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Special Issue Reprint

The Archaeology of Climate Change

Edited by
Sharon R. Steadman and John Frederick Haldon

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The Archaeology of Climate Change

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Guest Editors

Sharon R. Steadman
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Cover image courtesy of Sharon Steadman
The plain around the archaeological site of Çadır Höyük, Yozgat province, Türkiye

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Contents

About the Editors . . . . . **vii**

Sharon Steadman and John Haldon
The Archaeology of Climate Change: Perspectives and Challenges
Reprinted from: *Heritage* **2026**, *9*, 251, https://doi.org/10.3390/heritage9070251 . . . . . **1**

Lee Clare
Göbeklitepe in Palaeoclimate Context: Human Responses to Climate Change in the Upper Tigris and Euphrates Basins from the Younger Dryas to the Early Holocene
Reprinted from: *Heritage* **2026**, *9*, 179, https://doi.org/10.3390/heritage9050179 . . . . . **6**

Sharon R. Steadman, Jennifer C. Ross, Marica Cassis, Anthony J. Lauricella, Emrah Dinç and Laurel D. Hackley
Empty Shelves: Tracking the Flow of Goods During Ancient Climate Crises in Central Anatolia
Reprinted from: *Heritage* **2025**, *8*, 354, https://doi.org/10.3390/heritage8090354 . . . . . **33**

Julia M. Koch
Palaeoclimate Change in the Southern Black Sea Region and Its Impact on the Fate of Rome—From Megadrought to Collapse of Rome's ›Polis Command Economy‹
Reprinted from: *Heritage* **2025**, *8*, 160, https://doi.org/10.3390/heritage8050160 . . . . . **67**

John Haldon
Coincidence and Complexity: Complex Interaction of Society, Environment, and Conjuncture in the Eastern Roman World ca. 500–1100 CE †
Reprinted from: *Heritage* **2025**, *8*, 235, https://doi.org/10.3390/heritage8060235 . . . . . **89**

Arlene M. Rosen, Julia Clarke, James Eighmey, Jennifer Farquhar, Dalantai Sarantuya and Tserendagva Yadmaa
Neolithic Bird Folk of the Mongolian Gobi Desert: Climate Change, Ecological Knowledge and Intangible Heritage in an Ancient Persistent Place
Reprinted from: *Heritage* **2025**, *8*, 433, https://doi.org/10.3390/heritage8100433 . . . . . **116**

Joseph G. Manning
The Nile and Climate History, 3000 BCE to 30 BCE
Reprinted from: *Heritage* **2025**, *8*, 509, https://doi.org/10.3390/heritage8120509 . . . . . **137**

Hollis K. Miller and Ben Fitzhugh
The Little Ice Age and Colonialism: An Analysis of Co-Crises for Coastal Alaska Native Communities in the 18th and 19th Centuries
Reprinted from: *Heritage* **2025**, *8*, 499, https://doi.org/10.3390/heritage8120499 . . . . . **162**

Catherine Kearns
Everyday Climates: Household Archaeologies and the Politics of Scale
Reprinted from: *Heritage* **2025**, *8*, 227, https://doi.org/10.3390/heritage8060227 . . . . . **184**

Sturt W. Manning
Climate and the Ancient World: Beyond Present Concerns to Complications, Where Details Matter
Reprinted from: *Heritage* **2025**, *8*, 168, https://doi.org/10.3390/heritage8050168 . . . . . **204**

James Newhard, Tingting Tong, Antonia Lombardi, Haley Bryan, Kelsey Campbell, Emma Jansen and Matthew Titzler
A Cross-Comparative Framework to Explore Land Use Histories of the Northeastern Peloponnese, Greece
Reprinted from: *Heritage* **2025**, *8*, 298, https://doi.org/10.3390/heritage8080298 . . . . . **226**

Jacob C. Damm
Risk, Uncertainty, and Resiliency in the Face of Ancient Climate Change: The Case for Legumes
Reprinted from: *Heritage* **2025**, *8*, 252, https://doi.org/10.3390/heritage8070252 . . . . . **252**

Rowan Jackson and Andrew Dugmore
Interpreting Collapse in Norse Greenland: Why Similar Data Produces Different Conclusions
Reprinted from: *Heritage* **2025**, *8*, 293, https://doi.org/10.3390/heritage8080293 . . . . . **265**

Yitzchak Jaffe, Andrew Womack and Anke Hein
The Evolving Landscape of Inquiry: Climate's Growing Importance in Reconstructing Ancient China
Reprinted from: *Heritage* **2025**, *8*, 125, https://doi.org/10.3390/heritage8040125 . . . . . **286**

Paul J. Lane, Freda Nkirote M'Mbogori, Hasan Wako Godana, Margaret Wairimu Kuria, John Kanyingi, Katelo Abduba and Ali Adan Mohamed
Climates of Change in Northern Kenya and Southern Ethiopia: From Scientific Data to Applied Knowledge
Reprinted from: *Heritage* **2025**, *8*, 352, https://doi.org/10.3390/heritage8090352 . . . . . **299**

About the Editors

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Editorial

The Archaeology of Climate Change: Perspectives and Challenges

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The archaeology of climate change and environmental archaeology—each of which, in many respects, embraces the other—reflect our own times as much as they reflect both scientific advances and intellectual curiosity [1]. Over the course of the last two to three decades, archaeological research and interpretation has become increasingly integrated into a broader group of natural as well as social scientific disciplines, many of which are designed to address the ways in which shifts in climate conditions have impacted human societies in the past and with what effects and outcomes. Historians similarly have begun, somewhat more recently, to join these efforts and use historical archives in combination with data from other disciplines to think about how climate change has impacted past societies, state systems, and social, cultural, and economic relationships and processes. This has not been an easy path nor was the outcome we see today predictable, with respect to transdisciplinary research and research funding. Research frameworks that integrate environmental and human systems have become the norm. Human interventions in landscape evolution are better understood, and differences in scale with respect to chronology across the various contributing sciences are recognised as significant aspects in interpretating both longer- and shorter-term socio-ecological dynamics. While an overly simplistic opposition between "external" and "internal" causal relationships has been largely abandoned, as concepts such as "socio-ecology" indicate, the interaction between human systems and the environment is seen as dialectical rather than simply two-directional. Much of the debate surrounding this topic will be familiar to most readers of this volume, and we do not need to repeat what is already either well-known or easily accessible in the literature [2–6].

Clearly, there now exists a widespread and actionable consensus to the effect that an approach which balances agency, structure, context, and cultural dynamics is the most productive way forward within archaeology and that scientists and archaeologists/historians need to work collaboratively and in an integrated way to make sense of past societal evolution [7–9]. As the title of a recent article expressed, the archaeology of climate change is "a blueprint for integrating environmental and cultural systems" [10]. Integrating climate and palaeoecological science with archaeological and historical data has signficantly enhanced our ability to understand how past human societies responded to challenges instigated by shifts in their environmental and climatic conditions of existence. This permits the application of mass quantitative data analysis to isolate long-term evolutionary responses in human populations to significant shifts in their environment and climate, e.g., [11,12]. Computational modelling has been a major contributor in this respect, allowing for a more refined approach to analysing correlations between archaeologically indicated changes in social–ecological systems (embracing demographics, land use, and settlement distribution and density, for example) and in climate. Simultaneously, such

computational archaeological approaches make it possible to model the impacts of a range of climatic or ecological phenomena on human systems at different scales and to test hypotheses about societal responses [13]. Clare's contribution to this collection, which examines the impact of rapid climate change through the framework of the adaptive cycle model and vulnerability studies and highlights the potential impacts and influence of climate change and climate instability on early agricultural communities, illustrates some of the potential of this. The availability of high-resolution reconstructions of past climatic and ecological/environmental conditions permits a more granular understanding of premodern socio-ecological systems and of societal transformations at the highly local scale of an individual settlement and its evolution over decades, centuries, and sometimes millennia [14], as can be seen in the chapters by Koch, Haldon, and Steadman et al. It also provides better insight into how, in what forms, and at what levels a society demonstrated resilience or fragility, asking questions about which elements of a cultural system bore the costs of resilience, the extent to which a system was able to maintain a sustainable local ecosystem, and what threats to this may have existed, as well as how such threats may have been realised, mitigated, or obviated at different scales of societal life—and, as the chapters by Kearns and Rosen in this volume show—the awareness of scale and an appreciation of the causal role of culturally determined agency, belief, and social praxis are especially important in efforts to understand these aspects.

However, many challenges remain, most obviously that of determining what were the causal mechanisms underlying the relationship between society, climate, and environment, a key aspect in S. Manning's discussion but present in several of the contributions in this collection. Monocausal explanations still appear from time to time, but it is increasingly accepted that significant socio-ecological transformations were the product of multiple factors that combined and recombined in different ways and contributed to both systemic continuity and discontinuity or system collapse. Complex adaptive systems thinking, evolved first in ecological science and increasingly adopted in the social sciences, offers a valuable practical framework for thinking about the dialectics of multicausal relationships. In conjunction with the explanatory framework provided in resilience–theoretical approaches, this further enhances the potential for identifying cross-scalar connections and the forms through which socio-ecological systems respond to tipping points—as in the contribution by Newhard et al. This includes methods for evaluating the adaptive capacity of human systems, for example, by simulating the effects of changing decision rules about land use, crops grown, reproduction, or mobility in response to environmental change. In a crucial intervention, Jacob Damm's chapter in this volume examines in detail the specific ways though which archaeobotanical data—in this case, from legumes—provide a valuable means of approaching regional and local impacts of climate change through a close investigation of the agricultural strategies employed to mitigate risk and/or uncertainty. Coupled with the potential offered by creating a computational model of past climatic conditions and their impacts on societies and their responses, both extremely long as well as relatively short timescales can be analysed by integrating many types of data. Integrating instrumental, palaeoenvironmental, archaeological, archaeobotanical, archaeozoological, and documentary data permits the construction of "socio-ecological profiles" [15–17]. Through these, path dependencies and processes can be identified through which the competitive selection of social practices [18] leads to socio-cultural success as well as to maladaptations [19], as the chapter by Dugmore and Jackson in this volume illustrates using a different perspective. We can thus build causal complexity into our understanding of transformations in practice and deepen our socio-ecological and holistic understanding of cause-and-effect relationships.

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Archaeological evidence contributes not only to studying the past in its own right but has also increasingly been called upon to inform contemporary debates about environmental policy and questions of ecological as well as societal sustainability [20–25], points illustrated in the chapters by Lane et al. and Miller and Fitzhugh, for example. As the chapter by Jaffé et al. shows, this debate also overlaps into examinations of political evolution and contemporary political–cultural identities, with implications for national education policy, conservation, and heritage management. Archaeological models can be deployed predictively to consider climate change impacts on contemporary societies in the long term [26,27]. Humans have been an integral element in ecosystems worldwide since the early Holocene (ca. 9000–7000 BCE); as such, much of environmental history is also cultural history [28], and long before the Common Era, most ecosystems owed their particular characteristics to centuries of human activity. While premodern cultures learned how to manage the landscapes they inhabited, they could still face problems of over-exploitation, surface erosion, and deforestation [29], and anthropogenic environmental damage could be a significant problem [30,31]. Nevertheless, there is no doubt that premodern societies or cultural systems, as with contemporary societies, generally understood the need to maintain the resources to sustain their livelihoods at an appropriate level and to protect those resources from depletion, although they would rarely have expressed it in such terms. Humans, in general terms, have proven to be uniquely adapted to coping with climate variability [32–37]. We have possessed many ways of combating predictable or potential climatic events, such as unusually severe seasonal weather, flooding, and drought, and we have evolved a range of responses to deal with or mitigate threats to agriculture, settlements, and administrative infrastructure. Many cultures maintained a sustainable existence not just across several centuries but millennia [38–40]. Because we can reveal some of the ways in which past societies responded to environmental challenges and adapted to maintain a sustainable existence—or failed to do so—we can exploit some of these examples to inform discussions of how we might address the climatic and environmental challenges that confront us today [13,41,42]. One conclusion that we may draw from integrated palaeoecological/archaeological research is that the culture and vulnerabilities of a society are as significant as the magnitude of the hazards a society may have faced, just as the ways through which a society could respond were determined by culturally moulded social praxis and belief systems, points illustrated in J. Manning's chapter on ancient and Hellenistic Egyptian management—or failure to manage—the annual Nile flood.

Many past adaptations to environmental change were not only successful in their own time but could suggest approaches for policy responses relevant to modern challenges [43,44]. The rapid increase in interest among the wider public as well as in engagement with the relationship between archaeology and climate change reflects many of these themes, and several of the chapters in this SI reflect that trend. It is also reflected in the 2010 launch of a dedicated journal, *AP: Online Journal in Public Archaeology*, and in numerous articles as well as community engagement projects, e.g., [45–47]. The larger role of archaeology in the broader framework of policy and environmental politics has thus grown rapidly in the last few decades, particularly in connection with contemporary and predicted climatic threats to heritage and community identities [17,48–51]. We hope that the chapters in this collection will both add to the existing and growing body of research in the field of the archaeology of climate change as well as further enhance efforts to broadcast the value of understanding the past in responding to modern challenges and in planning for the future.

Conflicts of Interest: The authors declare no conflicts of interest.

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Article

Göbeklitepe in Palaeoclimate Context: Human Responses to Climate Change in the Upper Tigris and Euphrates Basins from the Younger Dryas to the Early Holocene

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Abstract

The upper Euphrates and Tigris basins are located in modern-day Southeast Türkiye, on the northern periphery of the Fertile Crescent. From the eleventh to the eighth millennium calBC, during the Younger Dryas and the Early Holocene, human communities in this region transitioned from mobile hunter-foragers to settled agriculturalists. This process went hand in hand with the construction of the first monumental buildings, such as those at Göbeklitepe and its sister site Karahantepe. Although the Early Holocene is broadly understood as a phase of climate amelioration following the Younger Dryas climate reversal, it also featured short and abrupt phases of climatic instability, so-called rapid climate change (RCC) intervals. This contribution examines demographic trends against the backdrop of climate change to highlight potential impacts on human communities in this key region of Neolithisation, placing Göbeklitepe in its broader cultural and palaeoclimate context.

Keywords: Younger Dryas; Early Holocene; rapid climate change; hunter-gatherer crisis; adaptive cycles; vulnerability

1. Introduction

Since the first excavations at the prehistoric site of Nevali Çori (1983–1991) in the frame of the Atatürk Dam construction project [1] and subsequent fieldworks initiated at Göbeklitepe in 1995, the Şanlıurfa region of modern-day southeastern Türkiye has become a hub of research on the transition from hunter-gatherer to agricultural economies in the Early Holocene (EH). Located in a *core zone of Neolithisation* [2], which includes the Upper Euphrates Basin, extending into Northern Syria, and the Upper Tigris Basin around the city of Mardin, expanding into northern parts of modern-day Iraq, this region is situated on the northern fringe of what is commonly referred to as the Fertile Crescent. In 2021, research into the EH of the Şanlıurfa region received a boost from the newly formulated Taş Tepeler project by the Ministry of Culture of the Republic of Türkiye [3]. This project has brought together fieldwork at several Pre-Pottery Neolithic (PPN) sites [4–10], which include continued excavations at Göbeklitepe and its sister site, Karahantepe [11–18]. Although settlements coinciding with the preceding Younger Dryas (YD) have not yet been definitively encountered among the Taş Tepeler, further south and east, a small number of PPN sites with Epipalaeolithic settlement phases have been excavated along the Euphrates and Tigris rivers [19–23]. Neolithic research along the Tigris has been conducted within the framework of the Ilısu Dam project, which has also included excavations at other PPN settlements [24,25], thereby adding to the insights gained from earlier research in this region [26–30].

One aim of the Taş Tepeler project is to investigate the palaeoenvironmental conditions of the Şanlıurfa region from the Late Pleistocene to the Early Holocene, particularly in relation to the transition from hunter-gatherer to agricultural economies. Within this framework, the present contribution identifies periods of abrupt climate change and instability that may have influenced socio-economic adaptations across the upper Euphrates and Tigris basins. Beginning with the Younger Dryas and continuing through the Early Holocene climatic amelioration, the focus is on intervals of rapid climate change (RCC), considered alongside regional archaeological evidence from the same period. These observations are discussed with reference to vulnerability studies [31–37], resilience theory [38], and the adaptive cycle model [39], which are employed here in a heuristic sense to explore possible correspondences between broad socio-ecological dynamics and archaeological trajectories, without implying formal phase assignment or model testing [40]. Regional palaeoclimate records are treated as general environmental background, while available radiocarbon dates and settlement patterns provide a framework for situating long-term socio-ecological change.

2. Göbeklitepe

Göbeklitepe is a Pre-Pottery Neolithic (PPN) site located in the Germuş Mountains, east of the modern city of Şanlıurfa, on a limestone plateau overlooking the Harran plain to its south (~775 m a.s.l.) (Figure 1). Initially identified as a prehistoric site in 1963, excavations at Göbeklitepe were initiated in 1995, when it was already being referred to as a cultic site of major significance [41]. The last three decades have seen continuous research at the 9-hectare large mound, culminating in its inscription as a UNESCO World Heritage Site in 2018 [42]. Notably, over the last several years, re-evaluations and new excavations have revealed that Göbeklitepe was also a significant domestic settlement [14,43]. Although not detracting from its importance, this realisation has served to relativise earlier claims that Göbeklitepe was the smoking gun of Neolithisation, where early sedentism, the domestication of plants and animals, and the emergence of more complex socioeconomic systems were triggered by the demands of more organised forms of religion [12]; indeed, this narrative proves especially difficult to uphold considering there is still no evidence for domesticated animals at Göbeklitepe [44], and there are only extremely sporadic remains of morphologically domesticated cereals from stratigraphically late (PPNB) deposits (pers. comm. F. Antolin).

The restructuring of an earlier formulated stratigraphic sequence at Göbeklitepe became necessary following the realisation that the special (monumental) buildings (former Layer III, assigned to the Pre-Pottery Neolithic A/PPNA/~9600–8700 calBC) were long-lived structures, their later phases contemporaneous with the smaller rectangular-trapezoid (domestic) buildings (former Layer II, assigned to the Early Pre-Pottery Neolithic B/EPPNB/~8700–8200 calBC) [14]. This has demonstrated that by the EPPNB, Göbeklitepe had evolved into a substantial domestic settlement, with the special buildings as a spatial focal point. The gradual abandonment of the site from the late 9th millennium calBC, which saw the disappearance of its characteristic monumental architecture with its T-shaped limestone monoliths, heralded the onset of early farming in the region and the foundation of new settlements in the Harran Plain, e.g., Gürcütepe [18,41]. A key focus of recent research at Göbeklitepe is the diachronic study of settlement structure, aimed at improving our understanding of the vulnerability of this early Neolithic community to ecological and social change and its resilience through adaptive forms of community organisation.

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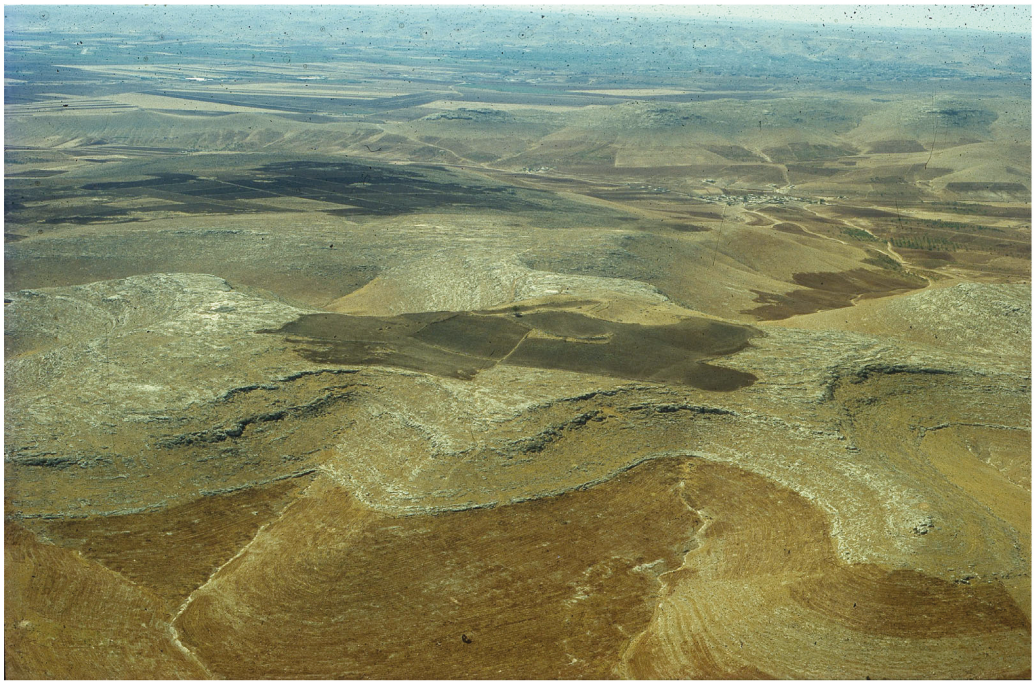


Figure 1. Aerial photo of Göbeklitepe (centre) and its surrounding landscape before the commencement of excavations in 1995. The prehistoric settlement is located on a limestone spur in the Germuş Mountains. This landscape is characteristic of the entire Taş Tepeler Project area. In the southwest, the Harran plain is visible towards the top of the picture, with the Fatik (Cudi) Mountains on the horizon. Author unknown, German Archaeological Institute, Göbeklitepe Project.

3. Methodology: Absolute Chronologies, Palaeoclimate Data, Adaptive Cycles and Vulnerability

A first step will see the generation of a radiocarbon-based demographic proxy that is directly comparable to palaeoclimate records. This will include the systematic assessment of radiocarbon data from a total of 22 Epipalaeolithic and PPN sites. Following established procedures, summed probability distributions (SPD) will be used as a demographic indicator [45–48]. The resulting radiocarbon chronology is then compared with selected palaeoclimate proxy records to assess potential temporal correspondences.

Using SPD curves as a proxy for population trends is not a new method, and its limitations have been recognised [48]. Among the main criticisms of this approach are sampling errors and the effects of calibration on the data. However, it is also acknowledged that data in this form can still be useful, especially when analysing long-term trends over millennia. For this reason, SPD will be considered, even though the data should not be regarded as definitive proof of the implied demographic trends. In an effort to address some criticisms of this methodology, the radiocarbon data analysed will be filtered, with problematic ages, such as outliers that do not reflect the archaeological material culture and those with high standard deviations (>100 14C years), excluded.

Over the years, doubts have also been raised regarding whether the socio-cultural changes and the coincident periods of YD and EH climate change were causally related or, at best, whether this issue has been oversimplified [49,50]. Nonetheless, there is a tangible consensus that adaptation to changing climates certainly played a role in some cases, especially considering that humans are inherently intertwined with their environments, as originally expressed in the concepts of cultural ecology after J.H. Steward [51]. In fact, dedicated research continues to uncover new correlations between climate proxy data, changing settlement patterns, (material) culture change, and the adjustment of subsistence strategies in the Late Pleistocene and during the Holocene in the Northern Hemisphere [52–57].

Certainly, temporal correlation does not imply causation, but this does not mean that correlations between climate upheaval and shifts in material culture should be wholly ignored; indeed, environmental change is one factor among many that can influence socio-cultural processes.

Instead, discussions need to approach how we can best combine palaeoclimate and archaeological data and use them to shed light on the prehistoric past. The approach taken in this contribution is to harness the concept of adaptive cycles, which describes the application of cultural cycles [39] to the archaeological record [38,58]. Cultural cycles are understood as developments in demographics, economy, and social relations, based on which regional and cultural comparisons can be made. These comparisons facilitate a deeper understanding of the internal dynamics and external influences on cultural developments [59]. Adaptive cycles become visible when considering collectively acting group sizes, which are deemed representative of different prehistoric periods, and can be calculated by applying geostatistical methods to archaeological spatial datasets. As such, they are an excellent tool for studying complex (chaotic) prehistoric systems [60–64]. Following the adaptive cycles model, cultures are subject to a constantly recurrent cycle that comprises four phases: reorganisation (α), growth (r), rigidity (K), and decline (Ω).

To highlight the potential impact of climate change on adaptive cycles, it is also beneficial to consider insights from studies on vulnerability, a concept examined across various spheres of risk and disaster research [31–37]. Interpretations of vulnerability are influenced by two distinct paradigms: the first reflects a traditional behavioural risk notion, while the second adopts a more structuralist approach. The traditional behavioural risk notion views vulnerability as determined by the proximity of a community to a given threat, such as underdeveloped technologies. The structuralist approach, on the other hand, considers the physical hazard to be secondary, instead proposing that the occurrence of catastrophes also depends on the prevailing (more or less vulnerable) socioeconomic systems. To account for the two paradigms, a differentiation is often made between biophysical vulnerability and social vulnerability [61,65].

Biophysical vulnerability is best described as the exposure of human systems to natural extreme events and hazards, or the harnessing of natural events by humans. As such, it must consider the hazard dimensions (magnitude, frequency, duration, speed of onset, aerial extent, spatial dimension, and temporal spacing), as well as factors such as the location of residence, availability of natural resources, and housing quality. In other words, societies already residing in isolated and harsh environments with limited access to natural resources and inadequate housing are already more at risk in the face of natural extreme events. Social vulnerability refers to the human dimension of hazards, i.e., the socioeconomic circumstances of affected communities. The most prominent example of social vulnerability relates to the integration of subsections of a society within the mainstream system: disasters are the product of the social, political and economic environment because of how they structure the lives of different groups of people.

4. Upper Tigris and Euphrates Basins

The Tigris and Euphrates rank among the world's major river systems. The Euphrates, at 2700 km, is the longest river in Southwest Asia, while the Tigris, measuring 1840 km, carries a greater peak average discharge. The Euphrates originates from the confluence of two tributaries northwest of Elazığ, then cuts through the southeastern Taurus Mountains and enters Syria near Karkamış, from where it flows southeast across the Syrian Plateau within a deeply incised valley. The Tigris rises near Lake Hazar and flows southeast across the Diyarbakır basin to Cizre, where it forms part of the Turkish–Syrian border for

approximately 30 km before entering Iraq. Both rivers are primarily fed by snowmelt, with peak flows occurring in April and May [66].

The region between the two rivers, south of the Eastern Taurus mountain range and within the modern borders of Türkiye, is commonly referred to as Upper Mesopotamia. Here, the landscape descends into low-lying limestone plateaus, separated from the high mountains by a narrow belt of foothills. The plateaus (<900 m a.s.l.) gradually transition into the wide plains of Syria and Iraq to the south (~400 m a.s.l.). With mountains blocking the area to the north and west, and the land opening towards the steppe-like semi-deserts of northern Mesopotamia, the region experiences hot, dry summers and winters that are relatively cold but remain dry [67]. In Şanlıurfa, the mean temperature for the hottest month (July) is 39 °C, while the mean value for the coldest month (January) is 2.7 °C [68]. Long-term (AD 1991–2020) mean annual temperatures at Şanlıurfa, Diyarbakır, and Mardin are 19 °C, 15.9 °C, and 16.6 °C, with annual (predominantly winter) precipitation of 451 mm, 498 mm, and 610 mm, respectively [69].

Soils are predominantly arid, red steppe types with high lime content, and vegetation is largely xeric and steppe in character: spring grasslands quickly desiccate in summer, while tree communities are mostly restricted to stream valleys and higher elevations [70,71]. In recent decades, large-scale projects such as the Southeast Anatolia Project (*Güneydoğu Anadolu Projesi*, GAP) have expanded irrigation and agricultural productivity, yet the region continues to face significant challenges from global warming [66,72]; indeed, the vulnerability of the region to current climate change echoes the profound impacts that past climatic shifts may also have had on its prehistoric populations.

5. Younger Dryas

The YD was a cooling period at the close of the Pleistocene that lasted approximately 1300 years, from around 12,900 to 11,600 calBP [73]. Triggered by the disruption of the North Atlantic thermohaline circulation due to a meltwater outburst from the Laurentide ice sheet, the YD was a cold reversal following the Bølling-Ållerød interstadial, a warming phase after the Late Pleniglacial. Some general trends observed in multiple palaeoclimate proxies include the occurrence of a phase of maximum cold in the early part of the YD, followed by a warmer phase as thermohaline circulation in the North Atlantic began to recover [54,74,75].

The YD in the Eastern Mediterranean was characterised by increased aridity and lower temperatures compared to the preceding Bølling-Ållerød interstadial, though with frequent ambiguities regarding space, timing and intensity [76–80]. The climate reversal led to a decrease in mean winter temperature and monthly precipitation, opening up the dense oak woodland that had developed during the preceding interstadial. This was accompanied by an increase in dense stands of annual grasses and complemented by riverside taxa along the Tigris and Euphrates rivers and their tributaries [80–83]. A recent geomorphological investigation of the Culap Suyu Basin in Şanlıurfa provides tentative insights into the YD–EH transition in the immediate vicinity of Gobeklitepe, which is located on the southwestern watershed of this basin. Notably, neither this transition nor the emergence of herding during the Pre-Pottery Neolithic produced a clear geomorphological signal; in particular, and contrary to the generally accepted climate reversal of the YD, there is no evidence of a large-scale shift from dry to wet conditions that might otherwise be expected at this time [84]. This pattern may indicate that the local climate during the YD was wetter in the region, a possibility that aligns with recent studies from the adjacent Levant that suggest increases in spring, summer, and autumn precipitation, accompanied by reduced evaporation associated with cooler YD temperatures [85–88].

6. Early Holocene

The Holocene is an interglacial characterised by substantial increases in precipitation and warmer conditions compared to the YD. Commonly subdivided into three phases, including the EH (11,700–8326 yr b2k), the Middle Holocene (8326–4250 yr b2k), and the Late Holocene (from 4250 yr b2k) [89], the transition from YD to EH was swift, potentially spanning just fifty years [90]. During this extremely short time, wind speeds, precipitation, temperatures, and sea ice changed throughout the Northern Hemisphere [90]. However, whether this transition was felt just as abruptly in the Eastern Mediterranean is a matter of debate; at Lake Nar in the Cappadocian region of central Türkiye, the process could have lasted less than two centuries, with half of it occurring within a decade [78]. In any case, it was likely an abrupt transition that would have become discernible over just a few human generations.

Following the onset of the EH, a period with particularly high moisture levels ensued (ca. 10,200–8600 calBP), best visible in the abrupt increase in Dead Sea water levels, the accumulation of sapropel S1a on the Eastern Mediterranean seabed, and fluctuations in stable isotopes in speleothems at different cave sites in the same region [61,91]. Although the Holocene is commonly associated with more favourable climate conditions, it has never been a period of climate stability. The end of the EH and the onset of the Middle Holocene (MH) coincide with a perturbation phase lasting some six centuries (8600–8000 calBP), referred to as a rapid climate change (RCC) interval [92–94]. This interval is the first and one of several to have occurred during the Holocene. Characterised by an abrupt onset and a relatively short duration (between two and several centuries), RCCs are marked by a strong Siberian high-pressure system over Eurasia, increased storm activity over the North Atlantic, and cooling of sea surface waters in the Eastern Mediterranean [92–94]. The climate during these periods can be described as highly variable, featuring extreme weather conditions, including harsher winters, abnormal precipitation, and frequent droughts, often occurring in successive years [61,91]. Historical data from the last RCC interval, the so-called Little Ice Age (LIA, AD 1400–1850), provide numerous accounts of these conditions and the humanitarian catastrophes they can trigger [61,63]. Meanwhile, in addition to the RCC at the EH-MH transition (8600–8000 calBP) and the LIA (AD 1400–1850), further (potential) intervals have been identified at 10,800 calBP (Hunter-Gatherer Crisis) [43,95], 10,200 calBP [96], and 9200 ka calBP [97,98], as well as at 6200–5000 calBP and 3100–2900 calBP [99–101].

7. Approaching Human Responses to Climate Change in the YD and EH

Figure 2 presents an overview of some palaeoclimate datasets from the Eastern Mediterranean. These datasets include stable isotopes (18O and 13C) from speleothems at the cave site LoNAP514 in the northern Kurdistan region of Iraq as a proxy for hydroclimate and vegetation type (Figure 2F,G) [102]; the Holocene water level of the Dead Sea as a proxy for precipitation levels (Figure 2H) [103]; the Aegean marine core LC21 (foraminiferal oxygen isotopes) as a proxy for marine surface water temperature (Figure 2I) [104]; and GISP2 potassium (terrestrial [K^+]) ions from Greenland ice as a proxy for the occurrence and intensity of RCC intervals (Figure 2J) [92]. Figure 2B–E present radiocarbon (absolute) ages from 22 excavated archaeological sites in the study region (Table 1), while Figure 2A shows the summed probability distribution (SPD) for all these sites, thereby indicating potential demographic trends between the 11th and 9th millennia calBC [45–47]. Observations derived from comparisons of these datasets may indicate societal responses to climate change during the Late Pleistocene and the Early Holocene (EH).

It should be noted, however, that both the state of research and the quality and reliability of available radiocarbon measurements can constrain the interpretative value of

SPDs, with additional pitfalls including calibration effects and sampling errors [48]. Consequently, prior to generating this figure, all radiocarbon determinations were systematically evaluated and filtered to exclude (1) measurements with standard deviations of $\geq$100 ^{14}C years and (2) obvious outliers. For Göbeklitepe, this also included the removal of dates obtained from bone, humic acids, and paedogenic carbonates, which have previously proven unreliable [14]. This filtering process resulted in the exclusion of 275 out of a total of 700 radiocarbon ages (Tables 1 and S1). The remaining 425 dates were used to construct the SPD (Figure 2A) and are also depicted in the barcode-style calibrations for each individual site (Figure 2B–E).

Table 1. Overview of radiocarbon data, with information relating to excluded ages (and reasons for exclusion) of radiocarbon data used in Figure 2A–E [9,14,19–24,26,105–131]. A full list of the radiocarbon data, including excluded data and bibliographic sources, is provided in Table S1.

Archaeological Site	Total 14C Ages (N)	Excluded 14C Ages (N)/Reason
Taş Tepeler (Şanlıurfa, SE Türkiye)		
Nevali Çori	30	5/standard deviation
Sayburç	11	0
Yeni Mahalle	5	0
Göbeklitepe	141	1/outlier 31/bone 20/pedogenic carbon/humic acids
Upper Euphrates Basin (SE Türkiye; N Syria)		
Mezraa Teleilat	27	0
Akarçay	26	3/standard deviation
Abu Hureyra	67	49/standard deviation
Dja'dé	47	6/standard deviation 2/outlier
Tell Abr'3	7	0
Jerf el Ahmar	26	1/standard deviation
Mureybet	42	30/standard deviation 1/outlier
Tell Qaramel	57	36/standard deviation 2/outlier
Upper Tigris Basin (SE Türkiye)		
Çayönü	43	18/standard deviation 2/outlier
Demirköy	2	0
Gusir Höyük	5	0
Çemka Höyük	2	0
Hasankeyf Höyük	31	0
Hallan Çemi	38	15/standard deviation
Körtiktepe	24	0
Boncuklu Tarla	3	0
Tigris (N Iraq)		
Nemrik 9	60	52/standard deviation
Qermez Dere	6	1/standard deviation

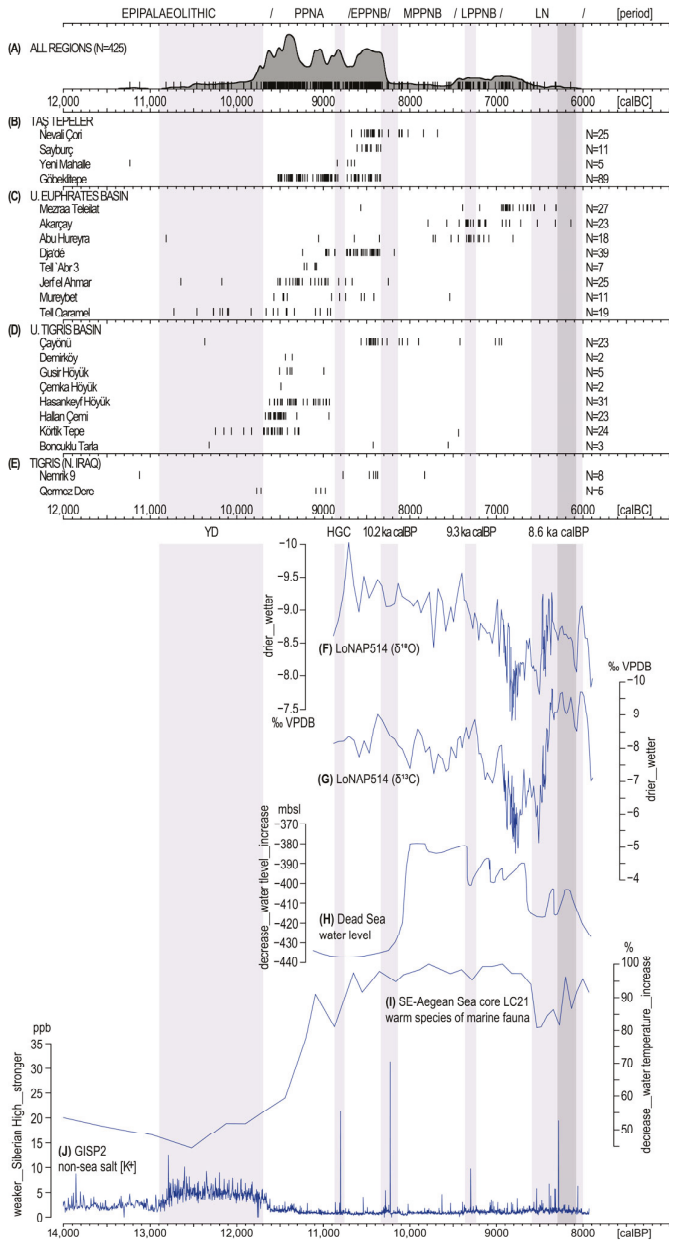


Figure 2. Barcode calibration of radiocarbon ages (N = 425) from 22 Pre-Pottery Neolithic sites in the upper Tigris and Euphrates basins (**B**–**E**); the occurrence of some data in the Late Neolithic (LN) reflects the continuity of some sites into this subsequent period. In the barcode method, each vertical line represents the calibrated median value of one 14C age using IntCal20 calibration data [132]. All radiocarbon ages are filtered to exclude apparent outliers and ages with standard deviations exceeding ±99 14C years. An overview of the number of radiocarbon data (and excluded data) from each site is provided in Table 1. Full lists of the radiocarbon data, excluded data and reasons for their exclusion, together with bibliographic references, are provided in the supplement (Table S1). All data (**A**) shows the summed probability distribution (SPD) across all sites. Bottom: stable isotopes (18O and 13C) from speleothems at the cave site LoNAP514 in the northern Kurdistan region of Iraq (**F**,**G**) [102]; Holocene water level of the Dead Sea (**H**) [103]; Aegean marine core LC21 (marine fauna) (**I**) [104]; and GISP2 potassium (terrestrial [K^+]) ions from Greenland ice (**J**) [92]. Grey bars indicate rapid climate change intervals (RCCs) in the Late Pleistocene and the Early Holocene, as well as other notable climate anomalies, including the Younger Dryas (YD) and the 8.2 ka calBP (Hudson Bay) event (dark grey bar). PPNA: Pre-Pottery Neolithic A; EPPNB: Early Pre-Pottery Neolithic B; MPPNB: Middle Pre-Pottery Neolithic B; LPPNB: Late Pre-Pottery Neolithic B; LN: Late Neolithic; YD: Younger Dryas; HGC: Hunter-Gatherer Crisis [95]. Graph compiled using CalPal 2024.7 [133]. Image: L. Clare, German Archaeological Institute.

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Epipalaeolithic: To date, seven sites in the study region have radiocarbon ages that fall within the YD; four are located along the upper Tigris, and three are settlements on the upper Euphrates (Figure 2C–E). The Tigris sites include Körtiktepe [21,134,135] and Boncuklu Tarla [23], where evidence for sedentary hunter-forager settlements begins in the late YD and continues into the EH (Figure 3). While the 14C age from Çayönü, for which an Epipalaeolithic settlement phase is unknown, is most likely an outlier, the two ages from Qermez Dere stem from an Epipalaeolithic-PPN transitional phase [26]. At Nemrik 9, all radiocarbon ages dating to the YD were excluded due to high standard deviations; however, the Epipalaeolithic (Zarzian) from the earliest layers of this site is attested through excavation [109]. Although not represented by radiocarbon ages, archaeological excavations at Çemka Höyük have also produced evidence of Epipalaeolithic occupations [22,136]. Along the upper Euphrates (Figure 4), the three settlements that have produced radiocarbon dates of YD age include Abu Hureyra, Jerf el Ahmar, and Tell Qaramel. Due to the high standard deviation of many of the Epipaleolithic ages from Abu Hureyra, all but one have been excluded from Figure 2 (Table 1). At Jerf el Ahmar, the YD ages are once again outliers, as the occupation at this settlement does not commence until after the Holocene transition [128]. At Mureybet, all 14C ages from the YD were disqualified due to high standard deviation; however, the occurrence of the Epipalaeolithic is confirmed through excavation [116]. At Tell Qaramel, the YD occupation is well-attested through 14C ages and material culture [20].

In the Upper Tigris Basin, additional evidence for YD sites comes from dedicated archaeological surface surveys in the Turkish province of Mardin, which have concentrated on the mountainous plateau landscape that separates the Tigris Valley in the north from the Upper Khabur Basin in the south. These surveys have culminated in the discovery of numerous archaeological sites (>150) from the Palaeolithic and the PPN, ranging from simple surface scatters to campsites, hunting traps (*desert kites*), caves, rock shelters and their terraces, and slope-settlements and mounds (Tr. *höyük*). Many of these sites are tentatively dated to the Epipalaeolithic/PPNA (Protoneolithic) based either on lithic assemblages or observed architectural features visible on the surface [137–141]. The comparative frequency and density of Protoneolithic sites in Mardin compared to the areas further west in Şanlıurfa is striking and could attest to adapted land-use strategies of a hitherto undocumented hunter-forager population from the Late Pleistocene and EH, referred to by E. Kodaş as the *Dokane Culture* [138].

There are still relatively few known Epipalaeolithic (YD) sites along the banks of the Euphrates on the Turkish side of the border and in the Taş Tepeler region around Şanlıurfa. Potential sites near the Euphrates include Biris Mazarlığı and Söğüt Tarlası [142,143], as well as Uluk Mevkii [144] and a few sites in the Birecik municipality [145]. In the western part of the Taş Tepeler region, several sites have yielded surface collections classified as Palaeolithic/PPN [146,147]. Furthermore, it is possible that Epipalaeolithic deposits remain hidden at some of the larger *höyüks* in the region. Therefore, YD conditions do not appear to have been entirely detrimental to human occupation in the upper Euphrates and Tigris basins, but a lack of dedicated palaeoclimatological studies in the region means that local environmental reconstructions heavily depend on bioarchaeological investigations from a limited number of excavated settlements, primarily Körtiktepe on the Tigris [21,82,135] and Abu Hureyra on the Euphrates [83].

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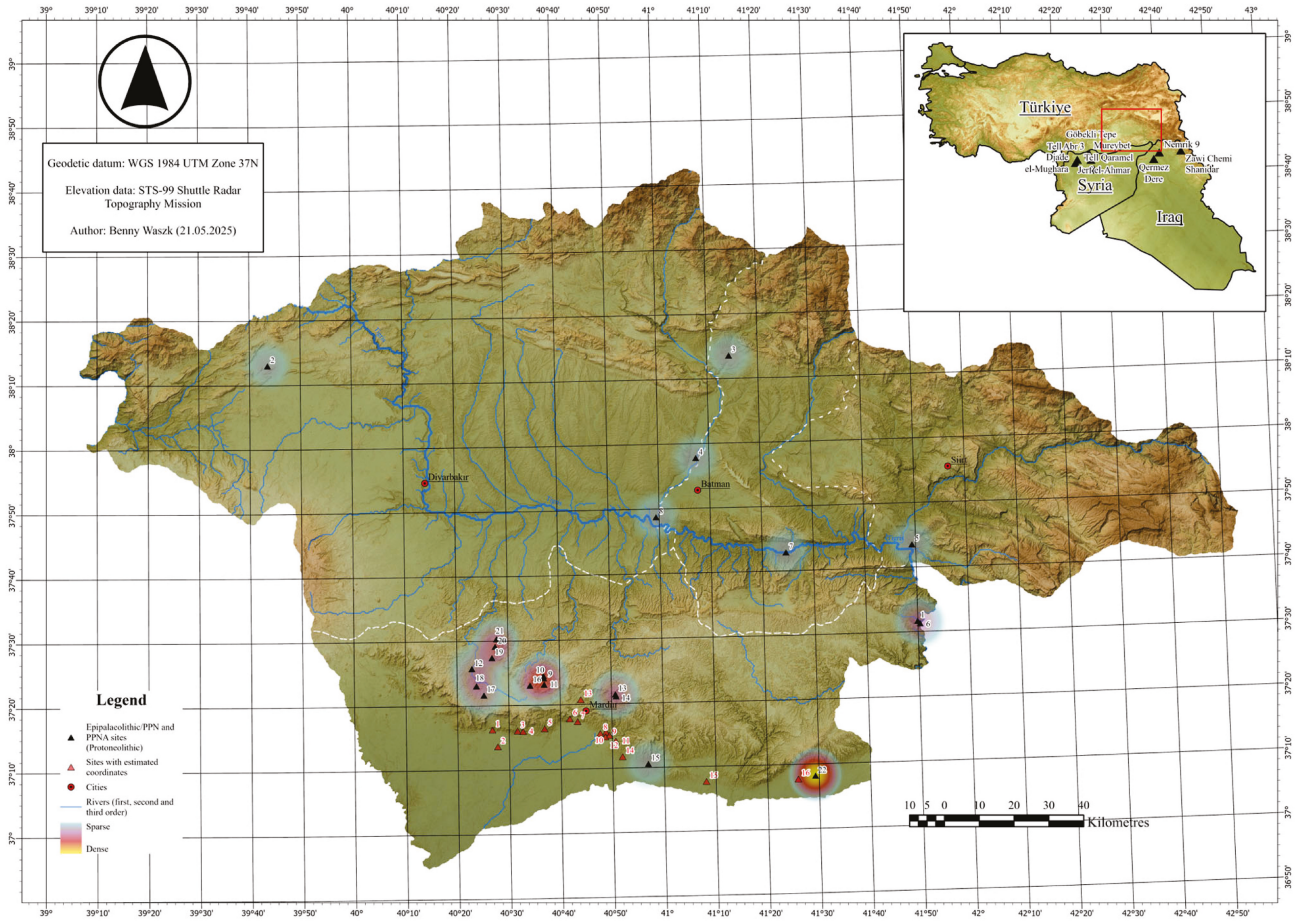


Figure 3. Map showing the distribution of Epipalaeolithic and PPNA (Protoneolithic) sites in Mardin, Diyarbakır, Batman and Siirt provinces [137–141]. White dashed lines show the province borders. Sites with confirmed coordinates (black triangles): 1. Boncuklu Tarla, 2. Çayönü, 3. Hallan Çemi, 4. Demirköy, 5. Gusir Höyük, 6. Çemka Höyük, 7. Hasankeyf Höyük, 8. Körtiktepe, 9. Hindilla Mağarası, 10. Hindilla Yerleşimi, 11. Hazreti Ali Mağarları, 12. Tarin Mağarası, 13. Bahçebaşı Mağarası 1, 14. Bahçebaşı Mağarası 2, 15. Dara, 16. Hemini Mevki, 17. Kerike Mevki, 18. Hirbe Mamede Mevki, 19. Mazıdağı Kalesi Mevki, 20. Enginköy Mağarası, 21. Hirbe Serif Mevki, 22. Kün Aftare 1–5. Sites with estimated coordinates (red triangles): 1. Milane 1–3, 2. Hane Sore Höyük, 3. Amrud, 4. Dokane 1–8, 5. Kure 1–3, 6. İstasyon, 7. Çiftlik, 8. Güneşli, 9. Bikeyre 1, 10. Bikeyre 2, 11. Kuraman, 12. Bikeyre Höyük, 13. 12 Mart (Brehi), 14. Şika Rika 1–4, 15. Gundike Use, 16. Mer Babe 1–5. Image: B. Waszk, German Archaeological Institute.

The data from these sites indicate that the two river basins never presented a homogeneous environment, and subsistence strategies were adapted to prevailing local conditions. Generally, the YD dry woodland steppe habitat, dominated by *Artemesia* and *Chenopodiaceae*, was home to multiple animal species, especially red deer, mouflon and wild goat in the hillier landscape around Körtiktepe and gazelle in the Syrian Tableland at Abu Hureyra [79,83,135]. Additionally, the wetland environment was exploited at both settlements, as attested by various species of ducks, waders and raptors from the Tigris at Körtiktepe and freshwater mussels from the Euphrates at Abu Hureyra. Notably, different land-use models must also be postulated for the higher elevated areas around Mardin, where caves and cave terraces were more densely settled than previously thought. As with hunting, YD communities practised site-distinct plant exploitation strategies. At Abu Hureyra, wild rye was dominant in the archaeobotanical record, although there is little evidence for tilling [148]. In contrast, at Körtiktepe, widespread, dense stands of annual

grasses, especially small-seeded species and riverine taxa, likely provided the staple plant foods for this population [82].

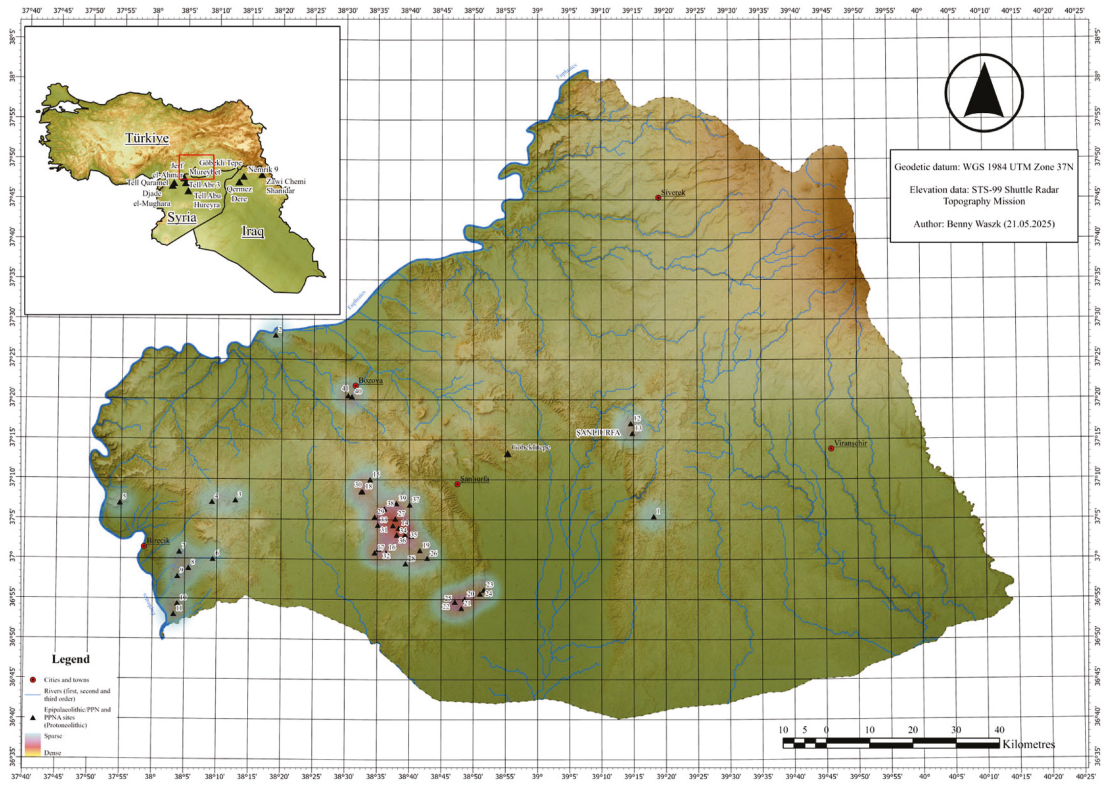


Figure 4. Map showing the distribution of Epipalaeolithic and PPNA (Protoneolithic) sites in Şanlıurfa province [144,145,147,149]. 1. Karahantepe, 2. Uluk Mevkii, 3. Kısakuyu Höyüğü, 4. Hayrat Mevkii Çevresi, 5. Tilmahmut Yatırı, 6. Mağaralı Dere, 7. Eske Harebe II, 8. Sınır Tepesi Höyüğü, 9. Girlavık Höyüğü I, 10. Kulbatar Kaya Sığınakları, 11. Camuz Tepe, 12. Sumaklı Köyü—Sumaklı Besta Faki Mevkii, 13. Sumaklı Köyü—İsmail Kalesi, 14. İkiztepe Buluntu Alanı, 15. Sesigür/Zengulup, 16. Haleklitaş, 17. Doğanlar/Tekyamaç, 18. Göbekli, 19. Gotik Tepesi, 20. Cudi Zeytini, 21. İkiz Kuş Yamaç Yerleşmesi, 22. Erken Yamaç Yerleşmesi, 23. Tahta Harabesi Kesimhane/Kamp Yerleşme, 24. Cudi Deresi Kesimhane/Kamp Yerleşmesi, 25. Hasmezra Yerleşimi, 26. Yanıkçöğür Açık Hava İstasyonu, 27. Çakmaktepe, 28. Nergislik Yamaç Yerleşmesi, 29. Eski Harabereler/Xrabete Qewın, 30. Ebu Abit Tepesi, 31. İki Ağız, 32. Oluk Yanı, 33. Tül Harabesi, 34. Borbore, 35. Mendiktepe, 36. Nur Tepe, 37. Şebeke Harebeleri, 38. Sayburç Bademi Höyük, 39. Sayburç Sanayi Mevkii, 40, Biris Mezarkığı, 41. Söğüt Tarlası. Image: B. Waszk, German Archaeological Institute.

Pre-Pottery Neolithic A: In the EH, there is an increase in settlement activity in the study area (Figure 2A). In addition to the sites where occupations had already commenced during the YD, late hunter-forager populations were now settling at Demirköy, Gusir Höyük and Hasankeyf Höyük along the Tigris, Gre Fılla on the Ambar Çayı (a tributary of the Tigris), and at Jerf el Ahmar, Dja'dé and Tell 'Abr 3 on the Euphrates. In the Taş Tepeler area, excavations at two sites have recently produced evidence of PPNA occupations at Çakmaktepe [10,18] and Mendiktepe [18]; earliest activities at Göbeklitepe and Karahantepe are also attested [16,18]. A larger number of excavated sites also means a greater abundance of bioarchaeological data. Especially at settlements with earlier Epipalaeolithic (YD) occupations, clear environmental changes can be noted. At Körtiktepe, although wide-spectrum hunting strategies continued, there were changes in the local environment reflected in different ratios of exploited wild animals; larger sized fish and an emphasis on the exploitation of waterfowl are indicative of changes to local waterways, and an increase in aurochs is suggestive of more marshland, with more wild boar remains

implying gully side vegetation and oak forest [135]. On the other hand, specialised hunting of gazelle is attested in the Taş Tepeler region (Göbeklitepe) and at the northern Syrian and Iraqi sites [150]. In addition to the lack of evidence for ungulate management in the study area, there are no indications for the intensive exploitation of crop progenitor species [151], except perhaps at Mureybet, Jerf el Ahmar and Tell 'Abr 3 in northern Syria (incipient pre-domestication cultivation) [152]. However, along the upper Tigris, as at Gusir Höyük, even wild cereals are absent in the PPNA, appearing only in the subsequent EPPNB. Sites such as Hasankeyf Höyük, Hallan Çemi and Demirköy were all sedentary hunter-gatherer sites where sedentism developed around hunter-gatherer-fisher systems. Generally speaking, the Epipalaeolithic and the PPNA can be assigned to a *Protoneolithic* phase, as presented in Figures 3 and 4.

Early Pre-Pottery Neolithic B: By the late PPNA, a detectable depopulation was taking place along the upper Tigris and Euphrates rivers (Figure 2A,C), accompanied by a quasi-contemporaneous surge in EPPNB sites in Şanlıurfa (Figures 2B, 5 and 6), a trend previously referred to as the hunter-gatherer crisis (HGC) [43,95]. In the coming years, an even greater increase in the EPPNB signal of the SPD can be expected as more 14C ages become available from the Taş Tepeler project. The causal mechanisms behind this demographic shift remain elusive; the only indication that it could be related to climate comes from (non-local) palaeoclimate proxy data (Figure 2H,J), which hint at a short-lived RCC interval at approximately 8800 calBC. However, given the lack of local paleoclimate proxy data and the absence of attested impacts on the local environment, this conclusion remains tentative. Archaeological surveys in the study region have also led to the discovery of numerous (N = 289) prehistoric hunting traps, so-called *desert kites* (see https://www.globalkites.fr (accessed on 23 March 2026)), for which it is currently unknown whether these were constructed over a large space of time (Epipalaeolithic-PPNA-PPNB) or are attributable only to the EPPNB, thus reflecting either the increased demands of a growing population from the early 9th millennium calBC [146,147,153–155] and/or the practice of meat caching as a buffer for times of scarcity [156]. Alternatively, the high number of traps may reflect shifts in the migration routes of animals, such as gazelles, over time and could also testify to the use of hunting dogs [43]. Whatever the case, the high work investment required suggests that these projects either contributed to the consolidation of regional cooperations or that they are a testimony to the challenges faced by different groups as they competed for resources and access to the landscape [157]. The EPPNB is also noted as the period in which the first morphologically domesticated einkorn wheat is observed at Nevali Çori [152], together with the possible breeding in captivity of sheep, pigs, and goats [114]. However, Nevali Çori is an outlier, as no other sites have thus far produced similar evidence. On the whole, in the EPPNB (and MPPNB), there was a coexistence of foraging-focused and crop-dominated strategies, as well as mixed subsistence economies; however, for the most part, crops still appear closer to their morphologically wild forms.

Middle Pre-Pottery Neolithic B: The number of settlements declines markedly during the MPPNB (Figure 2A). Notably, this trend contradicts earlier conclusions by Roberts et al. [45], who identified an initial demographic increase in southern Türkiye beginning around 10,300 calBP. The transition from the EPPNB to the MPPNB also coincides with the 10,200 calBP climatic event, which is thought to have involved highly variable and extreme weather conditions, including harsher winters, anomalous precipitation regimes, and recurrent droughts, often occurring in successive years [61,91]. Indeed, B. Weninger [96] has suggested that the 10,200 calBP RCC coincides with the earliest appearance of domesticated barley and cattle at several sites in the region and may be causally linked to these developments. However, although a few MPPNB sites exhibit a shift toward more

agricultural practices, such cases remain exceptional rather than representative of broader subsistence patterns. It is only during the Late (Pottery) Neolithic that a substantial shift toward crop-dominated economies becomes apparent [152].

Turning to the available palaeoclimate proxies spanning the 10200 calBP RCC interval, a rise in the water level of the Dead Sea may indicate elevated precipitation levels across the Eastern Mediterranean during this period (Figure 2H). Indeed, the influence of RCCs on the northern periphery of the Fertile Crescent is underscored by the speleothem record from LoNAP514 in northern Iraqi Kurdistan (Figure 2F–G) [102]; this cave lies comparatively close to the upper Euphrates and Tigris basins, approximately 170 km southeast of the Ilısu Dam area (Boncuklu Tarla, Çemka Höyük) and 400 km east–southeast of Göbeklitepe. However, while all RCC intervals (Figure 2, grey bars) correspond to low water levels in the Dead Sea (Figure 2H) [103] and cooling sea-surface temperatures in the Aegean (Figure 2I) [104], the LoNAP514 oxygen-isotope record displays a more complex pattern. It indicates increasing aridity at 10,200 calBP and contradictory signals at 9300 calBP, while the alternating wet and arid phases between 8600 and 8000 calBP may either reflect the intrinsic variability of RCC conditions or point to pronounced micro-regional climatic heterogeneity.

