specific traits in pre-modern domestic animals that could be introduced back into current domestic animal populations using genome editing technology. This project will attempt to mine the genetic heritage of domestic animals that can be found within the faunal component of archaeological sites to create resources that increase the resilience or reproductive capacity of current populations of domestic animals. Given the stresses and hazards that anthropogenic climate change will generate, this project is also attempting to utilize historical data as a tangible resource for mitigation and adaptation to climate change threats and the improvement of animal well-being. The sequence data and results from subsequent analyses that includes information from the archaeological long-term observational networks will form the basis for direct and tangible resources for mitigating against climate change threats to food animal production while also producing key data for understanding the dynamics between social and ecological systems.

This is, of course, a 'brave new world' for the potential uses of historical genetic material. The most dramatic and potentially visible impacts that aDNA could have in the near future are best demonstrated in the projects that are investigating the possibility of reviving extinct species (Charo and Greely, 2015; Diehm, 2015; Edwards, 2015; Shapiro, 2015; Weaver, 2015). Such projects could not be possible without access to genetic material from either museum or archaeological specimens. A vigorous debate is developing around the ethical and practical ramifications of such approaches (Kristensen et al., 2015; Martinelli et al., 2014; Oksanen, 2008; Oksanen and Siipi, 2014; Siipi, 2016). Yet what can be said without debate at this point is that developing biotechnologies focusing on editing genomes will have a profound impact on the way historical genetic material is perceived and utilized.

3. Discussion

The article presents just a few of the projects that illustrate how data from archaeological sites can be mobilized for application to contemporary problems. This idea is at the core of the concept of DONOP. Indeed, an important difference in perspective between traditional archaeological research focused on the interpretation of specific sites and the DONOP concept is the selective use of records from archaeological contexts to tackle specific ‘grand challenge’ research agendas of demonstrable importance beyond narrow disciplinary confines (Kintigh et al., 2014; Armstrong et al., 2017; Jackson et al., in review). They represent research projects that could form key contributors from the historical sciences towards navigating the future challenges of global change. Cooperative scholarly organizations such as IHOPE are driving efforts to increase engagement with GCR, while governmental and non-governmental organizations have recognized the potential of archaeological data, and threats to cultural heritage arising from anthropogenic climate change.

The archive of DONOP sites and the behavioral, baseline, and biological data they contain is unique. Yet this archive is threatened with destruction by the very global changes it records; this is a modern equivalent to the burning Library of Alexandria. The rate of damage to archaeological remains is continuing to accelerate as ground temperatures, moisture regimes, and erosion patterns change (Rockman, 2015; Hollesen et al., 2016; Hambrecht and Rockman, 2017; Hollesen et al., 2017). Without the mobilization of substantial international resources to recognize, manage, and when needed, rescue these endangered archaeological archives, irreplaceable records will be lost. DONOP sites are important not just because of the inherent value of our shared human historical inheritance but also as a direct cultural archive of social-ecological interaction over the *longue durée*.

Recognition of the importance and utility of DONOP has grown beyond direct practitioners. The US National Park Service has taken the lead within the US government, setting out federal policy and strategic guidance on the importance of addressing impacts of climate change on cultural heritage (including archaeology) and using cultural heritage to inform both research and the management of climate science, adaptation, mitigation, and communication policies (National Park Service, 2014; Rockman, 2015; Rockman et al., 2017). In this approach, it is recognized that cultural heritage is both affected by climate change and is a source of data on how to address climate change (Harvey and Perry, 2015).

There are many other international, national, and local efforts addressing the interaction of climate change with cultural heritage but there is a danger that a piecemeal approach will not be the most effective. A global response to threatened archaeological sites focused on their utility as DONOP is likely to produce the most effective global outcomes. International funding organizations such as the US National Science Foundation, the Belmont Forum, the EU Science Commission, and Future Earth have the potential to create funding streams that are focused on utilizing the past to better understand the present and navigate the future (Costanza et al., 2007, 2012). Many archaeological sites, especially in coastal, montane, and polar regions, are now at critical risk of loss to climate change. Saving all threatened sites will not be possible. Many will be irrevocably lost over the next century due to the impacts of climate change. Guided by a series of focused research questions, it is essential that archaeologists identify, excavate, or at least sample ‘at risk’ sites and, where possible, protect key archives under threat (Van de Noort, 2013). The issue is no longer one of just preserving archaeological sites so that they survive for future generations, though that is important on its own terms. It is now an issue of protecting and/or rescuing key data sources that will help us better face the future. On a local and regional scale, past societies have experienced global changes that have dramatically altered the structure of their spatially-limited worlds; the scale of future change is such that it is likely to have unknown impacts on contemporary societies and their cultural, social, environmental, and economic capital. Archaeological sites and heritage in general should be redefined to include their utility towards addressing and recording anthropogenic global change. Funding organizations and governments are recognizing the importance of archaeological data, but more needs to be done to encourage engagement between archaeologists, GCR, and practitioners.

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