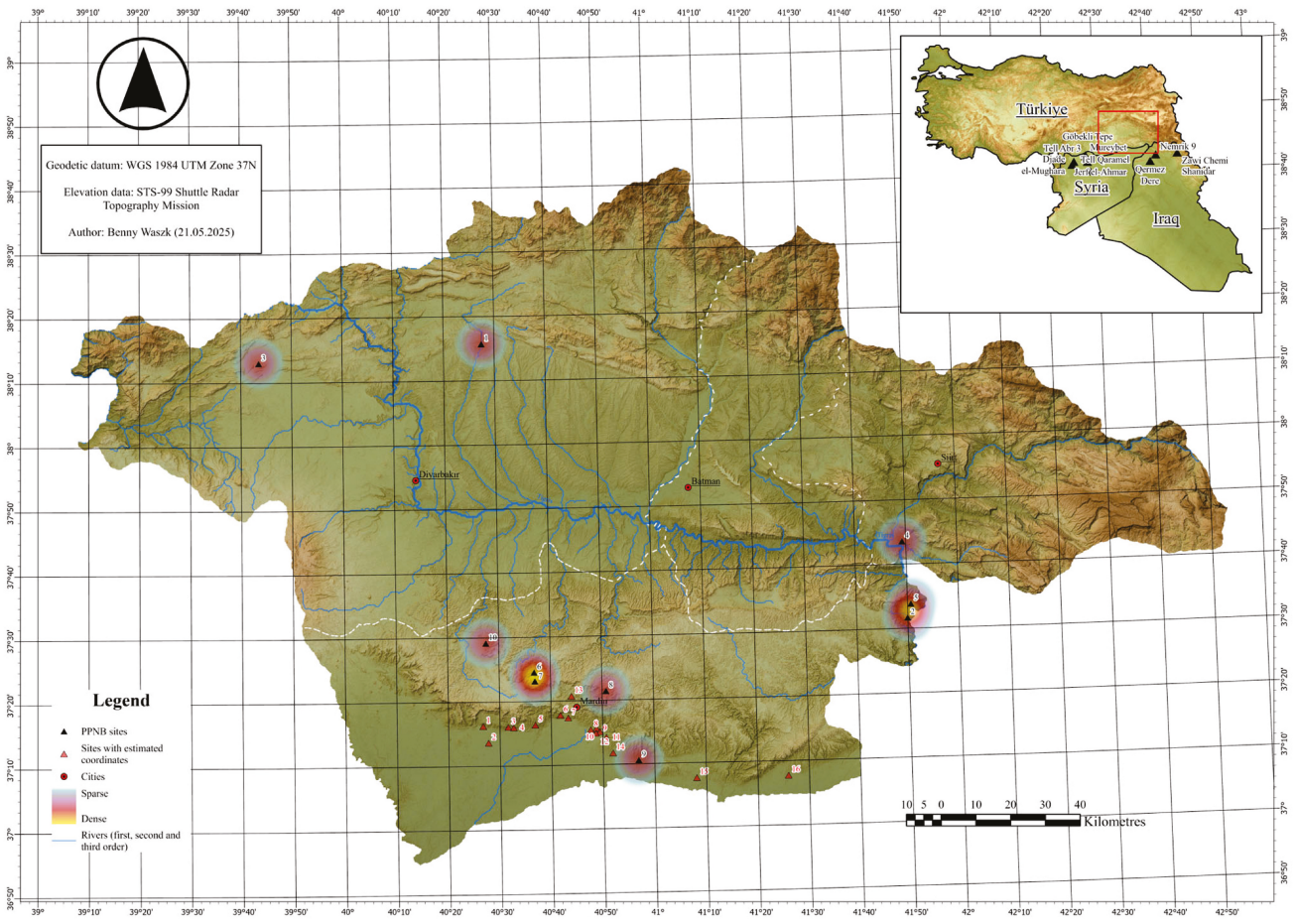


Figure 5. Map showing the distribution of PPNB sites in Mardin, Batman and Siirt provinces [137–141] (https://www.globalkites.fr). White dashed lines show the province borders. Sites with confirmed coordinates (black triangles): 1. Gre Filla, 2. Boncuklu Tarla, 3. Çayönü, 4. Gusir Höyük, 5. Serre Şippe Höyük, 6. Hindilla Mağarası, 7. Hazreti Ali Mağarları, 8. Bahçebaşı Mağarası 1, 9. Dara, 10. Enginköy Mağarası. Sites with estimated coordinates (red triangles): 1. Milane 1–3, 2. Hane Sore Höyük, 3. Amrud, 4. Dokane 1–8, 5. Kure 1–3, 6. İstasyon, 7. Çiftlik, 8. Güneşli, 9. Bikeyre 1, 10. Bikeyre 2, 11. Kuraman, 12. Bikeyre Höyük, 13. 12 Mart (Brehi), 14. Şika Rika 1–4, 15. Gundike Use, 16. Mer Babe 1–5. Image: B. Waszk, German Archaeological Institute.

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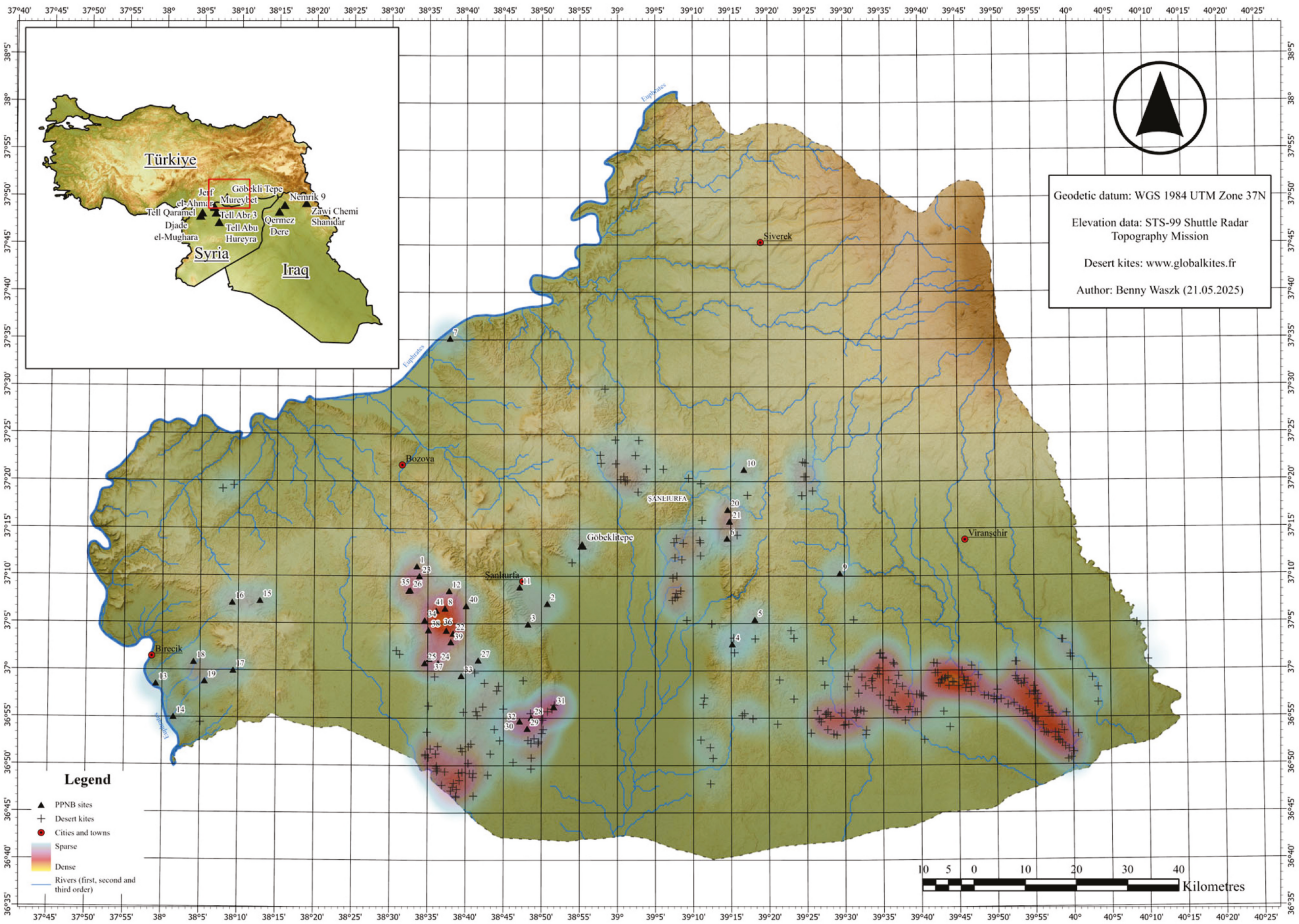


Figure 6. Map showing the distribution of PPNB sites in Şanlıurfa province [144,145,147,149] (https://www.globalkites.fr). 1. Ayanlar, 2. Gürcütepe, 3. Hamzantepe, 4. Harbetsuvan, 5. Karahantepe, 6. Kurttepesi, 7. Nevali Çori, 8. Sayburç, 9. Sefertepe, 10. Taşlı Tepe, 11. Yeni Mahalle, 12. Yoğunburç, 13. Mezraa Teleilat, 14. Akarçay Tepe, 15. Kısakuyu Höyüğü, 16. Hayrat Mevkii Çevresi, 17. Mağaralı Dere, 18. Eske Harebe II, 19. Sınır Tepesi Höyüğü, 20. Sumaklı Köyü—Sumaklı Besta Faki Mevkii, 21. Sumaklı Köyü—İsmail Kalesi, 22. İkiztepe Buluntu Alanı, 23. Sesigür/Zengulup, 24. Haleklitaş, 25. Doğanlar/Tekyamaç, 26. Göbekli, 27. Gotik Tepesi, 28. Cudi Zeytini, 29. İkiz Kuş Yamaç Yerleşmesi, 30. Erken Yamaç Yerleşmesi, 31. Tahta Harabesi Kesimhane/Kamp Yerleşme, 32. Hasmezra Yerleşmesi, 33. Nergislik Yamaç Yerleşmesi, 34. Eski Harabereler/Xrabeti Qewın, 35. Ebu Abit Tepesi, 36. İki Ağız, 37. Oluk Yanı, 38. Tül Harabesi, 39. Borbore, 40. Şebeke Harabeleri, 41. Sayburç Bademli Höyük. Image: B. Waszk, German Archaeological Institute.

8. Human–Environment Interactions in the Tigris and Euphrates Basins: Insights from Adaptive Cycles and Vulnerability

Based on the admittedly limited empirical data from the study area, including available radiocarbon ages (SPD) and settlement counts, it has previously been suggested that each of the periods considered in this contribution could be assigned to a phase of an adaptive cycle: Epipalaeolithic (α), PPNA (r), EPPNB (K) and MPPNB/LPPNB (Ω) [43]. Any assignment of prehistoric periods must remain tentative, given the spatial gaps in surface survey work and the difficulty of reliably dating surface sites. Whereas adaptive cycles can inform us about when socioeconomic systems are most resilient and most at risk of abrupt climate change intervals, vulnerability studies can guide us in identifying the potential background factors that contribute to their respective resilience levels.

As the α phase is the starting point of the cycle, it is characterised by the establishment of new residential, descendant and heritage rules, the construction of new traditions, and

high vertical social mobility. Although open to external influences, which are advantageous for spatial (demographic) dispersal, socioeconomic systems are still subject to manifold, ongoing transitional processes, rendering them inherently unstable; for this reason, they remain vulnerable to external perturbations, still lacking the essential buffering mechanisms.

In contrast, the r (PPNA) and K (EPPNB) phases are the most resilient to external climatic perturbations. The r phase is a time of growth and interaction, with vulnerability levels decreasing to their lowest point in the adaptive cycle. This phase is synonymous with demographic expansion and yield optimisation. In small-scale societies, social differentiation can be legitimised through kinship ties and cultural homogeneity, and newly emerging kinship institutions ensure the balanced distribution of resources throughout the community (access to assets), resulting in the higher resilience of the entire system. The subsequent K phase is marked by low vertical social mobility, culminating in social tensions (reduced access to assets) and a rigid reference to traditions. Slightly higher levels of vulnerability are now discernible, attributed to a decreasing density in large-scale communication (increasing regionalisation) due to the gradual disbandment of the previous cultural homogeneity. Therefore, given the very weak palaeoclimate evidence for RCC during the hunter-gatherer crisis (early 9th millennium calBC) and the potentially high resilience of the socioeconomic system at that time (late PPNA-early EPPNB), it is unlikely that the HGC was related to climate change and that the observable developments in the archaeological record were more likely of a cultural origin.

The Ω phase marks the downswing in the adaptive cycle. It is characterised by the loss of traditional values and a distorted or failed legitimisation of systems; frequently associated with emigration, this phase is the most vulnerable as systems are at their weakest. Interestingly, the earlier assignment of the MPPNB to the Ω phase and its temporal coincidence with the decline and abandonment of the Taş Tepeler sites suggest that the prevailing system was especially vulnerable (biophysically and socially) at this time and that the climate instability associated with the 10,200 calBP event could have contributed to the collapse of the PPN monumental sites, such as at Göbeklitepe and Karahantepe.

9. Göbeklitepe in Palaeoclimate Context

Against the background of the palaeoclimate record, three milestones in the archaeological sequence of Göbeklitepe can be considered which coincided with or were subsequent to intervals of climate change; these include (1) the foundation of the settlement following the YD, during EH climate amelioration; (2) the inundation of parts of the site by slope-slides during the HGC; and (3) abandonment processes in the contexts of the RCC interval at 10,200 calBP.

According to the earliest reliable radiocarbon dates, initial (PPNA) occupations date back to the mid-10th millennium calBC. In this respect, Göbeklitepe is just one of many settlements in the upper Euphrates and Tigris basins that appeared during this period. As noted, the r phase of the adaptive cycle, to which the PPNA has been assigned, is a time of growth and interaction and is synonymous with demographic expansion and yield optimisation. With excellent views over the surrounding landscape and situated at a key thoroughfare for gazelle herds, the site offered hunter-gatherer groups numerous advantages, encouraging initial occupation [150]. In addition to the early phases of the special buildings, this earliest settlement phase features round-oval dwellings, typical of the period, constructed directly on (or just above) the natural limestone plateau [14,158]; however, it remains unclear when the transition to potential semi- to full-sedentism occurred. Climate change likely played a part in this initial settlement process, as a (semi-) permanent occupation at this location may only have become possible due to increased rainfall. In the absence of natural springs, for which there is currently no evidence, rainwater-harvesting

using channels and cisterns carved from the natural limestone plateau would have been the only way of securing the water supply. Although not dated with confidence, examples of cisterns are known not only from the surrounding plateau of the site but also from internal settlement areas [13,159] (Figure 7).



Figure 7. Göbeklitepe—Aerial view of a partially excavated cistern? (on-site) in trench K10-55 in 2015. Carved into the natural limestone bedrock, this feature has a diameter of 8.00 m and a maximum depth of 2.80 m. The edge of the pit features two to three courses of corbelled walling, constructed from large limestone slabs, held in place by smaller rocks (ballast). The feature is difficult to date, though its PPN age is confirmed stratigraphically. Image: N. Becker, German Archaeological Institute, Göbeklitepe Project.

The onset of the EPPNB at Göbeklitepe saw the site enter its most densely occupied phase. The appearance of increasingly rectangular and trapezoid-shaped structures could be explained as a more economical approach to utilising available space, especially considering that the inhabitants of these buildings seemed to be competing over the proximity of their dwellings to the special buildings. Over time, in the southeastern part of the site, this led to the formation of tell deposits on the slopes surrounding the special buildings, which had been constructed on an area of lower-lying natural bedrock. Earlier excavations had already revealed that by the PPNB, the slopes overlooking the special buildings had become inherently unstable, as evidenced by the construction of retaining terrace walls (Figure 8). Nevertheless, recent studies have demonstrated that the slopes indeed slipped on more than one occasion, leading to considerable destruction in this part of the site, including the inundation of the special buildings with mixed PPNA and EPPNB deposits [160]. The question remains as to the role of abrupt climate change in this process; certainly, increased levels of rainfall or heavy snows connected with RCC (HGC/10.2 ka calBP event) may have, on occasion, increased the weight of the slope, thus promoting slippage. It is, however, more likely that seismic events played a more significant part in weakening the slope fabric,

as evidenced by the detected earthquake damage in numerous buildings [160]. Although the EPPNB has been assigned to the K phase of the adaptive cycle, generally characterised by lower levels of vulnerability, it appears, at least in this very special case, that the behaviour and (building) traditions of the inhabitants had increased their susceptibility to be impacted by natural disasters.



Figure 8. Göbeklitepe—The terrace wall on the northern slope above Special Building D during excavation in 2001 (**top left**, vertical) and 2002 (**top right**). Note the steps in the centre of the terrace wall, leading down to the area below. Possible slope slide damage in Special Building D under excavation in 2023 (**bottom**). Images: author unknown (**top left**), author unknown (**top right**), L. Clare (bottom), German Archaeological Institute, Göbeklitepe Project.

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Currently, there are no absolute radiocarbon dates for the final settlement phase at Göbeklitepe. This absence reflects a lack of organic samples from post-EPPNB contexts at the site, a gap that will be addressed in upcoming seasons. However, despite the absence of radiocarbon dates, there is architectural and stratigraphic evidence of post-10.2 ka calBP occupation at the site; notably, this phase saw a return to smaller and more round-oval-shaped spaces, which appear to have been scattered throughout the ruins of the settlement, stratigraphically above EPPNB structures, perhaps serving as shelters for ruin dwellers or squatters [160]. The processes leading to the (gradual) abandonment of the site could be linked to numerous factors, including unsafe conditions due to erosion, further exacerbated by RCC conditions, earthquake impacts, and changes in subsistence strategies and socioeconomic systems. Indeed, Göbeklitepe was not the only site to have been abandoned at this time, as the focus of settlement in the area shifted from the hilly and rocky areas around Şanlıurfa to the Harran plain (Gürcütepe) and the Euphrates River Valley (Akarçay and Mezraa Teleilat).

10. Conclusions

Although no claims of causality can be made, the overlap of abrupt climate change, settlement dynamics, and socioeconomic developments in the archaeological record represents the first step towards identifying any such relationships. At this point, a significantly more crucial task is to identify periods when socioeconomic systems were more vulnerable to climate-induced hazards, thereby warranting further investigations, particularly if these coincide with known climatic perturbations. Some notable observations can now be drawn regarding potential human responses to abrupt climate change in the upper Euphrates and Tigris basins from the YD to the EH:

1. In contrast to the Southern Levant, where the milder and moister conditions of the Bølling-Ållerød interstadial had already promoted sedentism, there are no indications of this development in the upper Tigris and Euphrates basins, where sedentary lifeways among hunter-gatherer populations first become visible in the YD climate reversal. This process unfolded against inherently unstable socioeconomic systems, as characteristic of an α phase in the adaptive cycle, which, nevertheless, proved advantageous for spatial (demographic) dispersal.
2. The PPNA saw the adaptation of Epipalaeolithic (YD) subsistence strategies to the emerging EH environments. Climate amelioration at the onset of the Early Holocene was accompanied by an increase in the number of settlements and, consequently, population growth. The earliest settlements in the Taş Tepeler (also at Göbeklitepe) indicate that sedentism and associated socioeconomic systems had become established in this area, in line with the r phase of the adaptive cycle, when growth and interaction occur, with vulnerability levels decreasing to their lowest point. In small-scale societies, social differentiation becomes legitimised through kinship ties and cultural homogeneity. As such, this phase sets the stage for the subsequent EPPNB, when the large central sites, such as Göbeklitepe and Karahantepe, reach their demographic and cultural pinnacles.
3. The transition from PPNA to EPPNB is synonymous with the HGC, which coincided with a shift in material culture and settlement patterns. According to the model, the socioeconomic systems of the PPNA were already more resilient than those of the Epipalaeolithic and the EPPNB (K phase) even more so, meaning that communities would have been better able to cope with external impacts, including adverse (RCC) climate conditions. Despite the low vulnerability, this was the period which saw major changes in settlement patterns, including the abandonment of numerous sites along the Tigris and an explosion of (T-pillar) sites around Şanlıurfa. However, the

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palaeoclimate evidence for an RCC interval in the early part of the 9th millennium calBC remains weak; as such, the reasons behind the changes should probably be sought elsewhere.

4. Based on the available radiocarbon evidence, the 10.2 ka calBP event may have contributed to the social collapse in the MPPNB. The RCC interval coincides sharply with the rapid drop in available radiocarbon ages, perhaps suggesting that it would have impacted the more resilient part of the adaptive cycle (EPPNB; K phase) rather than its most vulnerable part (MPPNB; Ω phase). This can mean one of three things: (1) despite their high resilience, the impacts of the RCC at 8200 calBC were so severe that EPPNB buffering mechanisms were inadequate and unable to cope; (2) the available radiocarbon ages are still too few to sufficiently place the onset of the RCC interval in the archaeological sequence; or (3) the transition from EPPNB to MPPNB was not climate-related. At Göbeklitepe, the settlement was impacted by a series of slope slides, possibly triggered by earthquakes combined with the adverse effects of heavy rain and/or snowfall (erosional processes) associated with this RCC interval.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/heritage9050179/s1, Table S1: Radiocarbon data from Pre-Pottery Neolithic sites in the upper Tigris and Euphrates basins used in this study. Refs. [161–178] have been cited in Supplementary File.

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Data Availability Statement: No new data are presented in this paper; all sources of data used are cited.

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

calBC	calibrated Before Christ
calBP	calibrated Before Present
EH	Early Holocene
PPNA	Pre-Pottery Neolithic A
EPPNB	Early Pre-Pottery Neolithic B
HGC	Hunter-Gatherer Crisis
LIA	Little Ice Age
LN	Late Neolithic
LPPNB	Late Pre-Pottery Neolithic B
MPPNB	Middle Pre-Pottery Neolithic B

PPN	Pre-Pottery Neolithic
PPNB	Pre-Pottery Neolithic B
RCC	Rapid Climate Change
SPD	Summed Probability Distribution
YD	Younger Dryas
yr b2k	Years before AD 2000

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Article

Empty Shelves: Tracking the Flow of Goods During Ancient Climate Crises in Central Anatolia

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Abstract

Archaeological investigations of ancient climate change have become an important focus for many researchers. A number of studies have focused on scientific techniques to identify the intricate details of the event, and the subsequent impact of these climatic changes on the ecological landscape. These more scientifically oriented studies have allowed the present authors to investigate a more subtle impact on the landscape: trade disruption during ancient climate crises viewed from the rural settlement of Çadır Höyük on the north central Anatolian plateau. The ebb and flow of trade networks in the past can be tied to many external sociopolitical and socioeconomic factors that may have had little to do with the air outside. We investigate here whether climate change was a significant factor that interfered with trade networks during three periods: The 4th millennium BCE Late Chalcolithic (the 5.2 ka climatic event); the late 2nd millennium BCE (3.2 ka climatic event); and the Medieval Warm Period from the 10th to the 13th century CE. This study presents the evidence for regular, and sometimes robust, trade or provision of goods and resources prior to these three climate events, and the disruption or dissolution of these during the height of each climate crisis, particularly in the earlier two periods; in the last period, climate variability was only one of many factors affecting trade networks on the plateau. We profile how the residents of ancient Çadır Höyük managed these intermittent "empty shelves" and filled in gaps using local resources and ingenuity.

Keywords: climate; trade; Chalcolithic; Late Bronze Age; Hittite; Late Roman; Byzantine

1. Introduction

As the contributions to this theme issue illustrate, climate change affects every aspect of human life, no matter the time or place. This study investigates the effect of climate change on trade patterns at the site of Çadır Höyük in central Türkiye during three separate past climate events: the 5.2 ka event (3200 BCE); the 3.2 ka event at the end of the Late Bronze Age (ca. 1200 BCE); and the Medieval Warm Period (900–1200 CE). The site of Çadır Höyük, approximately 5 ha in size including the terrace, is located on the north central plateau in Yozgat province (Figures 1 and 2). Multi-year excavations have documented a largely unbroken occupation at Çadır beginning at least as early as 5200 BCE, with final

abandonment as late as the 13th century CE. During this time there were at least six climate events (Table 1); the three noted above are the focus here.

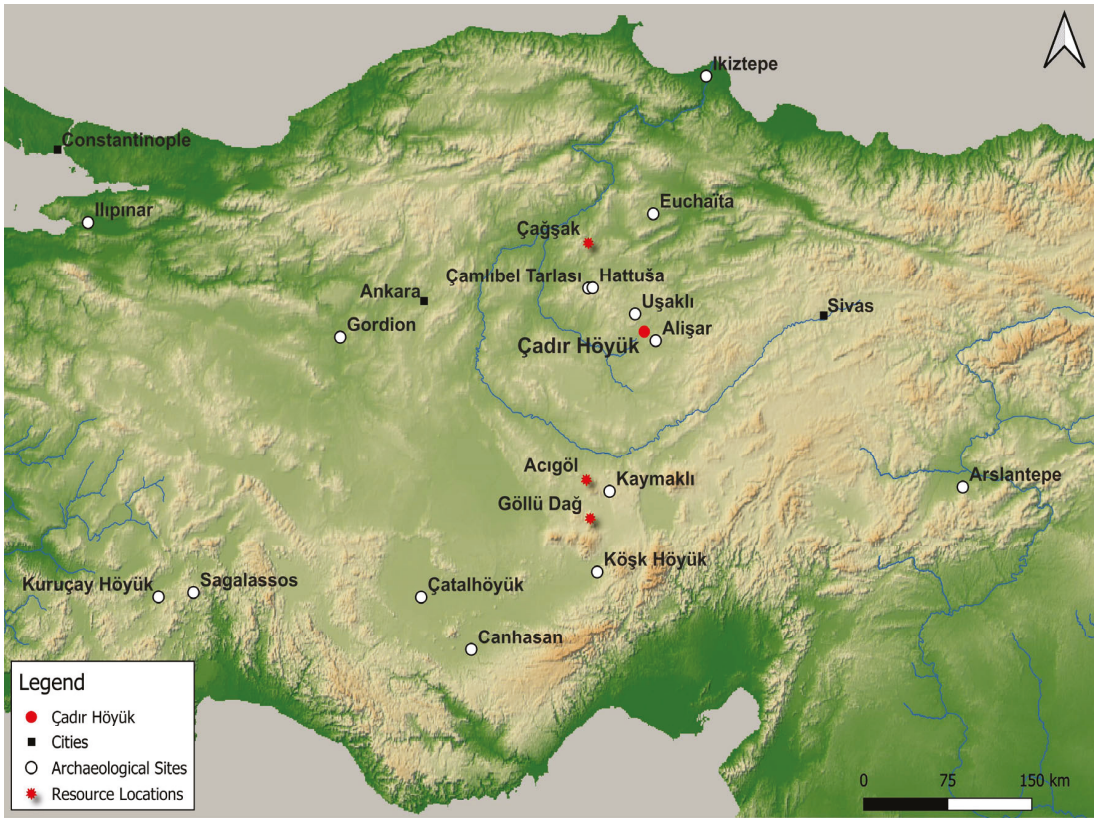


Figure 1. Map of Anatolia showing Çadır Höyük (map created by Anthony J. Lauricella).



Figure 2. Aerial view of the Çadır Höyük archaeological site (courtesy of the Çadır Höyük Archaeological Project).

Table 1. Table listing the six major climate events mentioned in the text, their corresponding archaeological periods in Anatolia, and references discussing each event.

Climate Event	Calendar Date	Archaeological Period in Anatolia
5.9 ka	3900 BCE	Late Chalcolithic [1–3]
5.2 ka	**3200 BCE**	Late Chalcolithic [3–5]
4.8 ka	2800 BCE	Early Bronze 1 [6–8]
4.2 ka	2200 BCE	Early Bronze 3 [9–12]
3.2 ka	**1200 BCE**	Late Bronze Age [13–17]
Medieval Warm Period	**900-1200 CE**	Middle Byzantine [18–20]

Long-term and meticulous excavations at Çadır have documented both minute and major changes in material culture distributions that signaled increased, decreased, or steady rates of local, regional, and long-distance trade relations. The waxing and waning of trade in these periods are also viewed in the context of regional and super-regional changes, some of which were loosely or primarily initiated by climate variability. The following study tracks this activity during periods of occupation that encompass the three intervals of erratic climate outlined in Table 1 (in bold). The data unequivocally demonstrate that climate change, which included increasing aridity and decreasing rain, impacted long-distance and regional trade for those living in this small, rural community, particularly in the earlier Chalcolithic and Late Bronze periods. In the Byzantine period, climate was only one of many factors affecting trade networks on the plateau. Though Çadır residents may have had to contend with intermittent "empty shelves," they developed ways to fill in material culture gaps by employing local resources and ingenuity, demonstrating a resilience lasting through six millennia of occupation at this rural farming settlement.

Investigations of climate change and ancient settlements commonly begin with the examination of subsistence provisioning such as agro-husbandry patterns traceable through standard scientific methodologies including archaeobotany, zooarchaeology, and soil analyses. These types of studies have indeed been conducted at Çadır Höyük [8,21–23]. However, archaeological excavations rarely reveal the entirety of a community. Given the nature of the Çadır Höyük site, i.e., a steep-sided höyük (human-created mound), exposing an entire settlement, let alone one belonging to three different periods in time, is impossible. For this reason, only trends in agro-pastoral management strategies, alterations in socioeconomic patterns, and settlement size over time, can be suggested. Measuring the effects of these trends is possible only in broad terms given that the relevant data derive from less than 100% of the settlement. However, we have collected an enormous amount of data over the past three decades of work at Çadır Höyük; these data allow us to offer a series of "snapshots in time" that enable a localized and detailed view of lifeways at a rural settlement. Here we investigate the three episodes of climate variation, each involving significant aridification which had a variable, but largely negative, impact on trade networks in this small rural farming community on the Anatolian plateau.

These three points in time were chosen for analysis due to their correspondence to significant climate events and because we have robust material culture and architectural data from these occupational periods, acquired during our 30+ years of work at the site. We also have nearly 80 radiocarbon and bone collagen dates from critical contexts in these stratigraphic layers, allowing us to key these three settlement periods to the climate events. Prior to an examination of the Çadır Höyük material culture that serves as our proxy for trade during these periods, the data used to identify these climate events are briefly reviewed. In addition, the locations of desirable raw resources and the likely travel routes

between these and the Çadır community are described. This tri-faceted approach presents a full picture of the trade process, from acquisition of raw resources to finished products recovered from excavations.

Archaeological analysis of trade patterns informs researchers about regional and long-distance networks, socioeconomic organization, community structure, and influence on sociopolitical patterns in a community; investigations at Çadır Höyük have demonstrated the intersection of trade with all of these factors during much of the site's occupational history [24–27]. Recent archaeological and scientific analyses identify the enormous and usually deleterious impact climate change has on these social institutions. Previously successful trade systems declined due to disappearing products, more dangerous (ecologically and socially) trade routes, and the difficulty of obtaining increasingly rare resources. The literature on ancient climate changes causing major regional migration, and the demise of ancient complex systems and empires across the globe, is too voluminous to list. The same can be said for the present century, which has seen a growing corpus of studies on how global trade patterns will suffer from current climate variations (e.g., [28–30]).

2. Climate Events and Subsistence Adjustments at Ancient Çadır Höyük

Common factors in the three variable climate periods examined include reduced rainfall—resulting in greater annual aridity—and variable but overall increasing annual temperatures. This section provides a more detailed description of each of these climate events. The diagrams and photos below are simplified visualizations based on paleoclimatic data and proxies from central Anatolia, including Tecer Lake, Nar Lake, Eski Acıgöl, and Lake Engir; they are all located on the central Anatolian plateau and can be regarded as suitable reference points for understanding the paleoclimate of Çadır Höyük. These diagrams are intended as visual summaries of the referenced climatic data associated with each of the major climate events.

2.1. The 5.2 ka Climate Event

There is a fairly substantial compendium of data documenting a climatic shift in Anatolia, and in fact across the eastern Mediterranean, in the late 4th millennium BCE (e.g., [3,5,17,31,32]). During the mid-Holocene, periods of aridity and decreasing rain occurred in roughly 500-year cycles, with one taking place near the beginning of the millennium, and another near the end, around ca. 3200 BCE; the latter is known as the 5.2 ka BP event. These data were derived from cave speleothems in Israel and Lebanon [33], lake cores and fossilized pollen samples in Anatolia [1,34–36], as well as syntheses of a variety of proxy data used to model climate fluctuations over the mid-Holocene millennia (ca. 5000–1200 BCE) [37].

The Tecer Lake core records a humid phase (3900–3300 BCE) indicated by a high intensity of clay deposition with numerous plant remains [34]. This long humid period corresponds with a dominance of woodland pollens [34,38] (Figures 3 and 4). Lake sedimentation also records the following 300 years (3250–2950 BCE) when Tecer Lake dried up, demonstrated by the dramatic decline in percentages of calcite, organic carbon, clay, and silt [34].

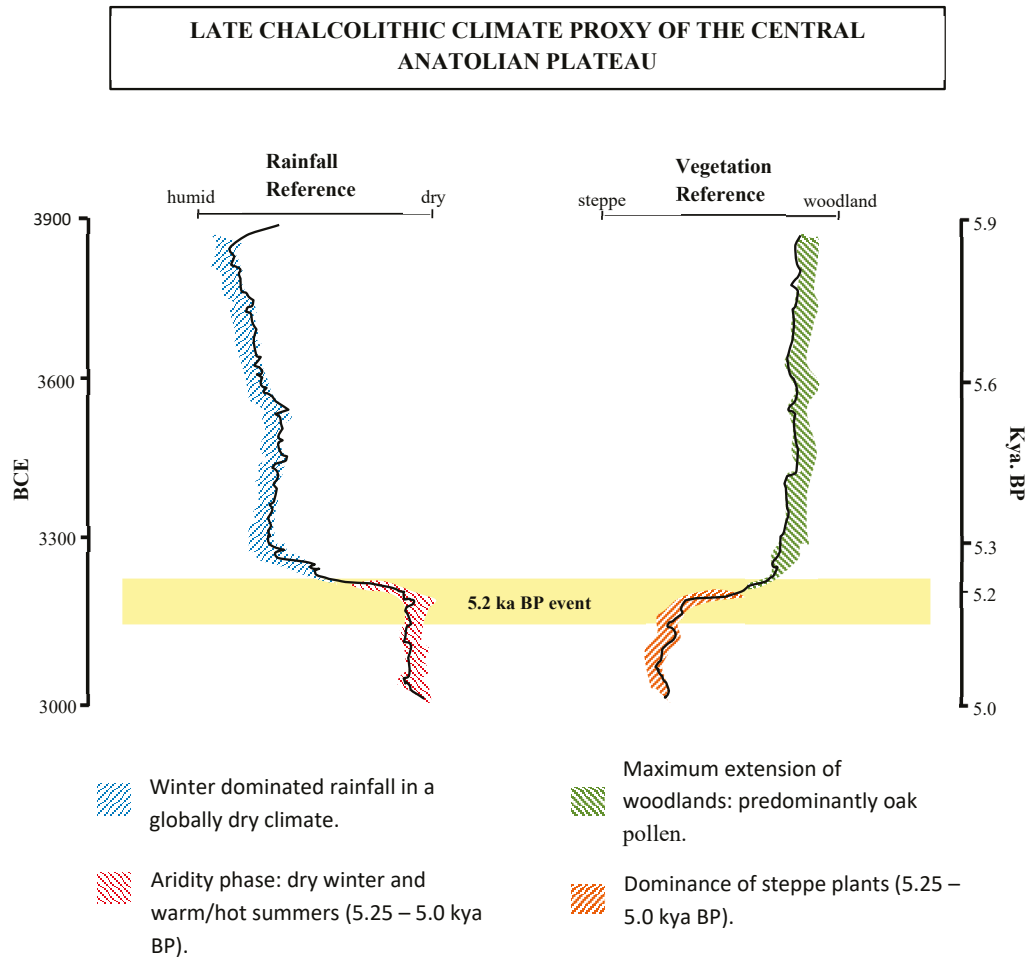


Figure 3. Rainfall and vegetation proxy diagram of the Çadır Höyük region during the Late Chalcolithic period using the paleoclimatic data from Tecer Lake, Nar Lake, and Eski Acıgöl Lake [5,34,38] (diagram created by Emrah Dinç).



Figure 4. Digital rendering of the probable woodland landscape around Çadır Höyük in 3200 BCE. The water south of the mound represents the Eğri Su, which fluctuated from a much smaller stream to a wider river depending on snowmelt and rainfall (photo courtesy of the Çadır Höyük Archaeological Project; Photoshop by Virginia Alvisi).

2.2. The 3.2 ka Event

The 2nd millennium BCE witnessed climatic instability in central Anatolia, indicated by data that are also derived from lake cores [34,38]. These climatic shifts manifested as a general drying trend, known as the 3.2 ka event, which peaked between 1200–1000 BCE [14,16,39]. Over the millennium, rainfall and vegetation ranges indicate an increasing arid trend interspersed by short humid episodes (Figure 5). The Tecer Lake core displayed high but fluctuating values of aragonite and sand, pointing to a shallow and often saline lake [34,40]. Rainfall variations (Figure 5) are reflected in erosional patterns, such as the high sand input during the more humid intervals between ca. 1900 and 1800 BCE, 1650 and 1600 BCE, and ca. 1480 BCE, due to springtime snowmelt and precipitation. The "humid intervals" served only as phases of abatement; the drying trend continued, peaking between 1300 and 1100 BCE [34].

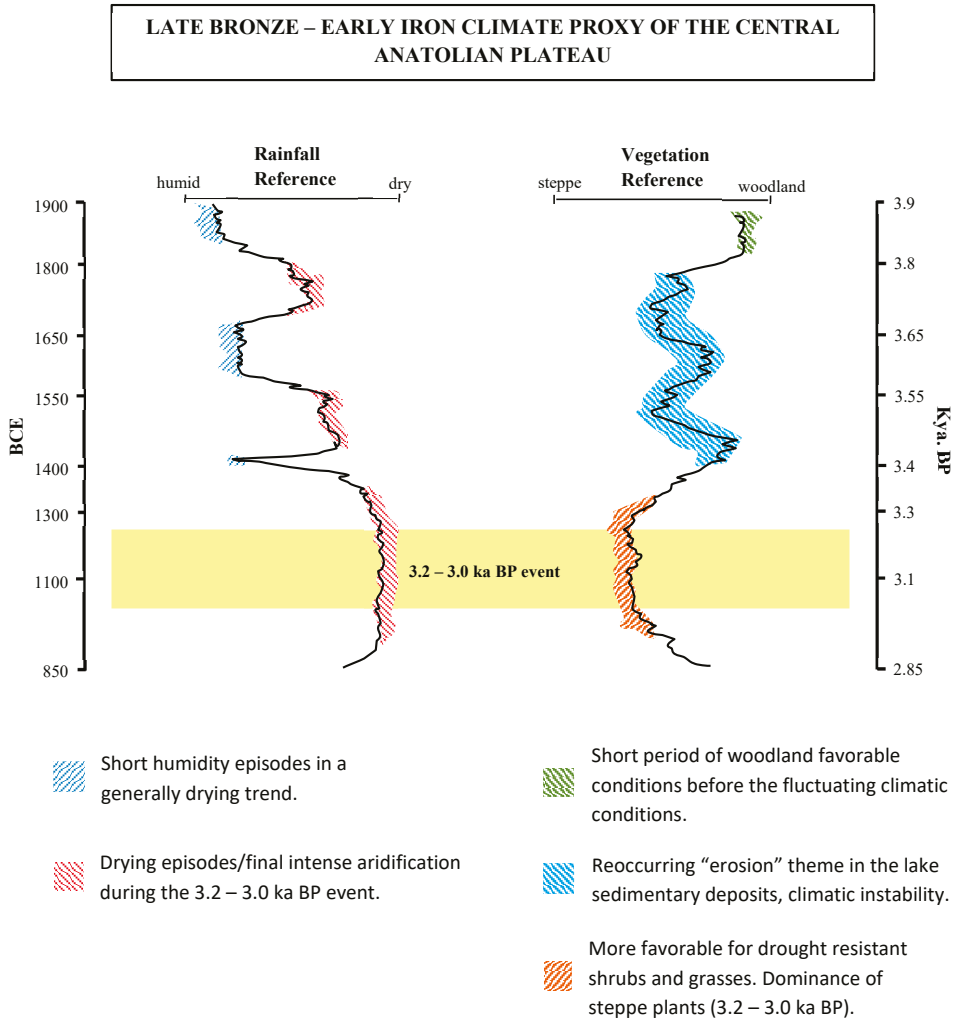


Figure 5. Rainfall and vegetation proxy diagram of the Çadır Höyük region during the Late Bronze and the Early Iron Age using the paleoclimatic data from Tecer Lake and Eski Acıgöl [16,32,34,38,40] (diagram created by Emrah Dinç).

Sediment data from Nar Lake and Eski Acıgöl present corroborative evidence. At Nar Lake, moisture availability was at the lowest beginning in the late 3rd millennium BCE until 600 BCE, and Eski Acıgöl sediments document the driest periods occurring between 1250 and 250 BCE [38,40]. The lake core vegetation indicators (Figure 5) point to more drought resistant shrubs and grasses after recurring erosional periods during and after the 3.2 ka event [38,40] (Figure 6).



Figure 6. Digital reconstruction of the probable woodland landscape surrounding Çadır Höyük just prior to the beginning of the 1200 BCE drying trend (photo courtesy of the Çadır Höyük Archaeological Project; Photoshop by Virginia Alvisi).

2.3. The Medieval Warm Period

Between 850 and 1300 CE, there were a series of widespread climatic anomalies across Europe and northern Eurasia, referred to as both the Medieval Climate Anomaly and the Medieval Warm Period [19,20,41]. To narrow down the highest period of impact on the Anatolian plateau, this study relies primarily on the sedimentation data in cores acquired from Tecer Lake, Nar Lake, and Lake Engir [32,34,38,40]. While these data show that the Medieval Warm Period was not a globally uniform event, they help to narrow down the highest period of impact on the Anatolian plateau. The Tecer Lake core suggests high rainfall rates between 500 and 850 CE, indicated by accumulations of sand over the lake floor [34]. Data also suggest that the Medieval Warm Period began in 850 CE and ended in 1130 CE (Figure 7); Nar Lake sedimentation suggests a different situation, during which a regional drying phenomenon was apparent before ca. 500 CE. This was followed by relatively wetter conditions until 1350 CE. However, a comparatively dry period paused the generally more humid conditions that existed after approximately 750 CE, which lasted roughly 200 years [34,38,42].

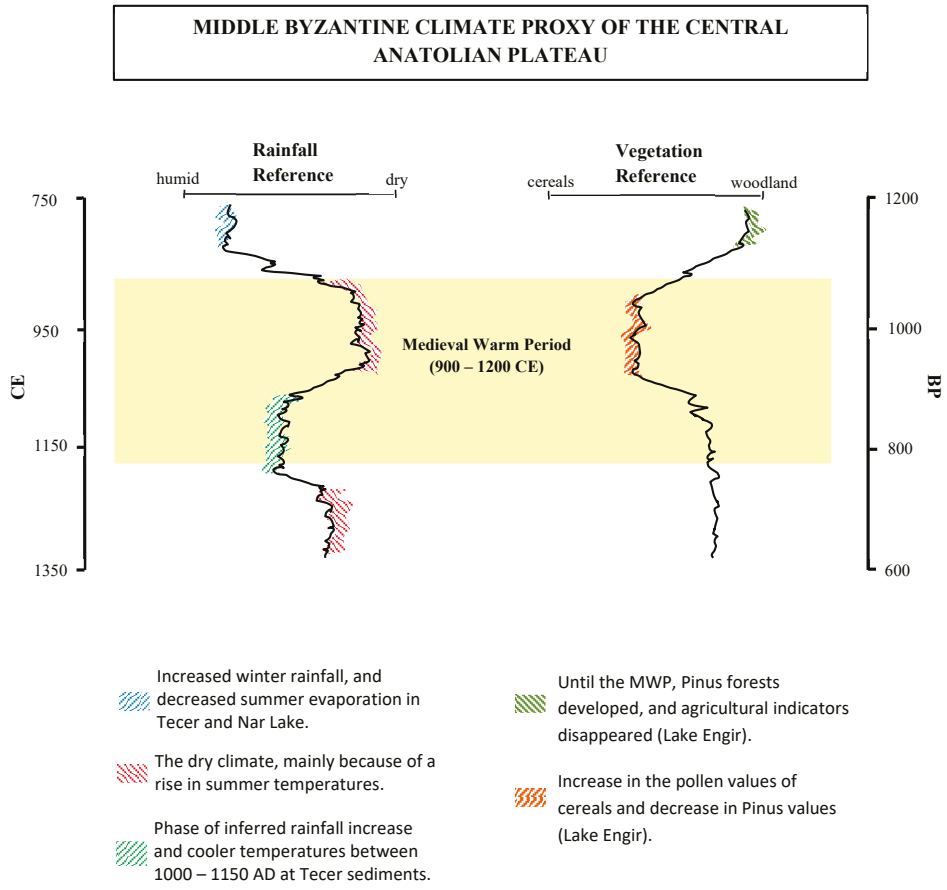


Figure 7. Rainfall and vegetation proxy diagram of the Çadır Höyük region during the Middle Byzantine Period using the paleoclimatic data from Tecer Lake, Eski Acıgöl, and the vegetation data from Lake Engir [18–20] (diagram created by Emrah Dinç).

Lake Engir vegetation data indicate that near the beginning of the Medieval Warm Period, cereal pollen values increased (Figures 7 and 8), and Pinus values decreased in response to lowered rain supply. By 1200 CE the woodland landscape seems to have been re-established [32]. The entire climatic anomaly appears to begin around 900 CE with temperatures abating and a more regularized rainfall pattern occurring between 1100 and 1200 CE. This study examines trade patterns before 900 CE and during the period spanning 900–1200 CE.



Figure 8. View of Çadır Höyük today showing sparse woodland coverage of the landscape, likely similar to that during the Medieval Warm Period (photo courtesy of the Çadır Höyük Archaeological Project).

2.4. Summary

Research at the site has always included intensive analysis of subsistence strategies (e.g., [43–47]), with recent analyses focusing more closely on how residents coped with these various climate events [8,21,22,48,49]. Zooarchaeological data are strong indicators of adjustments to animal husbandry patterns during these climate events. For instance, in the 4th millennium, Çadır residents began to dispense with the keeping of pigs, a water-loving animal that provided few secondary products [23,49]. More detailed analyses of our faunal data can be found in the discussions below.

The majority of the Çadır settlement's agricultural fields were most likely located in the area between the mound and the river to the south. Over the years, Gelingüllü Lake, which was created by a dam built down river, has deposited several meters of sediment over what was prime agricultural land, severely limiting our ability to identify subtle land management activities such as ancient irrigation systems. Though Çadır residents consistently preferred wheat, or a wheat/barley balance, archaeobotanical analysis has demonstrated that during the height of the 5.2 ka episode, wheat, which generally requires a steadier annual rainfall, fell out of favor [22,23]. A pilot soil health study also indicates that soil health decreased during the 5.2 ka event, perhaps from heavier field use (e.g., lack of fallowing) [49]. In contrast, initial comparative archaeobotanical data corresponding to the 3.2 ka event suggest a steady wheat to barley ratio and an absence of soil health decline throughout the later 2nd millennium. Earlier standardization of fertilization and possibly irrigation systems during the Hittite Empire period may explain the greater stability during the 3.2 ka event [49].

During these three periods of fluctuating temperature and rainfall, the matter of groundwater may have become an issue. This possibility is based on current ethnographic work being conducted in the region. Farming families have repeatedly noted that springs and wells are severely depleted or entirely dry; deeper drilling is now continuously required to access groundwater for field irrigation [21]. It is perhaps likely that a similar depletion of groundwater in the past, either as decreasing availability, or as disappearance of easily accessed water sources, might have seriously impacted movement (trade) across an increasingly arid landscape.

3. The 4th Millennium Late Chalcolithic

The Chalcolithic occupation at Çadır is found only on the mound (approximately 2.3 ha in size), and thus far, only on the southern slope. To date, there are five Late Chalcolithic phases at Çadır (Phases V–I); Phases III–I are the focus here (Table 2). The Burnt House ("BH") Phase III, subphases BH 3–2, occurred during a climatically stable period termed the Humid Intermission. The BH 2 subphase dates to the last several decades before the brunt of the climate event, though some climate variability may have already begun; we therefore term the BH 2 occupation the "Lead Up" period. The BH subphase 1 falls just before and at the beginning of the 5.2 ka event. The Phase II "Transitional" occupation spans the period during and just after the climate event. The Early Bronze ("EB") Phase I occupation is situated in the aftermath of the 5.2 ka event, potentially a period of "recovery."

Table 2. Table describing the Çadır Höyük names and dates of the Late Chalcolithic and Early Bronze Age stratigraphic phases relevant to the discussion, with corresponding subphases and descriptions of climatic periods.

Phase	Subphase	Tentative Dates	Climate Event
Phase III ("BH")	BH 3	ca. 3600–3300 BCE	Climatic Stability (Humid Intermission)
Phase III ("BH")	BH 2	ca. 3300–3200 BCE	Climatic Stability/Variability (Humid Intermission & Lead Up)
Phase III ("BH")	BH 1	ca. 3200 BCE	Onset of 5.2 ka event
Phase II *Transitional*	Tr 3–1	ca. 3200–3000 BCE	During/After 5.2 ka
Phase I *Early Bronze* ("EB")	EB 3–1	ca. 3000–2800 BCE	After 5.2 ka (Recovery Period)

3.1. Occupational Phases: Description

The majority of the Phase III BH (Humid Intermission/Lead Up) occupation saw a thriving Late Chalcolithic community composed of Eastern, Western and possible (currently unexcavated) Northern Compounds in the "Lower Town." At least one additional compound in the "Upper Town" (a terraced occupational level ca. 1.5 m above the Lower Town) was built during this phase [21] (Figure 9). The BH 3 Western Compound featured a ceramic production area ("Ompholos Building") which also functioned as a ceramic distribution center in BH 2 [50–53]. During subphase 2, a substantial Enclosure Wall and Gate system was constructed south of the settlement [25,54]. The gate led into a "street" separating the Western and Eastern Compounds with broad terraces rising to the Upper Town.

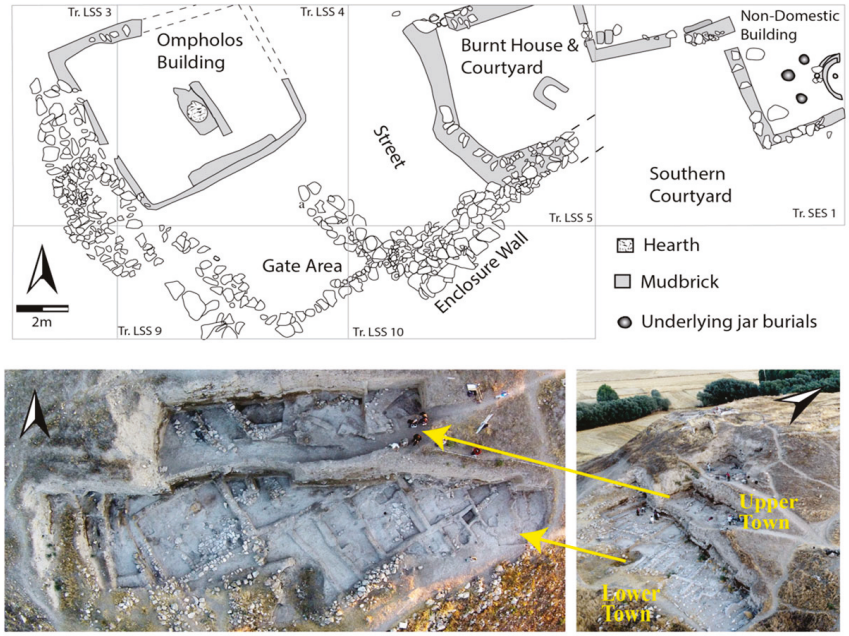


Figure 9. Top: drawing of the combined Phase III BH 3–2 subphases in the Late Chalcolithic Lower Town at Çadır Höyük showing the major areas mentioned in the text; **Bottom**: aerial photos (taken in 2017) showing location of the Upper Town in relation to the Lower Town at Çadır Höyük (drawing and photos courtesy of the Çadır Höyük Archaeological Project).

The BH 3–2 Eastern Compound was entirely domestic, comprising a residence known as the Burnt House, accessed from the street via a western courtyard [52,55]. Material culture in the courtyard included tools and materials associated with ceramic, lithic, and textile production [56]. East of the Burnt House was a "Non-Domestic" area that likely served a ritual purpose for the community [57,58]. A final notable area in the Lower Town was the "Southern Courtyard," which featured several hearths and work areas primarily for food processing and the production of pottery. It appears to have been accessible to the community, but may have also been partially or wholly supervised by the Burnt House residents [51,52,56].

The BH 1 Onset period saw the Lower Town slowly fall out of use and the gate blocked. By the subsequent Phase II Transitional height of the 5.2 ka period, the entire Lower Town was relegated to storage and some production activity (mainly lithics and textiles) [56]. In the EB (Phase I) Recovery period, small, rickety, rectangular structures were built, possibly as storage facilities. The Upper Town Transitional and EB periods saw a far more robust occupation, with work areas and ceramics production, including probable kilns. A large EB wall was built to surround the Upper Town community [56,59]. The Lower Town was effectively out of use by this period except for storage and temporary housing facilities.

3.2. Trade During the Late Chalcolithic 5.2 ka Event

At the center of the Chalcolithic materials analysis are obsidian, copper, and textiles. Metal and obsidian are present in measurable quantities throughout the target periods, and the production of textiles, ostensibly at levels sufficient for trade, is inferable through tracking herd ratios and slaughtering patterns.

In the 3rd millennium BCE, a major east–west trade route [60] likely passed somewhere north of the modern city of Sorgun, which rests 16 km north of Çadır Höyük. It is quite possible that this route was also used in the 4th millennium, with smaller networks connecting it to Çadır and nearby contemporary sites, such as Alişar Höyük and Çamlıbel Tarlası. As at Çadır, the Chalcolithic occupation at Alişar Höyük is found only on the mound. Alişar Höyük consists of a 3 ha mound with a surrounding terrace; overall the site is slightly larger than Çadır, while Çamlıbel at 0.25 ha is far smaller (other nearby unexcavated Late Chalcolithic sites identified in survey [61], such as Orta Höyük and Küçük Höyük, are smaller, at 2 ha and 1.44 ha, respectively). It is unclear whether residents at Çadır and neighboring sites traveled along the northern trade routes to obtain raw resources or awaited traders and "deliveries" to their communities.

The modes of transport for traders in the 4th millennium were limited. Though wheeled carts had likely been invented by the middle of the millennium [62], they may not have been widely used until somewhat later. The widespread presence of domesticated donkeys on the Anatolian plateau is not evident until well into the 3rd millennium [60,63]. The primary mode of transport available to traders, therefore, was likely human power. On average, depending on terrain and available resources such as food, water, and shelter, humans can travel approximately 25 km/day, somewhat less if heavily laden. It is this calculation that will determine journey-days in the discussion below.

3.3. Lithics

The lithics at Çadır Höyük are categorized here as "chert" (which includes chalcedony and jasper) and "obsidian." Weight calculations included recognizable tools, flakes, and cores; collections of debitage were excluded. Scientific analysis of chert sources has not been conducted at Çadır, though a regional survey has provided some indications of raw resource locations. Data on chert and obsidian sourcing are described in more detail below.

In the 4th millennium, chert was the primary tool-making material at Çadır Höyük (Figure 10). A regional survey identified small chert and jasper cobbles (50–89 mm in size) 2 km away in a river drainage [54]. Geochemical studies in the Yozgat province identified large chert/chalcedony deposits located to the north [64–66], the closest of which are ca. 50 km away from Çadır. The easy two-day journey to these sources would lead through landscapes similar to that surrounding Çadır, which featured hills and valleys of open steppe interspersed with pine/oak forests, streams, and natural springs. While "local" in nature, the retrieval of raw chert by Çadır residents or the distribution of these by regional traders required some effort.

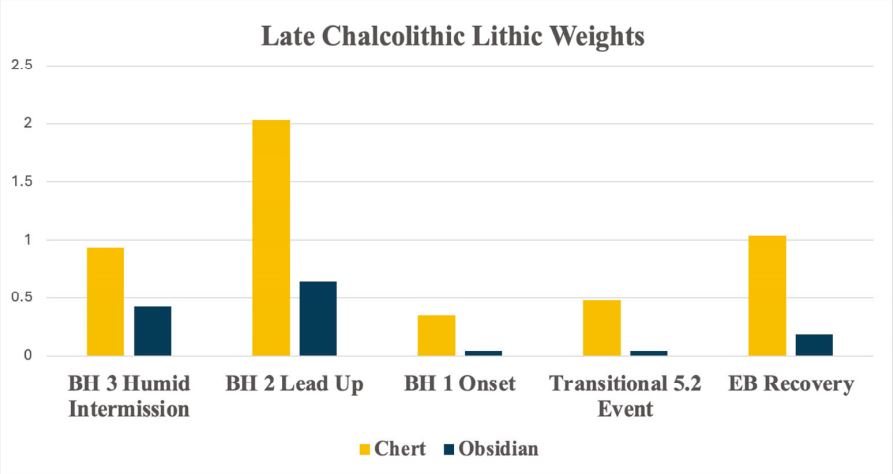


Figure 10. Top: map showing travel routes between Çadır Höyük and nearby Late Chalcolithic communities in relationship to chert and obsidian sources; **Bottom**: examples of chert tools (**left**) and obsidian flakes and tools (**right**) from Late Chalcolithic Çadır Höyük contexts (map created by Anthony Lauricella; photos courtesy of the Çadır Höyük Archaeological Project).

Obsidian is plentiful in Anatolia, but the closest sources are at Acıgöl, Göllü Dağ, and Nenezi Dağ in Cappadocia, some distance from Çadır Höyük (see Figure 10); pXRF analyses suggest that Çadır's obsidian indeed came from these sources [67]. The 180 km journey to Cappadocia would require an approximately seven-day trip. Traders between the two locations would likely have traveled through landscapes similar to that around Çadır as well as through river valleys. The Cappadocian landscape, even today, is considered somewhat arid; secure water sources would have been vital along the route.

Figure 11 charts both a visual ratio of obsidian to chert at the site and the associated weight data; also shown is the percentage of obsidian in each assemblage. These data indicate significant changes just before and during the 5.2 ka event. In the more climatically stable (Humid Intermission/Lead Up) BH 3–2 subphases, the sheer amount of chert and obsidian present at the site demonstrates robust lithics production. It is likely that lithics

were produced at capacities beyond household and community needs, perhaps at levels contributing to local and regional trade [51,52]. Obsidian made up over a quarter of the entire assemblage during this period. During the BH 1 "Onset" period, the amount of obsidian in the assemblage drops considerably; the distribution of tools, cores, flakes, and debitage in the Lower Town suggests that knapping activities, and possibly tool storage, were occurring at this time [56]. During the height of the 5.2 event (Phase II Transitional), the amount of obsidian decreased again, to 7%. In the EB "Recovery" period, there is a modest but noticeable increase of obsidian in the assemblage (15%), which might suggest that the residents were reconnecting to trade networks for this important raw resource.



Archaeological & Climate Phase	Chert: Wt. in Assemblage (kg)	Obsidian: Wt. in Assemblage (kg)	Obsidian: Percentage in Assemblage
Phase III BH 3 Humid Intermission	0.940	0.424	31%
Phase III BH 2 Humid Intermission & Lead Up	2.028	0.646	24%
Phase III BH 1 Onset of 5.2 ka Event	0.350	0.043	11%
Phase II Transitional During 5.2 Event	0.479	0.04	7%
Phase I EB Recovery	1.04	0.189	15%

Figure 11. Top: chart showing weights (in kilograms) of chert and obsidian tools, flakes, and cores at Late Chalcolithic Çadır Höyük during the periods discussed; **Bottom**: table showing percentage of obsidian in the lithic assemblage in each of the relevant periods (chart and table courtesy of the Çadır Höyük Archaeological Project).

These patterns suggest that obsidian trade declined rather significantly in the periods just before and during the 5.2 ka event. While this was expected, what came as a surprise was the apparent decrease in the amount of *chert* present in these assemblages. While the substantially lower weight in BH 1 may be partially due to its short (two generations or less) timespan, lower weights of lithics continue into the longer Transitional phase, suggesting that acquisition of raw resources may have become more limited. Both Phases II–I last roughly two centuries, and yet, they show a substantially different presence of lithic material. An accident of excavation areas may be the simple cause of this discrepancy. Another possibility is that even the acquisition of chert, especially during the peak climate event, grew more difficult. Studies to examine whether there was extensive reuse of all tools at this time are beginning. The EB Recovery period shows a substantially higher weight total possibly reflecting a reconnection to trade networks for this important raw resource.

The significant decrease in obsidian at Çadır Höyük during the 5.2 ka episode suggests that climate change may have figured prominently as a causative factor. The multi-day journey to Cappadocia would have required the surety of finding water along the way, making freshwater replenishment from potentially declining sources more precarious. Residents at Çadır may have thought twice before straying too far from home, and traders carrying obsidian nodules may have traveled routes closer to Cappadocia, turning it into a "rare resource" on the north central plateau. The two-day journey to chert sources was more manageable, but weight counts suggest that even this trek became less desirable during the 5.2 ka event.

3.4. Metals

Unlike obsidian or chert, which can be considered primarily utilitarian, metal was more of a luxury item in the Late Chalcolithic. At Çadır Höyük, the most common metal artifacts were copper pins, needles, and jewelry (Figure 12), all of which could be fashioned with other materials, such as bone or shell. Possessing copper items was likely a status marker. Copper pins and needles were scattered throughout the settlement while jewelry (bracelets, hair slides, rings) was primarily found in infant and child burials in both the Eastern and Western Compounds [57,58]. Our most remarkable metal find was a copper axe recovered from the Non-Domestic area. There is currently no indication of 4th millennium copper-working at Çadır Höyük. It would appear that copper-based items arrived in finished form via an active trade network.

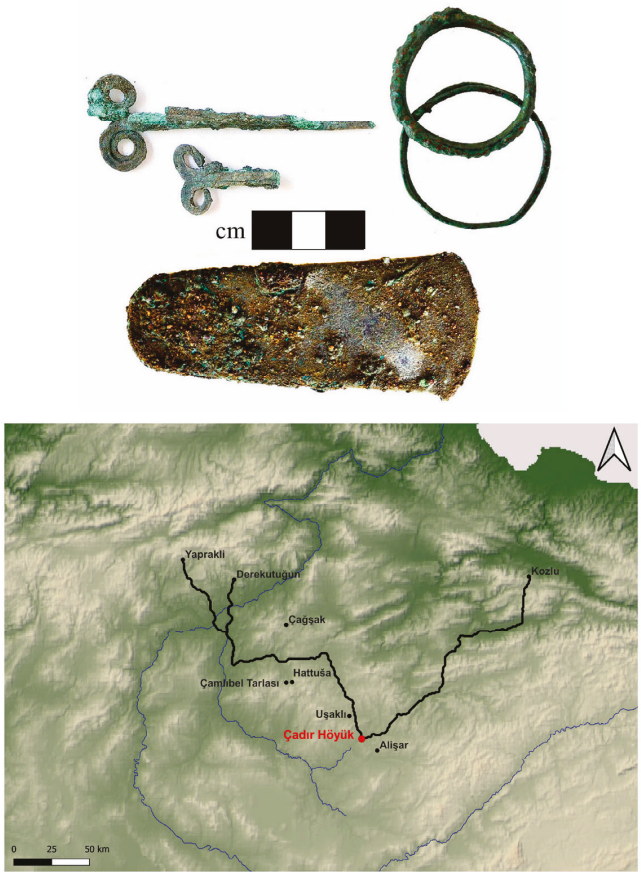


Figure 12. Top: examples of metal (copper) artifacts found at Çadır Höyük during the BH III 3–2 subphases, pins (**left**), jewelry (**right**), and axe (**bottom**); **Bottom**: map showing location of Çadır Höyük and nearby sites with Late Chalcolithic (and Late Bronze Age) occupations in relationship to copper ore sources (map created by Anthony Lauricella; photos courtesy of the Çadır Höyük Archaeological Project).

There are various zones of copper ore sources scattered across the northern plateau [68]; some are native (pure) copper ores and others are arsenical copper. Zones include the Yapraklı district northwest of Ankara (some native ore sources) [31,59], and the southern Pontic Mountain belt at the northern boundary of the plateau [69,70]. Some evidence of 3rd millennium BCE copper mining activity was discovered at Kozlu northwest of Tokat (mainly arsenical copper ores) [69,71,72]. Evidence of Chalcolithic mining activity of native copper was discovered at Derekutuğun in the Çorum district [73–75]. These sources range from 195 to 230 km from Çadır (Figure 12); the closest (Kozlu) required a roughly 8-day journey. The best route between Çadır and the closer metal sources crosses similar landscapes to those described for chert. To reach sources further north, traders would have to cross a broad open valley and the Delice Irmak River valley. Regular water supply points would have been essential on portions of this journey.

There is evidence of copper smelting at Çamlıbel Tarlası, located near the later Hittite capital, Hattuša. Çamlıbel was occupied from ca. 3590 to 3470 BCE [76], which corresponds to the BH 3 subphase at Çadır. Metallurgical activities took place throughout the occupational period there [76,77]. A survey of the region identified chalcopyrite vein fillings in basalt deposits just 2 km from Çamlıbel, which appear to be native copper [78,79]. Analyses of the slag indicate that Çamlıbel residents were making use of these nearby copper resources. However, the finished metal artifacts also contained arsenical copper, suggesting that local copper was alloyed with arsenical copper ores [79], possibly retrieved from the more distant sources, such as those described above. Çamlıbel Tarlası is much closer to Çadır, an easy 2-day journey, and may well have been part of a regional trade network.

Figure 13 shows the dramatic decrease in the presence of metal (as indicated by weight, in kilograms) at Çadır Höyük as the residents approached and then endured the 5.2 ka climate event. Unlike the rise in the acquisition of chert during the Recovery period, metal remained scarce. The data suggest that the metal/ore and finished product supply lines to the Çadır community became far more limited just prior to, during, and after the 5.2 ka event.

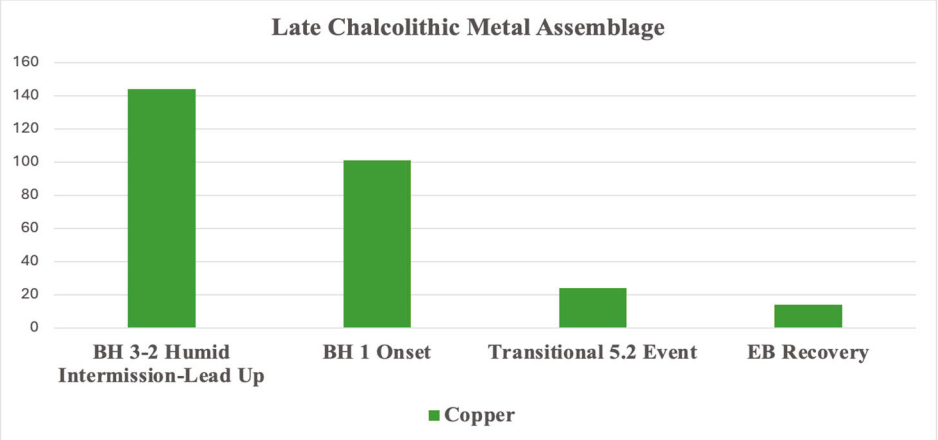


Figure 13. Chart showing the weights (in grams) of copper artifacts in the Late Chalcolithic periods at Çadır Höyük (chart courtesy of the Çadır Höyük Archaeological Project).

3.5. Textiles

The availability of textiles for trade is difficult to assess due to two main obstacles. The first is that some textiles were likely produced from plant fibers such as flax, as was the case at Çamlıbel Tarlası [80]. Flax, however, is present in only small quantities at Çadır. The second obstacle is that zooarchaeological data at Çadır has been recovered from only a percentage rather than the totality of the settlement, making it difficult to

determine the *size* of the herd through time, even if the ratio of species within the herd can be tracked. Nonetheless, a brief summary of our faunal analyses suggests that caprines at Çadır Höyük functioned as a critical source of secondary products throughout the periods under discussion, and as a consequence, residents may have served as producers of textiles to contribute to a dwindling trade network as the 5.2 ka climate event wore on.

In the BH 3–2 Humid Intermission/Lead Up periods, tools associated with textile production were a regular occurrence across the domestic Eastern Compound [56]. At this time, well over half of the herd assemblage consisted of caprines (Figure 14), of which nearly three-quarters were sheep [23]. Elsewhere, we have discussed the importance of wool trade with regions southeast of Çadır in the mid-4th millennium [51,52], which may explain the substantial sheep presence in the herd. In BH 2, the caprine percentage reaching adulthood increased substantially, indicating an importance of secondary products. The percentage of goats also increased; residents may have been experimenting with adding goat-hair felt production to their textile trade (Early Iron Age contexts have offered evidence of felt production at Çadır Höyük) [26,81].

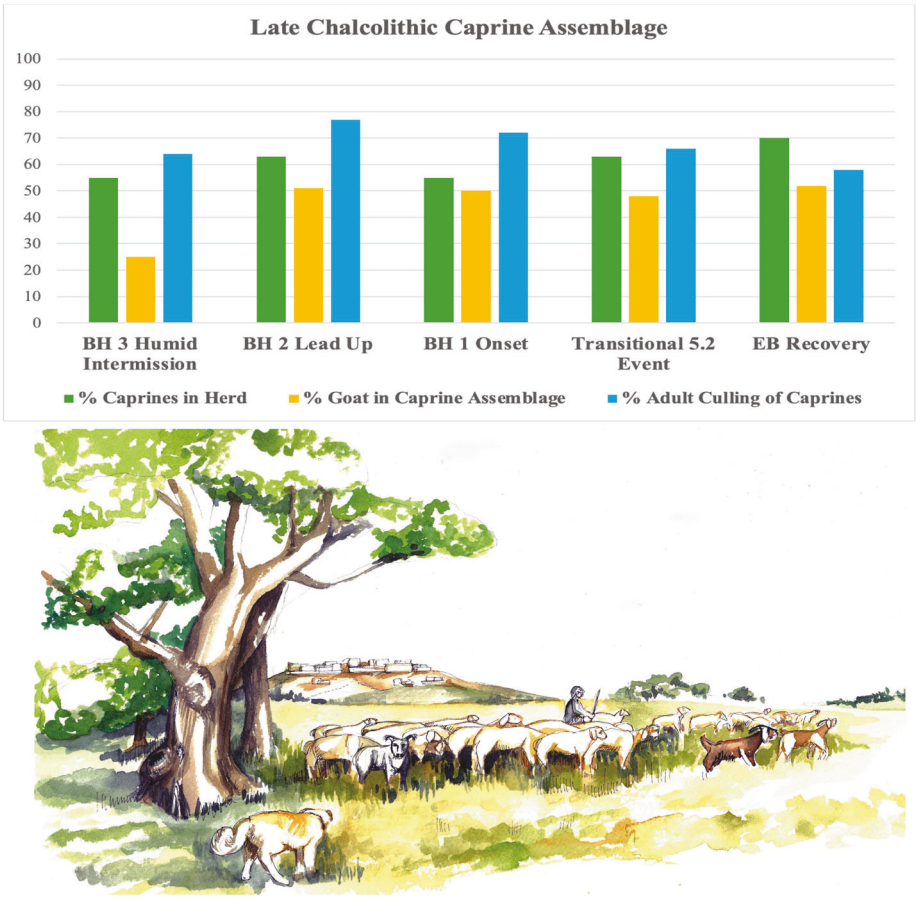


Figure 14. Top: chart showing the Late Chalcolithic caprine faunal assemblage data discussed in the text (chart courtesy of the Çadır Höyük Archaeological Project); **Bottom**: reconstruction of a Late Chalcolithic herd with a mix of sheep and goat, Çadır Höyük in the distance (watercolor drawing courtesy of Laurel D. Hackley).

In the shorter BH 1 Onset period, caprine percentages decreased somewhat. Adult culling remained steady at three-quarters of the herd, indicating a continued importance of secondary products in the community. During the 5.2 ka event in the Transitional period, caprines again increased in the assemblage, with sheep still dominating. A majority of caprines survived into adulthood. Though the human population had moved to the Upper

Town, there is extensive evidence of tools associated with textile production in the former Lower Town Eastern Compound courtyards. In the EB Recovery period, the caprine portion of the herd increased again; the sheep-to-goat ratio remained largely in balance, with adult culling dropping [49]. Textile production continued to take place in the Lower Town, and for the first time, extensive evidence of production tools is found in the Upper Town [56].

Secondary-product provisions from the caprine herd, especially fibers for textiles, were perhaps far greater in quantity than that needed to supply the relatively small Çadır community. Wool and felt may have been employed as trade products throughout the 4th millennium. The prominence of goats, which can range more widely for food and require less water than sheep, may have also reflected a more careful herd management strategy in an increasingly variable climate. Whether the size of the overall herd decreased during the 5.2 ka event is not known.

3.6. Summary

The lack of excavated Late Chalcolithic sites in the region surrounding Çadır Höyük does not allow us to assess whether regional trade suffered at the time of the 5.2 ka event. Çamlıbel Tarlası was not inhabited at this time, and Alişar's exposure is too small to assess trade involvement, or lack thereof. The few other very small sites discovered in our survey have not been excavated, so our understanding of trade networks in the region during the fourth millennium rests primarily on data from Çadır Höyük. The microscale excavations at Çadır allowed a detailed analysis focusing on the acquisition and possible distribution of utilitarian or luxury items over the course of the climate event. Data on obsidian and copper suggest a potential "empty shelves" situation; Çadır residents may have had little control over supply lines for these materials. There was some success at maintaining the acquisition of chert resources which were possibly procured by residents themselves. Evidence suggests extensive management strategies concerning the production of textiles; these potential commodities may have helped residents stay connected in what were likely quite diminished trade networks.

Though Çadır residents could "do without" metal, lithics were another matter. The drastic reduction in the chert/obsidian weight during the greatest climate variability period may have many explanations, including a reduced population (or one relocated to an as yet unexcavated Upper Town), though the far larger lithics weight in the Recovery period provides evidence that seems to refute these. Alternatively, stone tools used for some tasks could have been replaced by wood, bone, or even ceramic tools [82], but knives, blades, and projectile points really require stone. Careful reuse and reshaping of knapped tools could have become something of a cottage industry at this time. A detailed analysis of reuse/retouching may yield answers. The steady presence of a caprine herd, the products from which may have provided goods for local trade systems, and careful crop management strategies, allowed the Çadır residents to "weather" the 5.2 ka event into the Bronze Age, only to find themselves in the midst of additional episodes of climatic alterations in the 3rd millennium.

4. The Late Bronze Age and Early Iron Age

A significant amount of archaeological information from the central Anatolian plateau is available on the 3.2 ka climate event, a time that coincides with a set of larger-scale disruptions and collapses across the eastern Mediterranean at the end of the Bronze Age. In Anatolia, this change contributed to, but was not solely responsible for, the decline and disappearance of the Hittite Empire. Çadır is one of many mound sites in the area with evidence for occupation during the Hittite Old Kingdom (1700–1500 BCE) and Empire period (1400–1180 BCE); Hittite texts indicate that the central government, located about

70 km away at Hattuša (modern Boğazköy), administered towns within its core region in a variety of ways. Given its size, Çadır is likely to have been subordinate to one of the larger settlements in its vicinity, either to Uşaklı Höyük (10 ha in size) to its north or Alişar Höyük (at this time, possibly over 18 ha including its terrace) to its south [83–85], or perhaps to both.

4.1. Occupational Phases: Description

Çadır was occupied throughout the 2nd and 1st millennia and thus during the 3.2 ka event. Evidence for Hittite-period/Late Bronze Age occupation has been recovered predominantly in the Step Trench on the east side of the mound (Figure 15, top), where architecture and material culture of the Hittite Old Kingdom and the Empire period is spread over at least 400 square meters [53,54,59,86]. More limited exposure on both the north and south slopes of the mound has also revealed Hittite-era remains; following the 3.2 ka event, occupation in the Early Iron Age (1180–900 BCE) has been attested in situ only on the upper southern slope [26,27,81,82].

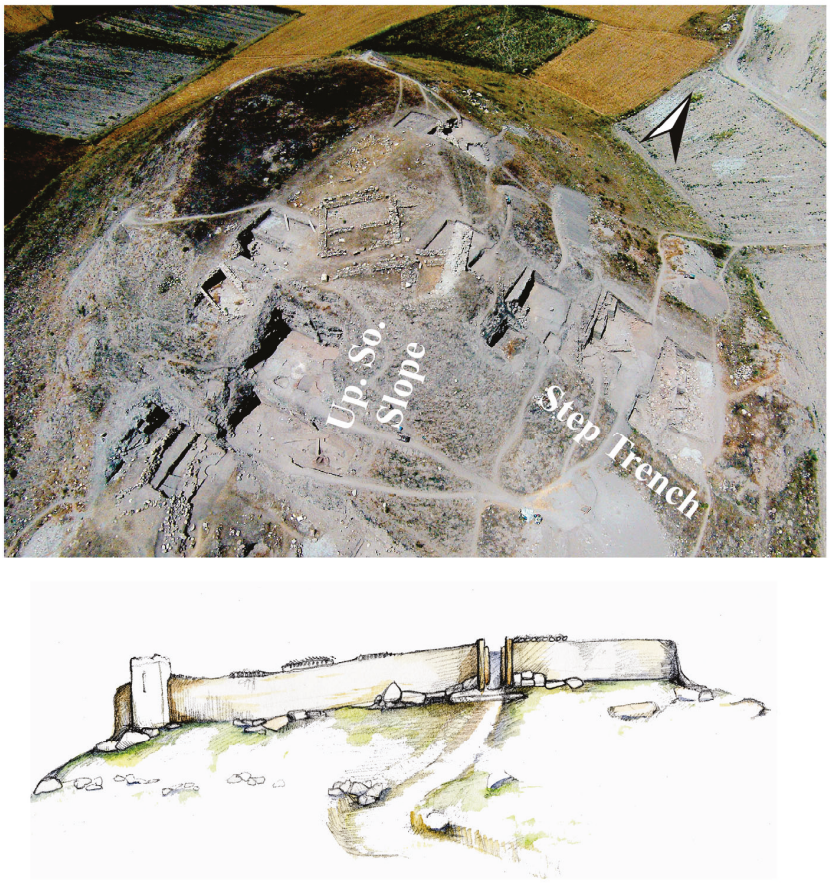


Figure 15. Top: Aerial photo of mound showing locations of the eastern slope Step Trench and the primary Late Bronze/Iron Age trenches on the Upper Southern Slope; **Bottom**: reconstruction of the Hittite wall at Çadır Höyük, the Step Trench tower on the left (photo courtesy of the Çadır Höyük Archaeological Project; watercolor drawing courtesy of Laurel D. Hackley).

Precise dates for the Hittite-period occupation in the Step Trench are still in flux; recent C14 results required significant revisions to the dates of specific phases based on samples run in 2024 [87]. This new evidence indicates that the eastern slope of the mound, or at least a significant portion of it, was fortified in the mid-2nd millennium Hittite Old Kingdom period; these fortifications were of impressive size, and modified multiple times. They included a 3–4 m wide casemate wall and tower (Figure 15, bottom); a gateway with

massive stone foundations on the northern side of the mound may belong to the same phase, or to later during the Late Bronze Age phases (see below). These fortifications were probably repaired, strengthened, and reused during the Empire period.

Inside the wall in the Step Trench are additional architectural remains, many of them belonging to the Hittite Old Kingdom, and some post-dating that. Buildings were relocated further inside the walls during the Hittite Empire period, but no free-standing or fully-excavated structure from the Late Empire period has yet been explored as these lie below the Byzantine Upper Town. The northern gateway's orientation toward both Uşaklı and Boğazköy may indicate a new or renewed focus of attention toward political and religious sites to the north (Figure 15, bottom). Buildings within the walls on the east side of the mound were well-built, with significant attempts to level or terrace the sloping ground, and stone foundations atop which were mudbrick walls.

Toward the end of the Late Bronze Age, new occupation levels on the upper southern slope of the mound indicate a significant change in the nature of occupation. Here, a tall mudbrick perimeter wall stood during the Hittite Empire, though without the stone foundations typical elsewhere on the mound. Built into the superstructure of this wall were workspaces that reused the wall in support of activities that required heat/fire. One facility of uncertain function was rebuilt twice after its original use, the final time with the addition of a finely polished plaster surface surrounding a small burnt depression (visible in Figure 15, top). None of these features attest to the prolonged firing or baking activities of a kiln or oven; they seem to have been subject to short-term use. The only burnt material found in association with them consisted of animal bones that had been calcified beyond identification. This phase, as will be described in greater detail below, includes major material culture changes.

While post-Hittite empire occupation during the Late Bronze Age occurs at a limited number of sites on the plateau, Çadır is one of the only sites demonstrating continuous occupation through the collapse period and into the Early Iron Age (see below). During the Early Iron Age, which dates to just after the 3.2 ka event, the work areas for manufacturing processes expanded but likely shifted in function. Rather than a set of heat-based facilities, the southern slope at this time featured a series of open-air, rounded, plastered depressions, usually 1–2 m in diameter and 10–15 cm deep. Sometimes, low stone wall segments separated these installations from one another; in other locations, smaller pits surrounded larger ones. The only consistent contents were large pieces of charcoal or charred wood, but without evidence that substantial burning took place within the pits (they were not hardened by repeated or sustained heat). The care taken in the creation and maintenance of these frequently replastered features argues against a use for rubbish disposal. Based on similar but later Middle and Late Iron Age features in the same trench, which were associated loom weights and other textile production evidence, we have proposed that these Early Iron Age work areas were devoted to the production of leather and felt items [81]. Such a function would explain the ubiquitous presence of animal bones (see below).

4.2. Trade in the Age of the 3.2 ka Event

Hittite texts from Boğazköy and provincial centers offer a great deal of information on the basic workings of the Hittite imperial economy and on the central government's relationship with local centers. The focus of these texts mostly concerns how the economic workings of the local territories benefited the political and religious center. They also include reports from the countryside, where local religious festivals were observed by government officials [88].

The archaeological evidence afforded by sites like Çadır is no less illuminating. Residents at the site during the Empire period pursued an agro-pastoral economy, providing

for most of their own dietary needs. Hittite economic texts suggest that rural centers also provided significant numbers of animals and animal products to the government, with a focus on meat-heavy large animals like cows [89,90]. Rural settlements were also responsible for provisioning the king and royal court when they traveled from Hattuša to celebrate annual festivals. For Çadır's residents, that probably meant sending animals, dairy products, and other foods to larger towns with temples, like nearby Uşaklı Höyük. Faunal evidence from Hittite Empire contexts indicates that the local residents kept cattle and caprines; survival rates to adulthood in both categories suggest the importance of secondary products in this period [48].

Non-local materials during the Hittite Empire period at Çadır Höyük appear in small numbers, and are indicative of a moderate level of engagement in the larger political and economic sphere. The range of fabrics found in 2nd millennium ceramics is probably greater than would have been typical for local potters; instead, a wide array of combinations of clays, grit temper, mica, and crushed ceramics (grog) is probably due to ceramics arriving at the site (with or without contents) from other places. The same variety is typical of the forms as well. Cannon suggests that people from surrounding smaller settlements may have gathered at Çadır for religious festivals, bringing offerings and pots for their own use [91].

Coming from greater distances were metal (copper alloy) pins, beads, and other ornaments (Figure 16). The nearest copper source to Çadır is to the north [74] (see Figure 12), so the raw material may have passed through the political center at Ḫattuša and been shaped there into particular forms before being disbursed or sold to places further south. Obsidian, found in quantities that were much smaller than in the Chalcolithic levels, but still significant to the production of tools, would have come from the opposite direction (see Figure 10).



Figure 16. Late Bronze Age artifacts from Çadır Höyük mentioned in text: incised bone/ivory bird (**top**), copper nail or pin (**top right**), bone pin and plaque (**middle**), stamp seal with image of griffin (**bottom left**), and stamp seal with geometric design (**bottom right**) (photo courtesy of the Çadır Höyük Archaeological Project).

Other objects of more luxurious types and uses may have also arrived as gifts or precious belongings of the leaders and wealthiest residents at Çadır; these provide evidence of additional connections to the imperial capital. These included bone and possibly ivory objects of uncertain use, such as a long trimmed shaft culminating in the head of a bird (perhaps a pin), and bone overlay or segments from wooden objects like furniture (Figure 16). The earlier Hittite-period levels also yielded stone stamp seals of types found also at Boğazköy and Alişar [85,92] (Figure 16). These seals, which are engraved with geometric, floral, and animal designs, attest to involvement in administrative activities by residents of the site. While no clay tablets have been found, Çadır officials may have used their seals on door closures, to control and protect items in storage, or on vessel closures or bullae accompanying objects being sent to another settlement. These objects attest to connections with other production centers, and the supply of materials and goods beyond the immediate locality.

The closest parallels to the material culture of Hittite-period Çadır come from Alişar, a far-larger Hittite center of this time, with evidence for administrative functions in the form of cuneiform texts and larger numbers of excavated seals [85]. Those similarities extend to the presence of a hoof-shaped stamp seal with curving herringbone designs at both sites, and similar griffin designs as central seal devices. Çadır is so far missing seals bearing inscriptions, suggesting a more marginal location vis-à-vis central Hittite administration. Both Alişar and Çadır also feature bone plaques with carved concentric circle designs that came from boxes or furniture; these suggest a degree of luxury production, gift-giving, or access to the same suppliers.

In the years just prior to the 3.2 ka event, evidence from sites throughout central Anatolia suggests that the Hittite Empire was already losing its grip on territories close by, and even at the capital city itself [93]. Just after the collapse, there was a general abandonment of settlements across the plateau; these settlements may have previously acted as suppliers and consumers of Hittite trade items. This trend can be seen at sites near Çadır Höyük, such as Uşaklı Höyük and Alişar Höyük. At the latter site, the next recognizable occupational layer dates to the Middle Iron Age, suggesting an Early Iron Age abandonment; at Uşaklı Höyük, ceramics identified as Early Iron Age have been collected, but settlement remains above those belonging to this period are lacking [85,94]. At Çadır Höyük, the short-lived pyro-technological facility on the upper southern slope belonged to that period. Relatively few objects come from the levels belonging to this transitional period, compared to the contents of the Hittite Empire period contexts. Specifically, ornamental and administrative items disappeared. Very few metal objects were present, comprising just a couple of pins or nails, and a small copper alloy bead. The stone tool assemblage includes groundstone objects (from local granitic sources), chert, chalcedony, and a small amount of obsidian. Bone tools also appeared in these layers. Significantly, a wide array of shaped sherds (into various types of tools) also occurred, suggesting that the residents repurposed available materials to substitute for raw materials to which they no longer had access.

Finally, in the Early Iron Age, after the climate crisis had passed, Çadır rebounded in terms of the intensity of manufacturing activity and, presumably, other economic activities. Supplies of luxury items appear to have been more limited than previously, but copper-alloy objects were found in significant numbers, and in forms (pins and beads) familiar from previous periods. Recent NAA work indicates that Çadır shared ceramic wares, and even possibly clay sources, with nearby Alişar during the Middle Iron Age [95]. Previous testing revealed a wide range of compositional groups at Çadır during the Middle and Late Iron Age (and increasing with time), suggesting some movement of ceramics into the site [96]. Meanwhile, the assemblage of faunal material indicates that the number of caprines kept by

residents grew, with significant declines in percentages of cattle (70% caprines as opposed to 18–19% cattle) [48]. These numbers suggest that there were fewer administrative demands on production, and that the local residents pursued herd management strategies that were less dependent on water supplies, and would take animals to more distant pastures, acknowledging the local effects of a prolonged drought.

4.3. Summary

The picture presented above speaks to the stresses produced on the local and regional economy by the 3.2 ka event, and the simultaneous breakdown of political control that both exacerbated the crisis and left room for adaptations at a local level. Çadır Höyük's geographical position as a small center between two larger Hittite sites with administrative and religious functions suggests that it was subject to the economic forces that sustained the Hittite Empire, including demands on Çadır's resources and redistribution of trade goods (metals and fine objects) to its leaders. As the Empire declined just before the 3.2 ka event, Çadır may have found itself with fewer supplies, and fewer demands. The response by its residents seems to have been to turn to more local goods, especially animal products, to support its agro-pastoral economy, a strategy they built on as climatic conditions became more challenging, and maintained for some time following the amelioration of drought conditions.

5. The Late Roman and Medieval Period

Over the last two decades, excavations of Late Roman and medieval remains at Çadır Höyük have provided an important diachronic survey of a small rural community in central Anatolia. Very little has been written about the connections between small villages and roads (and links to larger regional centers), even though this is key to considering trade and communication in the region. Nevertheless, it is clear that the climatic events both at the end of the Roman Warm period (5th–6th century CE) and the subsequent Medieval Warm Period (900–1200 CE) contributed to shifting social structures throughout Anatolia, and this had a considerable impact on trade between the major coastal centers and the plateau. In considering trade in relation to the site, two seemingly contradictory points become clear from the material remains. First, the site was in almost constant use between the 5th and 11th centuries, with probable seasonal use by the Seljuk pastoralists during the 13th century. Second, even though there was continuity of habitation, the population was in continuous flux, reacting to changing social and environmental factors (e.g., the Medieval Warm Period). This has resulted in material culture that reflects the local community throughout most of this period, as opposed to providing obvious connections with the wider empire. Considering trade and roadways raises questions about what it meant to be an *active* rural site during the medieval period in Anatolia.

5.1. Contextualizing the Late Roman and Medieval Period on the Plateau

A number of sites surrounding Çadır provide evidence for Late Roman material culture, including Kerkenes, Alişar Höyük, Tavium (near Yozgat), and Sarıkaya, with its massive Roman bath complex (Figure 17). All of these sites were connected by complex road systems that allowed ease of travel and trade from the coast of Asia Minor to the inland parts of Anatolia [97]; these roads were established during the Imperial period. Earlier detailed studies of the road systems [98] identified Roman roads and milestones established throughout central Anatolia during the Imperial period, a process which continued into the 4th century at least [99]. Belke argues for the inclusion of road systems as part of the *structure* of empire, and suggests that these roads were built to allow for vehicles such as large wagons, making it possible to move goods across Anatolia. For example, even

sites off the major roads, like the one that ran between Tavium (near modern Yozgat) and Sebasteia (modern Sivas), and the road which ran towards the heart of Cappadocia, would have had access to some imports. However, the small finds and ceramics at Çadır suggest that it was never a key destination for imported material culture.

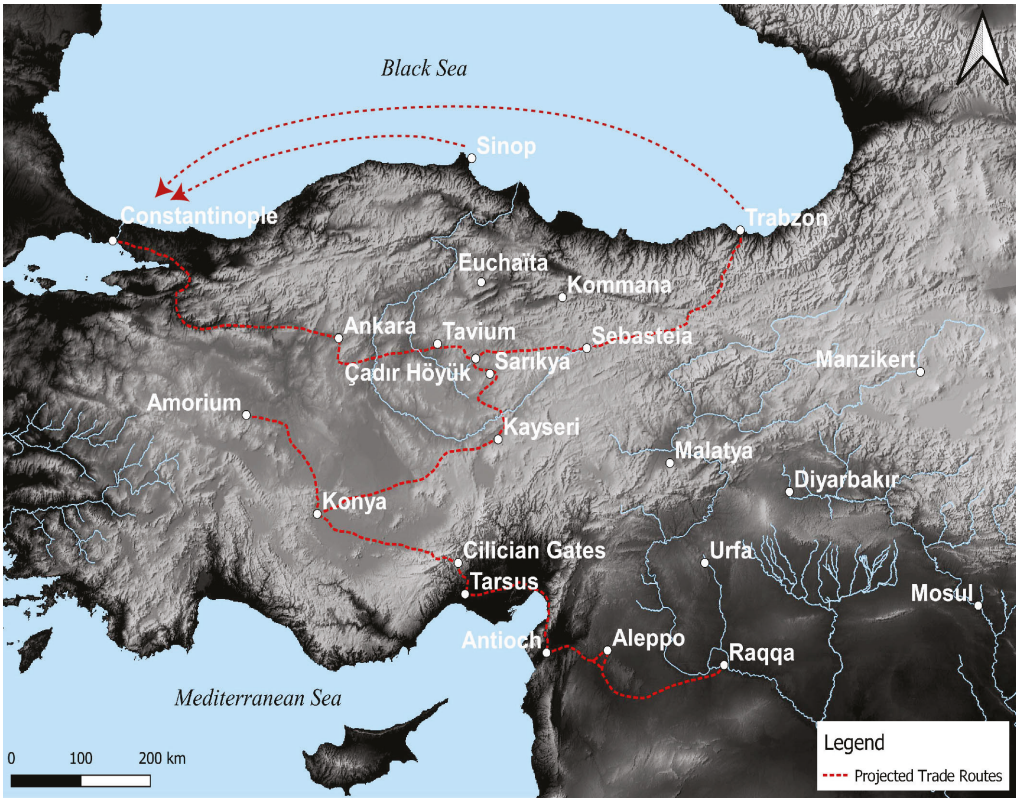


Figure 17. Map showing Çadır and other Byzantine-era sites discussed in the text (map created by Anthony Lauricella).

As the Late Roman world transitioned to the medieval or early Byzantine period (7th–9th centuries), there was a noticeable decrease in the kinds of material culture visible at Çadır Höyük. This parallels the decline of urban centers on the Mediterranean coastline, and the shift to more rural economies in Anatolia. Following Belke's (2020) assessment, *some* of the roads in the region fall into disrepair at the end of this period; there was simply not enough money to keep all of the roads established in the Imperial period in good repair. Belke points out the passages in Procopius' *On Buildings* [100] in which Justinian had to lay down money to make roads and bridges passable (V 4–5, for example), suggesting that even by this time some of the infrastructure in central Anatolia was weakened [97] (p. 81). As less and less traffic and trade moved through the regions, secondary and tertiary roadways became overgrown and some simply disappeared, a problem noted in sources like the *de Thematibus* into the 8th and 9th centuries [101].

Nevertheless, some major routes needed to be preserved. Those leading across the plateau to Sebasteia, for example, were essential to keep the newly developed theme system connected and to move armies across the landscape [101,102]. Armies, however, were not solely made up of manpower; they also included baggage trains, which required roads in good repair, as can be seen in Book V of the *Strategikon*, which focuses precisely on this problem [103]. For this reason, some major roads needed to be maintained, even as others were abandoned. Alişar Höyük, for example, seems to have minimal evidence for settlement during this period, although the oversimplified analysis of this period in the site reports may also be to blame [85]. Kerkenes needs further exploration to determine

whether it had an early Byzantine phase following its Late Roman one [104]. Overall, the impact of a variable climate, including uncertain rainfall and replenishing of streams and springs, may have had an impact on both landscape occupation and various tributary trade routes during this stage of the Medieval Warm Period, but not on the major arteries serving the larger centers [105,106].

During the late 9th and 10th centuries, central Anatolia resurfaced as a significant focus of attention, largely due to a renewed defense of the southern and eastern borders. Much of the renewed building in the region, however, was the result of the increased power of local families in provincial areas. Cappadocia and parts of Charsianon, including where Çadır Höyük is located, became known for raising and herding cattle, which was the purview of powerful local dynasties [107]. Other than the families who made it to the imperial throne, such as the Komnenoi from the Pontic region, most of these provincial families are known through prosopography, family connections with the imperial court, and localized rebellions evident in Middle Byzantine texts. Nevertheless, all of this provides circumstantial evidence for a resurgence at many sites, albeit with different foci of production.

Within the wider region of Çadır Höyük, choices were made about which sites were rebuilt or continued to function. Kerkenes underwent a transition in this period with the addition of a *kastron* (although the exact date of this construction is uncertain). Tavium and Sarıkaya continued to be in use, while Alişar seems to have had no substantial occupation. This probably accounts for attention to local roads as well. Some road systems—again the one linking Tavium to Sebasteia—continued to be in use, while others were revitalized. Belke draws attention to the fact that certain roads needed to be cleared, such as one of the roads in Cappadocia in the 9th century [97]. However, there was once again more money and infrastructure to do this than in the early Byzantine period, albeit now much of it was connected to powerful local families. Nevertheless, the focus on the local continued, and there seemed be no discernible need among the population for imported goods.

The reconstruction in this region was largely the result of social change coming from different directions. Less frequent attacks from the Abbasids as they underwent a period of change allowed for a renewal of defensive measures on the plateau. The early Macedonian dynasty also understood the significance of protecting rural communities, which once again began to thrive during this period. The effect of the Medieval Warm Period was largely felt as a trickle-down effect in the hinterland. It allowed for increased agriculture, although in central Anatolia, there was a wider shift to herding cattle. However, the growth of the provincial dynasties was largely the result of increased security working in conjunction with the early Byzantine isolation of the region—-which was then further supported by the better conditions of the Medieval Warm Period.

Though little explored, the landscape continued to be in use during the Seljuk period, again with a local focus. Some centers with earlier heritage remained significant, such as, most notably, Sivas and Kayseri. Others became secondary or tertiary cities, which was most likely the case for sites like Tavium [108]. Nevertheless, the system of roads and travel caravanserais remained intact throughout the Seljuk period, with considerable growth in the late twelfth and thirteenth centuries. The region around Çadır Höyük was utilized primarily by pastoralists who almost certainly used the area seasonally. While there is little evidence for this as a major trade route, it does seem, according to the routes posited by Yüksel, that the route between Sivas and Tavium remained intact, if less important [108]. Less direct contact between Kayseri and Tavium is suggested, which is in keeping with the localized and sporadic small finds and architecture dating to the Seljuk period in the region at sites like Sarıkaya [109]. Instead, material seems to have flowed from Aleppo and Mesopotamia through Kayseri, and then on to Sivas [108]. What does remain significant

is that the region continued to be utilized for its pasturing landscape, although less for agriculture than had been the case in the previous era.

5.2. The Late Roman and Byzantine Era at Çadır Höyük

Although there is evidence for occupation back to the Roman period, Çadır Höyük's current excavations have focused primarily on the Late Roman period (from approximately the 4th to 7th centuries) and to the medieval centuries, which include the Early Byzantine, Middle Byzantine, and early Seljuk periods (7th–13th centuries). The Late Roman constructions at the site are principally found on the terrace and are marked by what we would expect to find at a rural site in this period [110]: a well-maintained house, with evidence for courtyards, porticoes, and storage (Figure 18, top). It probably represented a localized villa-type structure, although the exact dimensions and format will remain unclear until excavation of the house resumes. Nevertheless, the material culture, through the presence of coinage and imitation red slip ware, speaks to a site with connections to the coast of Asia Minor (Figure 18, middle left). Indeed, although the majority of recovered coins date to the 11th century, this is followed in number by those from the 4th to 6th centuries, with a final Late Roman coin belonging to Justin II (565–574 CE). Further, the presence of a camel bone on the terrace also suggests a connection to the outside world [47]. As noted above, Çadır was part of the network of Late Roman sites in the region that included Kerkenes, Alişar Höyük, Tavium (Yozgat), and Sarıkaya. Thus, even without a large number of luxury goods or an extensive collection of fine wares, we can posit a consistent connection to the Mediterranean coast.



Figure 18. Top: aerial view of the North Terrace Byzantine occupation; Middle: example of red slip ware found at Çadır Höyük (**right**), example of pseudo fine wear (**left**); **Bottom**: examples of local coarse wares at Çadır Höyük (photos courtesy of the Çadır Höyük Archaeological Project).

The "end" of the Late Roman period in the 6th century led to a period of change on the Anatolian plateau. While some sites disappeared, many continued to function as small rural households. The stratigraphy on the terrace at Çadır Höyük suggests this, as the household continued in use throughout this period. It is the material culture from these levels that illustrates this period in the early Byzantine period. The material culture, primarily ceramics, illustrates an early Byzantine occupation through the presence of locally made imitation wares. The stratigraphy indicates a continuous occupation, one marked by a decline in the structures and by a complete absence of coinage or imported wares. These are common characteristics of the 7th through mid-9th century at sites in Anatolia, and have been traditionally used as ways of identifying abandonment. At Çadır Höyük, however, this period is marked by the creation of new ceramic types which reflect local production. The majority of ceramics are coarse wares (in all periods), but there is an attempt to hold on to a type of pseudo-fine ware for at least part of this phase (Figure 18, middle right). But what is key is that there are almost no imports, suggesting that both the trade to the region slowed down, and that rural settlements had very little contact with the Mediterranean coastline.

These patterns track with the environmental data, which indicate a depopulation of the region resulting in the return to indigenous weeds/plants, including some reforestation on the landscape [19]. While such an observation is not specific to roads, a decrease in agricultural production meant that some land—and most likely many lesser roads—were reclaimed by the environment. Thus, while major road systems in the eastern part of Anatolia were probably maintained where needed, others were not. It seems likely, then, that the disappearance of coastal imports at sites in inland Anatolia resulted from many factors: decreasing production in Mediterranean urban centers, diminished trade, shrinking communities, and a decline in the reliability of road systems. More regional lives are visible in some texts, such as the *Vita* of Theodore of Sykeon, where we watch the eponymous saint travel through byways and villages, all of which seem to be very locally focused [111,112].

As noted above, during the late 9th and 10th centuries, Anatolia resurfaced as a significant focus of attention, largely due to a renewed focus on the defense of borders. Çadır Höyük underwent a complete rebuilding on the terrace, one which added extensively to the earlier structures. The main house was given new flagstone floors, and the courtyards were plastered. A utilitarian area—stable, storage, and kitchen—was added to the southern half of the house. A small fortified center was also added to the mound, one that was primarily used for small-scale industry (metallurgy) and for processing grains in its earliest iteration.

The focus on the local continues in relation to the material culture at Çadır Höyük. Larger centers seem to have had more contact with the Mediterranean; certainly, sites like Komana and Tavium have evidence for things like sgraffito ware [113]. Yet at Çadır, we still find almost nothing of any significance in the way of imports. The overall economy changes substantially; now cattle ranching becomes a major focus, as can be seen in the results from the faunal data, which show the rising prominence of cattle [47]. Local ceramics also shift, and a new kind of thin-walled ceramic with a micaceous gold-colored glaze appears at Çadır, suggesting another new local kind of pseudo-fine ware (Figure 19a). Yet, other artifacts *do* mark connections with external populations. Personal religious objects (Figure 19b), processional crosses, and coinage almost certainly came in with military detachments—but in comparison with the locally-made ceramics and other local metal objects, these are statistically minimal finds. They are largely portable items, connected to individuals, primarily dating to the 10th and 11th centuries. Thus, while rebuilding, and connections to the coast increased, these small communities remained self-sufficient and localized. A minor passage in a Middle Byzantine strategic military manual *On Skirmishing*

admiringly discusses attacks that happened in the past, "among the villages," (i.e., offroad), suggesting this self-sufficiency ([101] p. 24, [114] p. 221).

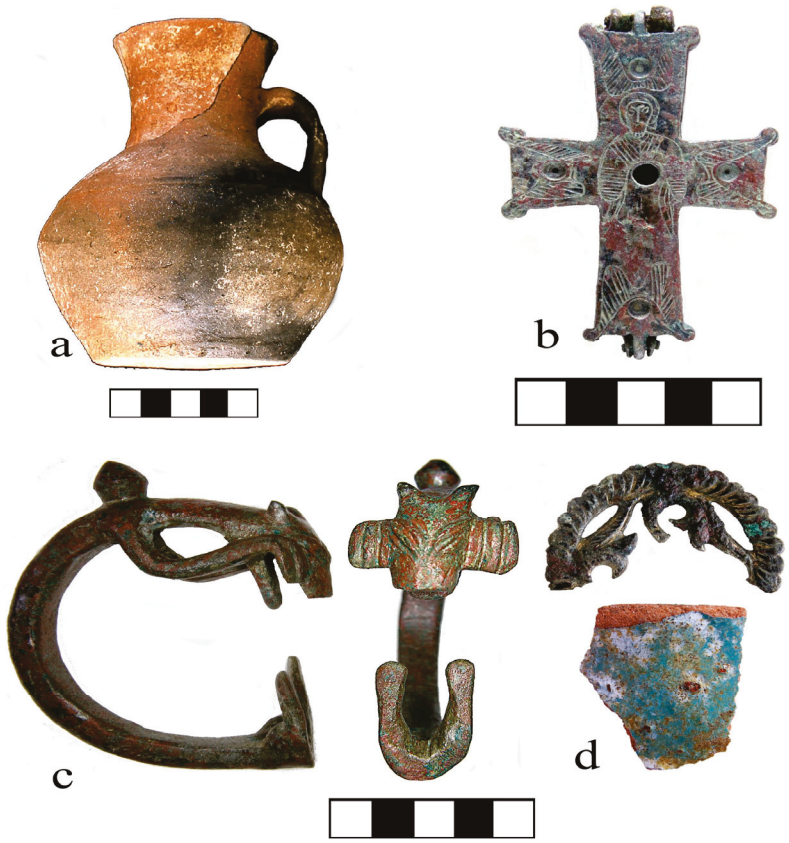


Figure 19. (**a**). Example of a micaceous vessel with gold-colored glaze; (**b**). Example of one of many personal religious crosses found at Çadır; (**c**). Example of the metal finds that may have originated in Mesopotamia or Iran; (**d**). Example of Raqqa ware (photos courtesy of the Çadır Höyük Archaeological Project).

Çadır Höyük was probably abandoned by its population in the 11th century, the result of an attack that left a few dead defenders and a large stable of animals, primarily cattle, indicating that the population believed they could return. This apparent evacuation was initially attributed to a Seljuk "invasion"; however, other evidence, including recent C14 results, suggest that this abandonment may predate the organized Seljuk arrival. The abandonment of live animals—in conjunction with the death of the guards—may rather be the result of marauding Frankish and Norman mercenaries who moved fast and left destruction behind them [115,116].

This abandonment was short-lived; the site seems to have been reoccupied during the late 12th or early 13th century, and this reuse and its relation to the abandonment phase are currently being explored as the new C14 dates suggest a more complicated use of the mound in the 11–13th centuries than we have previously considered. The mound was reoccupied, possibly by local inhabitants, or more likely by Seljuk pastoralists. While there is no evidence for widespread trade in this period, communication networks with northern Mesopotamia and Syria probably increased at this point. As Belke has discussed (and as discussed above), there is evidence for road systems being continuously in use throughout this period, coming via Cappadocia, and managed by the Seljuks [97]. Thus, it seems likely that we would now find material culture coming from new areas. Again, one cannot assume any sort of major rebuilding, particularly in the 13th century, as small groups of Seljuks moved across the plateau. Rather, what we see are small raiding and pastoralist

groups, and probably some seasonal usage of sites. This seems to be the case at Çadır Höyük, where some of the standing architecture is reused, windbreaks are constructed, and small areas on the mound are cleared.

Significant to this discussion is metal work at Çadır that looks very different from any seen before; these new discoveries have distinctive connections to types found in northern Mesopotamia and, indeed, even Iran (Figure 19c) ([117] pp. 104 and 122 for example). A few tiny sherds of what looks like Islamic period ceramics that parallel the famous Raqqa ware have also been found, although to date, there are no diagnostics or large sherds (Figure 19d). The combination of evidence suggests movement through the region may have shifted from the Mediterranean coast to northern Syria and Mesopotamia, including Eastern Anatolia.

5.3. Summary

Byzantine and Seljuk Çadır Höyük did not have empty shelves in terms of its ability to support itself. What the community lost after the 6th century was the type of artifact attributed to the complex Byzantine empire: the ceramics and glassware that characterize other Mediterranean sites. Rather, the appearance of new types of ceramics that are local in manufacture and design, and a dearth of luxury objects becomes the norm. Any non-local material in the Middle Byzantine period seems to be the result of individuals traveling to or through the settlement—reliquary crosses, coins, and larger religious objects, as these cannot be traced to any particular movement of trade. There appears to be a similar situation at Euchaïta ([118] pp. 222–223, 246–249). Finally, by the Seljuk period, it seems likely that material culture was coming from the east and the south, again largely as small personal objects. Evidence suggests that, while Tavium was no longer on a major north–south route, it remained connected to the wider Seljuk world. Only continued excavation will provide a more nuanced understanding of these patterns at Çadır Höyük.

The question of environmental impact on a site like Çadır Höyük is an important one, given the significance of these rural sites in the medieval period. Evidence from the site itself reflects the larger environmental data and a dramatic decrease in production in the early Byzantine period, with a resurgence in the Middle Byzantine period. However, it is too simplistic to draw a straight line between them. Rather, we need to see the site as reacting to social changes which altered the nature of the empire and the region over the *longue durée.* The Medieval Warm Period, for example, was one factor in the resurgence of the site, but only when taken in conjunction with the rise of the provincial aristocratic class, secure borders, and the move to herding, particularly of cattle. When the evolution of sites such as Çadır Höyük is considered, climate change becomes only one element of many that needs to be taken into consideration.

6. Discussion and Conclusions

At a macroscale level, the foregoing study demonstrated that severe climate variability, in conjunction with a constellation of other factors, had an adverse impact on ancient trade networks in all three periods. The same can certainly be said about the present-day. What is far less commonly understood is the microscale point-of-view, revealing how communities responded to decreasing provisions of goods, and indeed services, that once could be counted upon. Çadır Höyük is precisely the type of community capable of providing such data given its extremely long occupational history encompassing repeated climate events.

This study began with an overview describing the nature of the climate changes that occurred during the three periods under discussion. The study then asked and attempted to answer two interrelated questions: was there a change in the flow of trade goods to and from the Çadır Höyük community during these periods; and how did the community

react to an unpredictable climate and potential "empty shelves" resulting from diminished trade? Climate proxies clearly demonstrate that the Anatolian plateau experienced climate variability in the late 4th and late 2nd millennia BCE lasting several centuries, with the same situation occurring several millennia later in the Medieval Warm Period.

Regarding the first question posed, during the Late Chalcolithic, evidence suggested a marked decrease, perhaps to just a mere trickle, of both luxury and critical resources reaching this small farming community during the height of the climate event. There were noticeable changes in settlement infrastructure, including an apparent retraction in the size of the settlement. Though it was possibly smaller in size over time, the community was never abandoned; residents apparently developed alternative strategies to account for an absent supply chain during the 5.2 ka event. The picture during the late 2nd millennium is complicated by the fall of the Hittite Empire, which itself may have been partially due to the 3.2 ka event. Residents stopped receiving provisions from the Hittite center, but conversely may have no longer been required to contribute their own resources to that same center. Nonetheless, it seems clear that fewer items were arriving at residents' doors at this time.

Even more complicated is the situation during the medieval period, when climate was only one of many factors causing substantial variations in trade routes across the plateau. The slowdown of trade at the end of the Late Roman period reflected the effect that climate anomalies had on the larger cities on the coast, which made it increasingly difficult for material to reach the hinterland. Yet, even during periods of improving climate before and during the Medieval Warm Period, the local focus retained its importance, rendering the need for large scale trade obsolete. And so, during the Medieval Warm Period residents saw less imported "stuff" in the community.

What is equally clear in all three periods is that while the shelves were empty of luxury goods and imported wares, they were stocked full of items produced in the community itself. Çadır residents found alternative solutions to supply what was needed to continue their rural farming lifestyle. The location of this settlement in rich and well-watered farming lands, even if these yielded less during climate events, allowed inhabitants to adjust their socioeconomic strategies and innovate new uses for old materials to replace what once came from elsewhere. In this way, six millennia of residents at this small farming community demonstrated a remarkable resilience in the face of a multitude of challenges.

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Palaeoclimate Change in the Southern Black Sea Region and Its Impact on the Fate of Rome—From Megadrought to Collapse of Rome's ›Polis Command Economy‹

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Abstract: In recent scholarship, the impact of palaeoclimate change is often understood as a main factor contributing to the fragmentation and "fall" of Rome's empire. The various attempts at postulating disastrous effects of temperature shifts in the fifth to sixth centuries—cooling caused harvest failures, famine, political and social unrest, and disruptions in food supply—have been criticized for a good reason: compelling causal links between cooler weather conditions and decreasing agricultural productivity are missing. The socio-economic and political impact of a prolonged climate-related Late Roman drought (ca. 360–440 CE), however, has been widely overlooked. This paper aims to compare palaeoecological data from cave speleothems and lake sediments that indicate palaeoclimate and environmental change through precipitation shifts in the southern Black Sea region with the archaeological data of the urban granary in Pompeiopolis. Combining these data offers fresh insights into Roman environmental imperialism, command ecologies and economies, and the impact of climate change on Rome's tax system that kept the network of redistributive food supply running. This archaeo-environmental approach sheds light on the ecological vulnerability of integrated economies, failures of the dysfunctional metabolic regimes of ›polis command economies‹, and the chain of cause-and-effect provoking the "fall" of Rome.

Keywords: palaeoclimate change; megadrought; agroeconomy; granary; taxation; "fall" of Rome

1. Introduction—Palaeoclimate Change as Main Factor Triggering the Fragmentation and "Fall" of Rome's Empire?

Palaeoclimate change and pandemic disease were recently placed as the foreground explanations for the fragmentation and collapse of the Roman Empire from an environmental determinist perspective that postulated disastrous effects of temperature shifts on the food supply [1], following [2] already exploring the climatic impact on the rise and "fall" of Rome's empire. Harper's powerful narrative shared in his popular book *The Fate of Rome—Climate, Disease, and the End of an Empire* presents climate as the main driver of historical change through a consideration of the impact of palaeoclimate change on arable farming. In short, Harper argues that the warming of the climate increased the amount of arable land and thus the capacity for intensified agricultural production during the formative period of the Early Roman state, while droughts and food shortages led to the "first fall" of the Roman Empire that nonetheless survived through the age of restoration (fourth century). According to Harper, another climate-induced food crisis struck central Anatolia in the 380s that may have coincided with a short-term climate crisis even on

a larger scale and was followed by a period of epochal cooling that impaired the Late Roman agrarian regime and caused the "final fall" of Rome's empire. These palaeoenvironmental and economic developments were integrated into a model of three macroclimatic phases including:

(1) a "Roman Climate Optimum" spanning from ca. 200 BCE to 150 CE marked by warmth and precipitation that provided hospitable environmental conditions for Mediterranean wheat farming and amplified the productivity of land [1] (pp. 39–54); see also [3,4].

(2) a "Roman Transitional Period" stretching from ca. 150 to 450 CE with fluctuations in solar radiation as a main forcing mechanism that "pressed on the empire's reserves of strength" and a drought in the 240s striking the Levant and North Africa contributing to the "first fall" of Rome's empire. This empire entirely survived through the fourth century, which was marked by warming and dry, mostly favorable climate conditions, except for an acute interregional climate-induced food crisis in the 380s in central Anatolia that may have coincided with a climate crisis on a larger scale [1] (pp. 122–136, 162–172); see also [3,4] since the Eurasian steppe experienced a megadrought spanning two decades from ca. 350 to 370 CE: "the worst multidecadal drought event of the last two millennia" that even made the Huns into "armed climate refugees on horseback" [1] (p. 192) and showed "signs of sharp drying in (. . .) a belt of aridity running from Spain to central Asia" [1] (p. 250).

(3) the so-called "Late Antique Little Ice Age" (LALIA) spanning from ca. 450 to 700 CE with diminishing solar irradiance and a cluster of volcanic eruptions in the 530s and 540s that caused an episode of epochal cooling and climate deterioration that "overwhelmed what was left of the Roman state" [1] (pp. 15, 249–259); [4]. In the sixth century "the symbiotic town-hinterland systems went into simultaneous decline" [1] (p. 265), the cooling reduced land suitable for arable farming [1] (p. 266), and the ultimate failure of Rome's eastern empire around the mid-seventh century was already decided by the arrival of this cooler climatic regime [1] (pp. 245, 248, 275).

In his argument, Harper follows the group of scholars who identified the LALIA and considered the solar minimum and the cooling interval as a driving force for crop failure, food shortages, and famine that possibly triggered political, societal, and economic turmoil and thus contributed to the transformation of the Eastern Roman state and the collapse of the Sasanian Empire [5]. This proposed causal link between long-term cooling and the "fall" of Rome's agrarian empire in the east was questioned by another group of scholars including Greg Woolf, who pointed out that, "it is certainly possible to hypothesize scenarios in which global cooling (. . .) undermined the economic and demographic regimes on which ancient cities depended with long-term consequences for the network as a whole, but at the moment there remains room for doubt or at least alternative reconstructions" [6] (p. 413).

Before the cooling event of 536 CE was identified as a crucial moment in the history of the Roman Empire, Michael McCormick and his team had also drawn attention to the fourth century drought, which attracted only very minor scholarly interest [2]. Today this situation has not changed much, although the profoundly changing precipitation regimes were recommended as a promising future direction that "will need to be evaluated, alongside evolving patterns of urban demand, for their effect on production in some of the choicest agrarian areas of the later Roman Empire" [2] (p. 207). As emphasized in this early study of Roman-era palaeoclimate change, "the unquestionable sensitivity of the Roman economy's agrarian base to climatic factors provides an important potential link between historical and environmental change" [2] (p. 173). Instead of focusing primarily on centennial temperature shifts causing cool intervals, it was recently restated that we need to focus on climate dynamics that cause variations in precipitation and drought [7].

In contrast to Harper's narrative, the impact of palaeoclimate change on past vegetation and land use was seen as rather limited, particularly in the face of the given chronological gap between the end of LALIA in the seventh century and the much earlier climatic shifts [8–12]. Instead of climate-driven collapse, a period of political crisis and the effects of warfare upon a fragile economy during the Sasanian and Arab incursions into Anatolia such as the devastation of vast tracts of land are the most likely explanations for the decline in crop cultivation, the rapid regeneration and expansion of pine forests, the spread of nomadic pastoralism, and the collapse of the agrarian regime in Anatolia around the middle of the seventh century [9,11–21].

In northern Anatolia—much more so than in many other regions of the Anatolian Peninsula—the continuity of palaeoecological environments, settlement patterns, and the maintenance of agricultural productivity levels between Late Antiquity and the Early Byzantine period, has been considered to have largely contributed to the socioeconomic and political stability of the Eastern Roman Empire. Persisting "Roman" landscapes from Late Antique to Medieval times are proposed to support this stability [22] (pp. 205, 220–221); [23]; on the longstanding discussion about the trajectory of Late Roman urbanism between "continuists" and "catastrophists" see [24]. In general, the Late Antique rural economy is proposed to have flourished, perhaps until the seventh century [22] (p. 205), and the Late Roman state is thought to have survived without any major breaks [19] (pp. 154–155). In line with this "continuist" reading of palynological data, the negative effects of palaeoclimate change on the agricultural production and the rural economy in Late Roman and Early Byzantine Anatolia has been denied [19] (p. 149) and the "fall" of Rome's eastern empire is proposed to have started with the Arab raids in the seventh century and to have ended only with the coming of the Seljuk Turks in the 11th century [23].

As pointed out by Haldon, however, the regression of established agrarian regimes leading to reduced agrarian output did not coincide with the impact of warfare in seventh century Anatolia, but the regressive regime intensified during this period of intense political and socioeconomic pressure [8]. Although Roman political and economic institutions were previously accredited with outstanding resilience on the state level to environmental stress and profound climatic change in the sixth century [25] (p. 293), it seems indeed "paradox that the shifting environmental conditions that are generally seen as playing a contributory role in the processes that led to the breakdown and disappearance of Roman imperial power in Central and Western Europe (. . .) were the very changes that made possible the continued survival of the Eastern Roman Empire" [16] (p. 119).

In this paper, not only do I argue for societal resiliency during times of palaeoclimate change, but also for systemic change, socioeconomic crisis, and the fragmentation of Rome's empire caused by changing climatic conditions, which unleashed a major drought and famine that disrupted the redistributive political economy of Rome's empire and its supply lines. This approach is in line with recent research arguing that major disruptions in the archaeological record can indeed be linked to events of abrupt palaeoclimate change followed by megadroughts that spanned broad geographical areas, extended over a period of multiple decades, and thus are most likely to have had a huge impact on the palaeoecological system [26]. In consequence, such major drought events may have led to the fragmentation and collapse of the socioeconomic and political systems of predatory states with command economies extensively exploiting natural resources [26]. Understanding these periods of climate change and collapse is most critical if we wish to study the driving forces for system change in the Roman world [27].

By summarizing the current state of research and the contrasting positions, this first section aims at highlighting that we do "need to acknowledge that our efforts for mapping ancient climate and connecting it to historical events is still in its infancy, and as yet no

consensus has been reached" [6] (p. 375); similarly [28] (p. 34). As Woolf and others put it recently, "the relationships between temperature, rainfall, demography, and economics need to be worked out on a regional scale" [29] (p. 56) before we can integrate in-depth microregional studies into macroeconomic perspectives to better understand the impact of climate fluctuations on premodern societies and economies [28,30] (pp. 149, 172). Administrative and economic developments need to be integrated into our historical analyses more centrally in order to trace causal relationships of socioeconomic processes [30–32]. This is absolutely crucial since "the relationship between resources extracted by the state and agricultural productivity is (. . .) neglected but is significant when states tax landholdings or heads rather than productivity" [32] (p. 5). Additionally, societal responses of local communities need to be factored into palaeoecological change [32,33] and climate-induced changes in agricultural production.

Before LALIA, no significant climate-induced shifts in agricultural production are thought to have occurred in the fourth or fifth centuries because it is assumed that "temperature shifts remained well within the tolerance range of grains and other staple crops" [31] (pp. 435–436). The recession of established agrarian regimes in Anatolia, which seems to have started from about the mid-fifth century onwards as indicated by pollen data, does not offer any causal link to climatic shifts [8,34], nor does the presumed continuity of settlements in southwest Anatolia into the Early Byzantine period [35]. In sum, shifts in climatic conditions did not seem to coincide with changes in political regimes, regional settlement nor economic patterns, and little evidence has been found for the damaging impact of the extended fourth to fifth-century drought in Anatolia and the Levant [36]. It was therefore concluded that "there is no clear evidence that indicates a catastrophic impact of precipitation shifts on Mediterranean rain-fed agriculture" [31] (p. 436) and simplifying models of climate-related collapse primarily based on mono-causal explanations drawing on chronological correlations between dry climatic and negative socio-economic conditions were criticized [35,36].

That picture of a thriving Roman agroeconomy unaffected by palaeoclimate change is now challenged by stalagmite records from Kocain cave in southwestern Anatolia, showing that a decline in highland settlement numbers and the construction of water storage facilities likely reflects regional responses to drier climatic conditions from 460 CE onwards, with clear indications of less potential for local economic prosperity [37] (pp. 94–95, 104, 187, 190). The disappearance of fluvial systems from the fourth to the seventh centuries in the same region resulting from drastic decrease in rainfall also attests to this lessened potential [38]. The drier period is likewise present in a high-resolution lake oxygen isotope record from Lake Nar in Cappadocia that indicates major shifts in precipitation and evaporation between 300 and 530 CE [39,40]. Such abrupt changes in the hydrology (indicated by calcium carbonate mineralogy changes in aragonite depositions, typical of evaporated systems in the varved lake sediment sequence), were seen as a forcing mechanism for increased summer drought intensity and decreased winter rainfall in central Anatolia almost two decades ago [40]. More recent studies based on speleothem records evidence this long interval of dry weather causing arid climate conditions and drought even throughout the eastern Mediterranean as far as to the Italian Peninsula from the mid-fourth to the late fifth century [41].

Instead of focusing rather exclusively on the LALIA when it comes to the fading power of Rome's empire, it stands to reason to ask what role climatic variability might have played in the history of the Roman Empire from the middle of the fourth century onwards [41] (p. 541), especially since "drought events are more consequential than temperature anomalies" [1] (p. 254). By reducing the productivity of cereal agriculture, a decrease in precipitation could amount to serious environmental stress for ecologies

and ›polis command economies‹ (see [24] on this model) fully integrated into the Roman redistributive political agroeconomy with drastic consequences, e.g., for the food supplies of Roman military sites.

Yet, it is still "difficult to correlate variations in hydrological changes with regional to basin-wide socioeconomic transformations" [7] (p. 365); similarly [42]. Nonetheless, the impact of the decrease in rainfall "on dry-farmed cereal crop yields (. . .) must have been especially consequential during the period of dry climate during the fourth and fifth centuries" [16]. In this drier period—and the following centuries—"there was a general reduction in the scale of cereal-based agriculture (. . .) particularly in Anatolia" [10] (p. 240) that indicates changes in past land use from the fifth to eighth centuries. At this point, it certainly stands to reason to explain "how (. . .) we relate this data to questions of state and farmer resilience, and to climate change" [10] (p. 240).

In the following, I discuss the impact of palaeoclimate change on the fate of Rome's empire and its command ecology—an ecosystem manipulated through human agency working on intensifying agrarian production in order to meet the demand of a redistributive imperial regime—through a presentation of the currently available environmental data derived from climate-sensitive stalagmites and lake sediments in the Roman Black Sea region and the results of our stratigraphic excavation of the urban granary located in the city center of the Roman metropolis Pompeiopolis in the Amnias River Valley. By doing so, this paper puts climate-related megadroughts, changing modes of agricultural production, multiple scales of exploitation of natural resources, societal agency, and socioeconomic policies of a tributary state back on center stage to reveal substantial disturbances that altered the fate of Rome's empire. Integrating these two data sets into the broader history of the Eastern Roman Empire will allow us to reevaluate significant shifts in climatic conditions that were seen as a causal factor of the collapse and "fall" of Rome's empire, but synchronously point to a much earlier moment in Late Roman history for systemic collapse around the middle of the fourth century.

2. Research Methods and Palaeoecological Proxy Data—Tracing Palaeoclimatic Dynamics and Changing Agrarian Regimes in the Roman Black Sea Region

Exploring past climatic changes in the Roman Black Sea region is methodologically challenging, and palaeoenvironmental research is still in its infancy, although remarkable progress has been made through the availability of reliable hydrological records of high temporal resolution. These have provided palaeoclimate proxies sensitive to multiple climate signals (temperature, precipitation, and evaporation) from the southern Black Sea region. Geological archives allow regional palaeoclimate reconstructions through geochemical analysis of moisture-sensitive speleothem records derived from stalagmites in the Uzuntarla Cave in the southwestern Black Sea region in Turkish Thrace and the Sofular Cave located ca. 27 km southwest of the Roman seaport Tios (Figure 1). They show long-term and decadal to multi-decadal variations in humidity.

The more widely deposited lacustrine sediments of lower temporal resolution available in the southwestern Black Sea region from Lakes Küçük Akgöl and Akgöl in the Sangarios River Valley in Sakarya Province, Lake Melen in Düzce Province, Lakes Abant and Yeniçağa in Bolu Province, Lake Çöl ca. 12 km east of Çankırı as well as in the central Black Sea region from Lake Tatlı in the Bafra plain, Lake Ladik northeast of Amasya, Lake Kaz southeast of Amasya, Lake Sülük east of Boğazköy and Lakes Demiryurt and Tecer in the Sivas region (Figure 1) can support palaeoclimate reconstructions through the analysis of morphological variation in their geochemical composition. This variation points to landscape changes possibly triggered by moisture stress from high levels of evaporation.

Additionally, these lake sediments provide insights into changing vegetation and land use through variabilities in the pollen record that are, however, related to palaeoclimate change or changing economic systems and modes of agrarian production.

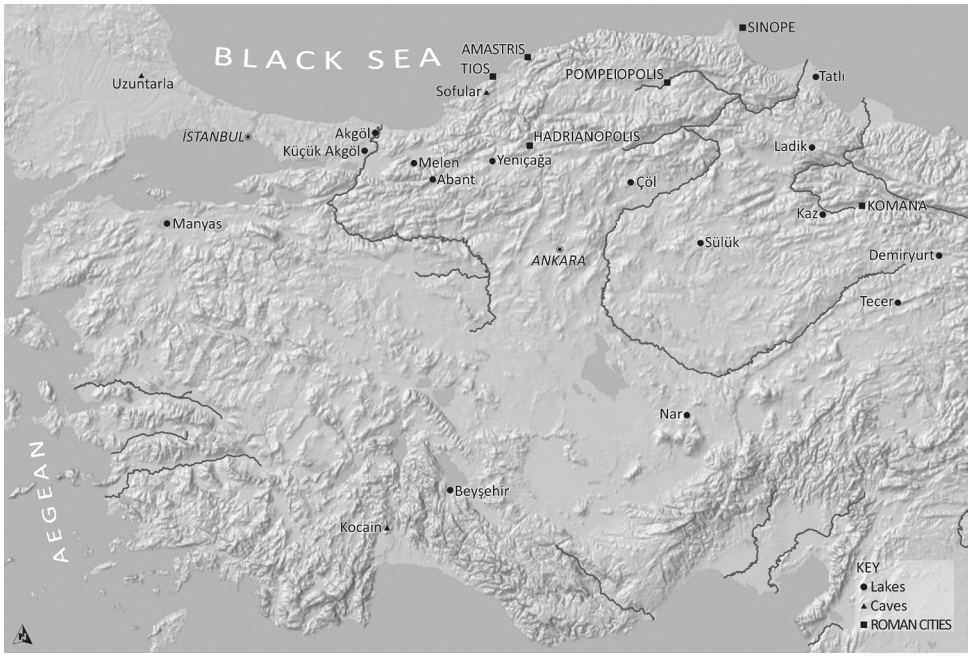


Figure 1. Map of the southern Black Sea region: Roman cities and coring sites for lacustrine sediments and cave speleothems ©P. Johnson, using Esri World Shaded Relief and Hillshade basemaps.

Let us start our survey with previous palaeoenvironmental research on the hinterland of the Pontic harbor city of Sinope. An intense expansion of rural settlements or large farmsteads, and possibly church-owned estates furnished with agricultural production facilities, can be observed from the fourth century onwards. This expansion is convincingly linked to an increase in the cultivation and processing of olives, which the pollen record indicates with a spike in olive pollen and a kiln site of centralized Late Roman amphora production in the Sinopean hinterland, probably connected to a villa estate or church property [43–45]. According to Izdebski, this intense agricultural exploitation of Sinopean land "was certainly due to the position of Sinop in the Roman commercial networks" [22] (p. 16); similarly [46] (pp. 93, 117); [43,44] and its engagement with long-distance Mediterranean trade. In contrast, the provisioning of the Eastern Roman capital, Constantinople, or the Roman army through the *annona* system, is thought not to have dominated economic transactions [47]. The abandonment of these rural settlements and farmsteads is considered to have been a direct consequence of either political turmoil during the Arab incursions [46] (pp. 117, 157) or palaeoclimate change and thus unfavorable climate conditions for oleoculture in the southern Black Sea region [44]. Both are proposed to have led to a sudden collapse of the local monocrop-oriented economy and the rural settlement system, but the timing of this change remains unclear and several dates have been suggested: the seventh century [43,44], agreed with by [48,49]; with doubts on the Late Roman settlement collapse: [22] (p. 36); the eighth century [46] (pp. 151, 156–157); [43,50] following a period of major infrastructural and agricultural investment and agro-economic intensification in the fourth century [43], similarly [18] or the fifth and sixth centuries [44]. While neither the dating of the archaeological survey material nor the pollen data derived from Lakes Ladik, Demiryurt and Kaz in the early 1990s with a dating precision that is no better than ±200 years due to lack of a chronostratigraphy based on AMS radiocarbon dating [18] allow a precise correlation of agrarian and settlement development, it is worth emphasizing that the abandonment of the

intensively cultivated Sinopean lands may chronologically correspond with the recession in established agrarian regimes in northern Anatolia. This process has been roughly dated by pollen records around the middle of the fifth century [8,49], while some parts of northwest Anatolia experienced clear and abrupt changes in land use from intensive crop cultivation to (agro)pastoralism as early as from ca. 400 CE [51] or the fourth century onwards [12,21].

This remarkable decline in viti- and oleoculture and the cultivation of cereals, as well as a major increase in grazing weeds points to steppe vegetation and (agro)pastoral activities with low intensity cereal cropping typical of subsistence peasant farming, which generates agricultural products and raises livestock for a self-sufficient food supply. In northern Anatolia, this changing mode in land use and agroeconomic production was set into operation perhaps in the mid-fourth century, if we consider the chronological imprecision of the pollen data and the available information of the exceptionally well-dated palaeoclimatic record from Sofular Cave.

Located in the northern foothills of the Akçakoca Mountain range, the stalagmite stable-isotope record from Sofular Cave shows long-term and decadal to multi-decadal variations in effective moisture (Figures 1 and 2). The stalagmite values analyzed through stable isotope ratios of carbon and oxygen are the most sensitive proxies for climate-driven changes in the local ecosystem [52]. Therefore, the Sofular speleothem "shows, for the first time, unequivocal evidence for a rapid and sensitive climate and ecosystem response in the eastern Mediterranean to GI [Greenland Interstadials]" which bears highly resolved and thus the most significant palaeoclimatic information for the Turkish Black Sea region [52] (p. 4).

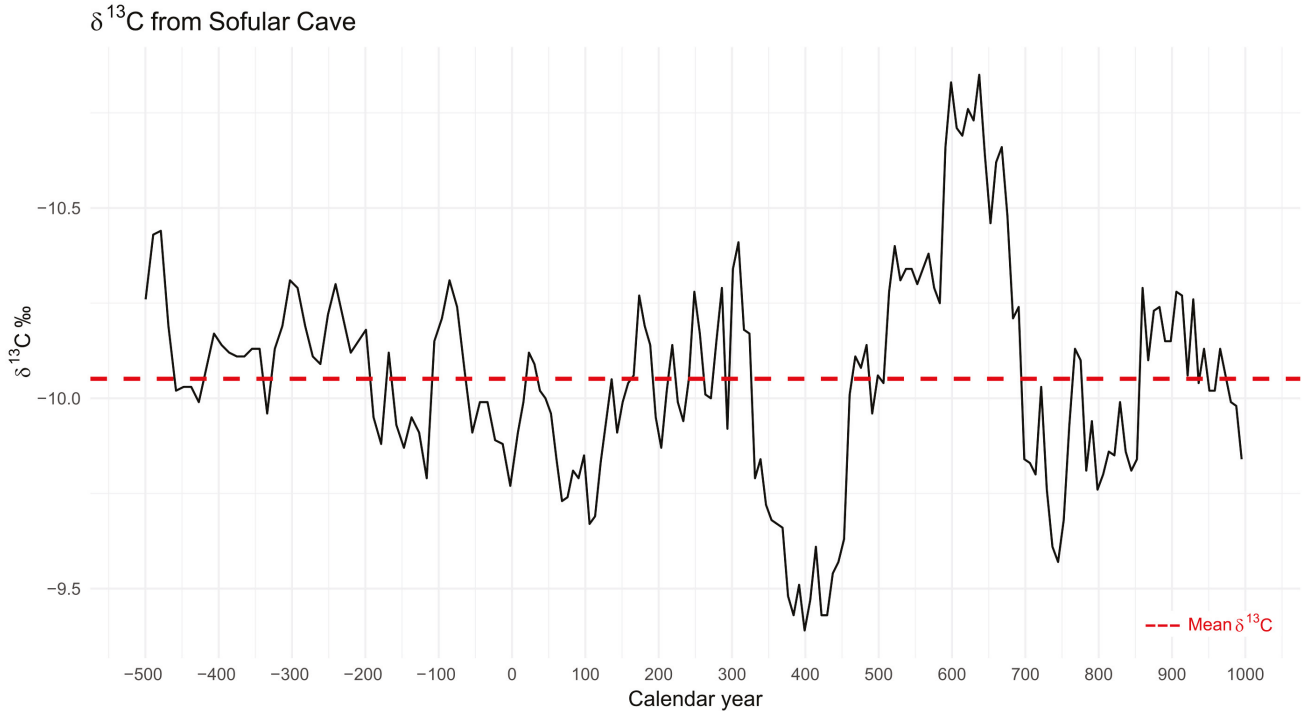


Figure 2. High-resolution stable-isotope speleothem record from Sofular Cave, Prov. Zonguldak, indicating climate moisture conditions ©R. Busch, using the speleothem data available open access from https://www.ncei.noaa.gov/pub/data/paleo/speleothem/asia/turkey/sofular2009-noaa.txt (accessed on 13 February 2025).

Most interestingly, the high-resolution palaeohydrological proxy record shows relatively high precipitation until ca. 340 CE when the climate sharply turned towards enhanced aridity from ca. 360 to 440 CE, with a dry peak around 400 CE (Figure 2). This is the most significant hydroclimatic shift during the first millennium, and similarly, the

oxygen isotope record from Lake Nar in central Anatolia attests to it, likewise well-dated by varves with annual to decadal precision in precipitation fluctuations [41]. According to Fleitmann and his team, who published the Sofular speleothem, this arid period is precisely dated by the stable-isotope record and strikingly coincides with pollen data that indicate steppe vegetation in the central and eastern Mediterranean [52]. As pointed out by Xoplaki, this extended dry weather condition caused a Late Roman megadrought, creating a large climate forcing covering not only the Black Sea area and the Anatolian Peninsula, but also the eastern Mediterranean [41]. Chronologically, this major drought corresponds to a decline in solar activity (ca. 370–435 CE)—the first phase of a prolonged period of significantly reduced solar radiation [53].

Historical sources provide causal links for the events and effects of these extreme dry weather conditions, such as a drought that caused famine between 451 and 454 CE in central and southeastern Anatolia and Palestine [18] (p. 126). Climate-related droughts are reported in the 360 s and 370 s during the much drier climatic phase from 340 CE onwards in different parts of Anatolia. Famine follows these in the early fifth century (ca. 400–435 CE), including a famine in Pontus and Paphlagonia (422 CE) and a grain shortage that struck Amaseia in the central Black Sea region (448–450 CE) [18]. A further shift towards more humid conditions in the eastern Mediterranean hydroclimate regime corresponds with the stalagmite record from the Uzuntarla Cave with its moisture proxies attesting to increased precipitation again only in the sixth century [41].

In the wider Pontic region, this Late Roman megadrought is attested and well-dated not only by the speleothem from Sofular Cave but also by the proxy data from Lake Tecer that points to moisture stress between ca. 360 and 440 CE (Figure 3) [54]. Another core sediment from Lake Çöl points towards a fifth-century drought [22] (p. 134) and an abrupt change indicated by salt inundation in the lacustrine sediment of Lake Manyas located south of the Marmara Sea points again to this palaeoecological change, roughly between 218 and 440 CE (according to recalibrated C14 data: [55]).

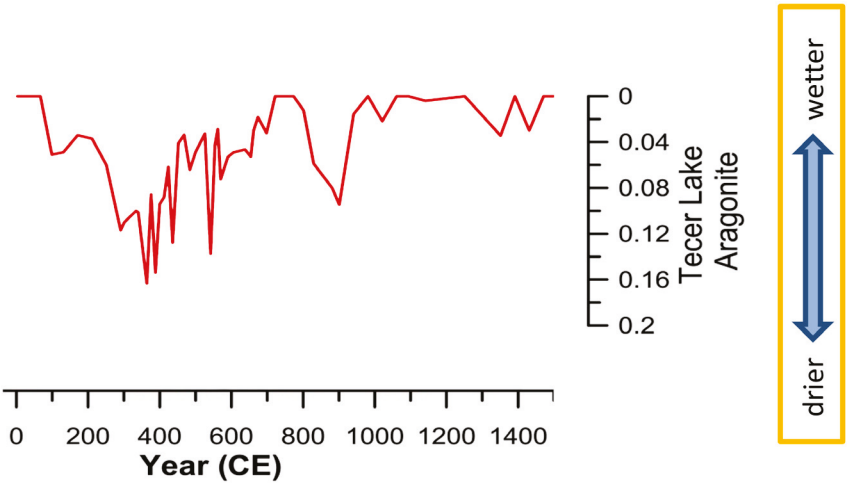


Figure 3. Aragonite values of the lacustrine sediment sequence from Lake Tecer, Prov. Sivas, indicating evaporative conditions in the hydrological system © [18] (p. 124 Figure 1 modified by J. M. Koch).

Based on the sediment records from the Lakes Tecer, Nar and Çöl, Izdebski suggested that central Anatolia "suffered from a relatively strong drought around the fifth century" [22] (p. 135). The "fifth century Cappadocian drought" was seen as not to have caused any major changes in the vegetation pattern around Lake Nar [22] (p. 141), although a peak in steppe indicators dated ca. 560 CE points to a collapse of the agricultural regime around Lake Demiryurt [22] (p. 196). In the region of Lake Küçük Akgöl, a decrease in

cereals points to a major decline of agriculture and an abandonment of farmland roughly around the late fifth century that enabled the regeneration of nature [22] (pp. 183, 186). This sequence is likewise attested in the increase in pine pollen at Lake Sülük, suggesting an expansion of pine forests between 400 and 650 CE [56].

Even though the timespan of the drought has more recently been adjusted towards the prolonged period 350–470 CE and is now considered to have caused socioeconomic difficulties and subsistence crises in Anatolia, it is still supposed to have brought about neither major societal changes nor a crisis in the socioeconomic system [19] (pp. 142–143); [20]. By contrast, it is proposed that "the abandoning of a complex agriculture involving a variety of cultivars and practices (. . .) was not a decision forced on it by external constraints, but rather a development towards economic specialisation making the best possible use of the location and environmental resources of the area" [47] (p. 358) with the result that "we can have no doubt that there existed various local centres of production and demand which were able to maintain this ancient system well into the Middle Ages" [47] (pp. 358–359).

In previous studies that suggest systemic continuity and an enduring Late Roman Beyşehir-Occupation-Phase-type vegetation in the Early Byzantine lands, the pollen stratigraphy was usually integrated into historical analyses as one coherent set of data. There is, however, a distinct change within this time period that can be traced in pollen deposits in Nar Lake with much more chronological accuracy than in lake sediments in the Black Sea region. Two phases that provide inferences on divergent types and intensities of agrarian land use can be clearly separated and well dated here: in the Late Roman period (300–450 CE) vine pollen are present, whereas in the Early Byzantine period (450–670 CE) vine is completely absent and grass pollen have an increase that attests to a grass-herb dominated steppe [13,14]. Similarly, the palynostratigraphy of an AMS-dated high-resolution pollen record from the Bereket Basin in the Western Taurus Mountains points to intensive crop cultivation until ca. 350 CE, with pastoral and minor cultivation activities setting in afterwards [57]. It is around 350 CE that "the driest episode during Roman times recorded at Bereket (. . .) had a major impact on soil dynamics and on the environment" [57] (p. 2212). This intense dry period of megadrought lasted from ca. 360 to 440 CE according to the recalibrated data [58]. Although the Bereket region never recovered from this breakdown of the agricultural system around the middle of the fourth century, which caused a shift away from the previous intensive crop cultivation, the sharp drop in land use was not seen as a contributing factor in the declining power of Rome nor in the large-scale changes in agricultural practices and modes of production [59] and the nearby city of Sagalassos did "not seem to have suffered very much from its effects" [58] (p. 264).

In the Black Sea region and beyond, dry climatic conditions prevailed between ca. 360–440 CE, and the changing palaeoclimate does appear to have had a lasting impact on the agricultural regime and the socio-economic system. Here, as pointed out by Neil Roberts, palaeoclimate change and environmental crisis were "acting not only as a stressor, but also as a stimulus to social evolution" [60] (p. 25). Changing modes of production from intensified agriculture to peasant economy triggered societal innovation and institutional change. Instead of focusing on temperature shifts and cooling intervals and tracing the impact of climate change mainly in the sixth and seventh centuries as a result of the LALIA, a more promising way forward may be to search for changing precipitation patterns, political ecologies, and ecosystems, and modifications to the tax system around the middle of the fourth century in order to elucidate the impact of a megadrought in Late Roman Anatolia and the Eastern Roman Empire. It thus stands to reason to consider the impact of palaeoclimate change on the fate of Rome's political power in West Asia much earlier than in the seventh century and to reveal not only changing settlement patterns and modes of land use in the Roman Black Sea region, but also the trajectories of the political economy in

the imperial landscapes. To establish firm links between the hydrological change of the Roman-era palaeoclimate and the changing agrarian regimes, we now turn to the urban granary in Pompeiopolis, partially unearthed through stratigraphic excavation between 2013 and 2016.

3. Granaries as Palaeoclimatic Proxy Data for Drought and Failures of Political Agroeconomies in the Roman Black Sea Region—Evidence from the Urban Granary in Pompeiopolis

During Augustus' provincial reorganization of the Anatolian Peninsula, the territory of Pompeiopolis was annexed to the province of Galatia in 6/5 BCE. Additionally, the Roman in-kind tax system, which demanded intensified cereal agriculture to feed the Roman army stationed along the Pontic limes, had most probably been implemented concurrently with the basic imperial infrastructure only a few decades after the military submission of the region to Pompey. Serving the needs of Roman imperial urbanism (on this model see [24]) and demanding the urbanization of the former realm of the Pontic kings in inland Paphlagonia for the first time, this infrastructure left its archaeological footprint in the city's center (Figure 4).

Above the banks of the Amnias River on the southern terrace of Zımbılı Tepe and along the city's main street close to the agora, one monumental building measuring ca. 68 × 98 m was identified as a peristyle courtyard granary serving for the large-scale storage of grain taxes due to its size, building typology (Figure 5), construction technique (Figure 6), and the empire's general demand to set up and run central collection points for the imperial *annona* throughout its provinces.

A sophisticated imperial redistribution system based on a network of urban granaries is anticipated in Roman borderlands such as the mostly rockbound coast of the *limes Ponticus* around Sinope and Amastris (Figure 1), which provided only very limited fertile land in order to secure military supply lines. While it is not possible to determine the function of urban granaries as centralized tax collection and redistribution points simply from their architectural design and spatial layout, their significance for *annona* transactions underlies an exceptional inscription from Larisa that reports the shipment of Thessalian grain to Rome from the Thessalian inland poleis via harbor cities [61].

Distinctive architectural features of the urban granary at Pompeiopolis, such as the colonnaded porch paved with travertine, gutters for draining rainwater into sewage systems, storerooms with buttressed walls, walls built of *opus quadratum* and waterproof floors built of *opus signinum* (Figure 6) closely resemble the courtyard granaries in Augustan Rome and Ostia, e.g., the Augustan Horrea Agrippiana below the Palatine next to the Forum Romanum, the Horrea Lolliana and the Horrea Galbana on the banks of the Tiber River, and the Iulio-Claudian Horrea of Hortensius located at the mouth of the Tiber at Rome's port at Ostia. The last had a working space of ca. 6000 m^2 available, which comes closest to the ca. 6664 m^2 of working space of the rectangular court at Pompeiopolis (see [24] for details of the architectural features and archaeological finds described in this section). Whereas the Storehouse of Hortensius was lately considered as an example of privately owned horrea [62] similar to the Republican storehouses in Rome associated with aristocratic families [63] (p. 188), large-size urban granaries located in public spaces are likely state or publicly owned storehouses administered by (and named after) members of the local elite commissioned by a city's authorities.

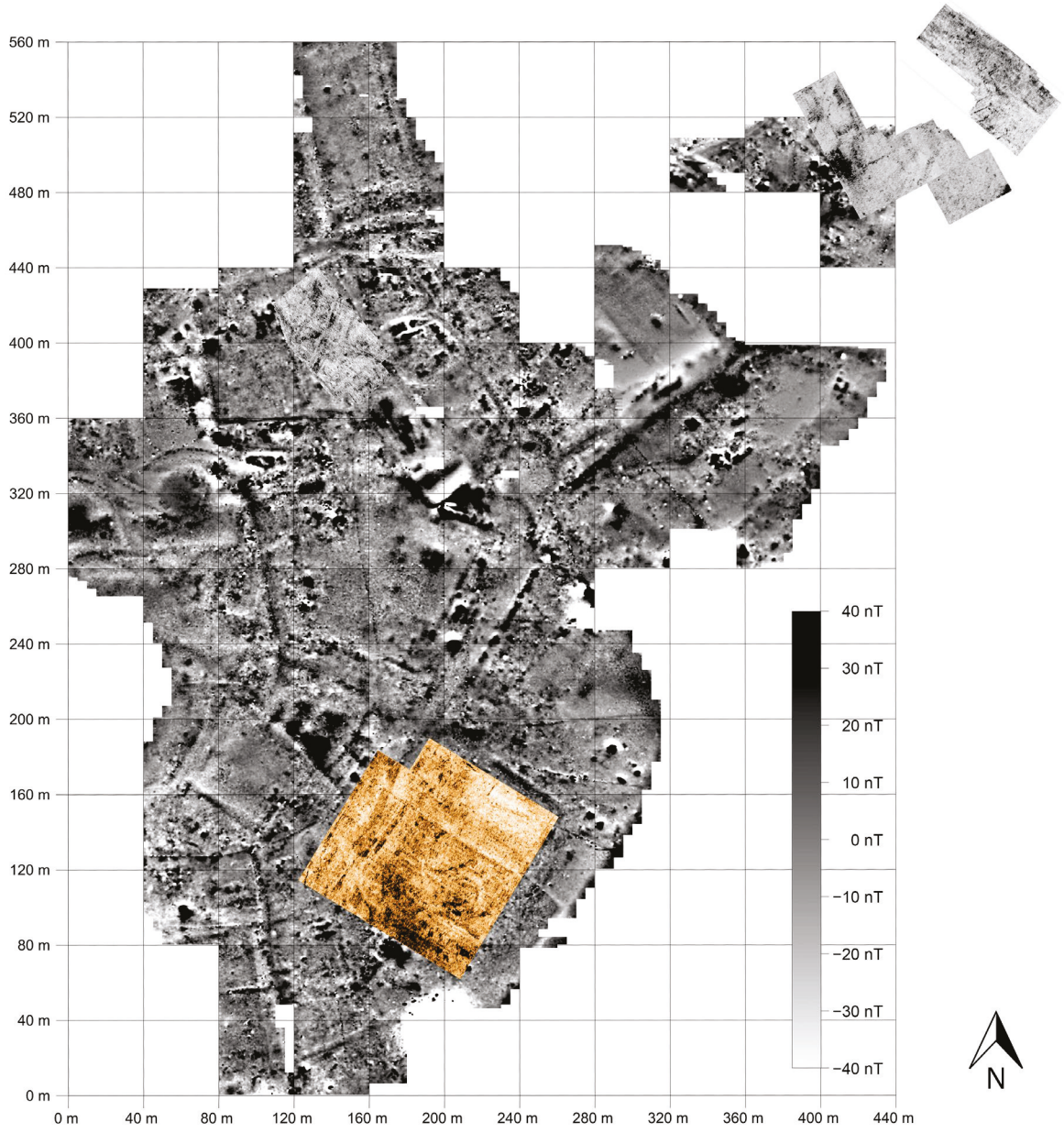


Figure 4. Magnetogram of the city center of Pompeiopolis on Zımbıllı Tepe; on the southern terrace, the area of the courtyard granary investigated through ground-penetrating radar ©Pompeiopolis Excavation Archive.

Urban granaries in *Hispania*, which are supposed to have supplied Roman towns by satisfying their territory's commercial needs and guaranteeing the local population's food supply, were regularly constructed during Rome's expansion and subsequent consolidation of power on the Iberian Peninsula [63] (p. 188). According to the Asian customs law referring to an export of tax-grain in 62 CE [64] (p. 219), »a tithe of the crops produced by the plough or a fifth of the wine or the oil« had to be handed over to the *publicani* who were in charge of extracting the taxes in kind on the Anatolian Peninsula [65] (p. 55); [66] (p. 218). In the early second century, Dion of Prusa in his speech addressed to the citizens of Nikomedeia explicitly mentions the tax in kind (tithe) of the Bithynians [66] (p. 218). Therefore, public storage facilities were needed for the stockpiling of taxed staple goods in northern Anatolia (and beyond) and the courtyard granary at Pompeiopolis was certainly well equipped to serve as a publicly owned fiscal storehouse for the centralized storage of

grain taxes before their further shipment by the Amnias River towards the Halys and the Black Sea (Figure 1).

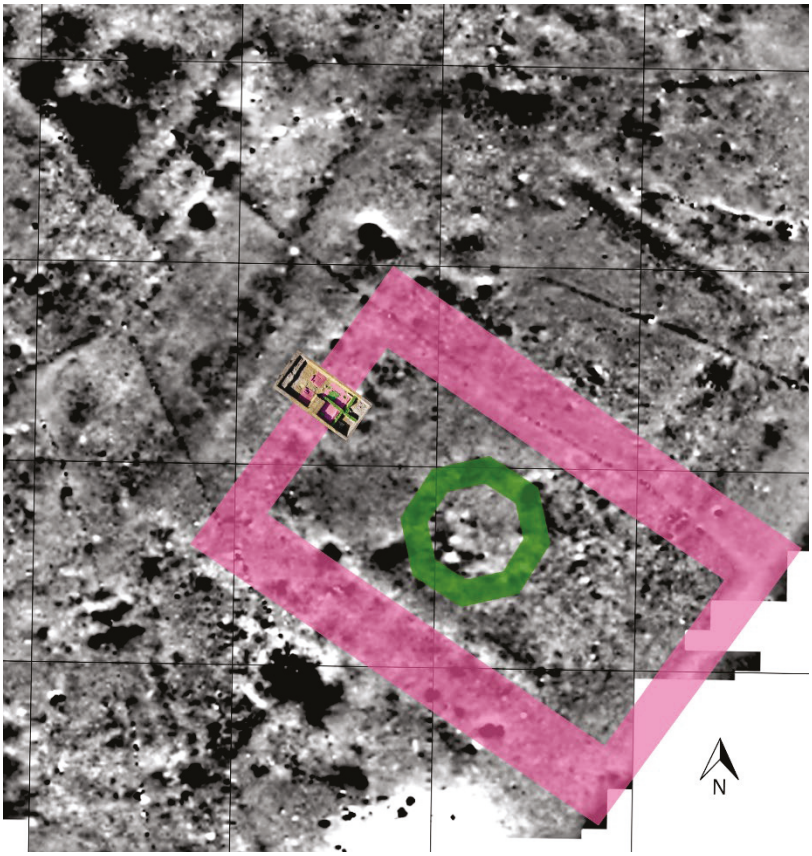


Figure 5. The courtyard granary in Pompeiopolis. In the northwestern wing, the excavation trench. Two building phases are presented on the magnetogram: the mid-Augustan courtyard granary (colored in violet) and its partial rebuilding with the construction of an octagonal martyrion church in the open court in the early fourth century (colored in green) ©J. M. Koch.



Figure 6. Excavation trench in the northwestern wing showing the Early Roman architecture (colored in violet) and the Late Roman partial (re)construction with architectural modifications (colored in green) ©J. M. Koch.

This reading of the urban granary at Pompeiopolis is in line with the previously reconstructed function of the courtyard granaries in Rome and Ostia as state or publicly owned storehouses for the city's corn supply as suggested by Geoffrey Rickman in his seminal study on *Roman Granaries and Store Buildings* [67] (pp. 53, 69, 174). Similarly, in Roman Gaul, an urban courtyard granary echoing its Italian predecessors has been associated with imperially administered grain storage and the food supply of the Roman army stationed along the northern frontier [68] (pp. 83–84). Imperial administration of peristyle courtyard granaries built in the first century becomes even more clear at Roman military sites, for example, on the Lower Rhine limes at the legionary fortress of Novaesium [67] (pp. 255–257); [69] (pp. 186–188 pl. 16 buildings no. 21–22), and already Caesar during his civil war against Pompey relied on grain supplies sent to military camps from urban granaries [70] (p. 587). In Pompeiopolis, this redistributive, institutionalized system of Roman taxation in kind newly comes to the fore in the city's management of large-scale grain storage.

Surprisingly, this most probably mid-Augustan urban granary, which incorporated a double-spaced northwestern wing with two-fold cellular storage units measuring 6.7 m in width and 4.4 m in depth (front rooms) and 2.4 m in depth (rear rooms, about half size in width) (Figures 5 and 6), was destroyed by fire in the late second or early third century (at the latest). This is according to the most recent finds of Pontic Sigillata, Early Roman coarse ware, and a fragment of a late secondcentury inscription within the building debris covering the rear rooms.

The wing was left derelict for decades before it was partially rebuilt in the early fourth century as a churchyard granary that centered on an octagonal martyrion (Figures 5 and 6). Already around the middle of the fourth century, the rebuilt grain storage and processing facility newly furnished with sunken pithoi—similar to the Late Roman pithoi found *in situ* east of the churchyard granary—and grinding stones anchored in the circular holes of the cemented floor (Figures 6–9) fell out of use again during the reign of Constantius II between 351 and 355 CE, according to a coin that was recovered directly atop the floor underneath the collapsed wall of the anterior room of the northwestern wing (Figures 10 and 11). After the collapse of the reused Early Roman walls, the Late Roman churchyard granary was never rebuilt, and the absence of occupational layers dating to the later fourth, fifth, and sixth centuries clearly reflects the abandonment of the urban settlement on the southern plateau of Zımbıllı Tepe.



Figure 7. Grinding stone found in the northwestern wing of the courtyard granary ©J. M. Koch.



Figure 8. Storage facility on the southeastern terrace of Zımbıllı Tepe, including three Late Roman pithoi for the storage of grain excavated during a rescue excavation in 2015 ©J. M. Koch.



Figure 9. Late Roman pithoi excavated in the storage facility in the city center of Pompeiopolis, east of the courtyard granary ©J. M. Koch.



Figure 10. Collapsed pisé wall of the excavated room adjoining the court in the northwestern wing of the mid-Augustan courtyard granary. Underneath this collapsed wall, directly atop the cemented floor, the bronze coin minted during the reign of Constantius II was found ©J. M. Koch.



Figure 11. Bronze coin minted during the reign of Constantius II (351–355 CE) found beneath the collapsed wall of the courtyard granary ©J. M. Koch.

In the late fourth century, the martyrion was transformed into a cemetery church and the court of the granary was filled with earthen debris: large-scale dumping activities that raised the ground level to create a new burial ground *ad sanctos* (centering on the cemetery church) that extended further towards the derelict peristyle wings until the early seventh century. In the area of the derelict northwestern wing and its porch, chalky layers and residues of lime plaster were observed in the earthen debris filling of "dark earth" (Figure 12). These residues of lime plaster and the chalky deposit point to the preparation of plaster burials and chalk-packed burials after 631/2 CE but prior to 656 CE that met the increased hygiene and thus public security measures in the aftermath of the devastating Iustinianic Plague, which started to spread throughout Anatolia in 541/2 CE.

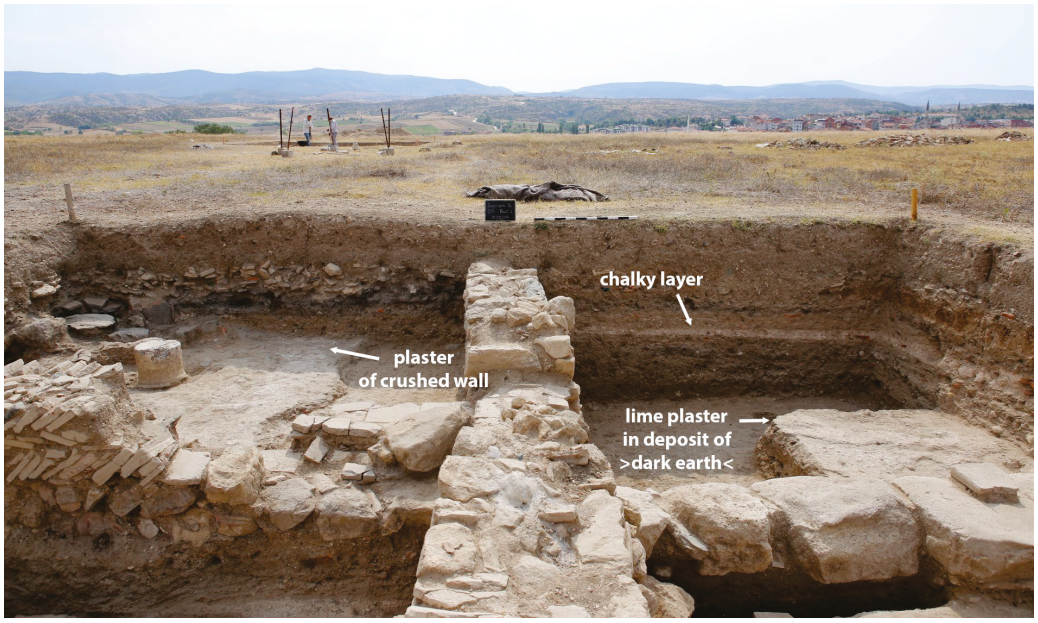


Figure 12. Residues for the preparation of plaster burials at the burial ground *at sanctos* in the derelict porch of the abandoned granary ©J. M. Koch.

Instead of the centralized storage of grain, subsequent efforts at the centralized storage of raw materials ready to be fed to lime kilns are indicated by the building of a humble storage facility built of pine wood at the derelict site of the churchyard granary around 656 CE (Figure 13). The reactivation of the "City of Pompey" as a central place during the reign of Constans II (641–668 CE) may reflect another imperial attempt to rebuild the city in order to sustain the Eastern Roman Empire against all odds—or may simply point to the reuse of the communal cemetery and the need for lime for plaster burials instead of any attempt at urban restoration.



Figure 13. Raw material storage for lime production in the Early Byzantine humble building (ca. 656 CE) reusing the partly preserved Late Roman architecture of the granary ©J. M. Koch.

The final abandonment of Zımbıllı Tepe and its humble storage facility came after another destructive fire event shortly after the middle of the seventh century, around

656/7 CE, during the period of the Arab raids (Figure 14). In any case, the Late Roman "City of Pompey" with its economic polis administration for collecting taxes in kind from the city's fertile territory had vanished already centuries earlier, around the middle of the fourth century, when the city center of Pompeiopolis was turned into a "city of the dead".



Figure 14. Ashy layer of pine wood of the humble Early Byzantine storage building burnt down shortly after the mid-seventh century before the final abandonment of the cemetery ©J. M. Koch.

According to our excavation results, the ›polis command economy‹ that contributed to a redistributive and integrated political economy of the tributary Roman state and exploited cellular microregional command ecologies through large-scale storage of taxed agrarian resources—first, in the Early Roman courtyard granary and subsequently in the Late Roman churchyard granary—had thus failed repeatedly (at least twice) in the Black Sea region.

4. Conclusions—Reassessing the Fragmentation and "Fall" of Rome's Empire: The Impact of Climate Change on Ecologies and Command Economies

Harper's assumption that droughts and food shortages, and the Antonine Plague led to the "first fall" of Rome's early empire has not been discussed in this short article, although a dry period during the reign of Trajan—as indicated in the Sofular speleothem (Figure 2)—may have triggered a disintegrated economic system in this region already during the first two decades of the second century, see [24]. In the past, "historians took the stability of the early imperial system for granted", while nowadays, the Roman imperial economy and "the urban system as a whole looks less stable" [6] (p. 411). At Pompeiopolis, the abandoned granary was left derelict in the late second or early third century, and its rebuilding in the early fourth century attests to a period of systemic crisis during the third century in the Black Sea region. This crisis, evident in many regions of the Anatolian Peninsula and beyond, see [24], thus offers some support to Harper's thesis of the "first fall" of Rome's empire. Again, around 360 CE, instead of severe temperature shifts and epochal cooling, the Roman Empire was struck by a centennial megadrought, triggering systemic collapse. In the southern Black Sea region, we are able to initially establish firm causal links between severe drought, harvest failures, and the collapse

of the imperial agroeconomy. As indicated by the abandoned granary, the Late Roman megadrought (ca. 360–440 CE) caused major disturbances within the ecosystem and the agrarian command economy. Paphlagonian societies adapted to these conditions from the middle of the fourth century by changing modes of agricultural production and scales of agroeconomic performance. The pollen data provide the evidence for changing land use, from intensified agriculture towards (agro)pastoralism. These climate-related changes in land use imply systemic change, from the redistributive ›polis command economy‹ that secured the vulnerable supply lines of Roman military sites to peasant-based agrarian management. In consequence, this significant shift in land use and the agrarian regimes, from intensified cereal-based agriculture and both oleo- and viticulture to a less labor-intensive agropastoral economy shortly after the middle of the fourth century is most likely to have acted as a causal force in the collapse not only of Rome's political economy, but also the imperial regime. In Pompeiopolis, we were able to trace poleis turned into necropoleis, disintegrated agroeconomies on a microregional scale, and the dysfunctional fiscal system on the macroeconomic level.

Our detailed multi-disciplinary study in the Roman Black Sea region—by integrating the available archaeological, palaeoclimatic, and palaeoecological data into historical research—points towards palaeoclimate change as a forcing mechanism in the systemic collapse of Rome's redistributive ›polis command economy‹ that triggered the failure of Rome's imperial regime and thus the fragmentation of Rome's empire in the East from as early as around 360 CE. Integrating the palaeoclimatic data into the history of the city granary in Pompeiopolis challenges the traditional view of the turning points in the history of the Eastern Roman Empire and prompts closer looks at northern Anatolian cities in the middle or later fourth century. As a consequence of the breakdown of imperial urbanism, institutional arrangements, and the political command economy of the Early and Late Roman state, the first excavation of a courtyard granary in Anatolia may be a promising way ahead to search for modes and moments of institutional change, more specific strategies for state and societal resilience in times of palaeoclimate change, and the impact of state taxation in the Roman world.

By associating the abandonment of the urban granary at Pompeiopolis with palaeoclimate change, it is also hoped to promote further in-depth studies on public granaries as a source of proxy data for failures of grain harvests because of extreme weather conditions and climatological research in general, as recently suggested [71]. Therefore, as archaeologists, we need to focus on the archaeology of taxation and urban economic architecture besides agorai and their supposed commercial markets, and we also need to supplement the fine-grained excavation of urban sites with rural lands and farmsteads.

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Data Availability Statement: The data that support the findings at the granary in Pompeiopolis will be available soon in [24].

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Coincidence and Complexity: Complex Interaction of Society, Environment, and Conjuncture in the Eastern Roman World ca. 500–1100 CE †

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Abstract: The eastern half of the Roman Empire between the end of the 5th c. and the end of the 11th c. CE (customarily referred to as the Byzantine Empire) experienced several significant fluctuations in its political and economic fortunes. Climate change, disease, hostile invasions, internal strife, and subtle longer-term shifts in social and economic structures, as well as cultural ideological identities, have all been invoked to explain this pattern, yet much remains unclear. This paper comments briefly on the palaeoclimatological, palaeoenvironmental, archaeological, and historical evidence for two periods in their broader context. It points out the limitations and challenges inhering in the different types of data; it reinforces the point that changes in climate, rather than having "negative" or "positive" impacts or directly causing societal change, indirectly facilitate or frame longer-term societal transformations. As the evidence for the two case studies indicates, even at the micro-level, it remains extremely difficult in the present state of our knowledge to draw firm conclusions about the role played by climate in stimulating societal change.

Keywords: East Roman empire; climate; environment; agriculture; chronology; land use; adaptive strategies

1. Introduction

The last decade has seen a considerable increase in the amount of literature devoted to the impact of climatic and environmental factors on the history and fate of the later Roman and Byzantine, or medieval Eastern Roman Empire. In part, this reflects a broader trend in history and archaeology to examine potential causal connections between climate and the evolution of human society over the long term, and especially during the Holocene. It also reflects an increasing availability and access to palaeoscientific resources that can be exploited to augment the traditional archaeological and historical documentation. But as we are all aware, this brings with it increased methodological challenges and the potential for the misuse or misunderstanding on the part of historians of what the palaeoscience data can tell us and what the limits are in their interpretation. In particular, the discussion around various forms of reductionist or deterministic argument has been very lively and led to often fierce disagreement among specialists. This is, of course, to be welcomed,

because in order to make the best use of the available evidence, whatever its origins, there needs to be an open and honest debate about method and application [1–3].

In light of this it is not surprising that the roles played by environmental factors (especially disease) and climatic factors (in particular drought and cooling), have come to the fore in recent accounts of the story of the collapse of the Roman Empire, one of the most popular tales of civilizational "decline and fall." Especially prominent, for example, has been the role of the so-called Late Antique Little Ice Age, or LALIA, a period of summer cooling lasting about a century beginning ca. 536–539, which has been credited with a wide range of indirect and direct consequences, including the outbreak of the first pandemic of bubonic plague, and the dislocation of nomadic peoples on the Eurasian steppe consequent upon drought and unusually severe winters [4–6]. The turbulent history of the eastern Roman world from the 6th to the 11th century (and beyond) is relatively well-documented, although there remain gaps and patchiness in the coverage of both the archaeological and written sources (e.g., [7]). As with any other socio-ecological system, East Roman society and history need to be understood within the framework of their physical geography and climate, because climate change impacts different regions and micro-regions in different ways at different times, and these nuances are vitally important if we are to grasp the causal association between climate and social and environmental change [8]. One of the most significant lessons to emerge from this research is that while changes in climate may have no negative impact on the economy and society of a pre-modern state, they may yet provide a context that facilitates a whole range of other societal transformations. The challenge is to integrate these climate data fully into the evidence for social, political, and cultural change. The discussion that follows offers an illustration of this.

In the following I will (1) briefly set out the historical context for the present discussion, followed by (2) an account of the evidence for climate conditions and climate changes for Anatolia across the period under discussion; (3) a discussion of the challenges associated with the proxy data for land-use and an account of what we know about land-use in central Anatolia between the 6th–7th and 11th c CE; (4) some comments on social, economic and administrative adaptive strategies, insofar as our evidence—archaeological, historical, and palaeoenvironmental—permits us to assess these; (5) two case studies illustrating the difficulties and uncertainties in interpreting the relationships between climate, environment, and societal change.

2. Historical Context

The East Roman state at its height in the middle of the 6th century was overextended. With its political center at Constantinople, it stretched as far west as the Balearic islands, across N. Africa as far as the straits of Gibraltar, and spanned most of Italy (with Sardinia, Corsica and Sicily) and the Balkans; in the east it included Egypt and greater Syria (modern Syria and N Iraq, much of Jordan, all of modern Israel and Lebanon) [Figure 1]. But beginning already in the 560s, effective imperial authority over this huge territory began to contract [7,9]. The Germanic Lombards invaded and seized much of Italy from 568. Slavic and then Turkic invaders seized control of much of the Balkans between the 560s and mid-7th century; the Arabs seized the wealthiest provinces in the east—Egypt, Syria, and N. Iraq—between 634 and 642. This limited imperial control to the southern Balkan littoral, northern and western Anatolia, the central plateau, and the Aegean region. At the same time, the 7th-century invasions deprived the government at Constantinople of its wealthiest tax-generating resources. But it also reduced it to a hard, defensible core, focused on Constantinople with its triple walls and sea-defenses, protected by an Anatolian hinterland sheltered behind the Taurus and Anti-Taurus mountains in the south, penetration beyond which always eluded the Arabs, partly because of geographical, partly

climatic conditions [7,10–13] [Figure 2]. In the course of the 8th and 9th centuries, the Empire was able to re-establish a degree of political parity with its Islamic and Balkan neighbors, and by the middle of the 11th century, become again the pre-eminent power in the E. Mediterranean. Although it suffered the loss of much of Anatolia from the 1070s onwards, until the 1180s it retained this position.

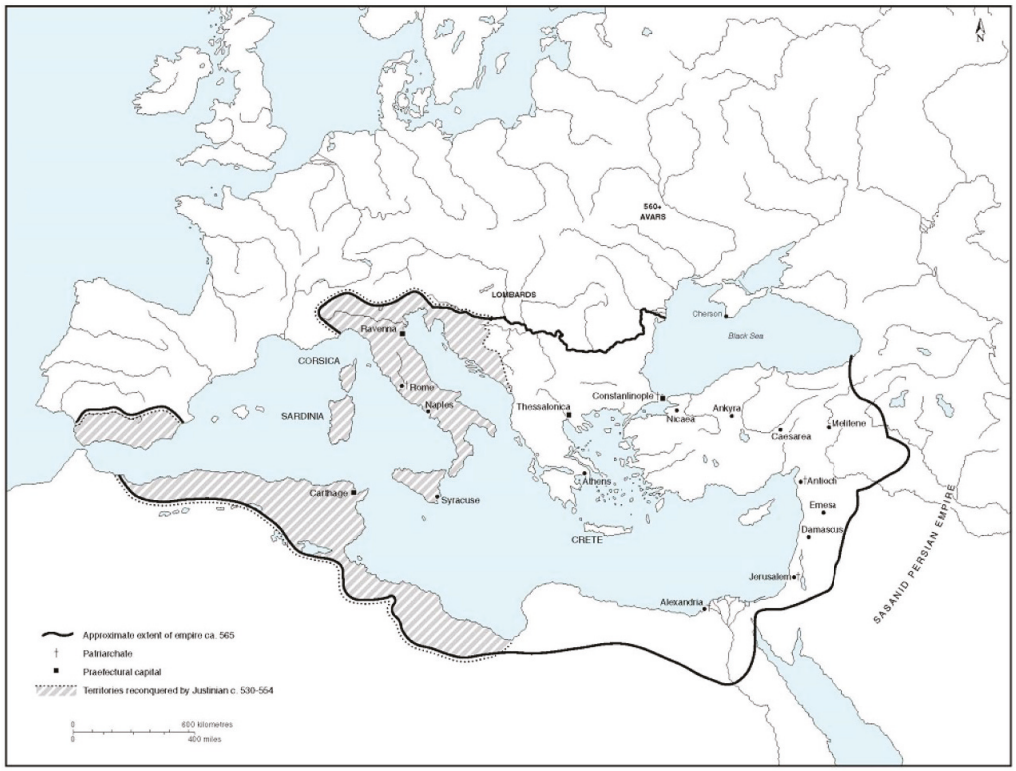


Figure 1. The Eastern Roman Empire at its greatest extent in the 6th c. CE (author's copyright).

Weakened thereafter by internal discontent, elite internecine strife and provincial rebellion in parts of the Balkans, its dominance was ended by the 4th Crusade in 1203–1204, after which it was broken up into a series of smaller polities, many under western European control, until its extinction at the hands of the Ottomans in the middle of the 15th century [14]. The pendulum of imperial recovery and failure swung dramatically across these centuries. Yet the Empire survived as an effective international power up to the end of the 12th century primarily because it retained throughout this period a powerful centralized political establishment; an elite that was never able to effectively challenge the center over the long term; an all-pervasive ideology of Empire embodied in the imperial church; good internal communications, and, crucially, a degree of systemic institutional redundancy that provided effective buffering at times of crisis.

While a great deal is now understood about the way the East Roman state functioned and how its institutions worked, little attention has until recently been paid to the potential role of shifts in climatic conditions in understanding either the causes or the configuration of the changes it underwent [15]. In part, this is a response of historians within a relatively conservative discipline, at least in respect of social theory, to the potential for environmental or climate determinism. Such determinism or reductionism frequently creeps into historical analyses where data permits a clear assessment of climatic conditions, in particular where there exist correlations between significant historical developments and significant climatic events or trends (see most recently on this [16]).

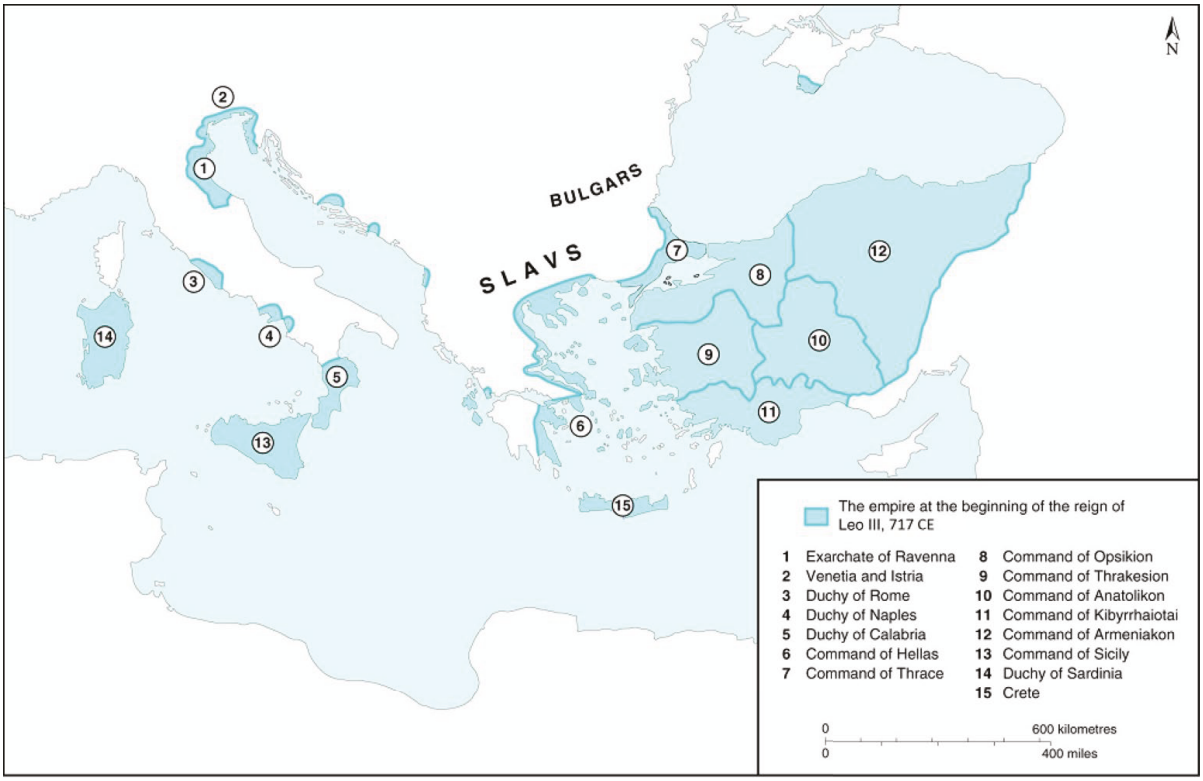


Figure 2. Fluctuating political borders of the Eastern Roman/Byzantine Empire ca. 640–1050 (author's copyright).

3. Climate

The climate history of the eastern Mediterranean-Middle East region across the centuries in question is a fundamental element in this picture [8]. Anatolia presents a complex climate regime, with several contrasting patterns, a result of a combination of the collision of air masses from the North Atlantic, the Mediterranean Sea, and Eurasia, together with a widely diverse topography: plateau grasslands, forest, desert, and mountains. The seven climate regimes that result from this combination of factors are highly variable both spatially and across time [17,18]. Palaeoclimate and palaeoecological data from each of these, even if not always as chronologically refined as we would like, often show very different patterns of warm or cold, arid and moist conditions at the same times in different regions. Since the pattern of change was by no means uniform either chronologically or spatially, drawing causal associations between climate and the wider social, economic, and political evolution of the period is particularly challenging [19–21].

It is possible to generalize, of course. In spite of such sub-regional variation, climatic conditions remained broadly stable across the wider Eastern Mediterranean zone until ca. 200 CE, giving way thereafter to a greater degree of regional variation with higher-amplitude fluctuations between cold/dry and warm/wet periods. Before the 6th century, conditions were, in general, dry, with regional aridity being most marked during the 4th and 5th centuries [22], [23] (pp. 164–165), [24] (pp. 191–202). In the decades around 500 CE, however, Mediterranean atmospheric circulation experienced some significant changes. Northern, central, and eastern Anatolia and the northern Levant became wetter, while other regions—including the Balkans, Greece, and southwest Anatolia, as well as southern Arabia—became somewhat more arid [25] (Figure 1c,d). Thereafter, while central and western Anatolia, along with Thrace, present a very broad (centennial) degree of spatial coherence in temperature and precipitation, a significant improvement in humidity in the Constantinople region—as indicated by the Uzuntarla data (see below)—from the 740s

onward contrasts with an increasingly arid climate in central and northern Anatolia from the same time [26], [27] (pp. 130–131). Yet when we zoom into specific local data, the picture appears even more complex, potentially falsifying any conclusions drawn only at this broader level about the relationship between societal change and climate. Eleven sites across northwestern, northern, and central Anatolia provide useful indications of this complexity [Figure 3].



Figure 3. 11 sites from which palaeoclimatic proxy data can be derived. 1—Sofular cave; 2—L. Nar; 3—L. Tecer; 4—L. Mogan; 5—L. Sülük; 6—Uzuntarla cave; 7—L. Yeniçağa; 8—L. Iznik; 9—L. Çubuk; 10—L. Çöl; 11—Kocain cave (Map courtesy Warren Eastwood).

Thus, relatively well-dated stable-isotope records from (1) Sofular Cave (reflecting the southern Black Sea environment), and (2) Lake Nar, in Cappadocia (indicative of central Anatolia) concur in suggesting that in these regions the 4th-5th c. dry phase was followed by a rapid change to a much wetter climate from the late 5th century persisting into the 8th century [Figure 4]. There followed a short-lived and somewhat drier phase in the 9th century, after which a period of greater humidity set in lasting well into the 14th century [28–30]. A similar, though less precisely dated sequence for central Anatolia is indicated by the data from (3) Lake Tecer [31]; whereas at two sites with more highly resolved chronologies (4) Lake Mogan (+/− 20 years), a little to the south of Ankara, the wetter phase begins over a century earlier [32] and at (5) Lake Sülük (+/− 18 years), 2 km southeast of Boğaz Köy, likewise on the central plateau, the record indicates a relatively dry environment stretching through Late Antiquity well into the medieval period [33].

In contrast, similarly well-dated speleothem data from (6) Uzuntarla cave in Thrace [Figure 5], some 15 km from the Black Sea coast and to the northwest of Istanbul, indicate a relatively humid period lasting from the middle of the 4th century to ca. 690 CE followed by the onset of a short dry phase from ca. 690–740 and a subsequent wetter phase thereafter that lasted into the first half of the 11th century [26]. The proxy data from (7) L. Yeniçağa (near Bolu, and located in the Pontic mountains some 250 km east of Istanbul) indicate fluctuations across the 6th and into the 7th centuries, with an arid phase lasting into the 540s followed by a wetter phase, returning to drier around the year 600, shifts that reflected both its particular geographical location as well as the varying impacts of the regional climate systems [34]. Since Yeniçağa is situated at the point at which four of the above-mentioned climate regions intersect, it provides a good illustration of the variation between

neighbouring zones, as indicated in the records from Sofular, L. Iznik, and L. Çubuk. Thus, the pattern indicated by the data from regional proxies at (8) Lake Iznik in northwestern Anatolia suggests a wetter climate up to the later 6th century, followed by a period of more arid conditions stretching from the early 7th into the 9th century [35,36].

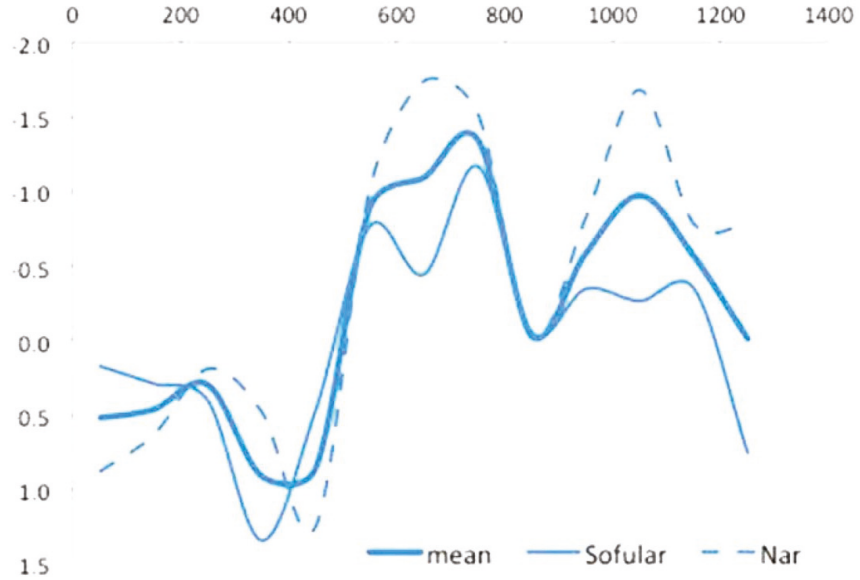


Figure 4. Century-averaged z-scores (the number of standard deviations of a value from the mean) for hydro-climatic change in northern (Sofular) and central (Nar) Anatolia. Wetter climatic conditions are marked by more negative z-scores [30] (Figure 5).

By the same token the data from (9) Lake Çubuk (south of Bolu in northwest Anatolia and approximately 150 km by road east of Iznik) indicate a largely humid climate, with a drier period from the later 5th into the mid-6th century, becoming briefly wetter thereafter, and drier again in the 7th c. [37]. Somewhat further to the east, palaeolimnological investigation at L. Çöl (10), on the relatively treeless plateau near Çankırı (Byz. Gangra), has generated some reasonably well-resolved chronology for premodern climate, and indicates a pattern of shifts from drier to wetter very similar to that for L. Nar [38]. Finally, as an important indication of regional variation in southwestern Anatolia, the overall picture is significantly different: the Kocain Cave (11) record indicates that this region experienced the inverse pattern to that which prevailed in the central regions, sharing instead similarities with the Aegean, with a relatively humid climate regime in the period ca 330–ca 460 CE, followed by a shift to drier conditions lasting well into the 9th century [19,39] (Figure 3).

These data, therefore, indicate (i) a very highly nuanced hydro-climatic trajectory between the 4th and 14th centuries CE across much of Anatolia [27]; (ii) a somewhat different trend indicated by the proxy climate data from the Balkans and Greece [20], which as noted above extended into southwest Anatolia [17,19]; (iii) a general trend in the Balkans, Greece and southwestern Anatolia during the first millennium frequently to run counter to that which can be reconstructed for the rest of Anatolia and the northern Levant (see Figure 6) [17,20,21,39,40]; while (iv) southwest Anatolia was nevertheless generally wetter from the 9th century into the late 11th or early 12th century, which thereafter saw the onset of a period of relatively dry conditions [41]. While similar variations between the southern and northern zones of the Levant are also apparent, the chronology remains insecure [21,23,42–44]. This highly inflected picture is expressed very clearly in graphic form in [33] (Figure 9).

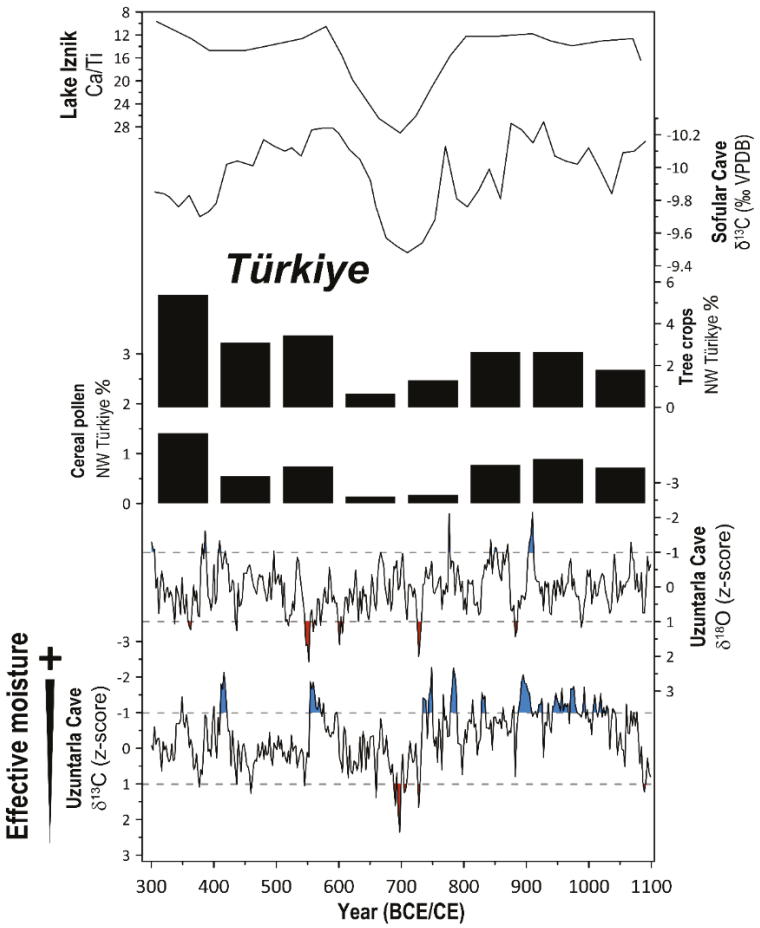


Figure 5. Stable isotope z-scores and textural aridity indicators from Uzuntarla stalagmite U-1 compared with regional palaeoclimate records sensitive to cold-season rains (Sofular Cave [35], and Lake Iznik [36]), together with a pollen record composite for northwest Türkiye [30]. Red shading indicates lower EM (effective moisture) than the mean, blue shading indicates higher EM than the mean. Diagram courtesy Alistair Morgan.

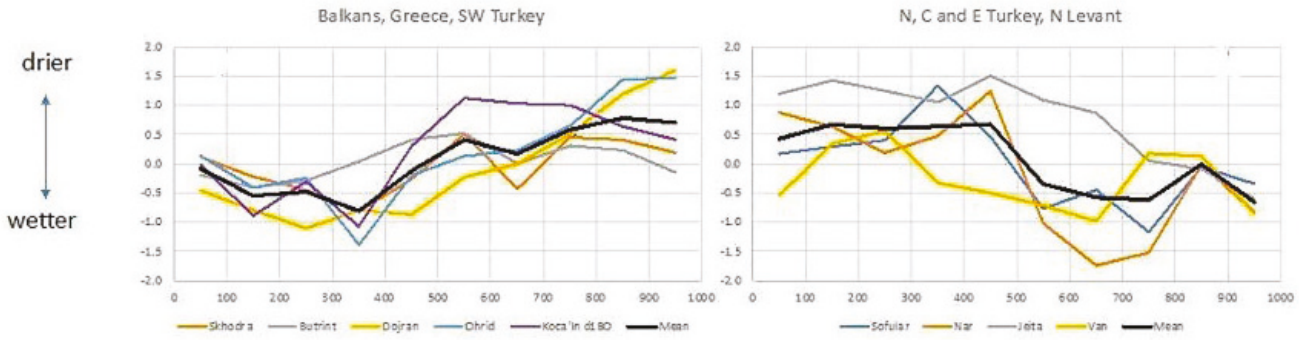


Figure 6. Regional hydro-climate based on century-average Z scores (courtesy Neil Roberts, modified and updated from [20]).

There is one further complicating factor: the evidence from tree rings and speleothems from the Alps, central Europe, and the Altai mountains indicates a colder and drier climate during the middle decades of the 6th century. This is marked in particular by the onset of the LALIA from the late 530s, probably triggered by a major explosive volcanic eruption in the tropics which made the 540s the coldest decade within the so-called Dark Ages Cold Period (ca. 450–800) and indeed of the last two millennia [5,17,23,45–47]. Drops in summer temperatures of as much as 4 °C in the Altai data indicate the nature of the impact,

certainly at higher elevations [43] (pp. 145–149); [48] (pp. 193–194). The exact impact of these conditions on lowland areas remains to be determined, and there is, for example, no obvious reflection of these developments in the Uzuntarla speleothem record [26] (p. 13). But there are some indications in the pollen record from some archives, which register a decline in pollen taxa from some crops: for example, a decrease in agricultural activity is indicated in the pollen signatures for the regions around both Lake Iznik after ca. 540 and at Yeniçağa a little later [34,49]. As we shall see below, the pollen chronology from the latter is reasonably well-resolved, with a +/− range of just 15 years. This corresponds to some extent with the evidence from contemporary or near contemporary written records for a period of a few years, where significant disruption of the usual patterns of seasonal climate promoted poor or failed harvests, subsistence crises, and famine in several parts of the Empire and beyond. Yet, as Newfield [5] (pp. 468–470) points out, the evidence currently suggests a short-term, regionally-inflected impact that did not necessarily have the dramatic consequences with which it has sometimes been associated. In the present state of our knowledge, therefore, we have some degree of correlation, but no clearly causal association.

In this context one issue that is rarely addressed—and which I cannot address here—is the important question of crop tolerances (see, for example, [50–52]), an issue that has not been taken into account in most discussions of the changes during this period of medieval East Roman history. But in thinking about the possible range of impacts of greater or lesser shifts in seasonal temperature and precipitation, it is important to bear in mind the type of crop, landscape, precipitation data, and geology in thinking about landscape change in general. Broad generalizations about 'cool' or 'cooler' and 'warm', or 'arid', for example, are so subjective as to be useless unless carefully specified by context. Data about temperature and effective moisture, both key to the success of crops such as wheat, can tell us more about the potential for a shift in climatic conditions to damage output, depending on the region. There are plenty of examples across the Holocene of dry climatic conditions where the local population appears to have been relatively unafflicted, or even to have prospered. As Jacobson et al. [19] (p. 19 of 31) remark, the Kocain data indicate that in SW Anatolia during the centuries of the Roman Climate Optimum, agriculture thrived in spite of relatively low effective moisture. For Late Antiquity, the shift to drier conditions occurred at least a century earlier than any significant changes in settlement numbers and investment, which can be broadly dated somewhere between 550 and 650 CE.

In summary, it is now possible to document more precisely the significant micro-climatic variations across the East Roman world, and more especially for the present context in Anatolia: between the Marmara transition region, the southwestern Black Sea region, northwestern Anatolia, central Anatolia and southwestern Anatolia, with asynchronic transitions between arid and humid, cold and wet occurring across the period from the 5th–6th centuries into the 10th and 11th (see, e.g., Figure 7). Not only this, but the fact of considerable intra-regional variation reflecting physical geographical factors all inhibit any attempt to generalize about climate conditions in respect of potential associations with socioeconomic and political developments. Spatial heterogeneity of climate in Anatolia as a whole is thus a very significant factor, and these regional variations are key factors that need to be integrated more carefully into the regional and sub-regional histories of both zones when considering their social and political historical evolution.

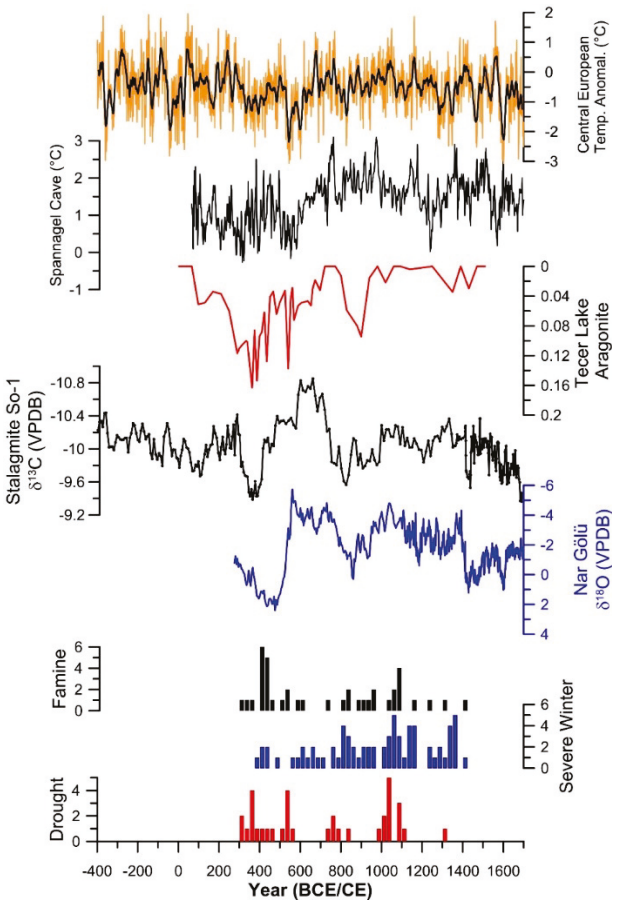


Figure 7. Comparison of proxy records of temperature from central Europe, climatic moisture conditions in central and western Anatolia, and historically documented climate-related events in Anatolia [27] (Figure 1).

4. Land-Use and Agriculture: Data and Interpretive Challenges

How are these shifts in regional climate reflected in the palaeoenvironmental records? The first and most obvious point to underline is that differentiating between anthropogenic and climate-driven impacts is rarely straightforward and sometimes not possible. As has recently been underlined, there are instances where agricultural activity appears not to have been significantly impacted during a period of relative aridity, although seasonality of rainfall is very important, especially for wheat cultivation; a dry winter and/or spring (April–May are crucial months) can mean crop failure. By the same token, more humid conditions did not necessarily lead to greater productivity or intensification of agriculture. Such is very clearly the case during the period stretching from the 1st millennium BCE to the medieval period in southwestern Anatolia (the Roman provinces of Lycia and Pamphylia), for example [19].

The major source for landscape evolution and land use is fossilized pollen, generally retrieved from cores sunk into lake beds or depressions in the landscape. Identifying the pollen in the cores is an immensely time-consuming and demanding process, but establishing chronologies and dating the material poses even greater challenges. If the layers of sediment can be dated, then comparisons can be made with archaeological and settlement survey data to assist in the investigation of the relationships between people and their landscape as well as of longer-term landscape dynamics [53] (pp. 109–143).

But the accuracy of the chronologies is often problematic: i. Sequences may be based on a limited number of radiocarbon (^{14}C) ages, with interpolation between adjacent ^{14}C

ages, therefore assuming a constant sediment accumulation rate between dated horizons. ii. Sediment accumulation rates may vary, and this will affect the dating (and duration) of recorded phases. iii. The top of a core is often assumed to date to the present day, but this may or may not be valid, introducing further uncertainty in the age-depth model of the sequence. iv. Accelerator Mass Spectrometry (AMS) is a more accurate method of dating, several times better than standard or bulk ^{14}C radiometric ages. But when calibrated to calendar ages, the resulting age range may still be unsuitable for direct comparison with historical and textual data sources at sub-centennial resolution, in turn rendering the elucidation of possible cause and effect relationships problematic and generating the so-called "suck-in and smear" effect [54].

All this means that while pollen data can often provide a centennial-level date, it can only rarely offer a dating as resolved as decadal or better, so that making clear connections between landscape or agricultural changes and the often more accurately dateable societal changes is hazardous, although by no means impossible.

By way of illustration, Owen Doonan's archaeological survey in the Sinop region has produced very good evidence for the growth and then the disappearance of a thriving late Roman olive cultivation. The archaeological evidence for the reduction or abandonment of the rural settlements associated with this agriculture currently offers no clear chronology, and dates between the late 6th and the 8th century have been suggested [55,56]. However, sediments from a recently (2015) extracted core from Lake Yeniçağa, in the Pontic mountains, have now been AMS dated, with the pollen sequence for the period 500–830 CE/1450–1120 cal BP having a mean chronological resolution of just 15 years [34], thus comparatively precise. The lake is located at the natural limit above sea-level for olive cultivation in the Pontic region, lies some 300 km as the crow flies from Sinop, and is in the same climatic sub-zone. The pollen evidence points to a short period of olive cultivation in the immediate locality in the middle decades of the 6th c., as well as to other indicators for reduced demographic pressure on the local landscape, evidenced in the recovery of woodland and in indications for the evolution of an agropastoral economy. It also points to a decline in vine cultivation shortly after ca. 600, coinciding with the onset of somewhat more arid conditions. These new data and the more reliable chronology make a significant contribution insofar as they strengthen the likelihood of a later 6th c. date for the rapid breakdown of the olive agriculture of the wider region and especially the Sinop peninsula. But it cannot help with the reasons for the change.

The Yeniçağa evidence also indicates a short-lived period of wheat cultivation in the 580s to early 7th c., corresponding with a decline in vine pollen percentages; then in the 670s emphasis on the more resistant crops of barley and rye, although this fades away by the early 8th c. From the middle of the 8th c there seems to be a more permanent recovery in agriculture, initially barley and rye, but with some wheat and oats, combined with grazing weeds indicative of livestock, and then gradually superseded by tree crops, walnut, hazel, chestnut, olive, and vine, especially from the last decade of the 8th c. [34]. Yet again, the precise role played by shifts in the climatic conditions and the range of possible anthropogenic factors remains unclear.

Pollen and palaeoclimate data from L. Iznik, close to Istanbul/Constantinople and within the so-called MTZ or Marmara Transition Zone, paint a similar picture [49]. Here, the onset of a slightly more arid climate can be dated ca. 580–600 CE, intensifying from 660 and lasting into the second half of the 8th c. This is paralleled by a decline in olive pollen as well as in other crops, including cereals. But here the temporal variation is at least 57 years, so the resolution is not precise enough to suggest a clear moment between the mid-6th and later 7th c for the changes in question. If we prefer a mid-7th c date for the decline of oleoculture in this locality, we could perhaps attribute the decline to anthropogenic causes,

including intensive Arab attacks in the 660s, 690s and leading up to the siege of CP in 717–18, as documented by Marek Jankowiak [57], for example. An earlier association might suggest the longer-term demographic impact of the Justinianic plague [5] (pp. 471–473), or a shift in local market demand and/or commercial networks, or perhaps a combination of many factors, including both cooler climate, shifts in market demand, and disease. This combination of factors would certainly fit the date range for the changes indicated by the Yeniçağa pollen.

Where correlations can be clearly pinpointed between chronologies for climate change and landscape evolution, or between the latter and events such as outbreaks of disease, the impact of warfare, or changes in the pattern of ceramic distribution associated with trade and commerce, one might plausibly argue that there are likely causal associations, even if weak ones; climate or disease as an exacerbating or intensifying factor, for example, if not as a major cause. Whether or not it is possible to build a persuasive argument along such lines at all depends upon the quality of all the different categories of data: palaeoecological, archaeological, and historical.

5. Land-Use and Agriculture: Central Anatolia 6th–11th c. CE

In what follows, I will focus chiefly on central Anatolia. The social and economic history of the period up to the middle of the 7th c. has been reconstructed in some detail from both written sources of many different kinds, as well as from archaeological and palaeoenvironmental evidence. But from the mid-7th c. to the middle of the 10th c., it has been the ever-expanding corpus of archaeological evidence for settlement, material culture, and economic life, including commerce and urban-rural relationships, that has been crucial in advancing our understanding of the period.

These well-established sources of evidence have for the last decade or two been increasingly complemented by palaeoecological and palaeoclimatic data. This has provided both context and depth to our knowledge, but it has also made it possible for the first time to answer questions about the landscapes that formed the backdrop to all these changes. The results of localised surface survey work in different parts of Anatolia, combined with the data from palaeoecological as well as palaeoclimatic research, alongside whatever historical evidence we may have, now provide enough material to speak about local developments with some degree of confidence. As was pointed out more than 10 years ago, and as has since been reinforced by others, the one thing we can say for sure is that the changes of the 6th–9th c. produced a far less homogeneous landscape, both within climatic and environmental sub-zones as well as between them [53] (pp. 217–225). The most important of these changes include the dramatic contraction of most larger and mid-sized urban centers, either to a fortified core and/or to a core with associated semi-urban suburbs or islands of occupation, but with significant differences between coastal and inland settlements, the abandonment of some urban centers and/or the migration of their inhabitants to more secure locations [58–60], [61] (pp. 81–141), and a thinning out of rural settlement, again with regional emphases, with a likely (but barely yet investigated) changing relationship in some areas between field, pasture and settlement [62–68]. As far as we can say at present, the only exception in central Anatolia to the first of these transformations, Amorium, remains just that, explicable in terms of its particular geostrategic significance across the 7th, 8th and first half of the 9th century, and thus comparable to some of the coastal port cities that can now be seen to demonstrate more continuity than used to be thought [69–71]. As we have seen in Section 3, there is little indication in the palaeoclimate data of significant shifts on the central plateau region between the 7th and 10th c., although a trend towards greater aridity from the mid-8th into the late 9th and early 10th c. will certainly have impacted agriculture in marginal and upland zones. But the social-economic and cultural

changes outlined above must have had a significant impact on rural hinterlands and land use patterns.

Until recently detailed information on how such shifts may have impacted land use was based entirely on a few indirect references from historical sources (such as, e.g., the so-called 'Farmers' Law' of 8th or 9th c.), and on what evidence for agricultural production could be retrieved through archaeological excavation and survey. With a particular emphasis on zooarchaeological and palaeobotanical evidence, the archaeological data for the evolution of the Anatolian landscape has recently been very comprehensively summarized by Marston and Castellano [72,73], to whose results we can add new data from ongoing work (e.g., the faunal evidence from the important rural site at Çadır Höyük [55]). But the availability of increasing amounts of proxy land-use data provided by fossil pollen analysis permits, for the first time, a more detailed account of the full scope and character of the changes that took place.

While several pollen cores from sites across the region need re-appraisal and chronological refinement (see Section 4 above), there exists enough relatively well-resolved evidence to corroborate and to add nuance to or to modify the conclusions drawn from the archaeological evidence [53] (pp. 194–201); [54] (pp. 285–295). Although the latter and the palynological evidence do not map entirely consistently onto one another, they nevertheless tell very similar stories. It is clear that there was relative continuity of crop regimes in areas least affected by warfare and economic disruption, and shifts to a different pattern in areas subject to various forms of disruption. There was a fairly generalized decline in arboriculture everywhere, although more pronounced in some areas than others [72] (Figure 8). In those regions on the plateau and its margins where olive and vine had been cultivated, these largely disappeared or declined to such an extent that they have left no signature in the pollen record. In the Mediterranean and Aegean coastal plains and river valleys, the classic late ancient agrarian tradition, characterized by a mixed regime of vine, cereal, and olive production, retreated to a much less intensive level. The traditional patterns were gradually replaced, at different rates according to area, either by a more limited range of crops or in some cases by natural vegetation and woodland regrowth [27] (Table 2); [19,34], [74] (Figure 5), [3] (pp. 145–215), [75] (pp. 277–278).

But the pollen data can now add some important new detail to this picture. The central plateau and upland regions, more generally, had traditionally been dominated by cereal agriculture and pastoralism. This did not change dramatically, except in intensity; pollen percentages drop sharply in the course of the 7th century (Figure 8). But in spite of this dramatic decline in the levels of agricultural production [30] (Figure 3), the pollen record also indicates an increased emphasis on livestock and cereals relative to other crops.

The data reveal that it was not simply a question of reduction of output, or of retrenchment, or of abandonment. To the contrary, the record suggests a positive move towards a different balance in agricultural production, a process that, again, does not coincide with any significant climate shifts. This is not to deny that local and micro-regional patterns may in some cases have run counter to a broader prevailing trend [62] (pp. 264–2670; [75] (pp. 276–278), nor indeed that the changes were all the result of the same factors at the same time. For example, changes in the pollen records at some sites in southwest Anatolia are evident already for the 5th c., suggesting local pressures on agriculture about which we still know little or nothing [19,75], [62] (p. 270), [76] (pp. 44–47, 177–192, 233–238). Yet in spite of the chronological uncertainties associated with some of the pollen data, the 7th c. appears to be the period during which the pace of such a rebalancing substantially intensified.

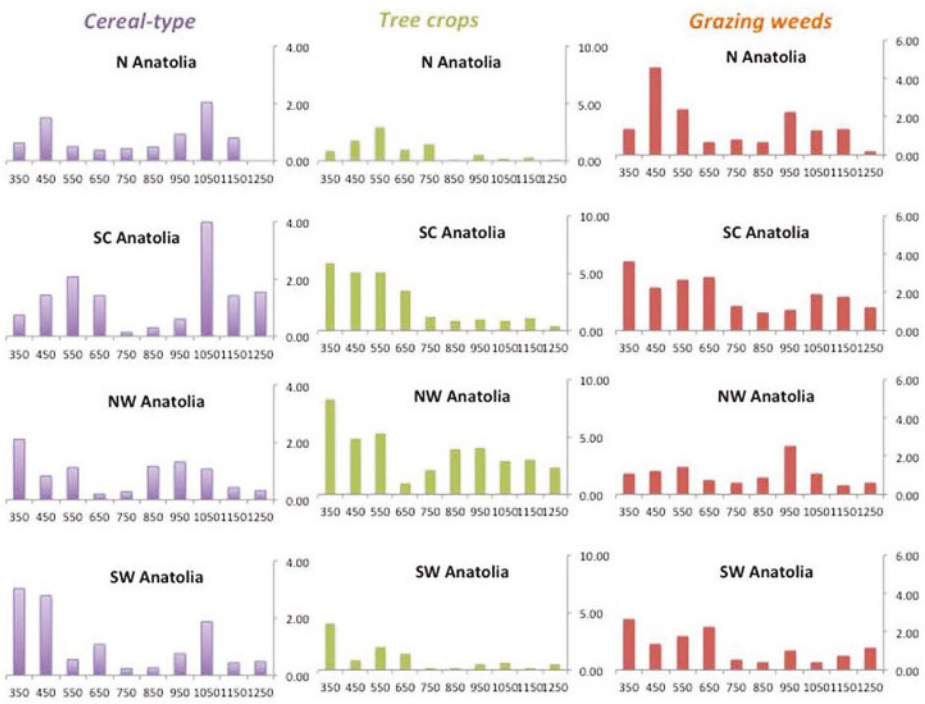


Figure 8. Century-by-century regional means for three agrarian pollen types (cereals, tree crops, grazing indicators), 300–1300 CE. NB: the vertical scales are the same for each land cover type but differ between types [30] (Figure 3). Note that these are aggregated from several sites across each region, and do not represent the specifics of each particular micro-region.

An important aspect of this is that the changing pattern is not uniform: the sites at which these shifts in pollen composition are observed do not necessarily represent more than their own immediate hinterland. Sites indicating change are located in the same region as sites with continuity (Figure 9). The conclusion must be that this pattern reflected the choices, needs, and priorities of rural communities, local exchange networks, and perhaps other pressures, rather than any universal forcing pressure. I will discuss some possible answers to this question below.

As the East Roman state reestablished political and military hegemony in S. Anatolia and N. Syria in the decades from ca. 850–1000, the process of social and economic recovery can be seen in the archaeological record, in the gradual recovery of new forms of urban life from the later 9th century in Anatolia and a little later in the S. Balkans, in the expansion of rural economies as indicated in site and regional surveys, and in the numismatic and ceramic data indicative of increasing commercial and exchange activity [77,78], [79] (pp. 43–89), [76] (pp. 145–158), [40] (pp. 233–236). On the basis of the palynological record, agricultural expansion in the southwest of Anatolia had already begun by the middle of the 9th century and at about the same time along the narrow southern Black Sea coastal plain. By the middle of the 10th century an expansion of cereal cultivation was under way in other regions of the Empire, such as central Greece and eastern Bulgaria, although considerably later, ca. 1100, in more northerly districts such as western Macedonia [62] (pp. 267–268), [80] (pp. 412–420); [41] (pp. 235–236).

To summarise: The changes that took place during the 7th–9th c. are generally interpreted as a shift towards agro-pastoralism, a view now corroborated by the palynological evidence. This was a pattern that appears to have dominated central Anatolia from the 8th century. Based in some districts on extensive ranch-like estates, it has also been linked to the rising political and economic power of the Anatolian magnates [81] (pp. 100–101), [82] (pp. 44–58). By the 9th–10th c., this had expanded into new areas, while with the return

of political and economic security, lowland areas of northern, western, and southwestern Anatolia returned to the cultivation of commercial crops such as olive trees. But the precise trajectories and forms of recovery as reflected in both palynological and archaeological evidence varied between different regions. Evidence for agro-pastoralism in western and southwestern Anatolia, for example, has been interpreted in part as an indication of dairy farming, and reflected the growth of new markets and a wider commercial exchange network across the E. Mediterranean basin and the Aegean [19,75], [76] (pp. 192–232), [30] (pp. 312–315). A somewhat wetter climate regime, as indicated by the proxy data for central and northern Anatolia from the middle of the 6th century into the 8th century [22], [41] (pp. 232–233 and Table 2), would have been favorable for cereal cultivation (which requires extended winter precipitation) as well as stock-raising. But as we have seen, no change in the general trajectory of the pollen signature for cereals can be observed until the middle and later 7th century, long after the climatic shift had taken place. The same applies to some of the declining signatures for vine and olive cultivation. The reasons for many of these changes in emphasis in land-use and the pattern of agricultural production cannot, in consequence, be linked to changes in climate. As far as the current state of our data permits us to say, therefore, there was never a period during which all regions of Anatolia, still less of the E Roman Empire as a whole, would have been placed at the same time under the same degree of climate stress resulting in the same consequences [5,19,30,39,72].

South-west Anatolia	
Beyşehir Gölü	Slight indication of stockraising
Hoyran Gölü	Some stockraising; + cereals from later 8th c.
Karamık Bataklığı	Stockraising
Bereket	Stockraising and cereals
Gravgaz	Stockraising and cereals
Ağlasun	Stockraising and cereals
Pinarbaşı	**Cereals, later stockraising**
Gölhisar	None indicated
Söğüt Gölü	**Stockraising 6th c – 8th c., grain c. 815 +**
Ova Gölü	**Stockraising, small-scale cereal production**
West Anatolia	
Köyceğiz Gölü	**Cereals**
Bafa Gölü	**Cereals and olives**
Gölçuk	Cereals, olives, stockraising
Alakilise	Cereals, fruit, livestock, olives, vines
North-west Anatolia	
Adliye valley	**Stockraising, small-scale arable farming**
Iznik Gölü	Stockraising
Manyas Gölü	Fruticulture until ca. 9th c.
Göksu river delta	Stockraising
Küçük Akgöl	Cereals, vines, fruit; olives from late 7th c.
Abant Gölü	**Stockraising, cereals, vines**
Melen Gölü	**Stockraising, cereals; vines from later 7th c.**
North-central and central Anatolia	
Ladik Gölü	Cereals and stockraising
Demiyurt Gölü	Cereals and stockraising
Çöl Gölü	Cereals and stockraising
Nar Gölü	None until 10th c.
Tuzla Gölü	None
Çadır Höyük	Livestock and some cereals
Pessinus	Livestock and some cereals

Figure 9. Summary table of regional patterns of agricultural production in Anatolia after ca. 660 and until ca. 1100 derived from the interpretation of pollen data. BOLD typeface indicates continuity in land use and agriculture.

A final point, although I will not pursue it here, concerns the extent to which agrarian communities planned for "normal" challenges, such as poor harvests. This can be deduced to some extent from both the archaeological and palaeoecological data, where available,

which serve as a record of societal responses to a range of pressures on land-use [83–87]. But we should bear in mind that agrarian populations did not always or necessarily take advantage of such shifts. While agricultural communities can be flexible and responsive to change, path dependencies—both cultural and practical—can inhibit societal responses to change. Modern surveys among traditional farming and pastoralist communities have shown that perceptions of changing seasonal climate vary according to cultural tradition, location, and a host of other factors, and can be very low even in societies with a higher degree of literacy than that typical of most pre-industrial cultures [88]. Such factors also need to be borne in mind when thinking about the reasons for shifts in patterns of land-use change in the Byzantine world.

6. Adaptive Strategies: Social, Fiscal, and Administrative

The acceleration in the shift in the patterns of agriculture in 7th-century Anatolia seems to have been relatively dramatic, especially for olive and vine cultivation [62] (pp. 264–267), [54] (pp. 301–302), [27] (pp. 146–147), [76] (pp. 44–47, 177–192, 233–238). The possible reasons for this and the particular factors that might have led to farmers changing what they produced at this particular point in time still require clarification. Here we must integrate all the sources, including the historical evidence, in particular that from the numerous lead seals of imperial officials, and legal and official or semi-official documents. More problematic sources—in respect of authorship, textual tradition, and personal political or ideological bias—are the anecdotal evidence of hagiography and the limited contemporary chronicle literature. All of these together provide some crucial information about society and state administration. Given the absence of any coincidence between climate changes and changes in agriculture, and assuming we can exclude, at this period, shifts in dietary habits, three possibilities for the changes in question remain: shifting market demand, warfare and insecurity, and pressure from a third party, such as a landlord, or the state.

In respect of the first of these types of pressure, the archaeological evidence is quite clear: across the course of the 7th century, international and regional markets shrank or changed, and local markets redirected their focus, so demand for a wide range of products must have been affected. At the same time, inland regions in particular became more than ever reliant on locally-produced resources [89–91]. So we cannot exclude market pressures as one possible reason for changing patterns of agricultural production. In respect of the impacts of insecurity and economic disruption, while many regions were negatively impacted by warfare well into the eighth century, the archaeological picture has been substantially complemented by new pollen evidence. For example, the chronologically highly resolved pollen evidence from Nar Lake in Cappadocia coincides with historical information to show that a period of continuous raiding and enemy occupation between 664 and 678 led to a near-complete collapse of agriculture in the area. Such a dramatic impact may not have been very common, but that it could occur is made clear by this example [62] (pp. 262–267), [92]. Archaeological survey data suggests that rural populations adopted economic strategies—including greater reliance on pastoralism, for example—that permitted a rapid evasive response to attack, a response reflected in the archaeological evidence for a thinning out of rural settlement in many regions, the fortification of small urban centers, and the re-use of upland refugia [89] (pp. 538–542, 551–559, 564–570).

As regards the third type of pressure that might impact agriculture, that brought to bear by a third party, we should consider the fiscal and related demands of the East Roman state. This had to negotiate an unprecedented crisis in resources as well as in respect of its military situation [30] (pp. 308–312), [10] (p. 230, Table 6.2). By the 640s and following the loss of the eastern provinces and much of the Balkans (losing something in the order of two-

thirds of its territory and three-quarters of its fiscal revenues in the years between 634 and 642), the imperial armies had been withdrawn from their original bases and garrisoned across territories in Anatolia that could provide for their needs. Here, it is notable that the smallest of these field armies, referred to as the *Armeniakon*, occupied an extensive region of eastern Anatolia, but one that was economically among the least productive. This contrasts very clearly with the more fertile districts to the west and southwest, where much larger forces were based.

In addition, we can point to some interesting changes in technical language to do with the tax system, indicating a realignment of key aspects of the state's fiscal administration, in particular in connection with the supply and management of grain. These shifts took place in the last 30–40 years or so of the 7th century. While the changes cannot be firmly assigned to a particular decade, the written evidence suggests the 660–680s as the most likely period [10] (pp. 258–282).

The fiscal arrangements are significant because they connect directly with the question of military supply. Here, the importance of grain cannot be understated [93]. After 642, the government lost access to the massive grain supplies delivered annually from Egypt, now under Islamic control, a substantial loss affecting both the government's ability to feed the population of the capital, Constantinople, as well as to supply some of its armies, especially in the Balkans. Locating new supplies of grain for the capital was a problem, but one that was resolved to an extent through the Empire's maritime resources as well as from local supplies.

More challenging was the fact that the field armies, newly relocated to the Anatolian provinces, needed to be provisioned, thus imposing a substantial new demand for grain on the areas where they were based. Conditions for cereal production are readily found in many districts of Anatolia, but the increased annual precipitation that affected much of the region from the 6th century also affected areas hitherto less well-watered and will have made the introduction or expansion of cereal cultivation both easier and more profitable [10].

It seems a reasonable working hypothesis, therefore, that together the different strands of evidence reflect in part the outcome of a state-directed adaptive strategic shift in resource production in response to the crisis it was facing. The administrative changes noted above, in association with the increased emphasis on grain production and livestock, and the changing pattern of agricultural production reflected in the pollen record, certainly coincide chronologically. This certainly makes sense in terms of generating the resources the government needed to feed and field its armies and thus to secure the continued existence of the state and its infrastructure: grain and livestock. How the policy was enacted will likely never be known; whether farmers or landowners in the regions where military units were based took advantage of the increased demand for grain, or whether the state manipulated the fiscal burden to facilitate grain production, is not known. The focus on cereal and livestock recurs in the (admittedly still very sparse) archaeological data (e.g., [73], p. 338–346) [75]. But similar shifts in imperial fiscal policy had occurred earlier, for example in 5th-century Italy. Here, both imperial legislation and the archaeology of the south Italian countryside, in particular with regard to the construction of granaries, attest to this policy [94] (pp. 265–270), [95] (pp. 224–27, 232). Viewed as a complex adaptive socio-ecological system, the East Roman state was able to adapt its management of manpower, material resources, and the redistribution of fiscal income in responding to the pressures and stresses it had to confront, and both the archaeological as well as the palaeoecological evidence hint as to how this was achieved.

7. Case Studies

One possible historical and archaeological indicator of this complex combination of developments may be illustrated by the fortunes of the small semi-rural semi-urban settlement of Euchaïta in the Pontus, located on the northern edge of the Anatolian plateau (Figure 10) and in a historically well-documented grain-producing district, with a major center at Amaseia (mod. Amasya). Today a small village (Avkat/Beyözü), its climate regime is typical of its situation between the Anatolian plateau to the south and the north Anatolian (Pontic) mountains to the north: semi-arid, with annual precipitation today between 400 and 440 mm, peaking in late spring (May), severe winters and hot, dry summers. Drought, and consequent reduced agricultural output, is not uncommon [54] (p. 283); [96]. The closest source of palaeoenvironmental data is at L. Çöl, a little to the east of Çankırı and some 140 km in a direct line to Avkat/Beyözü. Both share a similar situation in terms of soils and climate, although the sheltered valley in which Euchaita is located (at some 800 masl) is less barren than the plateau on which L. Çöl is located (1028 masl). During the Roman period the site of Euchaïta seems to have been little more than an obscure farmstead or hamlet, but from the 4th century, when it is first mentioned in the sources, it began to gain a reputation as the center of the cult of St Theodore *Tiro* ("the Recruit") [97]. It was walled in the early 6th century and raised to the status of a bishopric by the Roman emperor Anastasius, before 518. From the 7th century, with the Arab Islamic conquest of the eastern Roman provinces, and the retreat of the Roman, now Byzantine, frontier into Anatolia, Euchaïta became a military base behind the frontier. Archaeological survey indicated substantial evidence of late Roman/early Byzantine occupation and building, in both the area of the lower town, now covered by the modern village of Avkat/Beyözü, as well as on the fortified hill behind the settlement. It remained a provincial center until its conquest at the time of the Seljuk occupation of eastern Asia Minor, in the late 11th century. Thereafter, its importance dwindled, and throughout the period of the Ottoman Empire and until today, it has remained a small village below the hill on which are located the ruins of its fortress [98].



Figure 10. Euchaïta in its wider context (Map courtesy Warren Eastwood).

The ceramic material from the survey covers all periods from the Chalcolithic to the Late Ottoman, but with a predominance of Late Roman and Early-Middle Byzantine. The overall pattern in the survey material was of a relatively high density of Early Byzantine material (i.e., 7th–9th century) compared with that from the Middle Byzantine period (9th–12th c.). Just as significantly, it was calculated on the basis of the extensive survey of the area around the settlement itself that the land-use footprint of the Late Roman period differed from that of the subsequent Early Byzantine (7th–9th c.) period. Over 60% of the area identified as Early Byzantine outside the putative line of the city walls was located in spaces not exploited in the preceding period. Analysis and modelling of these survey data indicated a land-use pattern pointing to a relatively high level of persistence that entailed also expansion and changes in modes of landscape exploitation [99]. The evidence from the archaeological surveys of Paphlagonia and the region around Gangra/Çankırı or around the city of Sagalassos may offer parallels, with a thinning out of rural settlement, and a likely (but barely yet investigated) changing relationship in some areas between field, pasture, and settlement [62,63], [100] (pp. 193–199); [101]; [58] (p. 278); [64,68].

Euchaïta lay at the heart of an extensive cereal-growing district in the territory allocated to one of the major field armies of the Empire, the *Armeniakon*. There is neither fossilized pollen nor palaeoclimatological data from the immediate vicinity of the settlement, but that from L. Çöl and L. Nar share a similar profile in indicating wetter conditions throughout the 7th c., while the pollen record from Çöl shows a landscape dominated by small-scale cereal production and grazing. But it is not an especially fertile landscape, and it is remarkable that in some more fertile areas a steeper decline in cereal pollen can be observed in the 6th–8th c. than the relatively slight decline indicated by the Çöl data. This might support the suggestion that this north Anatolian plateau region retained its value for cereal farming even on a very small scale. The value of the wider region around Euchaïta would have been proportionately much greater. A similar situation may be reflected in the survey data from the rural hinterland of the ancient coastal settlement of Aegialos (modern Cide), which appears to have retained a degree of agricultural importance and continuity of rural activity through the 7th and 8th centuries [101] (pp. 388–389).

The analysis of the survey data from the environs of Euchaïta would tend to corroborate the development of an increased strategic and economic role for the settlement in the 7th–9th c. The continuing and indeed expanded presence of material dateable to the later 7th century and beyond, and the appearance of what appear to have been new functional sites—possibly workshops or steadings—in the hinterland of the urban settlement, are suggestive. It suggests that the latter achieved a raised profile as a center of activity at a time when grain was in high demand [102], [54] (pp. 298–299). This is in stark contrast to many comparable small or middling fortified urban settlements of the period across the East Roman world in this period [68,78,101,103].

The history of Euchaïta, insofar as we can reconstruct it from the evidence currently available, may be an example of one of the ways in which the longer-term change in climate could entirely fortuitously have benefited the East Roman Empire at a crucial period in its history by permitting a continuity, and possibly a relative increase, in grain production and agro-pastoral farming that responded to the immediate demands of the state in its struggle for survival. The extent to which landowners and peasant farmers took advantage of the needs of the government to supply its armies, or were simply responding to pressure imposed from above, remains unknown. The policy shifts promoted by the imperial administration could not reflect any conscious awareness of the shifting climatic trends that affected parts of Anatolia. But in any case, the small city of Euchaïta reaped the benefit for some two centuries before dropping back into relative obscurity.

Developments in the middle decades of the 10th century offer a second example. As noted briefly in the introductory sections of this article, from the middle of the 9th c., the Empire was able to go onto the offensive on a large scale in both the Balkans and along its southern and eastern frontiers [104]. The archaeological evidence for settlement expansion, the recovery of urban economies, and the re-establishment of imperial control over formerly frontier zones is well documented and continues to expand. This transformation is also evident in the paleoenvironmental evidence, and one site in particular offers particularly clear evidence for the impact of these changes.

The pollen data from Lake Nar in Cappadocia, as mentioned above, indicate a radical and dramatic retrenchment of human agrarian activities in the period 664–678, consistent with the effects of a decade of hostile raiding and occupation in the 660s-670s. The same data, however, also indicate a significant and very obvious recovery some 280 years later, around 950. But we see a very different configuration of the human economy of the region. The emphasis now is on cereal production and pastoral farming or ranching, in contrast to the much greater extent of orchard- and garden-crops of the earlier period before their abrupt termination. The recovery of agriculture and stock-raising suggested by the pollen evidence indirectly indicates both demographic and economic expansion. This is reinforced by the archaeology of the region, which attests to a significant recovery in settlement and of investment in the built environment, most notably but by no means only in ecclesiastical and monastic buildings (e.g., [105,106]) (and see below).

Just as significantly, however, the palaeoclimatological data from the lake-bed sediments at L. Nar also point to a significant improvement in the climate of the region, with the end of a relatively dry period and the beginnings of a century or more of wetter climatic conditions [28,92]. This shift in conditions is supported by a range of other palaeoenvironmental and historical evidence, not only from Cappadocia, but from other regions of Anatolia [41] (pp. 229–252).

A good indication of the change is offered by the case of the fertile imperial *episkepsis* (estate) of Drizion, with its fortress [107] (pp. 172–173), located not far to the south of Lake Nar (Figure 11), identified archeologically with the remains of ruins of both secular and ecclesiastical structures near Kınıkören, south of Antigus, mod. Altunhisar. Located on the road from Tyana northwards, it was in Roman times a station or hostelry of the imperial post. The emperor Nikephoros II passed through the locality with his troops on a campaign into Arab territory in 965, and a few years later, the estate was temporarily usurped by a senior palace official, Basil, before being restored to imperial control by the emperor John I in 975. The written sources suggest that Drizion was a wealthy estate and had only recently been restored to imperial control and made safe from hostile attacks after years of warfare and conflict. It may well be the activities of imperial estate managers, in expanding or re-establishing cereal production as well as other crops, which the pollen data from Lake Nar for the period from 950 onwards reflect [28,92].

The remarkable economic recovery that took place in Cappadocia and throughout central Anatolia from the middle of the 10th century onwards is reflected in new church building or restoration, in the settlement archaeological evidence, as well as in the written record of the period (contributions in [103], [105] (pp. 2–4, 201–205), [106] (pp. 432, 438–453). This also reflects the investment strategies of some of the great Anatolian aristocratic landlords of the 10th century and afterwards who figure very prominently in this period in Byzantine society and politics [108], [109] (pp. 448–449), [76] (p. 197). While it can to some extent be attributed to imperial military successes coupled with the dynamism of the aristocratic elite that spearheaded the process, there should be no reason to doubt that the relatively favorable climate conditions that set in during the middle decades of the century

must have been a further stimulus to the process of economic recovery and expansion across the region.



Figure 11. Location of Drizion in Cappadocia (Map courtesy Warren Eastwood).

While the Nar data indicate a significant change in terms of cereal production, however, the shift in climate encouraged a whole range of changes in regional agriculture beyond the immediate catchment of L. Nar, including the production of wine on a large scale. The impressive wine-producing establishment and farmstead attested archaeologically at Mavrucandere, not far from Drizion, which can be dated from the middle of the 10th c. into the later 11th c., is just one of several now identified in the region, possibly to be associated with elite investment for local and regional markets (including the military) [41,110] (for broader context see [79] (pp. 54, 63–90). While the recovery in imperial fortunes at this time begins before any changes in climatic conditions become apparent, it seems reasonable to suppose that climate was likely an additional stimulus and certainly beneficial to an already existing process of change.

When placed in the longer-term context of social, economic, and political developments, therefore, the archaeological evidence reflects the outcomes of the complex human adaptive responses to such developments. In this instance, the point is underlined by the fact that the pollen evidence in the Nar data indicates a sudden downturn in regional economic activity and the abandonment of cereal production on a substantial scale around ca. 1100 CE (Figure 12). Yet there is no indication of any contemporaneous shift in climatic conditions. This change, and the subsequent recovery about a century later, can surely be associated with the occupation of this area by the Selcuks, firstly, and secondly, the economic and agricultural recovery of the region as political and economic stability were restored at the beginning of the 13th century [28,92,111].

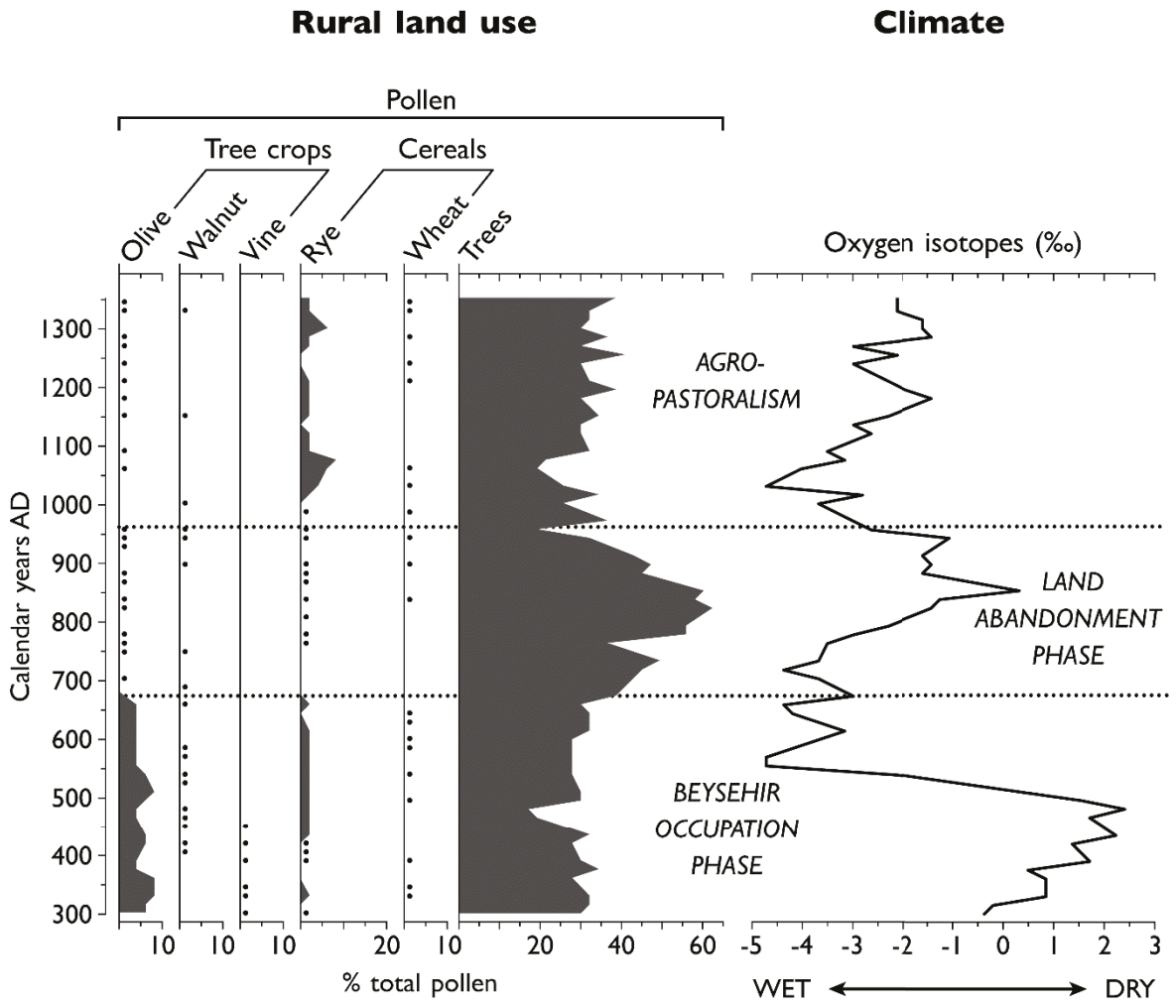


Figure 12. Simplified diagram of proxy data for land-use and climate from L. Nar, Cappadocia (copyright W.J. Eastwood).

8. Concluding Remarks

The "archaeology of climate change" thus presents many challenges in light of the current situation with regard to the archaeology of the Byzantine world in general. Firstly, we are faced with a continuously evolving interpretative situation as a consequence of our ever-expanding archaeological data. Secondly, obtaining sufficiently resolved chronologies for the proxy data, and in particular for the palynological evidence, remains challenging. In consequence, and thirdly, identifying a causal link between the material–cultural evidence for the evolution of settlement, settlement distribution and type, and demography, on the one hand, and on the other the information derived from the palaeoclimatic and palaeoenvironmental data, necessarily involves placing emphasis on degrees of correlation, and as we know, "correlation is not enough" [112,113]. At the same time, the archaeological data for landscape change and land-use associated with settlements remains extremely sparse for Anatolia, so that it is more than challenging to relate the latter to climate change, still less to the impacts of seasonal variations.

It is generally agreed that the transformation of the established "classical" pattern of urban life from the 4th century onward—a complex, multi-stranded process across all regions of the Roman Empire—was dramatically sped up by events of the 7th century. This is most obvious in the archaeological evidence for the fragmentation of long-established patterns of commerce and exchange and for the impacts of the Arab-Islamic invasions in the Near and Middle East. Historical and archaeological sources document changes in the

composition of the elite, loss of imperial revenues on a massive scale, recurrent plague, and demographic decline (see now the contributions to [114]). The proxy data, even taking into account the imprecision of some of the chronologies, suggest that the economic changes took place after the beginning of the 7th century rather than being coincident with the coolest period within the LALIA, the 540s and 550s [5,41]. They also indicate that such changes were micro-regionally highly nuanced and likely took place over decades [101] (pp. 385–388).

The changes in land-use, agriculture and settlement noted above that are reflected in both the palaeoecological and archaeological records for the most part do not coincide with any significant shifts in climatic conditions, except possibly for the impact on olive cultivation of the somewhat lower average seasonal temperatures indicated for the LALIA, from ca. 537 to the second half of the 7th century. This being said, however, I have argued above that one of the "invisible" longer-term outcomes of a wetter climate was the potential for an increase in cereal production relative to other crops and in the context of a considerably reduced producing population. The stimulus for change may have been pressure from the state alone, or a combination of this, together with shifts in patterns of consumption and thus in market demand. In either case the evidence is consistent with this potential only being realised as a result of a complex combination of the fragmentation of the established patterns of exchange with state fiscal policy in the second half of the 7th century; while in the 10th century the shift towards a more beneficial climate regime undoubtedly assisted the expansion of the Empire's agrarian economy as it coincided with its political and military recovery. We can argue plausibly that climate played an important role. But we should be clear that, in these examples at least, this was by no means a simple cause-and-effect relationship, a point that applies as much to that between settlement demography and climate as it does to that between climate and disease [4,5,115].

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Article

Neolithic Bird Folk of the Mongolian Gobi Desert: Climate Change, Ecological Knowledge and Intangible Heritage in an Ancient Persistent Place

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Abstract

There were profound changes in climate and landscape throughout the Early to Late Holocene in the Gobi Desert of Mongolia. The transmission of Traditional Ecological Knowledge (TEK) among ancient hunter–gatherer societies is key for resilient adaptations to such environmental shifts. Such ecological knowledge is often transmitted across generations through folklore and rituals. Evidence from the site of Burgasny Enger in Mongolia's Gobi Desert suggests a persistent place used for gatherings centered around ritual consumption of birds. Occupied seasonally from approximately 10,000–5000 years ago during a warm, wet Holocene phase, the site offers evidence of waterbird hunting, elaborate oven construction, and repeated occupations. We propose that such gatherings were occasions for storytelling and the cultural transmission of TEK, including the widespread Earth Diver Myth. This narrative, centered on the emergence of land from water, underscores the symbolic and ecological significance of wetlands in traditional cosmologies. With the disappearance of wetlands and changing climates, new herding societies replaced earlier lifeways. We highlight the importance of integrating Indigenous ecological knowledge into modern sustainability efforts. TEK, as demonstrated by these ancient practices, offers vital insights for biodiversity conservation, climate adaptation, and long-term ecological resilience.

Keywords: TEK; earth diver myth; hunter–gatherers; Gobi Desert; Mongolia; Holocene climate; neolithic period foragers

1. Introduction

Our hunter–gatherer ancestors have shown great resilience in adapting to broad shifts in climate throughout the Quaternary. They not only survived as a species but also were able to thrive in some of the most challenging environments on the planet while maintaining lifestyles as successful foragers [1,2]. Such success is largely a function of the profound ecological knowledge curated by hunter-gathering communities and the transmission of this knowledge across multiple generations. This information included how to switch from preferred food types to nutritious forms of famine foods [3], how to

manage plants and animals for successful foraging, and adapting methods for living off a landscape in ways that maintained sustainable foodways for thousands of years. Much of this information was handed down through generations via rituals, stories, and legends.

The site of Burgasny Enger is located in the Ikh Nartiin Chuluu Nature Reserve of Dornogov aimag, within the Gobi Desert of southern Mongolia (Figure 1). It represents a long-persisting seasonal camp of early to mid-Holocene Neolithic foragers. Archaeological and geoarchaeological evidence shows that these hunter–gatherers returned to this former wetland locality over the course of 5000 years, throughout the early to middle Holocene period from ca. 10,000–5000 years cal. BP. This lengthy period of seasonal occupation is unusual in the archaeological record of the Mongolian Gobi and highlights this locality as an important "persistent place" [4–6]. The fact that forager populations repeatedly returned to this locality is significant on multiple levels. One of these is the scope of ecological knowledge required to use this landscape sustainably over the course of 200+ generations, and throughout a period of time that encompassed multiple episodes of climate change, as well as many phases of landscape transformation. This alone speaks to a large body of knowledge about plant and animal habitats and behaviors that were transmitted over the course of thousands of years.

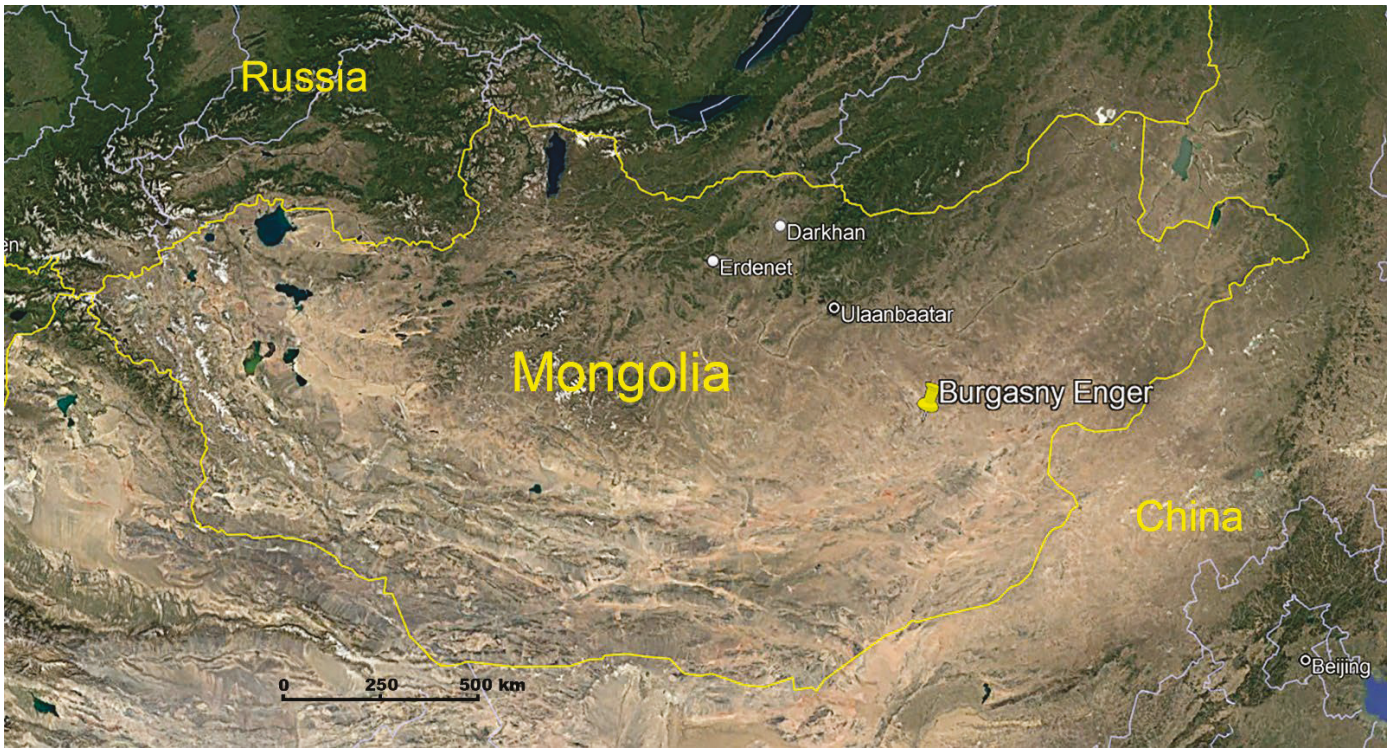


Figure 1. Map of Mongolia indicating the location of the Burgasny Enger site.

The methods for transmitting this knowledge can be as important as the knowledge itself. Some researchers have established that this depth of Traditional Ecological Knowledge (TEK) is commonly handed down through generations via emic media such as myths, legends, and folktales [7–10]. Ecological information is couched within the cosmological framework of Indigenous/Ancestral ways of knowing the world, something often quite foreign to those of us trained in Western Science traditions. An essential way that foragers were able to reaffirm cultural elements, strengthen social bonds, and broadly transmit ecological knowledge was in the gathering of small mobile groups for celebrations, ceremonies and feasting at annual intervals [11]. This is especially relevant for small-scale mobile communities such as the prehistoric societies in Mongolia which were thinly spread across

a vast landscape. Ethnohistoric and modern examples that hold over from ancient and historic times include the North American Powwow [12,13], and the Mongolian Naadam celebrations [14]—usually occurring in warm seasons when food and other resources are abundant.

Although cultural traditions including myths, legends, and folklore can potentially be transmitted over many thousands of years from ancestral to descendant populations, there are a number of factors that contribute to the breakdown of these traditions. The most obvious of tradition-altering forces in modern times is the impact of colonialism, missionization, global markets, and the lure of large cities, to name a few. For past societies, it is also possible that major climatic changes have exerted strong pressures on ancient traditions that forced migrations and/or new economic orientations leaving old traditions as less relevant. Likewise, the influx of new populations that have different relationships with the natural world could lead to the disappearance of older traditions. For example, in the case of the Central Asian steppes and desert steppe zones, a shift from foraging to herding with the cooling and drying climate of the late Holocene, and the subsequent disappearance of lakes and marshes from the basins and lateral valleys might have played a role in shifting ancestral populations away from ancient traditions and cosmologies. Such a case was noted for Siberia as manifested in distinct changes in the subject of rock art which shifted away from animal imagery to human images in the Bronze Age [15] (p.106).

Once these traditions are lost, it might be difficult to detect them archaeologically. Therefore, few studies have attempted to understand the more intangible motivations of social and cosmological incentives over deep time, and their roles in creating cultural and sacred landscapes within the home ranges of particular groups of foragers. Exceptions to this are a number of works from Australian archaeologists dealing with 'sacred geographies' [5,16], and a handful from the Americas and Europe [17].

Over the past two decades, a growing number of researchers have highlighted the importance of addressing Indigenous ways of knowing in concert with Western scientific methods of understanding as essential for developing new and more effective strategies for conserving natural resources through sustainable foodways, seasonal resource management, and biodiversity conservation world-wide. For the most part these types of studies have been conducted in environmental research, health, education, and sustainability studies within a rubric of "Two-eyed seeing" [18]. Two-eyed seeing expresses the value of integrating the vast understanding of nature and sustainable use of natural resources derived from Traditional Ecological Knowledge (TEK), combined with insights gained from Western scientific methods. Although there are numerous pitfalls and uncertainties when this approach is applied to the distant past, it is possible that this tactic might offer or at least suggest some unique insights that would not be evident whilst adhering strictly to Western scientific paradigms. We attempt such an approach in this paper.

The site of Burgasny Enger (BE) may suggest some elements of TEK and cosmology relating to bird-lore among early Holocene foragers of Mongolia. The site itself is not only unique in its longevity as a persistent place, but also in the large number of bird remains recovered from the excavations. Other contemporary sites in the Gobi contain faunal remains that reflect the matrix of diverse animal life found on the surrounding landscape at that time, including many large and medium-sized mammals such as wild cattle (*Bos primigenious*), wild horses (*Equus ferus*), wild camelids (*Camelus ferus*), marmots (*Marmota sibirica*), deer (Cervidae), and wild hogs (*Sus scrofa*). Bird bones form only a small percentage of these remains [19,20]. Conversely, a variety of avian fauna constitutes over half of the faunal remains at Burgasny Enger. Many of these are most likely associated with the now vanished wetlands formerly adjacent to the site and may also represent migrating

bird species which visited this locality on a seasonal basis. Likewise, the features and structural remains at the site are also unique for mobile foragers in these time periods.

In the interest of a "two-eyed seeing" approach we attempt to explore the heritage of ancient foragers in a way that goes beyond material culture remains to speculate about the intangible heritage transmitted through folklore. We will explore some of the potential implications of the unique features of Burgasny Enger, with respect to the reasons why this valley was a persistent place both economically and cosmologically. We speculate on some possible implications for linking the site to deep-time traditions as expressed in folklore, with a focus on the world-building story of the "Diving-Bird Myth" (DBM) prevalent ethnohistorically in Siberia. This ancient myth is also known as the "Earth-Diver Myth" (EDM), widely known across north Asia, South Asia, as well as North America [21,22]. We also examine the role of late Holocene climate change together with historical contingency in breaking the link to these ancient traditions in the Central Asian steppes, with the introduction of sheep/goat/cattle herder-based economies. To begin, we briefly outline the general climatic history of the eastern Mongolian Gobi.

2. Terminal Pleistocene to Late Holocene Climate and Landscape in the Eastern Mongolian Gobi

Climate change has played an important role in the subsistence economies of ancient hunter–gatherers in the Mongolian Gobi. As with many dryland regions, much of our information about these populations comes from sites that are situated near former lakes, ponds, and wetland areas [11,19,23,24]. These localities are highly sensitive to changes in temperature, precipitation amounts and yearly rainfall distribution. For the most part, Mongolia lies within a continental climatic regime with precipitation controlled by the westerly winds. Today, the climate has cold-dry winters, and short summers in which most of the yearly precipitation falls. Precipitation in the eastern Gobi Desert is also within the northernmost range of the East Asian Summer Monsoon (EASM), which brings summer rainfall to this semi-arid steppe zone [25].

Major climatic changes have occurred throughout the late Pleistocene and Holocene in the eastern Gobi. At the Last Glacial Maximum (LGM), large saline lakes filled many of the linear basins in the region. The presence of Paleolithic sites on the high beach ridges around these basins testifies to the use of these lake environments by Pleistocene period hunter–gatherers who visited these locations [26]. These high lake stands were most likely a result of cooler temperatures inhibiting evaporation from their enclosed basins, rather than significantly wetter environments. All indications from proxy data from lakes and speleothems suggest that most of the late Pleistocene was cold and dry, with increases in precipitation and warmth during the Bølling/Allerød period, from ca. 15,000–13,000 BP [27–29]. Subsequently, the Younger Dryas climatic phase marked a shift back to cold dry conditions which lasted for about 1200 years from ca. 12,900–11,700 cal. BP. At this time, many of the large basin lakes disappeared, and erosion pockets marked the valley floor. The end of the Younger Dryas marked the beginning of the Holocene Epoch, our current interglacial episode.

The Holocene began with a rapid warming, a strengthening in the EASM, an extension of its northernmost limit, and a marked increase in precipitation [30–32]. Geoarchaeological evidence points to perennial streams which flowed from the feeder valleys into the large linear basins, resulting in small ponds and wetlands dotting the basin floors, providing oasis-like microenvironments which attracted rich plant and animal life, and numerous visitations by hunter–gatherer groups to these localities [19,33]. This mid-Holocene climatic optimum reached its apex from ca. 8000–6000 cal. BP, then tapered off with a secular drying trend until around 4000 cal. BP, which heralded both the warm-dry conditions of

the Late Holocene, as well as the end of the Neolithic forager subsistence economies, and the introduction of sheep/goat/cattle herding societies around 3500 cal. BP [34–37].

3. Archaeological Background

Around 25,000 BP, at the cusp of the cold-dry Last Glacial Maximum (LGM), new cultural traditions made their way across Northeast Asia, resulting in the replacement of the Early Upper Paleolithic large blade technologies with microlithic assemblages. These microblade traditions signaled new types of hunter–gatherer lifeways and might have enhanced the ability of these mobile foragers to adapt to the harsh Pleistocene environments they inhabited [38]. Although sites from the early post-LGM are rare in the Gobi, they began to be more prevalent at the beginning of the warmer-moist Holocene with the bearers of the microblade traditions spreading out across the landscape in this ameliorated environment—at first very sparsely and later increasing in abundance. These sites are mostly known from surface scatters rather than excavations and are primarily located at the shores of dry lake basins, within dunes near extinct wetlands, and along shores of former perennial streams. These former watery localities were of great importance to the economies of the terminal Pleistocene to early and middle Holocene foragers to such an extent, that it led Janz to frame the distinctions of these occupations into three periods within the context of a model of oasis economies. These periods are Oasis 1 (13,500–8000 cal. BP), Oasis 2 (8000–5000 cal. BP), and Oasis 3 (5000–3000 cal. BP) [23,24].

Oasis 1 (13,500–8000 cal. BP) coincided with the Mesolithic of Europe and the Epipaleolithic periods of Western Asia [24,36]. There are very few sites dating to this phase in the Gobi, apart from Chikhen Agui, (Mongolian: "Ear Cave"), a rockshelter located in the foothills of the Gobi Altai in Shinejinst suum, Bayan khonggor aimag [39–41]. Although Gladyshev et al. [41] report one Early Upper Paleolithic radiocarbon date from a lower level of the site (27,432 ± 872 BP—AA-26580), numerous dates from the previous Russian excavation team place the site occupation more confidently within the range of ca. 13,405–8717 cal. BP (11,545 ± 75 to 7850 ± 110 BP radiocarbon years). There are some archaeological parallels between Chikhen Agui and the earlier occupation phases at Burgasny Enger which we will discuss below. The Oasis 1 hunter–gatherers utilized an evolved microlithic toolkit, which was sometimes crafted from jasper, and there are occasional occurrences of milling stones, notably from the site of Pigeon Mountain in northwest China [42]. The foragers of this time period were resilient enough to adapt to abrupt climatic changes that occurred during the final warm-moist phase of the Bølling/Allerød, the cold/dry reversal of the Younger Dryas, and finally the rapid warming and increased moisture of the early Holocene, by exploiting spring and wetland areas in the Gobi.

Oasis 2 (8000–5000 cal. BP), is contemporary with the Neolithic period in East Asia, and is characterized by chipped stone artifacts, including projectile points, ground stone axes and adzes, pottery, and sandstone milling implements. It is contemporary with the main episode of the Holocene Climatic Optimum, the wettest period of the Holocene, and sites are mostly located near the pond, wetlands, and associated dune features, indicating the more intensive use of a wider diversity of plants and animals associated with these watery localities [36,43–45].

Oasis 3 (5000–3000 cal. BP) marks the transition from full-time foraging to Early Bronze Age herding societies. The artifact assemblages are similar to those of Oasis 2, but new distinctive pottery styles appeared. With the adoption of domestic herd animals, dairying, and cereal crops, new patterns of land use were apparent, with concentrations of sites in upland pasture zones [34,36]. The influx of new herding populations into the region also brought with it new ideologies which were physically manifested by the prevalence of prominent enduring monuments and burial mounds erected on the landscape [35,37].

4. Burgasny Enger

Burgasny Enger is a late period hunter–gatherer site dating from the early to mid-Holocene Neolithic period (ca. 10,000–5000 cal. BP). The site is located on a raised late Pleistocene terrace adjacent to what is now an ephemeral drainage bisecting the Burgasny Enger valley in the Ikh Nart Nature Reserve (Figures 2 and 3). Numerous radiocarbon dates show it had a recurrent semi-sedentary occupation history spanning from the late Oasis 1 through to the end of the Oasis 2 periods (Table 1). Later Oasis 3 remains also exist on the other side of the drainage, although our excavations did not recover evidence of structures or features from that later time period [34].



Figure 2. Landscape context of the Burgasny Enger site.

The remains from the earliest occupation of the site are located at the base of this terrace, at the same elevation as the modern-day drainage channel (Stratum 8) [46]. Our excavations encountered one semi-circular structure (Features 19) and one potential structure (Feature 20). Feature 19 is ca.150 cm in diameter, consisting of four large angular stones set on their sides with smaller supporting stones between them (Figures 3 and 4). At the base of these two structures, the surface was lined with a clayey silt and contained patches of charcoal and black charcoal-rich sediment, indicating several small hearths. This early occupation surface contained fragmented bird bones, as well as some chipped stone artifacts. Radiocarbon analysis returned a date of ca. 9732 cal. BP (Feature 19), and ca. 10,001 cal. BP (Feature 20), placing this portion of the site within the beginnings of the Holocene Climatic Optimum, at a time period consistent with the later phase of the Oasis 1 archeological period [23,24].

These two features were subsequently buried by ca. 150 cm of alluvial sediments, beginning at about 6500 BP (Occupation Units 6 and 5). The stream deposits consist of sets of small well-sorted gravels interspersed with fine-grained clayey silts indicating seasonal occurrences of a steady semi-perennial flow. Many of these fine-grained sub-

sets contained small burn spots with charcoal, along with additional remains of burned bird bones indicating a recurrence of small ephemeral campsites over time, between ca. 6500–5000 BP. The stream activity continued until about 5000 cal. BP, and more marshy sediments (Occupation Units 4 and 3) were deposited after that time, before cessation of all wetland deposition after ca. 4000 BP. This indicates that hunter–gatherers continued to visit the Burgasny Enger and hunt birds close to the channel throughout the alluvial phases of this site.



Figure 3. Overview of the Burgasny Enger excavations from the 2022 and 2023 seasons. Dashed lines are the walls of semi-circular structures; solid lines outline ovens; dotted lines indicate bins. (**A**) Feature 19 structure (9732 cal yrs BP), (**B**) Feature 20 structure (10,001 cal yrs BP), (**C**) Feature 4 oven (8494 cal yrs BP), (**D**) Feature 7 oven (6294 cal yrs BP).

Table 1. Burgasny Enger Radiocarbon Dates.

Burgasny Enger Radiocarbon Dates						
ICA Lab #	**Sample ID**	**Material**	**Radiocarbon Age**	**Calibrated Age yrs BP**	**Ave Cal yrs BP**	**Context**
14C-8655	BE-23-09	Organic Sediment	3880 ± 30 BP	4233–4414	4324	N30/E10 Quad B; 43 cm bd;
14C-8665	BE-23-29	Organic Sediment	4080 ± 30 BP	4513–4649	4581	N30/E16 Quad A; 30 cm bd; Upper fill of Feature 7 Oven
14C-9980	BE-22-7	Organic Sediment	4250 ± 40 BP	4796–4874	4835	N35/E16 Quad D; 78 cm bd
14C-8656	BE-23-10	Organic Sediment	4860 ± 30 BP	5575–5608	5592	N34/E8 Quad C; 19 cm bd; Burned Sediment
14C-8658	BE-23-18	Organic Sediment	4890 ± 30 BP	5582–5662	5622	N32/E10 Quad A; 20 cm bd

Table 1. *Cont.*

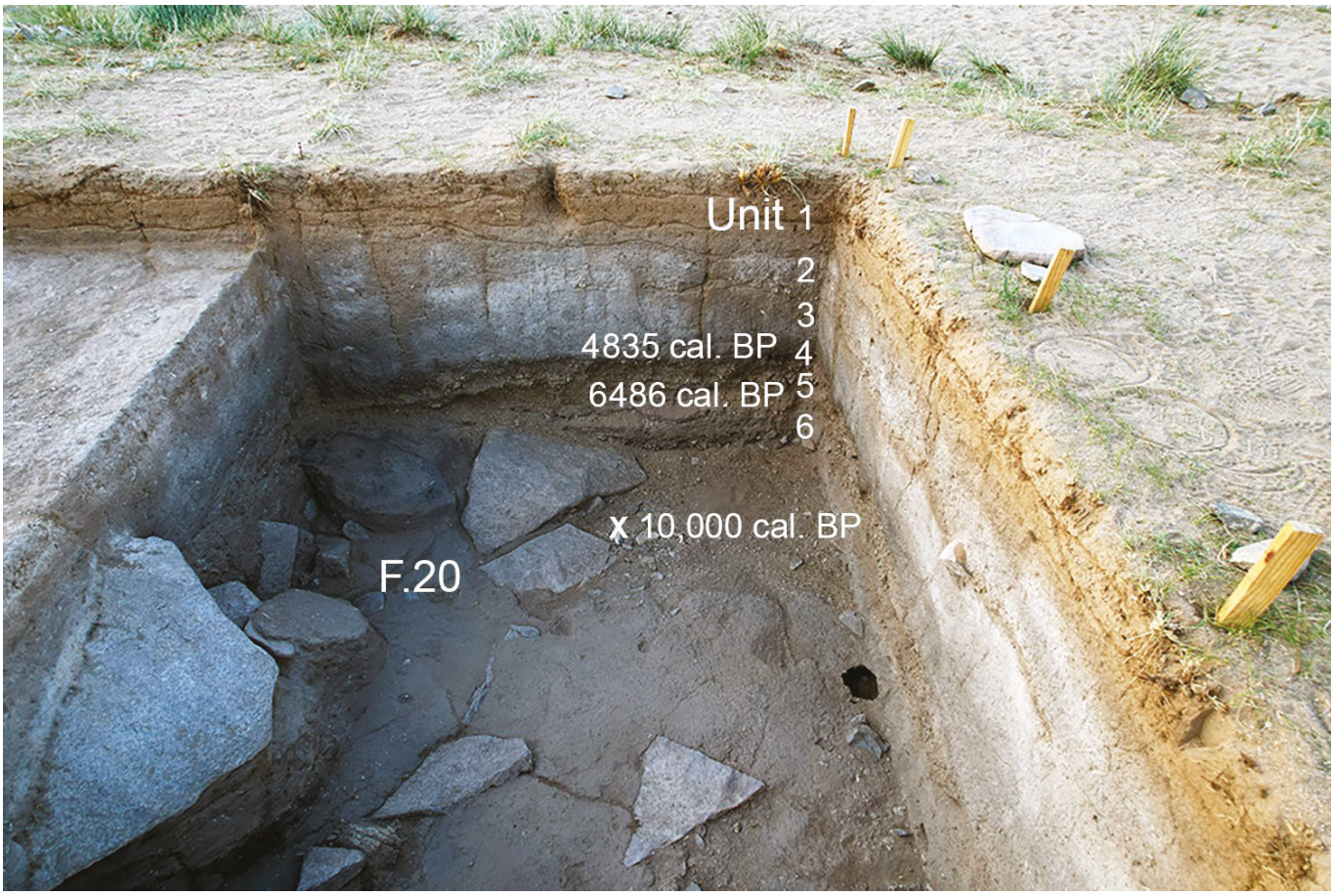
Burgasny Enger Radiocarbon Dates						
ICA Lab #	**Sample ID**	**Material**	**Radiocarbon Age**	**Calibrated Age yrs BP**	**Ave Cal yrs BP**	**Context**
14C-7523	BE-22-9	Charcoal	5040 ± 40 BP	5705–5902	5804	N35/E16 Quad D; 98 cm bd Unit 5d
14C-8659	BE-23-19	Organic Sediment	5080 ± 30 BP	5745–5834	5790	N34/E10 Quad C; 24 cm bd
14C-8660	BE-23-22	Charcoal	5100 ± 30 BP	5748–5829	5789	N35/E19 Quad B; Unit 5B; 79 cm bd
14C-7525	BE-22-16	Charcoal	5270 ± 40 BP	5933–6122	6028	N35/E16 Quad D; Possibly Unit 4?; Point 1
14C-8661	BE-23-24	Charcoal	5420 ± 30 BP	6188–6292	6240	N35/E19 Quad B; Unit 5B; 85 cm bd
14C-8664	BE-23-28	Organic Sediment	5490 ± 30 BP	6269–6318	6294	N30/E16 Quad A; SU 7B?; 31 cm bd; Feature 7 Oven Fill
14C-9981	BE-23-35	Organic Sediment	5610 ± 40 BP	6303–6454	6379	N35/E19 Quad A; 99 cm bd; SU 6 Floodplain facies
14C-7527	BE-22-18	Charcoal	5710 ± 40 BP	6402–6570	6486	N35/E16 Quad A; SU 5; 105 cm bd
14C-8673	BE-23-56	Charcoal	5860 ± 30 BP	6617–6747	6682	N35/E19 Quad C; Sediment from Feature 18 (Hearths); SU 5B; 85-90 cm bd
14C-8668	BE-23-34	Charcoal	5980 ± 30 BP	6733–6900	6817	N35/E19 Quad A & C; 119 cm bd Pt 2
14C-7529	BE-22-11	Organic Sediment	6210 ± 50 BP	6977–7179	7078	N32/E12 Quad C; Feature 3; Above F. 4 oven; charred sediment
14C-8654	BE-23-08	Organic Sediment	6570 ± 40 BP	7424–7516	7470	N30/E8 Quad D; 26 cm bd; Living surface SU 7B
14C-8670	BE-23-50	Organic Sediment	7680 ± 40 BP	8391–8545	8391	N35/E19 Quad C; 137 cm bd; Black smear on 'floor'
14C-7530	BE-22-12	Organic Sediment	7700 ± 50 BP	8430–8557	8494	N32/E12 Quad C; 40 cm bd; Feature 4 Oven
14C-8667	BE-23-31	Organic Sediment	8080 ± 40 BP	8972–9127	9050	N35/E19 Quad A; SU 6; 110 cm bd
14C-8666	BE-23-30	Organic Sediment	8410 ± 40 BP	9400–9529	9465	N35/E19 Quad D; SU 6; 122 cm bd
14C-8669	BE-23-38	Organic Sediment	8530 ± 40 BP	9475–9545	9510	N35/E19 Quad A; 129 cm bd; charcoal in bone concentration embedded in soft marl piece- 3 are likely bird bone
14C-8671	BE-23-51	Organic Sediment	8630 ± 40 BP	9534–9683	9609	N35/E19 Quad D; 147 cm bd; large pocket of black material from surface near Feature 19 Stone ring
14C-8672	BE-23-53	Organic Sediment	8770 ± 40 BP	9555–9909	9732	N35/E19 Quad C; 142 cm bd; SU 6;
14C-7522	BE-22-8	Charcoal	8950 ± 50 BP	9907–10,095	10,001	N35/E16 Quad B/D; 103 cm bd SU 6/8; Feature 20

The top of the Pleistocene terrace adjacent to the channel (T1) was also occupied by foragers beginning at about 8000 cal BP (Occupation Unit 7). These early remains on the terrace immediately post-date the structure at the base of the Pleistocene terrace. They represent a semi-sedentary settlement that is profoundly unique in the Gobi. The site on the terrace edge contains two residential structures defined by a single circle of stones, forming an interior about 2 m in diameter (Figure 3). There are numerous such circular structures on the slope above our excavation area suggesting the possibility of a larger settlement, but these are undated because the interiors have been eroded out and replaced with fine sands washed in from the surrounding Pleistocene fine sandy sediments. Where the structures are more intact within our excavation trenches, the floors are lined with a coating of an unburnt marl mortar mixture less than 1 cm thick. Such pseudo-plaster is known from contemporary sites in West Asia such as those coating floors and walls at Neolithic Catalhoyuk, Anatolia, ca. 9000–8000 cal BP [47,48]. In situ early Holocene Neolithic sites in the Gobi are rare, making it difficult to compare this tradition of mortar construction with other contemporary sites. However, there are possible parallel mortar types found at Chikhen Agui [40]. Burgasny Enger would overlap with the later occupation horizon of the Chikhen Agui rockshelter.



(**a**)

Figure 4. *Cont*.



(**b**)

Figure 4. (**a**) The earliest structures at Burgasny Enger ((**a**): Feature 19, (**b**): Feature 20). Numbers 1–6 refer to site occupation units.

Unique distinguishing features of Burgasny Enger are three pit ovens that were excavated into the sand of the T1 terrace and lined with a thick layer of white marl mortar. The stratigraphic profile of the ovens indicates that they were constructed by excavating a shallow pit (Figure 5). The builders then coated the base and sides with a marl pseudo plaster, making a large basin. They then placed several flat stones in the basin, presumably holding the food to be cooked. Two rectangular stones were placed upright at the boundary of the basin—perhaps for heat reflection, and long coils of clayey silt rods (ca. 5–10 cm in diameter) were wrapped around the edges, perhaps to seal in the heat. Finally, sediment was piled on the top after the food and fire were in place to begin the cooking process. These oven features display evidence of multiple phases of use and repair, with lenses of burning, replastering, and reburning, perhaps to clean and rebuild the oven with each return to the site (Figure 5b). Again, this parallels one of the hearths at Chikhen Agui which also had layers of charcoal and "burned soil" [39] (p. 54) or calcined earth ("прослоек угля и прокаленной земли") [40] (p. 7). At Burgasny Enger, we suggest that these ovens were meant to be significant features at the site because of the care with which they were constructed and maintained—presumably with each seasonal visit. Also, one of the ovens (Feature 4) was covered by a small mound of very large and heavy stones (Feature 3) which protruded above the surface of the terrace, as if to mark the site for easy identification and reuse. Feature 3 sealed charcoal within the oven 'rake-out' from the last phase of use of the Feature 4 oven. The date from that rake-out was 7078 cal yrs BP. The date from charcoal within the oven was 8494 cal yrs BP (Table 1).



(**a**)



(**b**)

Figure 5. Photos of Feature 4 oven. (**a**), looking west, showing burn levels, flat rock to place food, and two upright stones for heat reflection. (**b**), looking east, showing multiple burning and replastering episodes, forming a basin for cooking.

Another notable characteristic of the BE ovens was their association with multiple burned bird bones. We suggest that the care with which these ovens were constructed indicates their role as special-use features, perhaps for the preparation of meals involving

the ritual consumption of birds—primarily marsh or water birds. Evidence that birds were a prominent focus of site activity consists of the fact that bird bones constituted over half of the faunal remains at the site, with mammals only occurring as small fragmented mid-shaft bones (see Table 2). Many of the avian bones from Burgasny Enger lack the epiphyses at the ends of the bones, suggesting that many came from juvenile birds.

Table 2. Faunal Remains from Burgasny Enger; (a) Faunal Remains from the 2022 Season; (b) Faunal Remains from the 2023 Season.

(a)		
Taxon	**NISP**	**%NISP**
Aves (*Falco* sp. (?))	1	0.4
Aves indet.	128	46.5
Aves?	52	18.9
Mammalia indet.	15	5.5
Caprine/Antilopini	1	0.4
indeterminate	78	28.4
Total	275	100.0
(b)		
Taxon	**NISP**	**%NISP**
Aves indet.	2 *	-
Aves ?	59	-
Mammalia indet.	25	-
Rodentia?	10	-
indeterminate	30 **	-
Total	-	-

* 20 bones from two wings of a passerine songbird counted as 1 individual. ** Field counts did not include the small indeterminate bones. This number is an estimate until we receive the 2023 faunal collection for analysis.

Bugasny Enger does not appear to have functioned primarily as a residential site. We base this on several factors. An examination of 45 phytolith samples from oven rake-outs, and ashy deposits from all stratigraphic levels (A. Rosen), showed that the phytoliths represented mostly woody silica aggregates, and there was very little evidence for edible plant remains. Although oven rake-out deposits were present, there were no identifiable middens, and only fragments of unidentifiable mammal bones (S. Pleuger, personal communication). The dearth of plant remains, and the presence of two complete wings from a small passerine songbird in association with an adjacent smear of red ochre point to the site as a possible place for ritual and social integration, rather than activities of daily life [46].

To summarize, some of the prominent features of Burgasny Enger give us insights into its unique place in the Neolithic of the Gobi. These include the circular structures dated, respectively, to ca. 10,000 cal. BP at the base of the T1 terrace, and ca. 9000–7000 cal. BP on the T1 terrace tread, the plastering of floors in the latter two structures on the terrace, the well-built ovens indicating reuse and re-plastering, the later sequences of ephemeral hearths dating from 6000 to 5000 cal BP within the rising channel bed, and the occurrence of numerous bird bones, both burned and unburned within both the well-built ovens and the ephemeral hearths, throughout the period from 10,000 to 5000 cal years BP.

5. Faunal Remains at Burgasny Enger

This section is a consolidation of a laboratory report on all faunal remains from the 2022 field season analyzed by Dr. Sarah Pleuger-Dreibrodt (Freelance Zooarchaeologist), field notes on faunal remains collected in the 2023 excavation season prepared by Prof. J. Clarke—our team paleornithologist, and histological analyses on three small bones from

the 2023 season conducted by J. Clarke. At the time of writing, only a partial sample of the bones from the 2023 season were sent from Mongolia to our labs at the University of Texas, Austin for further analyses.

Both experts noted that taxonomic identification of faunal remains from the two seasons was hindered by the bad preservation of the bone, the fragmentation into small pieces, and in most cases the lack of epiphyses (the identifiable end of bone shafts). However, both researchers report that due to the small size, thinness of the shafts, and hollow configuration, most bones are consistent with bird taxa (Aves) (Table 2). In the 2022 Season report, Pleuger-Dreibrodt notes that the percentage of bird and likely bird bones constitutes 65.8% of the collection for that season. In addition, most bones were burnt, and bird bones were found in all occupation levels at the site. J. Clarke suggests the lack of any epiphyseal material may indicate that these elements are from neonatal birds that would not be capable of flight. The rough surface texture of some of the bird bones at BE is also typical of fledgling aquatic birds [49]. If this is the case, they would be from juveniles of a larger-size taxon perhaps duck- or chicken-sized. There were no preserved morphologies to further identify these elements. Three bones were selected for histological analyses. Two were determined to be from birds, and one of these was indeed from a juvenile bird (Figure 6). The third bone was possibly rodent.

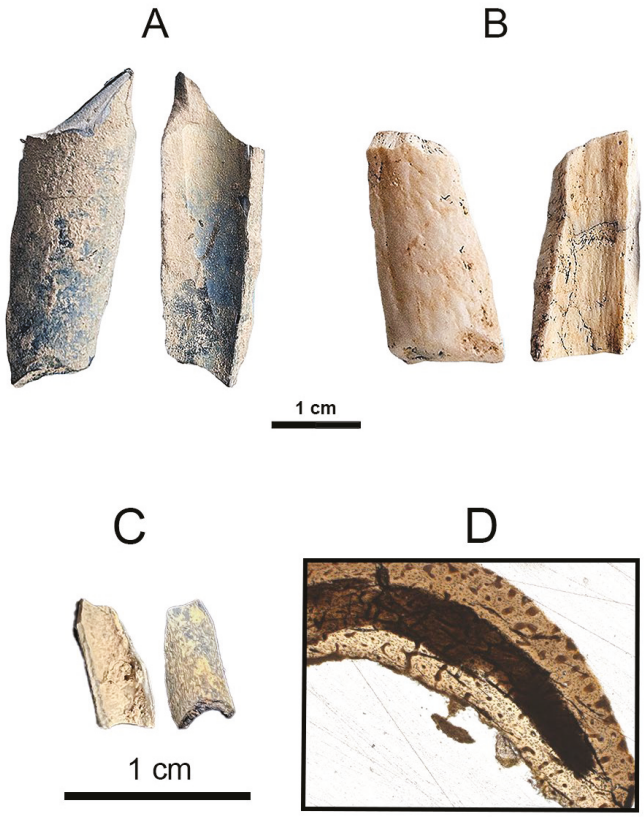


Figure 6. Selected samples of bird bones from Burgasny Enger, (**A**) burned bone shaft, (**B**) bone shaft with coarse surface typical of juvenile birds, (**C**) Sample #307 used for histological thin-section analysis, (**D**) thin-section of #307 showing a thin cortex, woven highly vascular bone as well as lack of an external fundamental system (EFS), and secondary osteons consistent with a juvenile avian.

In addition to the bird bones, partial mammal bones including several with morphology were also present. Most were small, but there were several large fragments of post-cranial remains. In comparison to other sites of this time range in the eastern Gobi, such as Margal [20], Zaraa Uul [19,50], and Tamsagbulag [24,51], there was a conspicuous

absence of many large and medium mammal bones that would indicate a more typical hunting camp.

An unusual bone find from the 2023 season was the wings and two cranial fragments of a small, morphologically adult passerine bird, all from the occupation level on top of the marl plaster (Occupation Unit 7) (dated elsewhere to ca, 8000 cal. BP), and adjacent to the find of red ochre. These bones did not appear burnt and were from an individual smaller than those of the many burnt, mid-shaft fragments described above. Parts of both a right and left carpometacarpus, both right and left humerus as well as ulnar, radius and manual phalangeal remains were present in the same area of one quadrant. Morphologically, and in size, all elements are consistent with being from a single individual. Further identification of these remains requires a comparative osteological collection not available in the field. The taxon to which this specimen belongs may inform why and/or how it may have been hunted. An animal of this size would not provide much food value but could have a symbolic, decorative or other use.

The presence of juvenile birds of a size consistent with waterfowl is significant. Currently, Mongolia is located at the convergence of three flyways for migrating birds: (a) the East Asian–Australian, (b) Central Asian, and (c) East African–West Asian. Even today the Mongolian wetlands are important as stopover points and breeding grounds [52]. During the mid-Holocene climatic optimum, there were wetlands and perennial streams in the vicinity of the BE. We suggest that hunters might have consistently targeted the young birds that nested there, as a practice to sustainably exploit these animals over long periods of time. A similar strategy was used by the inhabitants of Lake Mývatn in northern Iceland. Inhabitants of this region exploited waterfowl sustainably for 1100 years by targeting the bird eggs and protecting the adult members of the population [53].

6. Burgasny Enger Valley as a Persistent Place

The site of Burgasny Enger is geographically located at the node of two intersecting linear valleys running perpendicular to one another, and as such formed a natural crossing point of trails running north–south and east–west. Holguin and Sternberg [54] pointed out the importance of these linear valleys for movement through the drylands of the Gobi. Valleys such as Burgasny Enger also host springs, an essential resource for travelers across this landscape. In the early through mid-Holocene, the valley would have been dotted with wetlands and a seasonally flowing stream, again an important focal point for foragers traveling across the drier rangeland of the interfluves. Burgasny Enger was a significant point on the landscape that might have served as a seasonal gathering place associated with the former adjacent wetlands. The primary season for occupation was most likely in the summer months. The presence of juvenile avian bones at BE suggests a summer occupation coinciding with the annual return of migrating birds. Also, the site is located in an open-air location in the middle of a windswept valley, rather than a point on the landscape that would have been more protected, such as at the base of the cliff faces where modern-day pastoral winter camps shelter from the harsh winter storms.

As mentioned above, although we only found well-preserved huts on the edge of the first terrace (T1) tread, and below the later stream sediments (Figure 4), there were a number of circular stone features visible on the surface adjacent to our excavation area. The original in situ sediment of these structures had been eroded out in antiquity, so we could not date them, but it is likely that they represent the remains of a larger population of occupants than we found within our excavation trenches. This suggests the site was occupied by more than one family group over the course of deep time. Archaeological features such as carefully constructed and refurbished ovens, plastered floors, predominance of bird bones, and lack of evidence of edible plants, together suggest that the site does not represent a normal

residential campsite, but rather point to a possible focus on the ritual consumption of birds. The longevity of seasonal occupation over the course of thousands of years, suggests the importance of this site as a "persistent place" with a continuous history that extends into deep time. The recurrent visits by foragers only ended at the start of the late Holocene, with drying climate, disappearance of perennial streams and wetlands, and the introduction of herding lifeways and new cosmologies at the beginning of the Early Bronze Age, ca. 3500 cal. BP.

As a Persistent Place during the early and middle Holocene, we suggest that BE would have been the focus of many return visits by a number of small groups coming together to reaffirm their cultural values, ceremonies, belief systems, and identity, as well as practical concerns such as finding partners for younger members of the community, communicating ecological information about distributions of resources across the landscape, and sharing of food. These types of gatherings are reminiscent of North American Powwows and modern Mongolian Naadam celebrations. They take place during the summer months when food is abundant, and resources are available for large numbers of people to gather. They are extremely important for the perpetuation of traditional ecological knowledge and inducting new initiates into matters of privileged knowledge [12–14]. Summer months also would have been the time when migrating birds were present in the locality, nesting and rejuvenating their flight feathers in preparation for the next migration season in the fall [55]. They could have been easily captured in nets, and juvenile birds could be collected from nesting locations.

The significance of migrating water birds seems paramount to the interpretation of Burgasny Enger. This would have had economic, ecological, and symbolic importance for the hunter–gatherer groups that repeatedly assembled in this valley over the course of ca. 5000 years. But we also know that among traditional societies the interaction with the natural world and transmission of Traditional Ecological Knowledge constitutes a heritage of both pragmatic experiences as well as intangible cosmological beliefs that are embedded within accounts of folklore [10]. If we examine bird-lore from the region of NE Asia, there is one predominant tradition that stands out which has deep temporal roots across northern and southern Asia as well as North America. This is the "Diving Bird Myth" (DBM), more commonly known as the "Earth-Diver Myth" (EDM) [22]). The central importance of waterbirds, geographical range, and longevity of this story suggest the possibility that it might have played a role in the cosmology of hunter–gatherer groups who gathered at Burgasny Enger.

7. The Potential Significance of the 'Earth Diver Myth' for Burgasny Enger

Folklore specialists have highlighted the Earth-Diver Myth as one of the most important, enduring and widespread traditions of eastern Eurasia and North America [22,56]. It shares detailed components with cultures as far east as Finland, and as far south as India, although it never diffused into China. Interestingly, it also spans across North America as far as the East Coast. Significantly for our interpretations, in North America this common myth never penetrated south of the US/Mexico border, stopping close to the northern boundary of the Sonoran and Chihuahuan Deserts. Folklore specialists maintain that the elaborate details of this story preclude independent centers of origin, and they accept that the occurrence of the myth on both hemispheres speaks to the antiquity of this story, which reaches back into the Palaeolithic period at least as far as ca. 10,000 years ago [57].

The story tells of the origin of the terrestrial world as a home for the earliest humans. The basic outline begins with a watery earth completely covered by a vast ocean. The first creatures, sometimes ducks, sometimes humans—needed to settle on dry land, either

for nest-building or in the case of humans for the making of villages. A variety of kindly creatures (ducks, geese or loons in the Siberian versions) attempted to help by diving deep into the depths to reach the sediment at the bottom of the watery place. Most did not succeed due to the great depth of the water. In the end, only one creature accomplished this task. In many versions, especially in North America, it is the physically weakest of the animals but often one that has supernatural abilities. This creature (sometimes a bird, turtle, or salamander in N. American versions) arrived back to the surface with a mouthful of earth from which an island was formed and subsequently continued to grow into the continents. Often the kindly creature dies after this effort—making a much-appreciated sacrifice.

In North America and South Asia, the exact animal species that made this sacrifice varies, but in Siberia both the initial animals who tried and failed, as well as the successful animals are almost always water birds. Many such stories contrast the more locally occurring loon with the migrating ducks or geese. Often the loons are the first to try and fail, but the duck or goose succeeds. As migrating birds, they are imbued with supernatural powers because of their ability to traverse from north to south, along the metaphorical length of the "tree of life" whose roots in the south penetrate the underworld, with its trunk in the middle world of mortals, and its branches and leaves in the celestial world of supernatural beings [22,56].

Today this myth is most prevalent among folklore traditions in the far north of Eurasia and the far south. However, it is largely absent across the steppe zones of Central Asia. In historic and modern-day Mongolia, bird stories and traditions are more related to Buddhist and other world religious mythologies. However, folklorists maintain that the Earth-Diver was once a pan Eurasian tradition that had to exist within the Central Asian steppe lands as well as the north and south. This would include the northern Gobi as well—within the range of Burgasny Enger. One argument used to support this assertion claims that without pathways across Central Asia, the connection between the two separate regions (the far north and far south) would be unlikely, and the other argument is the striking similarity between the South Asian and some of the North American versions. Variations in the Earth Diver Myth are classified by the different types of animals involved. There are interesting parallels made between the similarities of multiple animal types from both South Asia and North America (either birds, salamanders, turtles, crayfish, etc.), with Siberia as a more unique example of only birds as actors [21,22,58].

An additional argument for pre-herding hunter–gatherer folklore traditions that potentially spanned across the northern to southern reaches of Central Asia, lies in the similarities of Terminal Pleistocene to mid-Holocene material culture. We see this in the microblade technologies that are typical of lithic assemblages beginning ca. 25,000 BP, from this vast region extending from north China, throughout Mongolia, across Siberia, Korea, and into the northwestern portions of North America [38]. It is also evident in the wide range of cord-marked and punctate pottery extending from Siberia south into northern China.

8. Climate Change, Herding Economies and New Cosmologies

In the Gobi, the landscape of the middle Holocene was characterized by ponds, wetlands and perennial streams in both the broad basins and the linear valleys which connected these basins [33,59,60]. These watery spaces were an integral part of the economy of mobile hunter–gatherers who crossed the landscape and focused on hunting both large and small game attracted to these water sources [19,36]. Neolithic period foragers were also dependent upon this mosaic of resource-rich microenvironments. These watery places were undoubtedly the seasonal home of numerous migrating birds, just as they are in the sparse remains of many fewer and smaller wetland areas in the Gobi today. In this paper, we suggest that the wetland birds were significantly more abundant during the

early and middle Holocene, and that they were key actors in the mythologies of foragers throughout the steppe lands of Central Asia, connecting with the folklore traditions of both Siberia and South Asia. This tradition, as we know it today from Siberia and N. America, is tightly woven into the lore of watery landscapes as well as bearing embedded traditional ecological knowledge that is transferred through generations from ancestral to descendant communities. It is possible then that the holders of these traditions were conversant with the widespread Earth-Diver Myth and its Siberian version of the Diving-Bird Myth, at the same time as its dispersal into North America at least during the early Holocene, and perhaps even earlier [22,56].

We know from numerous palaeoenvironmental studies that from the outset of the late Holocene, beginning around 5000 BP, desiccation led to the eventual disappearance of most of these small lakes, perennial streams and marshlands within the large basins and along the lateral valleys of the Gobi, resulting in a landscape that is today described as a dryland desert steppe [33]. As this climatic deterioration set in around 4000 BP across the Central Asian steppe zone, it coincided with the disappearance of full-time forager societies and the appearance of peoples with economies primarily based on sheep, goat, cattle, and horse herding. This new economic orientation radiated across the Central Asian steppes—moving from west to east. These societies brought new traditions to the region as seen from the associated archaeological features of prominent burial mounds, new types of residential sites, and new images in rock art [15,35,37,61].

We suggest here that different cosmologies and traditions accompanied this new economic orientation, along with new "ways of knowing" the ecology of this much-altered late Holocene landscape [62]. The drylands of the late Holocene Gobi Desert no longer accommodated the efficacy of a Diving-Bird Myth, or likewise an Earth Diver myth which was so dependent upon a watery-world inception. A suitable parallel to this might be the fact that in the ca. 10,000 years of the existence of the EDM in North America, the tradition never penetrated the desert regions south of the US/Mexico border lands [22]. Perhaps desert landscapes have their own unique spirituality, and the EDM resonated more with populations that had greater access to watery landscapes.

9. Final Remarks

In this paper we explore the potential transmission of Traditional Ecological Knowledge held by ancient hunter–gatherer societies in the Gobi Desert of Mongolia. TEK plays an important role in promoting group identity, subsistence resilience in challenging environments, and aids adaptation during times of climate change. Much of this information is handed down through generations by the act of storytelling during community gatherings. We illustrate this by our findings at the site of Burgasny Enger, located in the Ikh Nartiin Chuluu Nature Reserve in southern Mongolia.

The occupation of the site occurred during the warm–wet phases of the early to middle Holocene and existed in a landscape of streams and wetlands which subsequently disappeared at the beginning of the late Holocene. The site is distinctive in its evidence for recurring seasonal occupations over the course of some 5000 years from ca. 10,000–5000 cal. BP, highlighting its function as a "persistent place". The finds and features within the site also demonstrate the unique role of the location as a focal point for the hunting and consumption of aquatic birds, among other avians, and the construction of large elaborate oven features indicating many occasions of use, replastering, and preservation by burial under large stones after the seasonal occupation.

We suggest that the primary function of the site may be related to summer gatherings of family or tribal groups for consumption of birds, rituals, exchanging information, initiations and sharing of stories and folklore. Specifically, we suggest the retelling of the Diving

Bird Myth (also known as the Earth Diver Myth), a creation story beginning with a watery earth and the formation of the first dry land, that features a heroic animal which is often a waterbird. This story not only dates back to paleolithic times, but is also known across Northern Eurasia, South Asia, and North America.

With the onset of a drying climate, the wetlands disappeared, and the site of Burgasny Enger was abandoned, yielding to populations of herders who maintained different economies, lifeways and worldviews. New ways of understanding the natural world replaced the former traditional ecologies that were previously centered around the exploitation of wetlands and associated cosmologies.

Here we highlight the value of Traditional Ecological Knowledge (TEK) in sustainable resource management of waterbird populations, showing that hunter–gatherers of the Gobi successfully hunted birds throughout episodes of shifting climates over millennia from the early to middle Holocene. It is possible that this was achieved by targeting juvenile water and shore birds, as well as the transferal of embedded knowledge of bird habits and bird lore within their world-building stories. Granted, it is a difficult task to use a "Two-eyed seeing" approach to archeological remains that stretch far into the distant past, especially when folklore traditions have been ruptured. However, this does not mean archeologists should abandon these efforts. Every region and site have unique challenges, but with careful collection of paleoenvironmental data, "ecofacts," and the recognition that there is ecological information embedded in folklore and belief systems that extend through millennia, perhaps we can revive some of this ancient traditional knowledge.

As the modern world faces global challenges such as biodiversity loss, climate change, and ecological degradation, recognizing and integrating the intangible heritage of deep-time ecological knowledge of traditional societies alongside Western scientific methods can offer innovative solutions. For example, many Indigenous practices emphasize sustainable foodways, seasonal resource management, and biodiversity conservation—all of which align with current environmental goals. The cultural transmission of ecological knowledge through storytelling, rituals, and gatherings presents an opportunity to rethink environmental education. By incorporating Indigenous perspectives into conservation efforts, policymakers can foster more resilient strategies rooted in long-term ecological wisdom rather than short-term exploitation.

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The Nile and Climate History, 3000 BCE to 30 BCE

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Abstract

The relationship between Nile flood variability and Egyptian political stability has been studied since Barbara Bell's pioneering work in the 1970s, yet precise causal mechanisms linking environmental stress to societal crisis have remained elusive due to chronological limitations. This paper presents a methodological framework achieving annual to decadal resolution through volcanic forcing of the East African Monsoon. Large volcanic eruptions disrupt atmospheric circulation, suppressing monsoon rainfall over the Ethiopian Highlands and reducing Nile summer floods with impacts precisely dated through ice core chronologies (±1–2 years). Applied to Ptolemaic Egypt (305–30 BCE), this methodology demonstrates that volcanic-induced flood failures significantly increased revolt probability ($p < 0.02$) and correlated with land sales, warfare cessations, and economic stress indicators. Statistical validation distinguishes causal relationships from chance correlations, while comparative analysis of early versus late Ptolemaic responses reveals how political legitimacy, fiscal capacity, and institutional strength determined societal resilience versus vulnerability to environmental shocks. This approach achieves temporal resolution beyond the century-scale resolution of previous studies, determining temporal sequence essential for establishing causation. The methodology is replicable across historical contexts where documentary sources overlap with ice core volcanic chronologies, offering a template for integrating paleoclimatic precision with historical analysis to understand human–environment interactions in past societies.

Keywords: Nile floods; volcanic forcing; Ptolemaic Egypt; environmental history; climate and society; paleoclimatology; ice cores; statistical methods; causation; resilience

1. Introduction. Evolution of Nile Environmental History: From Correlation to Causation

The relationship between the Nile flood and Egyptian political history has fascinated observers since Herodotus. In fact, the direct connection between floods and political history was already clearly recorded in texts such as the Palermo Stone (ca. 2450 BCE) [1]. Yet for most of this long historiography, the precise mechanisms linking environmental stress to societal change remained speculative, based on correlations between multi-century climatic trends and equally broad political historical narratives. This changed fundamentally with Barbara Bell's landmark papers in the 1970s, which established a framework for understanding connections between disruptive Nile flooding and societal stress [2,3]. Bell's work on the Old Kingdom collapse (c. 2200–2000 BCE) and Middle Kingdom instability demonstrated that prolonged droughts—manifested as repeated low Nile floods—could serve as triggers for political crises.

Karl Butzer extended this approach in the 1970s and 1980s, systematically identifying four major environmental anomalies between 3000 and 1000 BCE and correlating each

with periods of political discontinuity [4]. His framework treated environmental stress not as deterministic cause but as "co-agent" in historical change, working alongside political succession disputes, administrative inadequacies, and other factors. Yet Butzer himself acknowledged the limitations: his environmental anomalies were characterized at multi-decadal to century-long scales, making precise causal arguments difficult.

The Precision Problem. To move from correlation to causation—to establish that environmental stress *triggered* rather than merely *coincided with* political crises—requires precision at annual to decadal scales. Recent advances in paleoclimatology, particularly our understanding of volcanic forcing of the East African Monsoon, now make this possible. When large volcanic eruptions inject sulfate aerosols into the stratosphere, they disrupt atmospheric circulation patterns, including the monsoon systems that feed the Nile flood. These disruptions are precisely dated through ice core records and can be traced through their impacts on Nile River hydroclimate with unprecedented chronological accuracy.

This paper presents a methodological framework for studying Nile environmental history that achieves annual to decadal resolution through a high-resolution ice core chronology that links explosive volcanic eruptions to the forcing of the East African Monsoon (Figure 1). While debates continue about environmental determinism in climate history, the volcanic forcing methodology avoids this pitfall through the integration of precise natural and human records. By combining a volcanic chronology derived from ice core geochemistry, climate modeling, and Egyptian documentary evidence, this methodological framework achieves annual to decadal resolution through volcanic forcing mechanisms. We can now identify specific eruptions, trace their hydrological impacts, and document Egyptian responses with a precision unavailable to earlier generations of scholars. Table 1 provides a chronological overview of major Egyptian periods and the environmental anomalies identified by previous scholars, situating the Ptolemaic focus of this study within the broader sweep of Egyptian history.

Environmental history of the Nile has evolved through three major phases, each achieving greater chronological precision. Barbara Bell's textual analysis (1970s) established climate-society connections at century scales. Karl Butzer's systematic framework (1970s–1980s) identified four major anomalies with multi-decadal resolution. Recent geochronological advances by Macklin and colleagues and geoarchaeological synthesis by Bunbury and Rowe achieved multi-decadal precision through radiocarbon dating and fluvial analysis [5,6]. Yet all faced the same fundamental limitation: insufficient temporal resolution to establish causation rather than correlation. Figure 2 illustrates the evolution of these methodological approaches.

Table 1. Chronology of Egyptian historical periods and major environmental anomalies identified by previous scholarship. The Ptolemaic period offers exceptional documentary density enabling annual-resolution analysis of volcanic forcing impacts on Egyptian society.

Period	Dates (BCE)	Environmental Anomalies
Early Dynastic	3000–2686	Anomaly I: ~1 m flood decline
Old Kingdom	2686–2181	Anomaly II: Sustained low Niles
First Intermediate	2181–2055	Continued drought
Middle Kingdom	2055–1650	Anomaly III: Extremely high floods
New Kingdom	1550–1070	Anomaly IV: Low floods, lake decline
Ptolemaic	**305–30**	**16 major volcanic events (this study)**

Note: Dates for periods before 664 BCE are approximate. Anomalies I–IV identified by Butzer [4]. This study employs volcanic forcing methodology to achieve annual-resolution analysis for the Ptolemaic period, where exceptional documentary preservation through papyri enables precise correlation between environmental stress and societal responses.

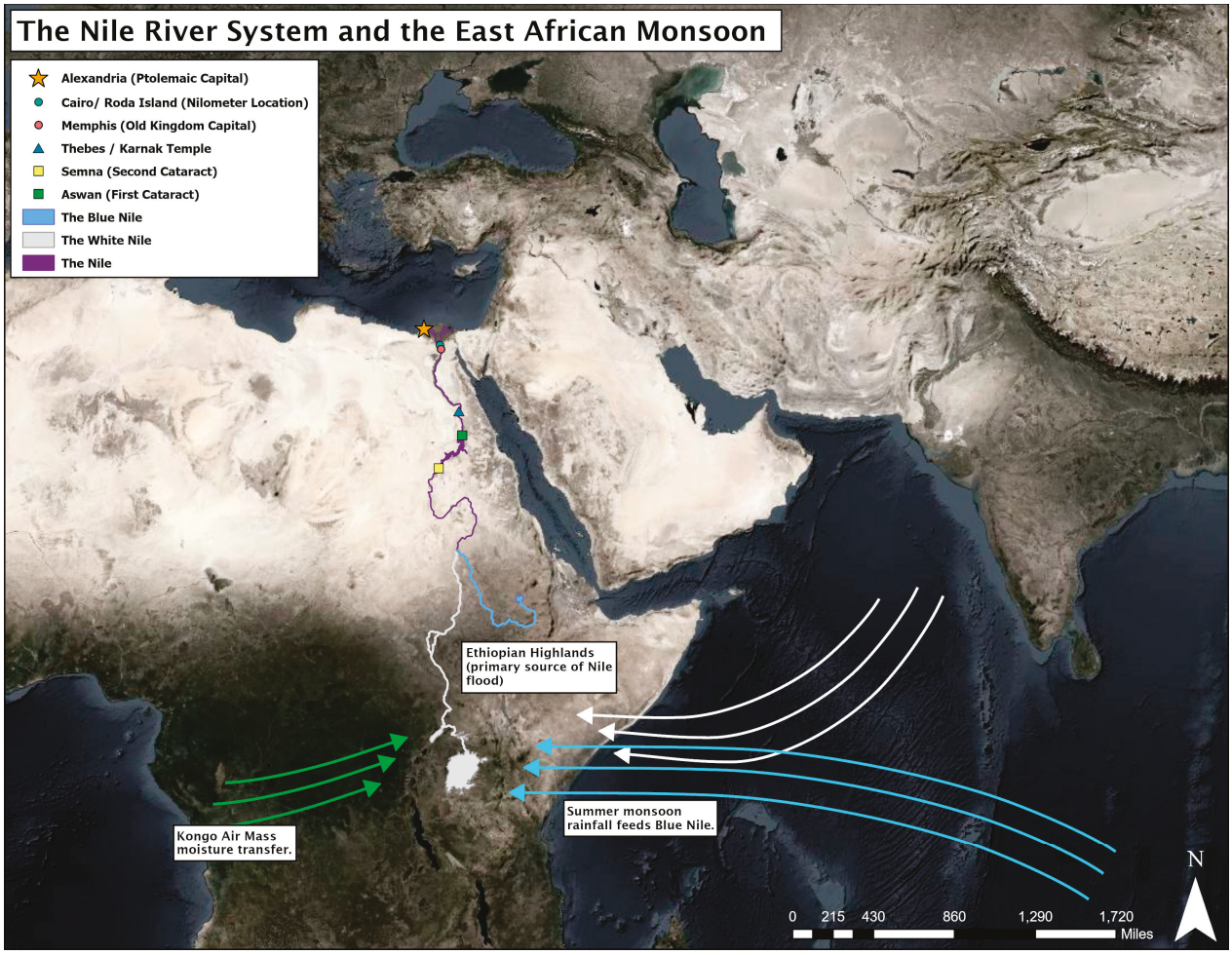


Figure 1. The Nile River System and East African Monsoon. Map created by Mr. William Kennedy, SUNY Cortland.

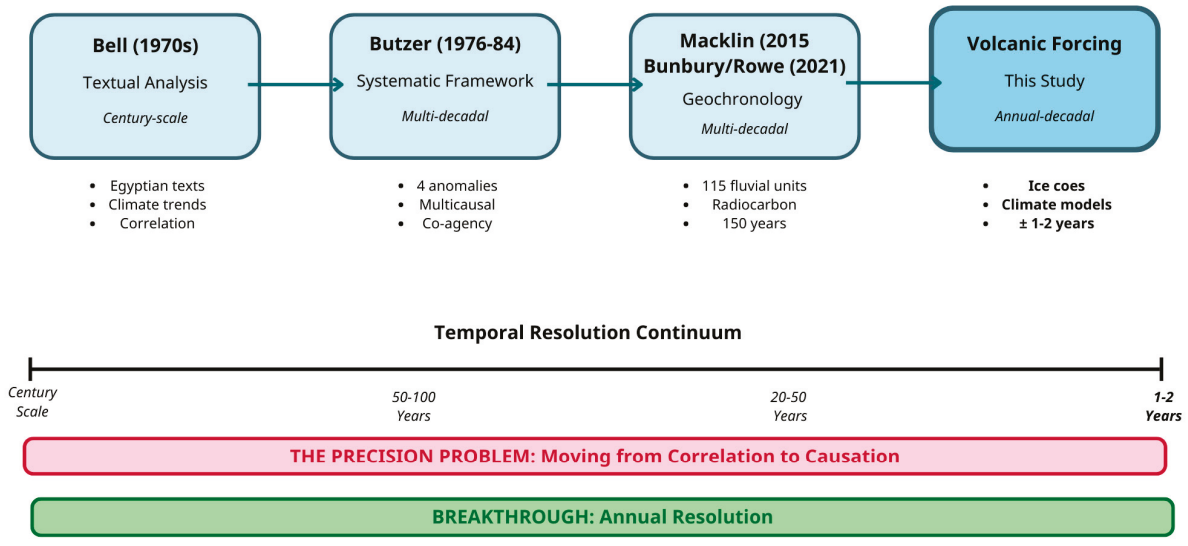


Figure 2. Evolution of Nile environmental history methodologies: From century-scale correlation to annual-scale correlation.

1.1. Barbara Bell and the Discovery of Climate-Society Connections

Barbara Bell's landmark papers established that prolonged drought caused the Old Kingdom collapse (c. 2200−2000 BCE) and Middle Kingdom instability [2,3]. Her innovation lay in systematic analysis of Egyptian textual evidence: Ankhtifi tomb inscriptions describing extreme famine, the Admonitions of Ipuwer detailing social chaos, and nomarch stelae claiming to have fed districts during "years of low Niles" (*tzw*, meaning exposed sandbanks). She interpreted *tzw* as specific indicators of drought-induced famine, linking Egyptian collapse to simultaneous destructions across the eastern Mediterranean and the end of the "Neolithic Wet Phase."

Her second paper proposed exceptionally high floods during the later Middle Kingdom (c. 1840−1770 BCE), analyzing Semna inscriptions recording floods 8–11 m above modern levels—three to four times normal volume. While groundbreaking in establishing climate as a serious historical factor, her work faced chronological limitations: dating relied on textual evidence with uncertainties of decades or more, and causal mechanisms remained theoretical.

1.2. Karl Butzer's Systematic Framework

Karl Butzer's work transformed Bell's insights into a systematic framework identifying four major Nile flood anomalies between 3000 and 1000 BCE, each correlated with political discontinuity [4]. His key theoretical contribution emphasized multiple causal pathways: environmental stress worked as "co-agent" alongside political succession disputes, administrative inadequacies, foreign invasions, and economic problems. Table 2 summarizes Butzer's four anomalies and their proposed societal impacts:

Table 2. Butzer's four environmental anomalies and political discontinuities.

Anomaly	Period (BCE)	Environmental Evidence	Environmental Agency
I	3000–2900	1 m flood decline (~30% reduction)	Plausible co-agency
II	2720–2002	Sustained low Niles; famine inscriptions	Probable trigger
III	1970–1770	Extremely high floods (8–11 m above present)	Conjectural
IV	1260–1070	Lake decline; agricultural collapse; grain prices 8–24× normal	Highly probable co-agency

Butzer's conception of Egyptian society emphasized dynamic equilibria—constant adjustments within a consistent framework, with multiple "layers" of buffering (technology, social organization, exchange) creating a high instability threshold but vulnerability when negative factors concatenated. His later work strongly criticized environmental determinism, arguing that societal collapse is multicausal, with environmental factors often secondary to sociopolitical variables [7]. For the Old Kingdom, economic decline preceded collapse by ~160 years through tax exemptions and lost trade revenue; possible Nile failures triggered the final crisis, but institutional weakness was the primary precondition.

1.3. Recent Advances and the Persistent Precision Problem

Mark Macklin's meta-analysis (2015) provided quantitative framework using radiocarbon and OSL dating of 115 fluvial units across the Nile catchment [5]. Applying cumulative probability density functions and distinguishing floodplain versus paleochannel deposition, Macklin identified specific channel contraction phases and demonstrated inverse relationships between floodplain and paleochannel deposition. This work quantified timing of hydrological changes with unprecedented precision, showed regional variability, and revealed how civilizations adapted to environmental stress—the Old Kingdom flourished despite increasing aridity until c. 2200 BCE, suggesting remarkable resilience to gradual change but vulnerability to abrupt shifts.

Bunbury and Rowe's geoarchaeological research (2021) provided crucial spatial context, demonstrating that environmental history requires understanding not only precise chronologies but also how hydrological changes operated at local and regional scales [6]. Their five-stage Nile development model offers chronological markers aligning with political instability periods. Their analysis of channel migration rates (2–9 km per millennium) provides concrete mechanisms for how environmental changes affected state capacity. Their site-specific case studies from Memphis, Karnak, and Hierakonpolis demonstrate how macro-level climate changes translated into local political and economic effects. At Karnak, flood level changes affected temple operations and royal legitimacy, since the pharaoh's ability to maintain cosmic order (*ma'at*) was symbolically expressed through control of water [8].

Yet even these advances achieved only multi-decadal resolution. Radiocarbon uncertainties (±50 years or more), fluvial depositional complexities, and challenges of correlating dispersed sites made year-to-year correlations impossible. This is the precision problem: to establish causation rather than correlation, to demonstrate that environmental stress triggered rather than merely coincided with political crises, requires resolution at annual to decadal scales.

The Research Gap. Despite progressive methodological refinement, Nile environmental history has lacked the temporal precision necessary to establish causation. Century-scale correlations between climate trends and political events cannot distinguish whether environmental stress triggered crises or whether political collapse caused apparent environmental degradation through reduced agricultural investment. Even multi-decadal resolution cannot determine temporal sequence with confidence sufficient for causal inference. The breakthrough comes from volcanic forcing of the East African Monsoon, which provides annual to decadal precision through ice core chronologies dated to specific years (±1–2 years).

2. Materials and Methods. The Volcanic Forcing of the East African Monsoon Framework: Achieving Annual to Decadal Resolution

2.1. Mechanisms: From Eruption to Nile Flood Failure

The key to achieving annual to decadal resolution in Nile environmental history lies in understanding volcanic forcing of the East African Monsoon—a mechanism that provides both precise dating and clear causal pathways from atmospheric disturbance to hydrological impact to societal response (Figure 3). Figure 4 illustrates this causal chain.

Large explosive volcanic eruptions inject substantial sulfate aerosols into the stratosphere, creating cooling by modifying solar radiation reflection [10]. This cooling impacts atmospheric circulation and the Intra-Tropical Convergence Zone (ITCZ)—the monsoon rain band converging on trade winds north of the equator. For regions dependent on monsoonal rainfall, these disruptions can be catastrophic. Large eruptions disturb upper atmospheric circulation, producing regional temperature anomalies and driving major short-term climate variability [11].

For the Nile, the causal chain is direct: The Nile summer flood depends critically on the East African Monsoon bringing rainfall to the Ethiopian Highlands. This monsoon rainfall causes the Nile to begin rising at Aswan from early June, reaching highest levels in August-September, with water receding by late October when sowing begins. Large volcanic eruptions—particularly those in higher northern latitudes—reduce the north–south temperature contrast driving northward migration of moisture-bearing summer monsoonal winds, thereby weakening monsoon circulation and suppressing the Nile summer flood.

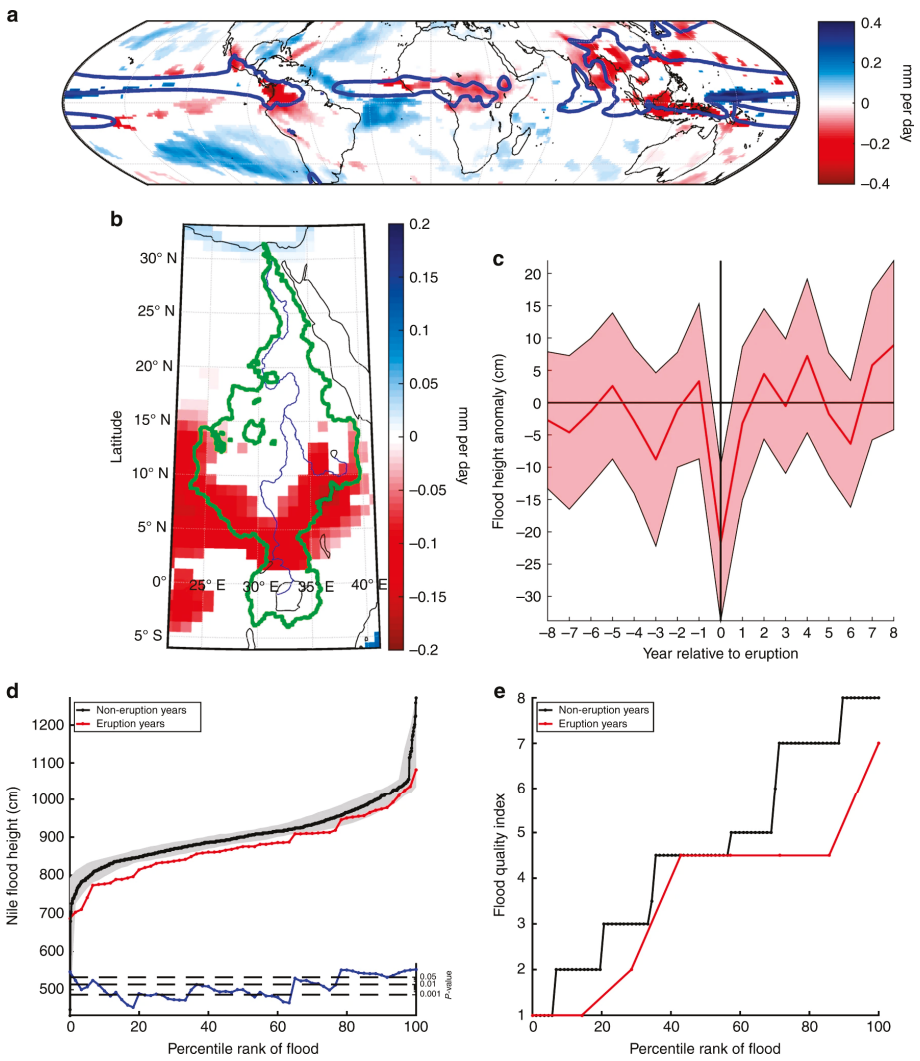


Figure 3. Response of the Nile to explosive volcanism. (**a**) CMIP5 ensemble mean precipitation minus evaporation (P–E) response to five 20th century volcanic eruptions (color shading, mm per day). The response is the average P–E over the first summer season (May–October) that contained or followed the eruption, relative to the five summers preceding the eruption. Only anomalies statistically significant at the 5% level are shown (Methods section). Blue contour is the 2 mm per day isoline of P–E. (**b**) As in (**a**) but showing the Nile watershed, which is outlined in green, with major Nile watercourses shown by thin blue lines. (**c**) Annual Nile summer flood heights from the Islamic Nilometer composited relative to the ice-core-estimated dates of eruption years for 60 large eruptions (Methods section) between 622 and 1902 CE (eruption years are represented at point 0 on the horizontal axis; years 1 to 8 then represent the first to eighth years after these eruptions, and years −1 to −8 the first to eighth years before). Data associated with secondary eruptions within this compositing window are excluded (Methods section). Shading indicates the 2-tailed 90% confidence interval, estimated using the *t*-distribution. Nile summer flood heights average 22 cm lower in eruption years ($p < 0.01$). (**d**) Annual Nile summer flood heights from the Islamic Nilometer ranked by percentile for eruption years (red; $N = 61$ (Methods section)) and non-eruption years (black; $N = 1030$). Gray shading indicates the 2-tailed Monte Carlo 90% confidence interval based on 1,000,000 draws from the non-eruption-year distribution. The blue line indicates the 1-tailed *p*-value for each of 61 ranks, when tested independently without accounting for multiple tests. (**e**) Annual Nile flood quality index for the Ptolemaic period, 305–30 BCE (Methods section) ordered by percentile for eruption years (red; $N = 8$) and non-eruption years (black; $N = 88$). High flood quality index values equate to documentary indications of high summer floods. Figure and text from [9].

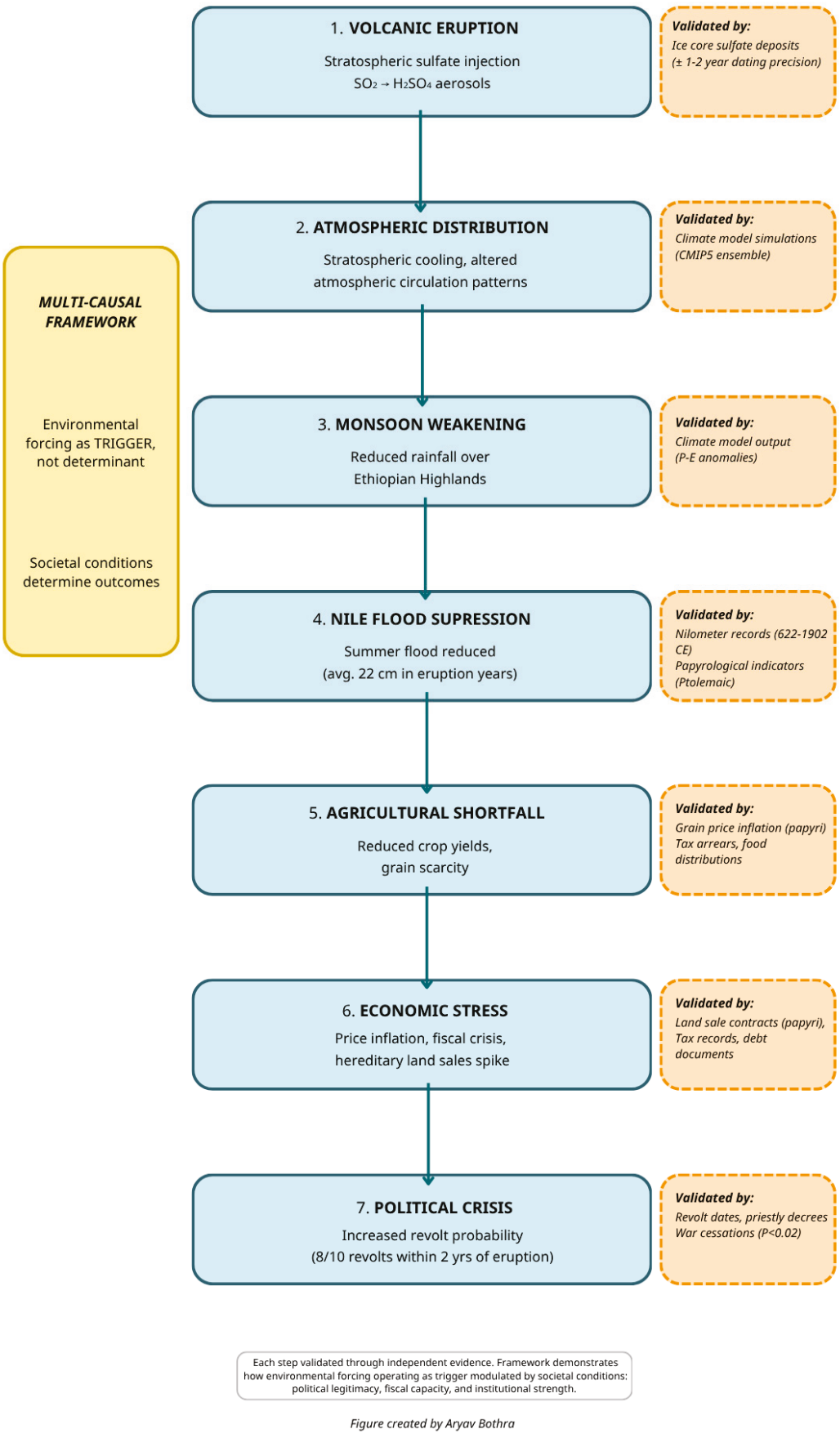


Figure 4. Causal pathways from volcanic eruption to political crisis in Ptolemaic Egypt.

Historical eruptions are typically compared to the 1991 Mount Pinatubo eruption to assess impact. Pinatubo, the last large eruption known to have impacted world climate, was studied with satellites and instruments, providing detailed understanding of its cooling effects at Earth's surface [12]. The Ptolemaic period experienced several significant volcanic events, including a cluster of eruptions in the 160s BCE that dramatically impacted Nile flooding, and the Okmok eruption in 43 BCE, which created global climate anomalies disrupting agricultural production from China to the Mediterranean.

2.2. Achieving Precision: Ice Core Chronologies and Multi-Proxy Integration

Ice core precision enables the volcanic forcing breakthrough. Eruptions inject sulfate aerosols into the stratosphere; these aerosols eventually fall as sulfate onto Greenland and Antarctic ice sheets. Ice cores preserve continuous atmospheric sulfate deposition records, with annual layers identifiable through physical and chemical properties (stable isotope ratios, ion concentrations, electrical conductivity). Recent advances have produced synchronized chronologies combining multiple ice cores, achieving dating precision of ±1–2 years for the past 2500 years [13,14].

The 2015 synchronization of Greenland and Antarctic ice cores by Sigl et al. provided eruption dates with unprecedented accuracy. Subsequent work by Toohey and Sigl reconstructed volcanic stratospheric sulfur injections and aerosol optical depth from 500 BCE to 1900 CE, providing quantitative magnitude estimates [15]. This precision transforms environmental history possibilities: rather than working with multi-decadal correlations that might arise by chance, we can identify specific volcanic events dated to individual years, trace hydrological impacts through multiple proxies, and examine historical responses in documentary sources also dated to specific years

2.2.1. Multi-Proxy Data Integration Methodology

Multi-proxy integration is crucial for robust causal inference. For the Ptolemaic period, several independent lines of evidence can be integrated:

1. **Ice core volcanic forcing data**: Precise eruption dates and magnitude estimates
2. **Climate model output**: Simulations showing how specific eruptions affected temperature, precipitation, and monsoon circulation patterns
3. **Nile flood records**: Nilometer readings from Roda Island (622–1902 CE) showing flood heights; for earlier periods, qualitative flood assessments from papyri and inscriptions
4. **Documentary evidence**: Papyri recording grain prices, land sales, tax receipts, and food distribution; royal decrees addressing crisis conditions
5. **Archaeological data**: Settlement patterns, agricultural remains, evidence of economic stress

Chronological uncertainties are largely independent. A radiocarbon date might have ±30–50-year uncertainty, but ice core volcanic dates have only ±1–2-year uncertainty. When multiple independent lines converge on the same temporal pattern, confidence increases substantially. This multi-proxy approach, combining ice core chronologies, documentary evidence, climate modeling, and geoarchaeological data, provides the robust evidentiary framework necessary for establishing causation.

2.2.2. Addressing Confounding Factors and Uncertainties

Several potential confounding factors must be addressed when attributing Nile flood variability to volcanic forcing:

ENSO (El Niño-Southern Oscillation) effects. ENSO variability affects African monsoon strength and Nile floods. Strong El Niño events typically reduce East African rainfall. However, volcanic eruptions can themselves influence ENSO patterns—large eruptions may trigger El Niño-like conditions through Pacific Ocean cooling [16]. While this

creates complex interactions, it does not invalidate volcanic forcing as a causal mechanism; rather, ENSO may be part of the causal pathway through which volcanic forcing affects regional hydroclimate. Climate model experiments help distinguish direct volcanic effects from ENSO-mediated effects, showing that volcanic cooling of the stratosphere produces monsoon suppression through multiple mechanisms, with ENSO being one contributing factor [16,17].

Non-volcanic climate variability. Natural climate variability unrelated to volcanic forcing (solar radiation changes, ocean circulation patterns, atmospheric internal variability) also affects Nile floods. The statistical approach addresses this by comparing eruption years with non-eruption years across the full period. If volcanic forcing were irrelevant, eruptions would show no systematic association with flood failures. The observed significant correlations ($p < 0.02$) indicate volcanic forcing effects exceed background climate variability.

Documentary preservation biases. Papyri survival is not random—crisis periods might produce more documentation (petitions, complaints) or less (administrative breakdown). This could create spurious correlations if crisis documentation systematically clusters around certain periods. However, the analysis uses multiple independent documentary categories (land sales, grain prices, revolt dates, priestly decrees) drawn from different archives and preservation contexts. Convergence across these diverse sources reduces bias concerns.

Regional heterogeneity. Volcanic effects on monsoon rainfall show spatial variability—some eruptions strongly affect Ethiopian Highlands while others affect broader regions differently. Climate models provide spatial resolution (~100–200 km) allowing assessment of which eruptions would most strongly impact Nile discharge. The analysis focuses on eruptions showing strong effects on the Nile watershed specifically, rather than treating all eruptions as equivalent.

These potential confounders do not invalidate the volcanic forcing framework but require careful methodological attention. The multi-proxy approach, statistical validation, and mechanistic climate modeling collectively address these concerns, providing confidence that observed correlations reflect genuine causal relationships.

2.3. From Correlation to Causation: Statistical Validation

The precision of volcanic forcing chronologies enables statistical approaches distinguishing meaningful patterns from chance correlations. Even if volcanic eruptions and Egyptian crises were entirely unrelated, some coincidences would occur purely by chance. The relevant statistical question is whether the observed coincidences exceed random expectation by sufficient margin to suggest real causal relationships.

For the Ptolemaic period (305–30 BCE), of ten documented revolt onsets, eight occurred within two years of eruptions—far exceeding random expectation. Similar patterns emerged for war cessations (6 of 9 within three years), priestly decrees, aimed at reestablishing political order (3 of 9 within one year), and hereditary land sales (84 sales with sufficient dating precision showing spikes post-eruption).

To test whether these patterns could arise by chance, Monte Carlo simulation methods were employed. For the revolt analysis, each eruption was randomly reassigned to a new year between 305 and 30 BCE, then correspondences between eruption dates and revolt onsets were counted. Repeating this process one million times built a reference distribution showing what pure chance would produce. The observed number of correspondences exceeded 98% of simulations, indicating less than 2% probability ($p < 0.02$) that the pattern arose randomly—strong evidence for real association.

This statistical validation is critical for moving beyond narrative arguments about causation to quantitative probability assessments. We can state with confidence that volcanic eruptions were associated with increased revolt probability, not merely that some revolts happened to occur after eruptions. The causal pathway proceeds from volcanic eruption through atmospheric disruption and monsoon weakening to Nile flood suppression, agricultural decline, and political crisis. Each step can be independently validated: ice cores date eruptions, climate models demonstrate monsoon impacts, Nilometers and papyri record flood failures, economic documents track social consequences.

Not every eruption produced revolt—Egyptian society had substantial resilience and buffering capacity. Not every revolt followed an eruption—other triggers existed, including political succession crises, ethnic tensions, military defeats, and fiscal pressures. But volcanic forcing significantly increased revolt probability, providing an environmental trigger that interacted with existing social stresses. This is multicausal explanation with environmental precision, avoiding environmental determinism while establishing environment as a real historical agent.

3. Results: Volcanic Forcing and Ptolemaic Political Crises

3.1. Why Ptolemaic Egypt? The Advantages of Documentary Density

The Ptolemaic period (305–30 BCE) provides an ideal test case for the volcanic forcing methodology for several reasons. First, the documentary evidence from Ptolemaic Egypt is extraordinarily rich compared to earlier periods [18]. The dry Egyptian climate preserved tens of thousands of papyri recording economic transactions, administrative communications, royal decrees, and private letters. This documentary density allows annual or even seasonal resolution for many types of evidence—grain prices, land sales, tax records, food distributions—providing the temporal precision necessary to correlate with volcanic events dated to specific years in ice core records.

Second, the Ptolemaic period experienced several major volcanic eruptions with well-established chronologies. The ice core records identify sixteen significant eruptions between 305 and 30 BCE, including a cluster in the 160s BCE and the major Okmok eruption in 43 BCE. These eruptions provide multiple opportunities to test whether volcanic forcing produced detectable impacts on Egyptian agriculture, economy, and political stability.

Third, Ptolemaic Egypt was a society particularly vulnerable to Nile flood variability. The Ptolemaic state extraction system depended heavily on agricultural surplus, specifically grain production. The Greek elite preference for free-threshing wheat—more vulnerable to drought than traditional Egyptian emmer wheat—increased the kingdom's sensitivity to hydrological stress. The Ptolemaic fiscal system, with its monetization, banking institutions, and tax farming, created economic mechanisms that could amplify the effects of agricultural shortfalls through price inflation and credit disruptions.

Fourth, the Ptolemaic period was politically dynamic, experiencing both periods of strength (the third century BCE, when Ptolemaic Egypt was arguably the wealthiest and most powerful Hellenistic kingdom) and increasing instability (from the late third century onward, with recurring internal revolts, Seleukid conflicts, loss of imperial territory, and Roman pressure). This variation allows us to examine how the same magnitude of environmental stress affected Egyptian society differently depending on political and economic conditions—testing the resilience concept and avoiding environmental determinism.

Finally, the Ptolemaic period sits at a historiographical intersection where traditional historical methods, papyrological expertise, archaeological evidence, and paleoclimatic data can be integrated. We have the documentary precision to establish causation, the paleoclimatic data to identify environmental forcing, and sufficient historical context

to understand the political and economic mechanisms linking environmental stress to societal response.

3.2. Establishing the Volcanic-Hydroclimate Connection

Before examining specific Ptolemaic political crises, we must establish that volcanic eruptions did indeed suppress Nile floods during this period. Direct evidence from later periods comes from Nilometer records. Comparing the Nilometer records from Roda Island (622–1902 CE) with ice core-based eruption chronologies reveals persistent reduction in the summer flood following large tropical and extratropical eruptions [9]. Compositing annual Nile summer flood heights relative to sixty large eruptions between 622 and 1902 CE shows that flood heights were on average twenty-two centimeters lower in eruption years ($p < 0.01$), with suppression often continuing into subsequent years. Climate models support this relationship.

Climate model output supports this relationship. Analyzing the ensemble mean precipitation minus evaporation (P-E) response to five twentieth-century volcanic eruptions in CMIP5 (Coupled Model Intercomparison Project 5) models shows significant drying across the Nile watershed during the first summer season that contained or followed the eruption, relative to the five summers preceding it. The spatial pattern shows strongest drying in the Ethiopian Highlands—precisely the region where monsoon rainfall feeds the Nile summer flood.

For the Ptolemaic period, we lack continuous Nilometer records but have qualitative flood assessments from papyri and inscriptions. Using the framework developed by Danielle Bonneau, we can create annual flood-quality ranks on an ordinal scale based on documentary references to flood conditions [19]. When these qualitative indicators are analyzed statistically, flood quality tends toward lower ranks during volcanic years, confirming that the volcanic flood suppression effect observed in later instrumental and Nilometer data also operated during the Ptolemaic period.

The 238 BCE Canopus Decree provides particularly valuable evidence. This trilingual priestly decree, issued during the reign of Ptolemy III, explicitly discusses both flood failures and the royal response. The decree praises the king for opening granaries and importing grain during a period of insufficient Nile floods, preventing what could have been catastrophic famine. The decree's reference to how such flood failures provoked "panic and fear as inhabitants recalled earlier episodes of crisis" demonstrates that Egyptians understood the potentially devastating consequences of repeated low floods, even when effective royal intervention prevented immediate disaster.

The causal pathway from volcanic eruption to Nile flood suppression can thus be established with confidence for the Ptolemaic period: (1) volcanic eruption injects sulfate into stratosphere [dated via ice cores]; (2) atmospheric circulation disrupted, monsoon weakened [demonstrated via climate modeling]; (3) reduced rainfall over Ethiopian Highlands [climate model output]; (4) Nile summer flood suppressed [evidenced in qualitative papyrological indicators and later Nilometer data]; (5) agricultural impact [documented in papyri through grain price changes, land sales, tax records].

3.3. Revolts and Volcanic Forcing: Statistical Evidence for Political Impact

With the volcanic-hydrological connection established, we can examine whether volcanic-induced flood failures triggered political crises. The most dramatic potential impact would be on internal revolts against Ptolemaic rule. The Ptolemaic period witnessed ten major revolts or periods of internal unrest, varying in duration, extent, and severity [20]. Some touched the whole of Egypt and lasted twenty years; others were more short-lived and localized.

A striking pattern emerges: eight of ten revolt onsets occurred within two years of major volcanic eruptions—far exceeding the 0.6 coincidences expected by chance given sixteen eruptions across 275 years. Observing three coincidences already exceeds random expectation, and observing eight revolts within two years of eruptions is highly improbable under the null hypothesis of no relationship.

Statistical simulation confirms this. Randomly reassigning eruption dates to different years between 305 and 30 BCE, then counting correspondences with revolt onsets, and repeating this one million times, produces a reference distribution. The observed number of correspondences exceeds 98% of simulations, indicating $p < 0.02$—less than 2% probability that the pattern arose randomly. This meets the conventional scientific standard for statistical significance and supports the hypothesis that volcanic forcing increased revolt probability.

The causal mechanism linking flood failure to revolt is multi-stepped but plausible. Reduced flood → reduced agricultural yields → grain scarcity → price increases → difficulty paying taxes → economic distress → increased social tensions → higher revolt probability. This pathway is not deterministic—other factors matter enormously—but volcanic forcing acts as a trigger that can push an already-stressed society past a threshold into open revolt.

Several specific revolt episodes illustrate this mechanism [20,21]. The Great Theban Revolt (206–186 BCE) began during a period of documented low floods, following the cluster of eruptions in the 160s BCE. Papyrological evidence shows grain price inflation, tax collection difficulties, and population movements during this period. The revolt emerged in Upper Egypt, the region most dependent on the Nile flood for agriculture and most vulnerable to flood failures. While the revolt clearly had multiple causes—including ethnic tensions between native Egyptians and the Greek elite, resentment of Ptolemaic taxation, and weakness of the central government after expensive wars with the Seleukids—the volcanic-induced agricultural stress provided the trigger that transformed simmering discontent into open rebellion.

The revolt of Harsiesis (131–130 BCE) provides another example. Following documented flood failures in the early 130s BCE, this short-lived revolt erupted in the Theban region. While quickly suppressed, the revolt's timing and location suggest environmental stress contributed to the outbreak. Papyri from this period document economic difficulties, and the revolt occurred in precisely the region where flood-dependent agriculture was most critical.

Importantly, not every volcanic eruption produced revolt. The methodology's strength lies in explaining why some eruptions triggered political crises while others did not. The political and economic context mattered enormously. During the early Ptolemaic period (late fourth and early third centuries BCE), when the kingdom was wealthy, politically stable, and administratively competent, volcanic eruptions might cause temporary agricultural difficulties, but the state could respond effectively—importing grain, distributing food from royal granaries, temporarily reducing taxes. The 238 BCE Canopus Decree documents precisely this kind of successful state response.

By the late third and second centuries BCE, however, Ptolemaic Egypt faced multiple stresses: expensive wars with the Seleukids draining the treasury, ethnic tensions between Greeks and Egyptians, succession disputes within the royal family, loss of foreign possessions reducing revenue, and inflation eroding the value of silver coinage. In this context, the same magnitude of volcanic-induced agricultural stress that the early Ptolemaic state handled effectively could trigger revolt because the weakened state lacked resources for effective response.

This interaction between environmental forcing and societal conditions exemplifies what Butzer called "multicausal" explanation. Volcanic forcing was neither necessary nor

sufficient for revolt—revolts could occur without volcanic triggers, and volcanic eruptions could occur without producing revolts. But volcanic forcing significantly increased revolt probability, particularly when other stresses were already present. The statistical evidence demonstrates this probabilistic causation: volcanic eruptions were associated with revolt onset at rates far exceeding chance, but the relationship was not deterministic.

3.4. Other Political and Economic Indicators

Beyond revolt onset, other types of recurring events show temporal associations with volcanic forcing, strengthening the case for environmental impact on Ptolemaic political economy.

Interstate warfare cessation: The Ptolemaic kingdom engaged in six major "Syrian Wars" with the Seleukid kingdom between 274 and 168 BCE, competing for control of Coele-Syria, Phoenicia, and the eastern Mediterranean [22]. Of nine occasions when these conflicts ceased (either through peace treaties or military exhaustion), three fell in volcanic eruption years, with two more within two years and one within three years. This pattern suggests volcanic-induced agricultural stress constrained military capacity—armies require food supplies, military mobilizations require tax revenue, and both become difficult when floods fail and agricultural productivity declines.

The Second Syrian War (260–253 BCE) provides a specific example. This conflict ended following the eruption documented in ice cores for 257 BCE. While multiple factors surely contributed to the peace—military exhaustion, diplomatic calculations, domestic political considerations—the timing suggests environmental stress may have limited both kingdoms' capacity to continue expensive military operations.

Priestly decrees: The Ptolemaic kings issued priestly decrees in Egyptian temples to legitimize their rule and maintain relations with the native Egyptian priesthood. These decrees were often issued during or after periods of crisis, representing royal efforts to maintain or reestablish political order. Of nine priestly decrees with secure dating, two were issued in volcanic eruption years, with one more in the year immediately following an eruption. This pattern is statistically significant ($p < 0.05$) and suggests that volcanic-induced crises prompted royal efforts to shore up legitimacy through religious and ideological means.

The Canopus Decree (238 BCE), already discussed, explicitly mentions flood failures and royal response. The Rosetta Stone (196 BCE), perhaps the most famous Ptolemaic priestly decree, was issued during a period of internal unrest following revolts and documents royal benefactions including grain distributions—suggesting response to economic stress potentially linked to agricultural difficulties.

Land sales: In Ptolemaic Egypt, hereditary land (γῆ ἐν ἀφέσει) was normally retained within families, and its sale was considered indicative of economic distress. Families resorted to selling hereditary land only when facing severe financial pressure. Eighty-four sales with sufficient dating precision (to within 5 years) can be identified in the papyrological record for the Ptolemaic period.

When land sales are plotted relative to volcanic eruption dates, a clear pattern emerges: Sales spiked upward for several years following eruptions. The increase begins in the eruption year, peaks 2–3 years after eruptions, and gradually returns to baseline by 5–6 years post-eruption. This temporal pattern is consistent with the expected economic impact of flood failures: immediate agricultural shortfall, followed by accumulated economic stress as families exhaust reserves and resort to land sales, then gradual recovery as floods return to normal.

Statistical analysis confirms significance: the number of land sales in the three years following eruptions significantly exceeds the number expected by chance ($p < 0.01$). This pro-

vides economic evidence complementing the political evidence from revolts and warfare—volcanic forcing impacted not only high politics but also the economic circumstances of ordinary Egyptians.

3.5. The 160s BCE Cluster: A Detailed Case Study

The cluster of volcanic eruptions in the 160s BCE provides an opportunity to examine the volcanic forcing mechanism in detail, as multiple eruptions occurred within a short period, potentially producing cumulative impacts [23].

Ice core records identify major eruptions in 168, 164, and 161 BCE. Climate modeling suggests these eruptions, occurring in rapid succession, would have produced sustained disruption of the African monsoon, leading to multiple years of suppressed Nile floods. The cumulative effect of repeated eruptions would be more severe than a single eruption, as Egyptian society would have little opportunity to recover between shocks [24].

The papyrological evidence from the 160s BCE documents cascading economic stress: grain prices doubled or tripled, tax arrears mounted, fields were abandoned, and populations migrated from rural areas to urban centers seeking food and economic opportunities.

The political impact was severe. The period witnessed intensified revolt activity in Upper Egypt, with insurgent forces controlling the Theban region for extended periods. Royal authority fragmented, with the central government unable to project power effectively into Upper Egypt. The Ptolemaic state responded with a combination of military suppression and economic concessions, but the weakness revealed by these crises marked a turning point in Ptolemaic history.

The 160s BCE cluster thus provides a clear example of how volcanic forcing can trigger cascading crises: environmental shock (repeated flood failures) $\rightarrow$ economic stress (agricultural shortfall, price inflation, fiscal crisis) $\rightarrow$ political instability (revolt, state weakness, territorial fragmentation) $\rightarrow$ social disruption (migration, abandonment, economic retrenchment). While each element of this cascade had multiple causes, the volcanic forcing provided the initial trigger that set the process in motion, and the rapidity of the succession of eruptions prevented recovery between shocks.

3.6. Understanding Non-Events: Why Some Eruptions Did Not Trigger Revolts

Understanding why some volcanic eruptions did not trigger revolts is as important as understanding why others did—revealing the factors determining societal resilience versus vulnerability. Of sixteen major volcanic events during the Ptolemaic period, eight were associated with revolt onset within two years, while eight were not. This variation provides crucial insights into the conditions modulating volcanic forcing effects.

Early Ptolemaic resilience (305–245 BCE). The early Ptolemaic period experienced several volcanic eruptions (including events in 274 and 257 BCE) without triggering major revolts. During this period, the kingdom was wealthy, politically stable, and administratively competent. The 238 BCE Canopus Decree documents successful state response to flood failures: "The king opened granaries, gave grain to the temples, imported grain from foreign lands, and prevented what might have been catastrophic famine." The state possessed both resources and institutional capacity for effective crisis response.

Political legitimacy as buffer. The early Ptolemies enjoyed relatively strong legitimacy—Ptolemy II successfully navigated the hybrid Greek–Egyptian identity, maintained good relations with the Egyptian priesthood (as evidenced by priestly support in the Pithom Stela and other decrees), and demonstrated military competence in foreign wars. When volcanic eruptions caused agricultural stress, the population was more willing to accept temporary hardships if they trusted the ruler to respond effectively.

Fiscal capacity and granary reserves. The early Ptolemaic state maintained substantial grain reserves in royal and temple granaries, accumulated during good harvest years. These reserves provided buffer capacity to distribute food during crisis years. The sophisticated fiscal system, while sometimes burdensome, generated resources for crisis response. By the late Ptolemaic period, expensive wars, loss of foreign possessions, and fiscal crisis had depleted both reserves and state capacity.

Concurrent stresses determine vulnerability. The eruptions of 168 and 164 BCE occurred during a period of multiple stresses: expensive Syrian Wars had drained the treasury, ethnic tensions between Greeks and Egyptians were intensifying, succession disputes within the royal family created instability, and inflation was eroding coinage value. In this context, volcanic-induced agricultural stress that the early Ptolemaic state had handled effectively now triggered revolt because the weakened state lacked resources for effective response. The contrast demonstrates that volcanic forcing was not deterministic—outcomes depended critically on societal conditions.

This analysis of non-events supports the multicausal framework: volcanic forcing significantly increased crisis probability but was neither necessary nor sufficient for crisis. The same environmental stress magnitude produced different outcomes depending on state capacity, political legitimacy, fiscal resources, and concurrent pressures. This finding is crucial for avoiding environmental determinism while establishing environment as a real historical agent whose effects were modulated by human institutions and decisions

4. Discussion. Methodological Implications and Broader Applications

4.1. What Annual to Decadal Resolution Enables

The achievement of annual to decadal resolution through the ice core chronology of volcanic forcing fundamentally transforms what environmental history can accomplish. This precision enables four critical advances Table 3.

First, temporal sequences can now be determined. With century-scale resolution, we cannot determine whether environmental stress preceded political collapse or whether political collapse led to reduced agricultural investment that appears in our records as environmental degradation. Did drought cause the Old Kingdom collapse, or did state weakness lead to irrigation system neglect that produced localized agricultural failure? With annual resolution, we can establish sequence definitively: volcanic eruption in year X, flood failure in year X or X + 1, grain price increase in year X + 1, revolt outbreak in year X + 2. The environmental stress demonstrably preceded the political crisis.

Second, statistical validation of hypothesized relationships becomes possible. With imprecise dating, we cannot distinguish real patterns from chance correlations. When both environmental events and political events are dated to "sometime in the third century BCE," any correspondence might easily arise randomly. With annual dating, we can calculate precise probabilities: given sixteen eruptions randomly distributed across 275 years, what is the probability that eight revolts would occur within two years of eruptions purely by chance? The answer (less than 2%) provides quantitative support for causation rather than mere correlation.

Third, causal mechanisms can be identified. The volcanic forcing pathway provides a concrete, physically based mechanism: stratospheric sulfate → atmospheric cooling → monsoon disruption → reduced Nile flood → agricultural shortfall → economic stress → political crisis. Each step can be validated through independent evidence (ice cores, climate models, Nilometer records, papyri). This is fundamentally different from vague assertions about "climate change" causing "collapse." We can specify exactly how environmental forcing propagated through social and economic systems to produce political outcomes.

Fourth, comparative analysis across different societal contexts reveals factors of resilience. By examining how multiple volcanic events affected the same society at different times (early versus late Ptolemaic Egypt) or how the same volcanic events affected different societies (Mediterranean versus Mesopotamian responses to the 43 BCE Okmok eruption), we can identify the factors that determined societal resilience versus vulnerability. This moves beyond simple environmental determinism to sophisticated analysis of human–environment interactions.

Table 3. Four critical methodological advances from annual to decadal resolution.

Advance	Capability	Ptolemaic Example
1. Temporal sequence	Determine whether environmental stress preceded political crisis or vice versa	Eruption 164 BCE → flood failure 164–163 → grain price spike 163 → revolt onset 162
2. Statistical validation	Distinguish real patterns from chance correlations through quantitative probability assessment	8 of 10 revolts within 2 years of eruptions: $p < 0.02$ via Monte Carlo simulation
3. Mechanistic understanding	Identify concrete, physically based causal mechanisms with each step independently validated	Ice cores → climate models → Nilometers/papyri → grain prices → revolts: complete causal chain
4. Comparative analysis	Reveal factors determining societal resilience versus vulnerability across different contexts	Early Ptolemaic resilience vs. late vulnerability: same volcanic stress, different outcomes

These four advances—temporal sequence, statistical validation, mechanistic understanding, and comparative analysis—collectively represent a methodological revolution in environmental history. They enable us to answer not merely whether environment mattered in history but precisely when, how, and under what conditions environmental forcing shaped historical trajectories.

4.2. Avoiding Environmental Determinism: The Multicausal Framework

The precision of volcanic forcing methodology creates a paradox: by establishing clear causal links between environmental events and political crises, it risks reinscribing the environmental determinism that historians have rightly rejected. The solution, now widely accepted, lies in a sophisticated multicausal framework that recognizes environmental forcing as one causal factor among many, but a factor whose timing and magnitude can be established with unusual precision.

The Ptolemaic evidence demonstrates that volcanic forcing was neither necessary nor sufficient for political crisis. Not every volcanic eruption produced revolt—the early Ptolemaic state successfully weathered environmental shocks that later triggered crises. Not every revolt followed volcanic eruptions—political succession disputes, military defeats, and ethnic tensions could trigger revolts independently. But volcanic forcing significantly increased crisis probability, particularly when other stresses are present.

This probabilistic causation can be formalized using the framework from epidemiology and public health. A risk factor increases the probability of an outcome without being strictly necessary or sufficient. Smoking increases lung cancer risk but does not always cause cancer (not sufficient) and cancer occurs in non-smokers (not necessary). Similarly, volcanic forcing increases revolt risk but does not always cause revolts (not sufficient) and revolts occur without volcanic triggers (not necessary).

The multicausal framework requires specifying how environmental forcing interacted with other causal factors. For Ptolemaic revolts, several background conditions modulated volcanic forcing impact: Political legitimacy mattered—when legitimacy eroded

through succession disputes or military defeats, environmental stress could catalyze revolt. The Ptolemaic fiscal system was both strength and vulnerability—efficient tax collection provided crisis response resources but created resentment that amplified impacts when agricultural stress reduced farmers' ability to pay taxes. External wars drained resources and manpower, so volcanic-induced agricultural stress could produce fiscal crisis and inability to suppress unrest. Population growth during prosperous periods increased vulnerability—the same harvest reduction magnitude affected larger populations more severely.

These background conditions were not themselves caused by volcanic forcing, but they determined how volcanic forcing translated into political outcomes. This is the essence of multicausal explanation: environmental forcing provided triggers whose effects depended critically on societal context.

The implication for environmental history methodology is clear: achieving precision in environmental forcing does not eliminate the need for traditional historical analysis of political, economic, and social factors. Rather, it enables more sophisticated integration of environmental and human factors by establishing exactly when environmental stress occurs and allowing precise examination of how societies responded given their particular circumstances.

4.3. Limitations, Uncertainties, and Future Research Directions

While volcanic forcing methodology represents a major advance, several limitations and uncertainties must be acknowledged:

4.3.1. Data Limitations and Biases

Documentary preservation biases. Papyri survival is not random—dry conditions in Upper Egypt preserved more documents than the Delta. Crisis periods might produce more documentation (petitions, complaints, administrative responses) or less (administrative breakdown, population flight). Urban centers with administrative archives are overrepresented relative to rural areas. These biases could create spurious correlations if documentation systematically clusters around certain periods or regions. The analysis partially addresses this by using multiple independent documentary categories from different archives, but some bias likely remains.

Chronological uncertainties. While ice core volcanic dating achieves ±1–2-year precision, documentary sources vary widely. Well-dated papyri with regnal year dates achieve ±1-year precision, but paleographically dated documents carry ±30–50-year uncertainties. Radiocarbon dates on archaeological materials have ±30–50-year uncertainties for this period. The statistical approach accounts for these uncertainties, but they constrain the ability to establish precise temporal sequences for some events.

Incomplete historical record. Many potential events—local famines, small-scale revolts, economic stress in rural areas—likely went unrecorded. The analysis focuses on major events (large revolts, interstate wars, royal decrees) that achieved documentation, potentially missing important smaller-scale impacts. This creates bias toward spectacular crises rather than slow-developing pressures.

4.3.2. Methodological Uncertainties

Climate model limitations. Current climate models capture broad patterns of volcanic impacts on monsoons but lack spatial resolution to predict localized impacts with high confidence. Models are validated against instrumental-era eruptions, but pre-instrumental validation is limited. Different model formulations produce somewhat different results, creating uncertainty about magnitude (though not direction) of volcanic effects. Higher-resolution regional climate models specifically designed for historical periods would improve precision.

Volcanic magnitude uncertainties. Ice cores provide excellent eruption dating but magnitude estimates carry uncertainties. Sulfate deposition in ice depends not only on eruption magnitude but also on eruption location, season, and atmospheric circulation patterns. Some large eruptions may be underestimated in ice core records, while some smaller eruptions may be overestimated. This creates uncertainty about which eruptions would have most strongly affected the Nile watershed.

Regional climate heterogeneity. Volcanic effects on monsoon rainfall show spatial variability—some eruptions strongly affect Ethiopian Highlands while others affect broader regions differently. The Nile watershed is large (~3 million km^2) with different sub-regions (White Nile, Blue Nile, Atbara) contributing differently to the summer flood. Climate models provide spatial resolution (~100–200 km), but finer-scale heterogeneity remains uncertain. This limits ability to predict which specific regions would be most affected by particular eruptions.

4.3.3. Future Research Directions

Improved climate modeling. Higher-resolution regional climate models specifically designed for the Ptolemaic period and validated against proxy data would improve ability to translate volcanic forcing into specific agricultural impacts for particular regions. Ensemble approaches using multiple models could quantify uncertainty ranges. Coupling climate models with crop models would enable estimation of agricultural yield impacts rather than relying on indirect evidence. Future work integrating detailed hydraulic and hydrological modeling with this climate forcing framework promises to further refine our understanding of how volcanic events translated into specific flood patterns and agricultural impacts in ancient Egypt [25,26].

Expanded documentary analysis. Systematic analysis of additional papyrological categories—tax arrears, credit transactions, migration patterns, wage rates—could reveal additional dimensions of volcanic forcing impacts. Machine learning approaches to papyrus transcription and analysis could enable larger-scale quantitative studies, potentially identifying patterns not visible in current sample sizes.

Archaeological validation. While this methodology focuses on documentary evidence, archaeological data could provide independent validation and reveal impacts on populations leaving limited written records. Settlement abandonment patterns, dietary shifts in skeletal remains, changes in craft production, and fortification construction might all respond to volcanic-induced economic stress, providing evidence complementing documentary sources.

Comparative study design. Systematic comparison of how different societies responded to the same volcanic events would reveal institutional and cultural factors determining resilience versus vulnerability. The 43 BCE Okmok eruption, for example, affected Ptolemaic Egypt, Republican Rome, Han China, and Parthian Mesopotamia simultaneously. Comparing responses across these societies would identify generalizable principles about human–environment interactions.

Integration with social science theory. Frameworks from resilience theory, complex systems analysis, institutional economics, and political science would strengthen causal understanding. Why do some institutions fail under environmental stress while others adapt? How do informal social networks buffer environmental shocks? What are the thresholds beyond which adaptation fails and transformation occurs? Environmental history methodologies informed by social science theory can address such questions with increased sophistication [27].

4.4. Replicability and Extension to Other Regions and Periods

The volcanic forcing methodology is replicable and extensible in ways that earlier environmental history approaches were not. This replicability rests on three foundations: the global coverage of volcanic forcing, the precision of ice core chronologies, and the existence of comparable documentary sources in multiple historical contexts.

Volcanic forcing is global. Large tropical eruptions affect atmospheric circulation patterns worldwide. Northern hemisphere high-latitude eruptions affect monsoon systems across Asia and Africa. Any historical society dependent on rainfall-fed agriculture or monsoon-fed rivers experienced volcanic forcing impacts. The same volcanic events that affected Ptolemaic Egypt also affected Han China, Mauryan India, Republican Rome, and Parthian Mesopotamia.

Ice core chronologies are continuously improving. The synchronization of multiple ice cores from Greenland and Antarctica now provides volcanic forcing histories extending back thousands of years with one-to-two-year precision. As ice core science advances—with better drilling techniques, higher-resolution sampling, and improved dating methods—the chronologies improve. Current projects aim to extend high-precision volcanic chronologies back through the entire Holocene.

Documentary sources exist in multiple contexts. Documentary sources from Mesopotamian, Chinese, Roman, medieval European, and Islamic contexts each offer distinct advantages—meteorological observations, astronomical data, administrative detail—enabling adaptation of the volcanic forcing methodology across diverse historical settings

Researchers are already pursuing several lines of new research elsewhere:

Mesopotamia: The Babylonian astronomical diaries (seventh to first centuries BCE) provide systematic daily observations of weather, astronomical phenomena, and commodity prices. The overlap with Ptolemaic Egypt allows comparison of how different societies responded to the same volcanic events. Preliminary work shows that volcanic eruptions correlating with Ptolemaic revolts also correlate with price spikes and conflict in Babylonian records, suggesting common environmental forcing with divergent societal responses depending on political and economic institutions.

Rome: The extensive documentation of the Roman Republic and Empire, combined with archaeological evidence, allows examination of how volcanic forcing affected Roman expansion, crisis management, and eventual transformation. The 43 BCE Okmok eruption, for example, occurred during the critical transition from Republic to Empire, affecting agriculture across the Mediterranean during the period of civil wars following Caesar's assassination. The environmental stress may have amplified the political instability, contributing to the collapse of the Republican system.

China: Chinese dynastic records contain extensive meteorological observations, harvest reports, and documentation of social unrest. The volcanic forcing methodology could test hypotheses about environmental triggers for dynastic transitions, peasant rebellions, and the "dynastic cycle" pattern of Chinese history. The precision would be particularly valuable given the contentious debates about climate's role in Chinese history.

Medieval Europe: The Irish annals example discussed in Izdebski et al. demonstrates successful application to medieval Europe [27]. The methodology could be extended to other medieval societies using monastic chronicles, manorial records, grain price data, and archaeological evidence. The precision would help resolve debates about the role of climate in events like the medieval settlement of Iceland and Greenland, the Great Famine of 1315–1317, or the Black Death's socioeconomic impacts.

Islamic world: Islamic astronomical observatories produced systematic observations potentially recording volcanic atmospheric effects (dust veils, unusual optical phenomena). Combined with agricultural records, tax registers, and chronicles documenting social

unrest, these could enable volcanic forcing analysis of critical periods like the Abbasid decline, Fatimid Egypt's crises, or Mamluk responses to environmental stress.

Each case study requires careful attention to the specific characteristics of documentary evidence, the particular environmental vulnerabilities of each society, and the political and economic mechanisms through which environmental stress propagated. But the core methodology—precise volcanic chronologies from ice cores, climate modeling to establish impacts, documentary evidence of societal responses, statistical validation of patterns—remains constant across applications.

4.5. Integration with Other Paleoenvironmental Proxies

While volcanic forcing provides exceptional temporal precision, it captures only one type of environmental variability: short-term (1–5 year) cooling and hydroclimate disruption following explosive eruptions. A comprehensive environmental history requires integrating volcanic forcing with other paleoenvironmental proxies that capture different types and timescales of environmental change.

Speleothem oxygen isotopes provide continuous records of hydroclimate variability at decadal to centennial scales. Unlike volcanic forcing, which produces abrupt short-term disruptions, speleothem records capture longer-term trends in precipitation and monsoon strength. For Nile history, speleothems from Northeast Africa and the Levant can identify multi-decadal periods of drought or enhanced precipitation that conditioned societal vulnerability to volcanic shocks. A volcanic eruption during a long-term wet period might have minimal impact; the same eruption during a multi-decadal drought could be catastrophic.

Tree-ring width and density measurements provide annual-resolution records of growing season temperature and moisture availability. Mediterranean tree-ring chronologies now extend back millennia, offering independent validation of volcanic cooling impacts and capturing non-volcanic climate variability. For regions with suitable tree preservation, dendrochronology can provide year-to-year climate reconstruction matching the temporal precision of volcanic forcing but capturing the full range of climate variability, not just volcanic perturbations.

Lake and marine sediments analyzed for multiple proxies (pollen, charcoal, geochemistry, biomarkers) provide local to regional environmental histories capturing vegetation change, erosion patterns, fire regimes, and human land-use impacts. As demonstrated by the medieval history of Greater Poland, palynological evidence of agricultural expansion or contraction can be correlated with historical documentation of settlement establishment, providing independent validation of economic trends and revealing dynamics not captured in written sources alone [27].

Nile sedimentological records from the delta and floodplain, analyzed using the Bunbury and Rowe methodologies, provide geomorphological context for understanding how hydrological changes translated into local environmental impacts. Channel migration, sedimentation patterns, and delta evolution operated on longer timescales than volcanic forcing but determined where and how volcanic-induced flood failures would impact agriculture, settlement, and infrastructure.

The integration of multiple proxies enables several methodological advances:

Distinguishing volcanic from non-volcanic variability: Convergence across tree rings, speleothems, and ice cores confirms volcanic forcing. Divergence—ice cores showing eruptions without tree-ring cooling—reveals regional variability. Tree-ring cooling absent from ice core records identifies non-volcanic climate variability.

Establishing baseline conditions: Longer-term proxies like speleothems establish the baseline climate conditions against which volcanic perturbations occurred. A "normal"

flood during a wet phase might represent a severe drought during a dry phase. Understanding baseline conditions is essential for assessing the severity of volcanic impacts.

Validating causal mechanisms: When multiple independent proxies (ice cores, tree rings, speleothems, Nile sediments) all show consistent patterns correlated with historical events, our confidence in causal mechanisms increases substantially. Convergence of evidence from diverse sources, each with independent uncertainties, provides stronger support than any single proxy.

Extending temporal coverage: While ice core volcanic chronologies are remarkably complete, other proxies fill gaps and extend coverage to regions or periods where volcanic forcing alone provides insufficient information. The combination enables comprehensive environmental reconstruction across timescales from annual (volcanic forcing, tree rings) to decadal (speleothems) to centennial (lake sediments, geomorphology).

The methodological challenge lies in handling the different temporal resolutions, spatial scales, and uncertainties of diverse proxies. A tree-ring measurement has annual resolution but typically $\pm$1-year dating uncertainty from cross-dating procedures. A radiocarbon date on lake sediment might have $\pm$30–50-year uncertainty. An ice core volcanic date has $\pm$1–2-year uncertainty. A papyrus might be dated to a specific regnal year (precise to $\pm$1 year) or might be dated paleographically ($\pm$50 years). Statistical methods must account for these varying uncertainties when integrating diverse evidence.

4.6. Implications for Contemporary Climate Policy

The volcanic forcing methodology's demonstration that precisely dated environmental shocks triggered historical political crises carries implications for contemporary climate policy, though these must be articulated carefully to avoid misuse. It must be stressed that volcanic forcing provides a model for *short-term shocks* but that longer-term anthropogenic climate change differs in its persistent, cumulative character.

First, the historical evidence carries multiple implications. Sophisticated societies remain vulnerable to environmental shocks—Ptolemaic Egypt's wealth and administrative capacity did not immunize it against volcanic impacts. Yet societal responses determine outcomes. Ptolemaic Egypt was not a "primitive" society vulnerable to environmental stress due to lack of knowledge or technology. It was one of the wealthiest, most technologically advanced, most administratively sophisticated societies of its era. Yet volcanic-induced harvest failures still triggered unrest, fiscal crises, and political instability. This contradicts naive optimism that modern technology and institutions render us invulnerable to environmental shocks.

Second, the evidence demonstrates that societal responses matter enormously. The same magnitude of environmental stress produced different outcomes depending on political legitimacy, fiscal capacity, and institutional effectiveness. Early Ptolemaic Egypt weathered environmental shocks successfully; late Ptolemaic Egypt experienced cascading crises from similar shocks. This demonstrates the importance of building resilient institutions, maintaining fiscal reserves, and ensuring political legitimacy—all factors that determine whether societies can respond effectively to inevitable environmental stresses.

Third, the historical evidence reveals that environmental shocks interact with other stresses in nonlinear ways. A volcanic eruption during peacetime was manageable; during expensive wars, it could trigger fiscal crisis. A harvest shortfall during political stability was surmountable; during succession disputes, it could catalyze revolt. This demonstrates the danger of multiple concurrent stresses—climate change, political polarization, economic inequality, pandemic disease—creating conditions when environmental shocks trigger cascading failures.

Fourth, the precision of volcanic forcing reveals that even short-term environmental variability matters. We often focus on long-term climate trends (decadal or longer), but the Ptolemaic evidence shows that even one-to-three-year agricultural disruptions can trigger major political and economic crises. This has implications for climate change adaptation: societies must prepare not only for gradual trends but also for the intensified short-term variability that climate change produces—more extreme droughts, floods, and heat waves even if average conditions change gradually.

However, the implications must not be overstated or misused. The historical evidence does not support environmental determinism or collapse narratives that ignore human agency. Societies responded differently to similar environmental stresses; effective governance mitigated impacts; institutions adapted and survived. The evidence supports neither fatalism ("climate determines history; we're doomed") nor complacency ("past societies survived climate stress; we'll be fine"). Rather, it supports vigilance: environmental stress is real, impacts are serious, but effective societal responses can successfully navigate environmental challenges.

The distinction between the modern situation and historical cases must also be emphasized. Modern anthropogenic climate change differs fundamentally from natural volcanic forcing: it is longer-term, affects baseline conditions rather than producing temporary perturbations, and is potentially reversible through human action. Historical volcanic eruptions were exogenous shocks beyond human control; modern climate change is endogenous, produced by human activities and potentially mitigated by changing those activities. The historical evidence demonstrates that environmental forcing matters—it should motivate climate action, not justify fatalism.

4.7. Future Directions: Methodological Refinements and Extensions

Future research should continue to build on recent work.

Improved climate modeling: Current climate models capture broad patterns of volcanic impacts on monsoons and hydroclimate but lack the spatial resolution to predict localized impacts with high confidence. Higher-resolution regional climate models, specifically designed for historical periods and validated against proxy data, would improve our ability to translate volcanic forcing into specific agricultural impacts for particular regions.

Expanded documentary analysis: The Ptolemaic application focused primarily on grain prices, land sales, and revolt dates. Systematic analysis of additional papyrological categories—tax arrears, credit transactions, migration patterns, wage rates, testamentary dispositions—could reveal additional dimensions of volcanic forcing impacts on economy and society. Machine learning approaches to papyrus transcription and analysis could enable larger-scale quantitative studies.

Archaeological validation: While this methodology focuses on documentary evidence, archaeological data could provide independent validation and reveal impacts on populations that left limited written records. Settlement abandonment patterns, dietary shifts visible in skeletal remains, changes in craft production, and fortification construction might all respond to volcanic-induced economic stress, providing evidence complementing documentary sources.

Comparative study design: Systematic comparison of how different societies responded to the same volcanic events would reveal the institutional and cultural factors determining resilience versus vulnerability. Why did some societies experience revolt while others maintained stability? What governance structures, economic systems, or cultural practices enabled effective crisis response? Such comparative analysis would move beyond single-society case studies to identify generalizable principles.

Extension to other forcing mechanisms: While volcanic forcing provides exceptional precision, other environmental forcings also matter: ENSO variability, solar radiation changes, non-volcanic drought, flooding from excessive monsoon rainfall. Methodologies developed for volcanic forcing—statistical validation, multi-proxy integration, mechanistic causal pathways—could be adapted to these other forcings, building a comprehensive environmental history framework capturing the full range of climate variability.

Synthesis with social science theory: Integration with theoretical frameworks from resilience theory, complex systems analysis, institutional economics, and political science would strengthen causal understanding. Why do some institutions fail under environmental stress while others adapt? How do informal social networks buffer environmental shocks? What are the thresholds beyond which adaptation fails and transformation occurs? Environmental history methodologies informed by social science theory can address such questions with increased sophistication.

5. Conclusions

The evolution of Nile environmental history from Bell's pioneering textual analysis through Butzer's systematic framework to Macklin's geochronological meta-analysis and Bunbury and Rowe's geoarchaeological synthesis represents progressive methodological refinement. Each generation achieved greater precision, more robust chronologies, and more sophisticated understanding of human–environment interactions. Yet even these advances faced the fundamental challenge of temporal resolution: establishing causation requires determining sequence, and determining sequence requires precision at annual to decadal scales.

Volcanic forcing of the East African Monsoon provides this precision. Ice core chronologies date eruptions to specific years with ±1–2-year uncertainty. Climate models establish how eruptions disrupted monsoon circulation and suppressed Nile floods. Documentary sources record Egyptian responses—grain price inflation, land sales, revolts—with annual or even seasonal resolution. Statistical methods validate that observed temporal associations between eruptions and crises exceed chance expectations, supporting causal inference rather than mere correlation.

The Ptolemaic case study demonstrates this methodology's potential. Sixteen major volcanic eruptions between 305 and 30 BCE correlate with revolt onsets, warfare cessations, priestly decrees, and land sales at rates far exceeding chance expectations ($p < 0.02$ to $p < 0.05$). The mechanisms linking eruptions to political crises—atmospheric disruption → monsoon weakening → flood suppression → agricultural shortfall → economic stress → political instability—can be validated through multiple independent lines of evidence. The variability in impacts—early Ptolemaic resilience versus late Ptolemaic vulnerability—demonstrates how societal conditions modulated environmental forcing effects, avoiding environmental determinism while establishing environment as a real historical agent.

This methodology is replicable and extensible. The same volcanic events affected multiple societies, enabling comparative analysis. Ice core chronologies continuously improve, extending high-resolution forcing histories deeper into the past. Documentary sources from diverse cultures allow adaptation of the methodology to different historical contexts [27]. Integration with other paleoenvironmental proxies—tree rings, speleothems, lake sediments—enables comprehensive reconstruction of environmental variability across multiple timescales.

The implications extend beyond Nile history or even environmental history broadly. The methodology demonstrates that sophisticated integration of natural scientific and historical evidence can achieve causal understanding previously considered impossible for preindustrial periods. It shows how quantitative methods—statistical validation, climate

modeling, multi-proxy integration—can complement rather than replace traditional historical analysis. It reveals that environmental forcing mattered in history: not deterministically, not exclusively, but significantly and demonstrably, shaping the trajectories of even the most sophisticated ancient societies.

As historians engage with the current climate crisis, understanding how past societies responded to environmental stress takes on contemporary urgency. The volcanic forcing methodology offers neither comforting precedents of inevitable resilience nor fatalistic narratives of collapse. Rather, it demonstrates that environmental challenges are real and consequential, that societal responses matter enormously, and that effective institutions and governance can successfully navigate environmental stress while weak institutions fail catastrophically. These are lessons, drawn from rigorous analysis of ancient evidence, that resonate powerfully in the present [28,29].

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The Little Ice Age and Colonialism: An Analysis of Co-Crises for Coastal Alaska Native Communities in the 18th and 19th Centuries

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Abstract

Native communities confronted Eurasian colonialism in ways that reflected their own unique histories, social organizations and cultural values. In this paper, we are interested in how such legacies shaped Indigenous survivance, the active presence of Indigenous peoples on the landscape or the refusal to disappear or assimilate into settler society. We seek to understand the climate changes that Native Alaskan Sugpiaq people faced during the Little Ice Age (LIA; ca. CE 1400–1850), how they responded to those changes prior to Russian incursion, and how new or renewed climate adaptations shaped Sugpiaq survivance. Drawing insight from a new multi-proxy analysis of climate change, ecological dynamics, human population history, archaeology, and ethnohistory of the Kodiak Archipelago, we argue that changes in climate *variance* during the LIA contributed to Sugpiaq cultural elaboration in the centuries prior to Russian colonialism. Persistent cultural values and relationships with marine resources, adaptations of those relationships under expanded levels of harvesting, and responses to evolving opportunities and political realities were key legacies carried into colonial circumstances by Sugpiaq people. In addition, we see the foundational role of Sugpiaq women in procuring and sharing subsistence foods and the development of regional Indigenous identities as important factors in Sugpiaq survivance in the Russian colonial period. While colonialism introduced novel threats, Sugpiaq people confronted those challenges with the tools and values they inherited from their past, and they persisted through the active deployment of creative and culturally appropriate responses to the co-crises of colonialism and climate unpredictability.

Keywords: archaeology; human communities; climate change

1. Introduction

Studies of colonialism in the Americas commonly treat contact as a singular and transformative event that eclipses whatever history and heritage Indigenous people may have carried into the new situation [1,2]. Often these accounts present Indigenous communities as passive victims of seemingly inevitable colonial expansion. As such, they strip the native experience of its own agency and history [3]. Despite growing consciousness of Indigenous agency, scholarly treatment of Native American histories, as told by outsiders, mostly perpetuates the sense of discontinuity between "pre-contact" and "colonial" narratives of change. Archaeologists may be particularly guilty of this error for both methodological and conceptual reasons related to the different character of source materials available for "prehistoric" vs. "historic" archaeological narratives. Here we seek to bridge this divide

by examining ways that Sugpiaq adaptations to climate changes prior to Russian arrival prepared them to respond to Russian colonial pressures.

The Sugpiaq of the central Gulf of Alaska are a maritime-focused people whose ancestors have been harvesting the natural abundance of the land and seascapes around the Kodiak Archipelago and surrounding coasts for at least 7500 years (Figure 1). They have not only endured but thrived in a region prone to violent storms, earthquakes, tsunamis, volcanic eruptions, and climate-induced ecosystem changes [4–6]. In the last millennium, the Sugpiaq population on Kodiak had reached at least 10,000 people. They used a range of intensive food harvesting technologies, negotiated far-reaching alliances, waged war on distant enemies, and lived in moderately stratified communities with elite ownership and maintenance of large hunting boats, community structures, and some resource hotspots [6,7].

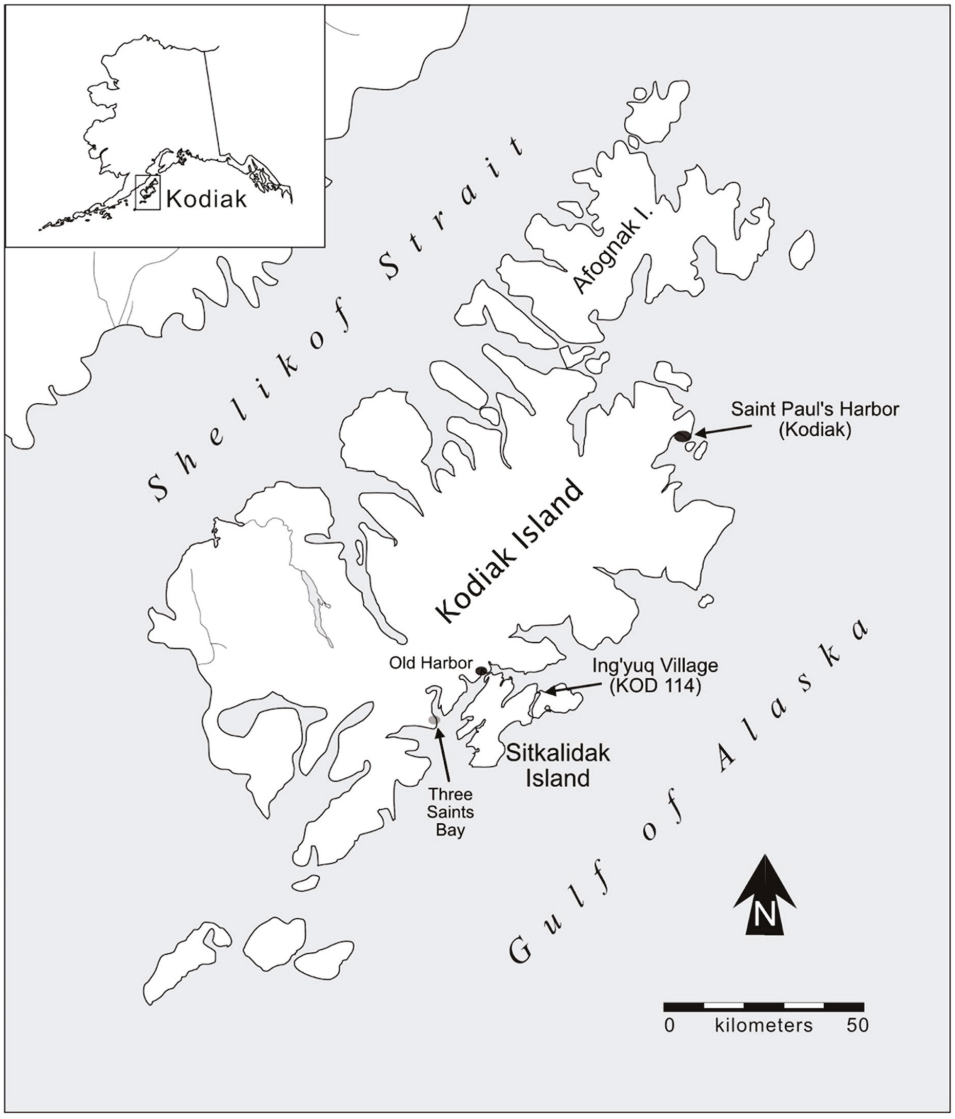


Figure 1. Map of the Kodiak Archipelago in the Gulf of Alaska showing locations mentioned in the text.

Russian explorers and entrepreneurs entered Sugpiaq territory for the first time in the mid-18th century CE, establishing their first Alaskan colony in 1784. It is significant that Russian colonization coincided with the later part of the Little Ice Age (LIA: 1400–1850 CE). In the Gulf of Alaska, the LIA manifested as a generally cool period punctuated by intervals of higher and lower variability. Our analysis of climate proxy evidence indicates that, in

the century before Russian contact, Sugpiaq people faced a significant climatic shift that would have compelled them to adapt in ways that gave them a measure of resilience to the unanticipated hardships imposed by Russian conquest and control. This paper seeks to understand how this may have played out, using archaeological, documentary, and oral historical information currently available.

This is a study of what Gerald Vizenor [8] termed survivance, the active presence of Indigenous peoples on the landscape or the refusal to disappear or assimilate into settler society [9]. Our goal in this paper is to situate Sugpiaq survivance during Russian colonialism within a longer cultural history of socio-ecological adaptation, inherited Sugpiaq kin structures, and creative resilience. How did pre-contact adjustments, within an enduring Sugpiaq worldview and way of living, influence Sugpiaq responses to colonialism in the late 18th and 19th centuries?

In what follows we construct a 'historical' model exploring colonial survivance rooted in Sugpiaq pre-contact history. The model is developed from an original analysis of multi-proxy evidence for climate change in the Gulf of Alaska that is then reflected against evidence of pre-contact and colonial-era developments. In the process, we seek to integrate modes of Western theory and scholarship and traditional knowledge in a novel way by framing this model in terms of core Sugpiaq values. These values are among the most durable cultural constructs and, we argue, least likely to have been altered by waves of colonial impact and cultural change. While elements of the model are hypothetical and should be clarified as more information comes to light, the account presented is scaffolded by multiple lines of available evidence. By framing the discussion in reference to core Sugpiaq values, we hope the analysis is also more culturally coherent than is typical of academic analyses of Indigenous responses to colonialism.

2. The Sugpiat of Kodiak: Indigenous Values as Resilience

The Sugpiat are an Alaska Native people from the central Gulf of Alaska (GoA), which includes the Kodiak Archipelago, Alaska Peninsula, Outer Kenai Coast, and Prince William Sound. Our primary relationship with Sugpiaq communities is in Old Harbor, which is one of ten tribal communities on Kodiak. Today, as in centuries past, Old Harbor residents harvest a variety of coastal and marine foods from the highly productive waters of the region. The Alutiiq[1] Tribe of Old Harbor and the Old Harbor Native Corporation (the main Indigenous organizations that represent and support the Old Harbor community) have worked tirelessly to ensure continued access to their homelands for subsistence, ceremony, and economic engagement. We have collaborated with these organizations on projects related to Sugpiaq archaeology and youth education and made many lasting personal and professional relationships. These relationships have shaped our thinking about Sugpiaq pasts by grounding our scholarship in the values that shape community life in the village.

2.1. Kodiak Sugpiaq History

Archaeologists typically subdivide Kodiak history into four or five periods (Table 1): Ocean Bay, Kachemak, Koniag, and Alutiiq/Sugpiaq, which may be divided, as here, into Russian and U.S. colonial periods. Ethnographically, Kodiak communities were traditionally matrilocal, with husbands moving into the villages of their wives (a tradition still common today) [10] (p. 72). Elder Sugpiaq women were typically the owners of their family sod house, wherein resided several generations of their descendants, and these women controlled the processing and distribution of food [11]. Village life was structured by ranked relations of relative power and influence. Families competed to amass surplus stored food and other items to share in competitive feasts. Village chiefs came from the more powerful/wealthy families, a role that was bestowed upon men by Elders (likely the female

heads of matrilineages). Chiefs maintained the most productive resource hotspots for their families and initiated war raids. Early on, these raids targeted neighboring families, but by the 16th and 17th centuries, regionally allied war parties traveled hundreds of kilometers to attack enemies in the eastern Aleutians and Southeast Alaska. Raids gave warriors opportunities to earn status while capturing women and children to contribute as slaves to family surplus production back home. Large populations were fed by a combination of extensive and intensive harvesting on the open ocean, shores and rivers. These included fishing from numerous riverine and intertidal weirs, using infrastructure that expanded dramatically in the Koniag period [6] (p. 67).

Table 1. Cultural traditions of the Sugpiaq region (after [6]).

Named Traditions	Time Range	Primary Characteristics
Ocean Bay	7500–4000 cal BP	Small and seasonally mobile groups who hunted sea mammals and harvested fish and other marine resources. Early Ocean Bay people may have lived primarily in tents and specialized in chipped stone tools. They armed their darts and spears with microblades made by a technique reminiscent of terminal Pleistocene traditions in Alaska and Siberia. Later Ocean Bay groups commonly lived in small sod houses and their lithic industry became dominated by ground slate tools.
Kachemak	4000–700 cal BP	The first durable villages appear at the start of this period. Labor-intensive net fishing and processing strategies for the first time make it possible to store summer harvests for consumption in the winter lean season. Around 2500 years ago, increased crowding may have promoted growing social unrest and political competition. People started marking status with conspicuous displays of art (e.g., elaborately decorated stone lamps) and jewelry made from exotic materials. The earliest defensive sites appear a few hundred years before the end of this period.
Koniag	700 cal BP to CE 1784	The apogee of Kodiak Indigenous political development and population growth, this period saw the expansion of sod-house villages to unprecedented size (50+ houses not uncommon), gradual transition to multi-room houses and co-residence of extended kin groups. Heads of large families emerged as influential chiefs who directed the labor of kin and slaves captured in war-raids against distant enemies. Russians make first contact in 1763, but have limited influence on Kodiak people until they return 21 years later.
Russian Colonial Period	CE 1784–1867	Many Sugpiaq people were defeated at the Awa'uq defensive site in Southeast Kodiak and villages around the archipelago were coerced into hunting sea otter and fur seals for the Russian fur trade. Sugpiaq men were conscripted into work parties and sent ever greater distances to harvest furs. Women were often compelled to provide food, clothing, and services for the Russian fur traders and many married Russian and Siberian colonists. Native populations plummeted through harsh treatment, disease and relocation. By 1840, only 7 Native villages remained out of well over 100 before contact.

Table 1. *Cont.*

Named Traditions	Time Range	Primary Characteristics
U.S. Colonial Period	CE 1867-present	The U.S. purchase of Alaska in 1867 led to fevered exploration of the territory for exploitable raw materials. Around Kodiak, salmon and remaining sea otters drew intense interest. Commercial fishing, canneries, and hatcheries were established around Kodiak by the 1890s. Through the mid-20th century, boom and bust fishing fortunes flooded communities with cash then crippled them with unemployment. Political organization at local, state, and federal levels settled land claims in 1971, and Native Corporations were formed to develop the resource capital of allocated lands. Cultural heritage is playing a strong role in revitalization. Archaeology, language revival, and oral history have become tools for restoring Sugpiaq pride.

Sugpiaq peoples first interacted with Russians in late 1762 and early 1763, when a Russian ship overwintered in southern Kodiak. Organized military resistance rebuffed the Russians, earning Kodiak Islanders a reputation as formidable defenders [12]. This reputation kept other Russian vessels away until 1784, when Gregorii Shelikhov, seeking to profit from the sea otter wealth of the islands, loaded his merchant ships with cannons and launched a surprise attack on the southeastern side of the archipelago [12–15]. This attack resulted in a massacre of Sugpiaq peoples at a defensive site on the outer coast of Sitkalidak Island [16]. Following this traumatic event, Shelikhov and his subordinates used continued violence to take political control of the archipelago. Shelikhov's men took wives and children of village leaders as hostages to gain compliance, if not loyalty, following a common practice from the Russian conquest of Siberia [17]. Shelikhov then extracted tribute of marine mammal skins and food. Under colonial conditions of violence and starvation, the Sugpiaq population declined from the first decades of colonial encroachment [18] (p. 193) [19] (p. 123). A particularly devastating turn was a smallpox epidemic from 1837 to 1838, which reduced the Native population across Alaska to a small fraction of its size at contact [20] (pp. 58–60) [21].

The first center of the Shelikhov-Golikov Company (predecessor of the Russian American Company) was set up on southeast Kodiak in Three Saints Bay. That settlement was not far from the modern village of Old Harbor, where we collaborate with Sugpiaq residents to better understand their rich history and heritage through archaeology, oral history and documentary analyses. The epicenter of Russian American colonial intervention soon moved away from Old Harbor, first to Kodiak (Saint Paul's Harbor) in 1792 and then to Sitka (New Archangel) in 1804, but Sugpiaq people from the Old Harbor area and around Kodiak remained entangled in colonial power.

2.2. Kodiak Sugpiaq Values

To this day, Sugpiaq people articulate a series of values that guide their sense of relation to each other and the ecology of their region [6,22]. Like other people of the boreal and Arctic regions, the Sugpiaq worldview sees human and non-human beings in kinship relations [23]. As such, humans are understood to have moral responsibilities within the social and natural environment to other humans and to non-human kin. These responsibilities can be divided into three broad values, which have been shared with us through many conversations about harvesting, food, and village life with Sugpiaq community members living in Old Harbor. These values are stewardship, reciprocity, and gratitude.

Good stewardship ensures the health of relatives (particularly non-human 'kin') so that they will continue to thrive and return to bring sustenance to Sugpiaq communities. Stewardship involves supporting the wellbeing of valued species through habitat enhancement (improving habitat, culling predators, weeding) or increasing capture reliability to minimize waste (e.g., construction of intertidal and riverine weirs). It involves taboos against hunting breeding females or harvesting before enough animals have reached their spawning/nesting grounds or rookeries (e.g., escapement monitoring, first salmon ceremonies timed after enough fish have made it to spawning grounds). Knowledge of these practices is preserved in Gulf of Alaska Native traditional knowledge today [24–28].

Reciprocity encompasses the ethic of relationality, or the understanding that all beings are interconnected. In relation to kinship, reciprocity involves obligations to 'share with' and 'give back to' kin (human and non-human) who have shown kindness over time [29]. The primary strategy for resilience that emerges from reciprocity is sharing. Families and communities shared (and share) resources with one another and even shared beyond their immediate communities during winter feasting events [4,6]. This reciprocity ensured that people had enough to eat and discouraged the hoarding of resources in times of stress. It also served as a primary currency for negotiating status between communities and productive kin groups.

Ceremonies for giving thanks to non-human kin are an important part of Sugpiaq cosmology and are rooted in a deep respect for the natural world that sustains human life. Gratitude undergirds stewardship and reciprocity-based strategies for resilience. It facilitates the formation of moral relationships between human and non-human kin. It also provides checks on the power of elites, who are held to high standards of prosocial behavior expected of good leaders.

While colonial impacts on Kodiak are known to have caused widespread loss of traditional knowledge [30], the spiritual/sacred nature of these values suggests deep roots in the ancient past. We believe that they served as core touchpoints used to navigate the ever-changing socio-natural world. Efforts to respond to difficulties in the past would have been grounded in these values [24]. Here we draw on these Sugpiaq values to frame our interpretations of Sugpiaq histories. In doing so, we attempt to engage directly with the ethical concepts through which Sugpiaq peoples understand their world. We also highlight the continued presence of Sugpiaq philosophies and use them to demonstrate continuity from the past to the present day.

3. Adapting to Uncertainty and Taking Sugpiaq History Seriously

It is our contention that understanding Sugpiaq survivance in the face of Russian colonialism requires attention to the social conditions, cultural practices and societal norms practiced in the centuries before Russians arrived. Archaeological information on pre-colonial lifeways provides relevant cultural information that can be supplemented with ethnohistoric reports documenting traditional Sugpiaq practices "at contact." We are interested here in going beyond a static representation of the pre-colonial "ethnographic past," to consider the ways life changed in those centuries in response to both climate and social developments. As our attention is specifically focused on the legacy of climate adaptation, in this section we start with an analysis of Kodiak climate and ecological change. We then draw on concepts from ecological anthropology to understand the dynamism of Sugpiaq history in the centuries preceding Russian arrival on Kodiak. In Section 4, we turn to consider the implications of that history for the Sugpiaq response to and survivance in the face of the Russian colonial presence.

3.1. Climate and Ecological Change in the Gulf of Alaska

Despite decades of paleoecological research to document past climate change, we still have relatively poor understanding of Alaskan Quaternary climate, especially in the Holocene and at spatial and temporal resolutions relevant to human ecological histories [31]. Fortunately, a robust and high-precision tree-ring climatology exists for the northern Gulf of Alaska (GoA) covering the past 1200 years [32] (Figure 2a). This record, compiled by Wiles and colleagues, tracks annual fluctuations in tree ring growth in forests on the eastern side of the Gulf. Tree ring widths in these stands have been shown to correlate with the average surface air temperature during the growing season (February to August) in a relationship that allows them to be converted to temperature estimates and projected back over the length of the record. This data set has the advantage over other proxies of annually resolved calibration to calendar years. The result is a proxy series with unusual chronometric resolution and an ideal source of information for the last millennium, from before the Medieval Warm phase (MWP; ca. 945–975 CE), through the Little Ice Age (LIA; here dated between 1400 and 1850 CE) and into the 20th century transition to industrial global warming. While less precise, oxygen isotope records from lake and ice cores show grossly correlated trends in precipitation [33]. These patterns have been linked to synoptic shifts in storm patterns of the North Pacific Aleutian Low (AL) weather system. Hemispheric warming strengthens temperature gradients, accelerates the circulation of currents around the Gulf of Alaska and bends stronger storms originating off East Asia on a more eastward trajectory, into the GoA. In the process, warm conditions deliver more rainfall (Figure 2b) [34–36]. Colder intervals generate weaker storms that track further north into the Bering Sea.

On the annual trends shown in Figure 2a, we have added a stepped regime shift trend (red line) that identifies intervals over which the multi-year average temperature remained relatively stable, even if individual years may have seen large temperature anomalies. These intervals are punctuated by jumps or steps that indicate points in time when the trending multi-year average jumps to a new position.[2] The regime shift method provides a consistent way to visualize trends in decadal and longer climate patterns. We use it in tandem with the underlying, interannual data to describe the changing character of regional climate that Sugpiaq people had to manage.

The regime shift analysis exposes a few patterns not readily evident in the background data. First, from the start of the record until just after 1500 CE temperature 'regimes' shift every few decades, with temperatures varying up to 2 °C annually, and regime-defining averages moving as much as 2 °C per century. In one case, ca 965 CE at the end of the Medieval Warm Period, the average temperature dropped 4 °C from one year to the next, the most extreme change in the 1200-year record! The Medieval Warm Period itself was an unusual warm interval lasting only about 30 years (yellow bar in Figure 2a) that capped a half-century of warming. From that high mark, the trend shifts cooler, but not consistently so, and it is only after 1400 CE that we might recognize the start of a persistently colder than average climate (the LIA).

The majority of the LIA is characterized by unusual stability in mean and variance compared to the rest of the record. Perhaps the most striking development is the persistence of a single regime from 1500 to 1700 CE, when temperatures hovered around 7 °C varying little more than 1 °C around it. Defined by its low variability, we choose to include the previous century in this phase, despite moderate shifts in decadal averages (regimes). Similarly, we exclude the last 40 years of the 17th century (1660–1700) for its large, interannual fluctuations. The interval of climate stability then stretches from 1400 to 1660 CE and would have presented uncharacteristically predictable conditions for more than 9 generations of Sugpiat. As we will see, that interval was unusually productive ecologically, demographically, economically, and culturally.

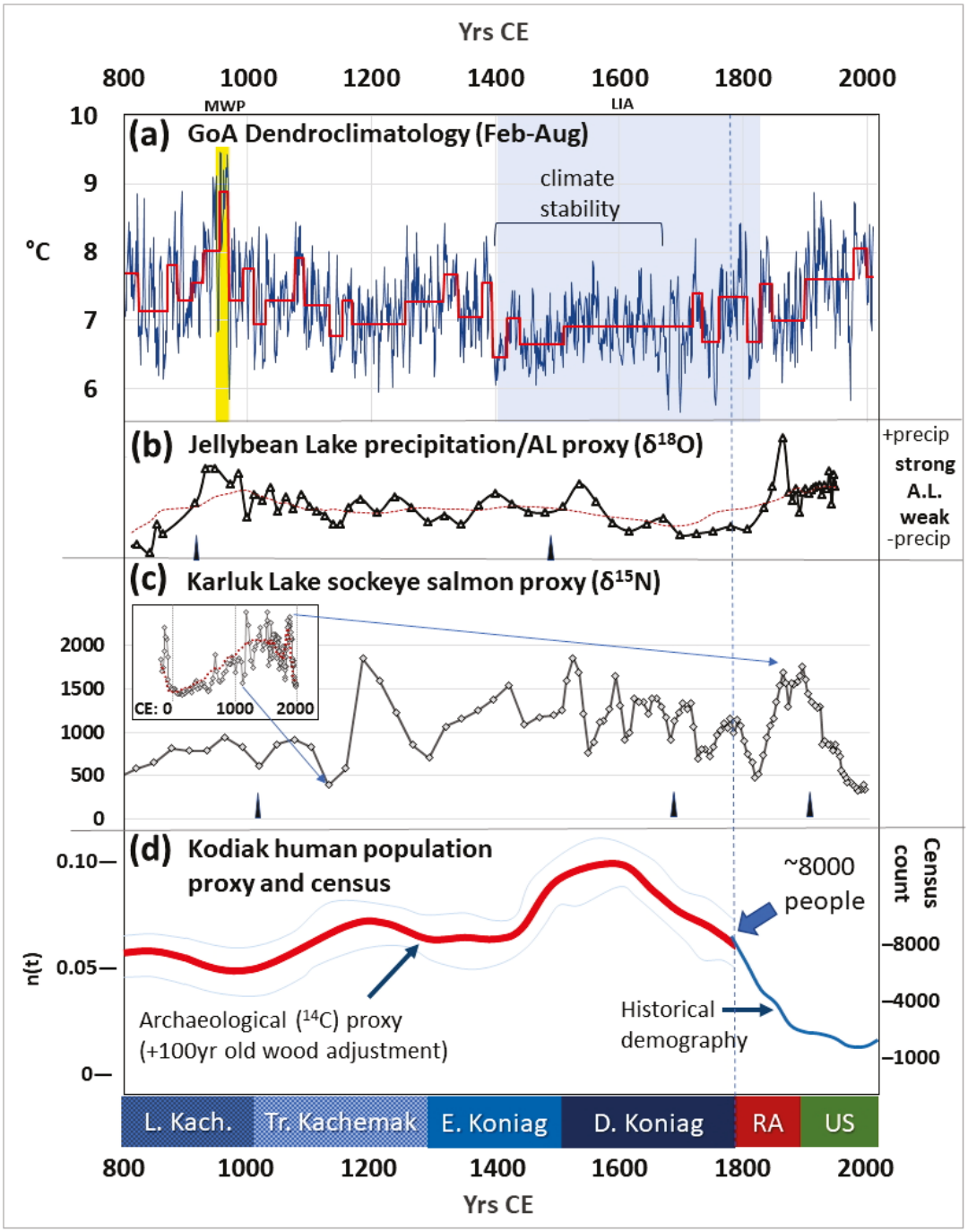


Figure 2. Gulf of Alaska climate trends and estimates of salmon and human population change on Kodiak from 800 to 2000 CE. Across the graphs, the dashed blue line marks the start of the Russian colonial period. (**a**) Tree ring data from the eastern Gulf of Alaska [32] showing regime shift analysis (red line). Yellow bar marks the Medieval Warm Period; light blue bar marks the LIA interval. See text for reference to annotations. (**b**) Oxygen isotope data trends from Jellybean Lake in the western Yukon Territory [33]. Here, solid triangles indicate the position of dated samples used in the age model (same in graph (**c**)). (**c**) Salmon escapement estimates from $\delta^{15}N$ isotopes in a Karluk Lake sediment core [37]. (**d**) Human population trends. Before 1784, the (red) trend line with error buffer is generated by kernel density estimation (KDE) of pooled archaeological radiocarbon dates and taphonomically adjusted for loss of data with age. The curve is adjusted +100 years as a conservative estimate of old wood bias [see text for explanation]. After 1784 CE (RA = Russian America, US = United States), population is estimated (solid blue line) from census records [38] (Box 4.7, p. 97).

High interannual temperature variability jumps markedly again after 1660 CE, and, from 1700 CE, interdecadal shifts like those prior to 1400 become commonplace again. Despite the fluctuations, temperatures remain relatively cold until 1900. The return to an unstable climate after 1660 is important because it represents what must have been a surprise to Sugpiat who, by then, were many generations removed from the experience of such unpredictability (in weather, seasonal change in plant and animal distributions, etc.). While we do not believe that the new climate dynamics were in any way as debilitating to Sugpiaq communities as forced subjugation to Russian control, it is an important element of what Sugpiaq people would have been adjusting to when the Russians arrived more than a century later. To explain why, we need to look at how climate is related to the ecosystems that Sugpiaq people depend on.

The development of commercial fisheries in the Northeast Pacific starting at the end of the 19th century and the growth of western science-based management of those fisheries in the second half of the 20th century brought big changes to the marine ecosystem and economies of the Gulf of Alaska. These industries also increased the observational data available to better understand the functional relationships between climate, ecosystems, and fisheries. Historical analyses have identified multi-decadal oscillations in sea surface temperatures and storm patterns that correlate with shifts in the composition and functioning of North Pacific ecosystems. For example, from the mid-20th century, salmon abundance and total commercial harvests have increased in the Gulf of Alaska when temperatures trend warmer, while gadids (Pacific cod and pollock) do better when temperatures are colder [39,40]. The mechanisms driving these patterns are only partially understood, but scholars have projected analogous ecological relationships to temperature changes revealed in paleo-proxies [41]. We are not convinced that temperature alone drives these ecological shifts. Paleoecological data as well as trends in the past two decades violate that expected relationship [37,42,43]. Nevertheless, supported by available data, we assume that temperature variability is a reasonable proxy for ecological change, whatever the specific driver or direction of relationships.

Fortunately, we have paleoecological evidence to track at least one valuable subsistence species. A nitrogen isotope proxy from cores in two of Kodiak's most productive rivers (Karluk and Red) follows trends in sockeye salmon abundance over the past 2200 years CE [37] (p. 320) [44] (Figure 2c), with peak productivity spanning the cool second millennium. At century scales, the entire second millennium shows incredibly high productivity compared to most of the first (Figure 2c—inset). At decadal scales the second millennium trend shows modest declines in the mid-12th and late-13th centuries, and from ca. 1720–1750 and ca. 1790–1835 CE [37] (Figures 1 and 2). During the two and a half centuries of cold and stable climate, stocks appear to have been robust, despite moderate short-term variability. The two intervals of stock collapse, several decades before Russian arrival and again during the first half of Russian colonial occupation, should be important in considering food security and the overlapping challenges facing Sugpiaq people before and during the Russian interval.

At present we do not know the extent to which the fortunes of other valued marine, river and land species follow those of sockeye salmon, though certainly other predators of the fish would have been affected. Declines in salmon could be balanced by increased availability of other foods, like cod. It seems likely, in any case, that regime shifts not only changed the menu, but also impacted the overall size of the feast. If Koniag communities were large enough to have strained their resources in lean times, as they may have been when climate stability gave way to instability after 1660 CE, then food insecurity and the effective stewardship of 'kin-species' would have become issues of concern. We anticipate that many of the more specific conservation strategies reported in Alaska Native oral

histories from around the GoA emerged or were elaborated in response to recognition that care should be taken to avoid harming fish populations in these lean times [24–28].

Finally, we include a Kodiak human population proxy model in Figure 2d, depicting approximate patterns of changing occupation intensity across the archipelago. The proxy is generated from cumulative archaeological radiocarbon dates, and interested readers are referred to the following articles for more on the method and its limitations [42,45,46].[3] The model captures the final stages of a two-and-a-half-millennia growth trend that began around 700 BCE [45]. The growing population continues through the Late Kachemak to Developed Koniag times and may start to decline around 1700 CE. Interestingly, the human population trends appear to correspond inversely to regional temperature and in approximate tandem with salmon abundance. If true and causally related, we could infer that colder climates have been significantly more productive than warm ones for the foods traditionally harvested by Sugpiaq ancestors. This would be an important insight, as archaeologists have previously assumed that Kodiak residents had a harder time under LIA conditions [49] (p. 745). A second interesting feature is the significant population decline, here shown accelerating after 1600 CE. If the old wood correction is properly calibrated, this would indicate that Sugpiaq people were already experiencing a demographic crisis when Russians arrived. A case can be made, however, that the population curve should be adjusted further forward in time (see note 3) [38,47,48], where it may instead document the precipitous decline from colonial diseases and violence.

3.2. Risk, Resilience and Koniag Historical Ecology

Anthropological archaeologists have long recognized the importance of ecological uncertainty in human decision making and cultural adaptations [50]. Among subsistence communities, a major tradeoff is expected between maximizing harvests and minimizing risks. Among hunter-gatherer and agricultural societies, risk minimizing strategies may include mobility, storage, passing on knowledge about infrequently needed survival foods, and maintenance of social networks to transmit information, resources, and aid in times of need [50–53]. In some cases, especially where inequality is marked, families may indenture themselves to more secure patrons to mitigate their greater exposure to risks of starvation [54].

Resilience is a more recently theorized concept in ecology and anthropology that also taps into the concept of risk. A resilient system, community, or culture is one that can recover from a preponderance of shocks that might otherwise trigger lasting change [55,56]. Risk mitigation strategies are the tools used by communities to increase their resilience to ecological and social threats. Those tools are not without costs as, to varying degrees, they require time, labor, resources, and infrastructure that could have been directed otherwise. As a result, we expect risk mitigation approaches to languish when unneeded over long intervals of time. Stability should allow for longer planning horizons, opportunities to invest in specialized infrastructure to increase harvest yields, and investments in the production of surpluses for use in fueling non-subsistence activities. On the flip side, growing unpredictability (increased incidence of shocks or surprises, bad years or decades) should inspire renewed efforts to develop (or recall) strategies for dealing with unpredictability.

Data from Transitional Kachemak, Early Koniag, and Developed Koniag phases have accumulated rapidly in recent decades. Evidence shows changes in site diversity, site size and configuration, house form, subsistence, trade, and conflict that paints a picture of uninterrupted change towards increased organizational complexity, social differentiation, scales of political alliance, long-distance trade, and military conflict [4,5]. Multiple lines of evidence indicate that population on Kodiak grew dramatically over the past two and a half millennia, reaching a peak in the Developed Koniag phase [5,40,44].

We expect that high interannual temperature variability from 900 to 1400 CE encouraged active risk mitigation. From year to year and decade to decade, people did not know if their non-human relatives would favor them with generous harvests, whether they would need to put up extra sea lion skins to repair deteriorating watercraft, or if a hungry neighbor would raid their winter stockpile. They likely ate well in good times and made do in bad, eating more shellfish, kelp and other low ranked foods to get them through hard winters. Those facing similar insecurity would share resources when they had them, reflecting deep seated generosity and reciprocity. People may have invested more effort in maintaining contacts with friends and relatives in distant communities, both for back up food security and as an outlet to escape tensions with neighbors. Where consistently productive and defendable harvesting patches were present, but limited on the landscape, some families may have been better able to secure their wellbeing by claiming and defending access to those patches. This created the conditions for the growth of patronage in return for services and the establishment of small-scale inequality [57]. In other cases, where productive hotspots were themselves less predictable and subject to failure, families would have less reason or leverage to draw others into their service.

By 900 CE trade networks had expanded significantly both within and beyond the Kodiak Archipelago. The expansion may have started in an effort to build more security through social networks. There is some indication that Kodiak residents from the west and north identified more with cousins on the Alaska and Kenai Peninsula, respectively, than they did with each other [58]. Partners on the Alaska and Kenai Peninsulas would have access to caribou, moose, and other game not available on Kodiak, and in return, Kodiak Islanders may have started harvesting and processing marine mammal and fish products for trade. Marriages likely followed these networks, initiating a process of cultural hybridization that was the basis for later social interaction, alliance, and military expansion during the Koniag period.

From 1000 to 1300 CE, populations continued to expand, perhaps rebounding from the strain of the warm interval in the mid-10th century (Figure 2c). Residential structures in what is called the Transitional Kachemak were reorganized with subterranean features (sleeping and storage rooms) arranged around small central depressions, where food processing and tool making took place. This was the precursor of larger multi-roomed houses in the later Koniag period. Steffian and colleagues [6] suggest that the new housing configurations were a response to the defense of family stores and the first manifestation of social competition. Climate variability remained high throughout this phase and storage would have been a response both to inconsistent foraging returns and the emerging social risks related to theft and violence. While status differentiation remains unmarked in this phase, the increasing atmosphere of competition, doubtless set the stage for emerging differentiation in the Early Koniag.

The Early Koniag is characterized by points with diamond cross-sections, stemmed ulus, and diagnostic engraved pebbles that depict stylized people dressed for ceremony, wearing feathered regalia and jewelry [59]. More recent investigations have shown that people were already building large, multi-family sod houses in the Early Koniag [60]. Side rooms in those houses were used for nuclear family bedrooms, steam baths, and storage chambers. Main rooms contained numerous large pit features, storage features and large roasting pits suggesting communal use for internal food processing and storage of large quantities of fish [5]. These house and storage features continue through the Developed Koniag phase and well into the colonial era [61].

Notably, the Koniag house represents a major change in community organization. Whereas Transitional Kachemak houses were the first to feature multiple connected rooms or structures, they remained too small to house more than nuclear family sized groups.

Within the Early Koniag, the multi room structure became a communal dwelling and workplace for extended family groups and enslaved workers captured in raids. This development appears to relate to the expansion of the domestic unit of production, where kin lived and worked together to out-produce other families in status competition. The abundance of processing and storage features in Koniag houses speaks to the importance of these activities throughout the Koniag Phase.

Unique diagnostics of the Developed Koniag phase include the introduction of clay pottery technology from communities on the Alaska Peninsula, and barbed points with endblades, interpreted as weapons of warfare [49] (pp. 237, 735–738). While small and more locally oriented defensive sites are dated to the Late Kachemak phase, large defensive sites positioned on islands facing the open coast emerged only in the Koniag and perhaps primarily the Developed Koniag phase [4] (p. 196, Table 8.6). Several winter villages also appear on the outer coast at this time, associated with access to defensive sites and whale hunting.

Other Koniag developments are not specific to phase. Koniag villages expanded greatly in size, many with over 50 houses. Across villages, variation in house size indicates the formation of communities structured around ranked household differences in productivity [4] (pp. 201–210). Labrets (facial jewelry worn in holes in the lower lip or cheeks) worn right up to Russian contact were often so large that they would have made eating and drinking a challenge. These are thought to have been worn predominantly by Sugpiat with high status and may have required the hosting of large ceremonial potlatch-like feasts to justify the wearing of ever larger labrets. Generous feasts sponsored by productive families would serve to support those less fortunate while literally wearing the principle of gratitude and reciprocity, all while simultaneously competing for power and status [4,6] (p. 69).

3.3. Evaluating the Climate Predictions

In the previous subsection, we highlighted a number of ways that Late and Transitional Kachemak may have dealt with the relatively high level of climate stochasticity that characterized their times. With settlements already filling the coasts and some rivers, increased home storage and trade may have provided alternatives for addressing unanticipated shortfalls. These and less visible strategies seem to have been successful in aggregate, since the population continued to grow (Figure 2d). Friend networks over distance provided social support but also opened Kodiak communities to exotic raw materials, new ideas and marriage alliances from other parts of the Gulf of Alaska. These developments paved the way for expanding 'internationalism' in the Koniag period. Significantly, we see the start of institutionalized violence at relatively local levels. Such violence might have occurred when tensions flared following a particularly bad harvesting season or the end of long winters, when those facing starvation may have sought support. Strategies for defending stores and harvesting patches from those more impacted by downturns could have included physical protection of harvesting locations, setting up defensive sites as deterrents, and appeals to spiritual guides. Probably most would-be conflicts were deflected with Sugpiaq generosity, acts that might have established social debts and could have provided the seed for expanding inequalities in the Early Koniag period.

The settling down of climate variability right around the shift into Early Koniag may or may not have been a factor in the changes observed. Certainly, increased predictability would have reduced the need to maintain many strategies for 'bad years' (at least against ecological threats), but social strategies developed previously to manage those threats in an egalitarian milieu created their own opportunities for the expansion of social competition and alliance during the Koniag. Without needing to maintain as diverse a suite of foraging

strategies and tools for risk-reducing pursuits, families could focus on applying their productive energies to harvesting the most productive resource with greater intensity.

In the Early Koniag, seasonal and even year-round settlement expanded along the major salmon rivers. The same settlement expansion happened on the outer coasts of the east side of the archipelago, where whaling was practiced. The development of new fishing technologies, such as composite bone harpoons used to fish on a proliferation of stone weirs constructed across rivers like the Karluk and Ayakulik, may have been attractive, in part, to help families expand their production of surplus in a good-natured competition for status with their neighbors. Not all social competition was peaceful, however, and the more localized violence from Kachemak times took on a new significance as social interactions at all scales became increasingly driven by the goals of surplus production. Defense also ceased to be an optional strategy, as challenges from distant competitors (Tlingit, Unangan, and others) would have compelled communities to meet hostilities in kind. The ability to capture slaves from raids to expand the family's productive labor would have helped to rationalize the further institutionalization of warfare. Over time, alliances united large numbers of regional villages, who would have supported each other reciprocally in defense from raiders.

Turning to more quantitative data on subsistence [60,62,63], here we look at evidence documenting changes in the relative importance of sea mammals, salmon, and marine fish in the economies of the last millennium. While the data come from a small number of sites in different locations around the archipelago, the sample sizes at each site were large, and consistent trends emerge in their comparison. The Late and Transitional Kachemak sites (Uyak and Crag Point) fall squarely in the 'unpredictable' interval before the start of the LIA. The Early Koniag falls on the boundary between these intervals. The Developed Koniag, in turn, straddles the 1680 CE boundary from predictable to unpredictable climate dynamics. Fortunately, our main source of archaeological data about the Koniag period, the Kal'unek site, contains distinct floors and middens, most of which can be assigned to one side or the other of the 1400 CE climate boundary. We have less data to work with in the critical century between 1680 and 1784 CE just before Russian arrival. Kal'unek's House Floor 1 is the best candidate for an occupation in this interval, while House Floors 2 and 3 may or may not fall in the earlier interval of greater stability.

Partlow [60], Kopperl [62] and West's [63] faunal analyses collectively show that salmon, cod, and marine mammals (Steller sea lion, harbor seal, northern fur seal, and sea otters) were among the most important stable foods harvested in the pre-LIA assemblages, in that order of relative abundance. These marine food species always outrank land mammals, of which there are few on Kodiak. By the Early Koniag, sea mammals had almost disappeared from the fauna at Settlement Point and declined at Kal'unek in parallel with a reduction in sea mammal hunting tools relative to fishing gear (especially nets floats and sinkers which grow in significance in the more recent floors) [49]. Comparing salmon and cod from Settlement Point [60] and Kal'unek [60,63], Partlow and West independently demonstrate a dramatic growth in the predominance of salmon in house storage assemblages compared to cod and other marine fish. For the rest of the record, salmon dominates the faunal assemblage. This development supports our hypothesis for specialization during more predictable intervals. Kal'unek was perhaps the ideal place to practice this specialization, since it is located at the mouth of one of the most productive salmon streams and was occupied during a time of high salmon abundance (Figure 2c). Hundreds of other families seem to have followed suit, as indicated by the miles of wall-to-wall Koniag settlements along the banks of the Karluk River from Kal'unek to Karluk Lake.

We conclude this pre-colonial review with the following observations. The available evidence supports the idea that Sugpiaq people took advantage of the Little Ice Age cold

phase, with its attendant reduction in temperature variance before 1680 CE, to ramp up the production of surplus by specializing in the harvesting of resources most abundant where they lived. On the Karluk system it was salmon. Such intensification would have brought the peak Sugpiaq population as close as it might come to impacting salmon populations, if not careful. It is in this context that we would expect communities with deep and observant relationships with their surroundings to recognize impending problems and expand their formal strategies for stewardship. The combination of high human population density (Figure 2d), intensive harvesting technologies, and the re-emergence of environmental fluctuations would be a time when innovative stewardship practices were needed. While we lack specific documentation of stewardship practices on Kodiak, there is now significant evidence from other Alaskan and western Canadian Indigenous peoples documenting deep and robust traditional knowledge about ways that their ancestors stewarded fish and other non-human kin [24,64]. We argue that Sugpiaq ancestors in the Koniag period would have developed similar strategies. Those strategies should have mitigated, but not neutralized, the impacts of the unpredictable climate dynamics that persisted through the Russian occupation.

4. Russian Colonialism and Sugpiaq Survivance

We now turn to the colonial period and consider the implications of Russian colonial enterprises for Sugpiaq communities already facing the crisis of climate instability in the Little Ice Age.

4.1. Indigenous Approaches to Climate Change and Colonialism

Indigenous climate change studies [65] and survivance [8,9] give us another dimension with which to examine Sugpiaq resilience strategies before and during the Russian colonial period on Kodiak Island. Kyle Whyte studies the intersections of climate change and colonialism. He argues that 21st-century climate change is an extension (and intensification) of colonialism and that we must study climate and environmental change using Indigenous heritage and living intellectual traditions to best investigate how humans can live respectfully with dynamic ecosystems [65]. Colonialism, particularly settler colonialism, altered the ecological conditions that support/ed Indigenous peoples, and settler governments have/had many strategies to sever relationships between Indigenous peoples and their environments. These strategies include the relocation of Indigenous communities, the extirpation of key animal species, and preventing Indigenous peoples from practicing traditional ceremonies, among others. Whyte's scholarship is future-oriented. He seeks to bolster contemporary resilience by drawing on Indigenous knowledges and practices that re-establish or reinforce healthy (or "moral," see [66]) human-environment relationships.

We apply Whyte's framework to the study of climate and environmental change in the context of 18th- and 19th-century Russian colonialism. Whyte and colleagues [67] discuss three aspects of colonialism that, in particular, reduce the flexibility of Indigenous communities (see also [68]):

a. Procedural injustice (Indigenous communities having diminished say in development decisions),
b. Containment (restricting Indigenous mobility), and
c. Settler centralization (making colonial needs and desires the focus of activities, creating dependence on colonial institutions or distributors).

These impositions "[...] inflict anti-adaptation against Indigenous peoples" [67] (p. 327) within environments and lands to which they had developed specific adaptations to thrive. We see all three of these aspects at play during the Russian colonial period on Kodiak, as we will describe in the following subsection.

Whyte's future-oriented environmental work meshes well with the concept of survivance as it has been used in archaeological scholarship. Derived from the work of Anishinaabe literary scholar Gerald Vizenor, survivance became a key critical framework for archaeologists, especially those practicing Indigenous-centered archaeologies or archaeologies of colonialism [69]. Survivance has forced archaeologists to consider the ways that their discipline contributed to narratives of Indigenous disappearance and how they can instead look for evidence of Indigenous presence and cultural innovation [70]. Importantly, a survivance framing also calls on archaeologists to reevaluate their methodological practices and engage collaboratively with Indigenous communities in ways that consider multiple ways of knowing and researching [16,71–73]. We draw on survivance and its accompanying practices to frame our argument about the continuity of Sugpiaq histories and the agency of Sugpiaq ancestors in the face of the intersecting challenges of the Little Ice Age and Russian colonialism.

4.2. Enacting Sugpiaq Survivance During the Russian Colonial Period

Russian colonialism was anti-adaptive for Sugpiaq communities. Colonial newcomers did not have established relationships to the lands and waters of the Kodiak Archipelago, nor were they familiar with the societal values of stewardship, reciprocity and gratitude that Sugpiaq peoples had cultivated over many generations. In fact, Russian depredation of the North Pacific Ocean in search of profitable marine mammal pelts led to the extinction or extirpation of numerous marine mammal species, with cascading ecosystem impacts [74]. Russian fur traders inserted themselves into the managerial echelons of Kodiak society and organized Indigenous labor to meet their needs [75]. Following Whyte and colleagues [67], these tactics involve procedural injustice and settler centralization, in which Russian decisions about the economy, the environment (and, eventually, its conservation; see [76]), religion, and education were the central forces shaping Kodiak society, while Sugpiaq (and other Alaska Native) contributions were sidelined. A consequence of this procedural injustice was that Sugpiaq stewardship strategies were no longer practiced on a regional or larger scale. Instead, Russian resource managers and naturalists, who had different understandings of the ecology of the Gulf of Alaska than Sugpiat or Creoles [76], were responsible for setting policies related to hunting, fishing, and conservation. Although the LIA was an ongoing hardship for the Sugpiat when the Russians arrived on Kodiak (Figure 2a), the colonial threats to Sugpiaq lives and sovereignty likely superseded Sugpiaq concerns about climatic instability. Yet the risk management strategies Sugpiaq people developed in response to climate change after 1680 CE primed them to respond creatively to colonial challenges as well.

A major feature of Russian colonialism in Alaska was conscripted service to the Company by Alaska Native peoples, which can be understood as containment [67]. Russian fur traders conscripted Sugpiaq and Unangaxˆ (Aleutian Islanders) hunters to go on seasonal (and longer) hunting trips to harvest fur-bearing marine mammals. These expeditions removed able-bodied men from their villages and from their roles as the primary hunters and fishers for their families during harvest seasons. Through the compulsory efforts of the hunting parties, the waters around Kodiak were soon depleted of sea otters [75], and subsequent hunting expeditions had to travel further and further from home. By the early 1810s, Sugpiaq men were sent as far away as the California Channel Islands and the Kuril Islands north of Japan in the pursuit of the valuable pelts. The work of hunting sea otters and other marine animals was dangerous, and many men never returned home, either due to death at sea or permanent relocation to other Russian outposts [77].

While conscripted hunters were primarily men, Sugpiaq women and Elders of both sexes were also forced into the service of Russian enterprises to produce gut and bird skin

parkas, skin boat covers, and dried salmon for the Russian American Company (RAC). Conscription, while undesirable, gave Sugpiaq people from many villages the chance to congregate. These circumstances facilitated construction of broader kinship networks and strengthened shared ethnic and class identities [78,79]. Those new social connections facilitated reciprocity (i.e., sharing of knowledge and resources), which supported community resilience across the archipelago and the GoA region. This social support network became especially important following the smallpox epidemic of 1837 to 1838, when the RAC consolidated the surviving Indigenous population from what had been 65 villages into just seven, all located near Russian outposts [75] (p. 39). The pre-established regional identities and social networks would have made this transition more manageable and facilitated the maintenance of Sugpiaq traditions and values through storytelling and shared cultural practices [29].

With colonial conscription of Sugpiaq labor, communities faced a reduced capacity for harvesting and storing traditional foods during the summer, and many villages suffered starvation in the lean winters and early springs [75,80]. This was an intentional strategy on the part of the Russian mercantile administration. The RAC wanted to control food distribution to ensure Sugpiaq dependence, so they removed most qayat (kayaks) and all the angyaat (open skin boats) from villages when hunters returned from their summer voyages [80] (pp. 46–48), [81]. Without access to their watercraft, Sugpiaq people could not effectively hunt for food or trade goods with other Indigenous communities. Cumulatively, these changes limited Sugpiaq peoples' participation in their traditional economy. Despite these hardships, initial archaeological evidence at the Ing'yuq Village site on Sitkalidak Island indicates that Sugpiaq diets did not change dramatically from the late Koniag to the colonial period, other than a greater reliance on shellfish, which likely sustained people during the late winter and early spring when food reserves dwindled and bad weather inhibited travel [61]. We suggest that Sugpiaq women and the matrilocal kinship structure are responsible for this stability.

In the late Koniag period, able-bodied men frequently left on trade or raiding parties for weeks to months at a time during the spring and summer. Some never returned home. With this context, the absence from the home village of a segment of the male population on Russian-conscripted hunting trips was not exceptional, and Sugpiaq women would have been accustomed to managing harvesting, stewardship, reciprocity, and foodways in their villages. In fact, we expect that Sugpiaq women took on more responsibility for food procurement (including hunting) when the environment became less predictable after 1680 CE, as men spent more time on unpredictable marine mammal catches and regional warfare. This experience prepared women, and Sugpiaq communities more generally, for the hardships of the colonial period, during which women carried on provisioning their communities, albeit with some of their labor also lost to Russian conscription. The anti-adaptation inflicted by Russian colonialism, not the failure of village communities, thus accounts for the starvation that many villages experienced in the late 18th and early 19th centuries, and this is clear in the continuity revealed at the Ing'yuq village site from pre-colonial to colonial times [61].

In the face of colonial assaults on their lifeways, Sugpiaq communities built upon the flexible harvesting strategies that they created in the late Koniag period and their strong matrilocal foundations to persist physically and culturally during the Russian colonial period. While Sugpiaq governance structures and trade networks were largely dismantled by the RAC, Sugpiaq communities responded by creating extended social networks centered around a shared Sugpiaq identity. These new social networks supported their expanded community by carrying out practices of stewardship, reciprocity, and

gratitude, thus maintaining these values for the generations to come. Cumulatively, these adaptations and practices facilitated Sugpiaq survivance.

5. Conclusions

In this paper, we have explored how Sugpiaq peoples on Kodiak drew on their pre-contact experiences with climate change and their longstanding cultural values to persist through the Russian colonial period. Prior to Russian arrival in the region, Sugpiaq ancestors developed technologies to maximize food harvests (especially fish), the yields of which bolstered their population and led to the emergence of influential families and marked social inequality. These practices were honed during the previous centuries in the context of climate dynamics both before and during an unusually long period of cold, but relatively stable, climate from 1400 to 1680 CE. A new climatic regime after 1680, with rapid and high amplitude shifts in temperature and storminess, presented renewed challenges for the Indigenous populations of the Gulf of Alaska. While evidence at a chronological resolution sufficient to observe this shift is sparse, we suggest that these less predictable conditions would have demanded greater flexibility in harvesting activities, intensified practices for stewarding vulnerable resources, and required the expansion of reciprocal social networks for both trade and warfare.

The subsequent period of Russian colonialism was anti-adaptive for Sugpiaq communities, as Russian officials sought to control Sugpiaq labor and land. While Kodiak suffered accelerated population losses in the decades following contact, Sugpiaq values, traditions, and stories survive to the present. We argue that flexible food harvesting strategies, the foundational role of Sugpiaq women in procuring and sharing subsistence foods, and the development of regional Indigenous identities collectively supported Sugpiaq survivance. The success of Sugpiaq ancestors is evident in contemporary Sugpiaq communities.

Having explored the interrelated histories of climate and colonialism on Kodiak in this paper, we see several areas for future archaeological research to further explore these issues. These include:

1. Refinement of chronological precision in archaeological dating over the past millennia to clarify the timing of social and cultural changes in relation to climate regime shifts. This is coupled with the need for more archaeological data, in general, from Developed Koniag period sites.
2. Evaluation of possible stewardship strategies developed by Sugpiaq ancestors both during the interval of peak population (when productive habitats would have experienced their highest rates of harvest) and under the increasingly unpredictable climates in the century before Russian arrival. Clearly resolving uncertainties surrounding the old wood offset in the paleodemographic population model is needed to determine when the population decline truly started—either before or at the inception of Russian colonization.
3. Clarification of the evolving role of women in Koniag and colonial-era Sugpiaq villages, in terms of their flexible engagement in harvest and processing activities.

Today in the Kodiak Archipelago, six Native villages and the town of Kodiak are home to 1800 Sugpiaq people. Sugpiaq identity is strong in Kodiak and in diasporic families from Anchorage and Fairbanks to Seattle and beyond [82]. Yet, the colonial strategies of settler centralization and procedural injustice continue, and Sugpiaq fishers continue to be pushed out of the commercial fishing industry in the Gulf of Alaska [83]. These practices of exclusion were initiated by the RAC's rejection of Indigenous knowledge in conservation policymaking [76] and have been continued and expanded by the State of Alaska and U.S. federal fisheries management practices. Despite these ongoing anti-adaptive structures,

Sugpiaq communities today are guided by their values to continue the fight to assert their sovereignty and steward their non-human relations in sustainable ways.

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Data Availability Statement: All data used in this article were previously published elsewhere, but can be accessed as follows: Figure 2a: Tree-ring paleoclimatology (surface air temperature) proxy series data downloaded in March 2025 from the U. S. National Center for Environmental Information (NCEI/NOAA) at https://www.ncei.noaa.gov/access/paleo-search/study/16015. Figure 2b: Oxygen isotopic precipitation proxy series presented in Figure 2c was downloaded from the U.S. National Center for Environmental Information (NOAA) at https://doi.org/10.25921/fk51-8b26. Figure 2c: Nitrogen isotopic sockeye salmon proxy series provided by Bruce Finney [email to BF 3/2/2022] from version published in [44]. Figure 2d: Archaeological human population proxy data derived from radiocarbon data base compiled by BF and William Brown as published in [40] (see Supplement). Data series available upon request to fitzhugh@uw.edu.

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Notes

1 Alutiiq and Sugpiaq are equivalent ethnonyms. In the local language, Sugpiaq means "a real person", while Alutiiq is an Indigenized version of the Russian term "Aleut" (based initially on lack of distinction between Unangan (Aleut) and Sugpiaq groups). Both Alutiiq and Sugpiaq are widely used and accepted by Indigenous people in the Kodiak Archipelago today.

2 We use Rodionov's "Regime Shift Detection" plug-in for Excel that identifies statistically significant amplitude deviations in the running mean of a time series (https://www.pmel.noaa.gov/arctic-zone/bering-sea-indicators/regimes/; accessed 11 August 2022). Parameterization in regime shift analysis has huge influence over the resulting regime shift patterns. For this analysis, we have tuned the parameters to reflect regime shifts at the two times in the late 20th century (1977 and 1998) when climate shifts correlate with the most significant marine ecological changes in the Northeast Pacific. Those shifts had major implications for marine food webs and fisheries. The model, projected back to the start of the series 1200 years ago, should then capture changes with at least comparable ecosystems effects. Tuning parameters used for the regime shift analysis are: Target $p = 0.05$, cutoff length = 20 years, Huber tuning constant = 5.

3 The curve illustrated in Figure 2d is smoothed just enough to remove century and shorter-scale anomalies indistinguishable from calibration artifacts. Without a method to attach population values to radiocarbon measurements, the model does not include a scale of absolute population. Instead the curve is better at representing trend inflections (increase or decrease) in occupational intensity. Also, for the North Pacific Rim, and indeed anywhere that archaeologists have historically run dates on charcoal from long-lived wood samples, we must assume an old wood bias in the source dates. We attempt to mitigate this bias using information about the average age of living trees studied by forest biologists in the source region. In Figure 2d, we use a +100-year correction based on research the authors conducted, with colleagues, to estimate this error for the Sea of Okhotsk region [47]. This may need to be revised for the Gulf of Alaska if the re-dating of the Kal'unek site [48], which calculated an

average offset of 250 years, is representative of the old wood offset for the region. There are statistical and functional reasons to consider 250 years to be an exagerated offset, so we stick to the +100 year adjustment here.

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Everyday Climates: Household Archaeologies and the Politics of Scale

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Abstract: The small scale is recognized as a necessary rebuttal to macroscalar narratives of climate–society relationships in the past, and archeologists and historians have increasingly turned to advocating smaller and shorter scales of analysis and interpretation, from "microclimates" to interannual droughts and single settlement histories. Such provocations rightly caution against the dangers of oversimplification and determinism in recent planetary or Earth-systems approaches to human history, as well as push scholars to acknowledge human-scale experiences: weather, seasonality, landscape change. When it comes to smaller-scale remains, however, like those of household practices, we often consider them data or proxies that validate larger-scale arguments about societal persistence or economic vulnerability. Yet the material and ideational ways that people in premodern worlds made sense of their surroundings, especially via gendered and class-based rhythms of production and consumption, were deeply entwined in the politics of everyday household life. What would a household archeology of climate entail? In this paper I highlight how households themselves were critical sites of environmental construction, experience and history-making through a selection of examples of archeological work from the Mediterranean. I argue that archeologists can critically rethink themes of persistence and adaptation by taking seriously the scalar constructions and varied politics of domestic life.

Keywords: scale; household archeology; Mediterranean; everyday; climate

1. Introduction

Climate change feels big. We recognize, to begin, that climate is a complex process whose interlocking dynamics and variables of atmospheric, oceanic, terrestrial and biotic components operate at large scales. While we often acknowledge that humans primarily experience climatic changes through weather, by perceiving transitions in expected norms and intimately engaging with shifting conditions of temperature or precipitation, we naturally turn to the bigger, regional and even global idea of climate to make sense of things [1,2]. When we then move to study premodern environments, that big scale, both temporal and spatial, seems fitting and even necessary, given the often coarse and widely varying records we have to reconstruct and interpret past environments. As archeologists, we speak most confidently in terms of societal relationships to climate, through structural forces like subsistence economies, institutions, migration practices, settlements or cultural ideas of nature. We tend to seek out diachronic patterns and regional variations in evidence that can provide comparative information on the impacts of climatic or environmental changes and how human societies might have responded differently across time and space.

A big-scale approach to premodern environmental or climatic history has therefore stuck, as historians and archeologists have turned to examining ancient human–climate

interactions and to the recognition that environmental records are key to more robust interpretations of historical transformation [3,4]. Shifts in historiographical conversations lend support to this larger focus—globalizing, deep or even planetary history has gained standing for its ability to synchronize varying complicated sets of data to narrate diachronic processes of societal growth and decline, topics clearly, even obviously, relevant today [5]. In new fields like the "history of climate and society," for example, scholars advocate analyses that integrate multiple kinds of natural proxies and historical and material evidence to reveal the complexities of past responses to and interventions in environmental changes [6]. The uneven resolution of many natural records, as well as the challenges of seeking out significant patterns from complex background noise, often attenuate our focus to centuries-long or millennia-long transformations. Despite these issues, these studies are clearly attractive for their apparent complexity in analyzing coupled human–nature systems [7,8]. In that vein, systems theory is re-emerging in archeological studies of societal persistence and adaptation, as recent work in resilience and sustainability studies shows [9–11]. Scholars acknowledge the risks of thinking big in recent planetary or Earth-systems approaches to human history—reductionism and overgeneralization, even determinism—but advocate the heuristic power of these frameworks, based on the records we have, e.g., [4]. Climate change in the past, then, can still feel big.

Efforts to descend beneath graphs of global atmospheric concentrations of carbon or regional surveys of data to think about people's real, lived or even imagined experiences with climatic or environmental change would seem, then, important to complementing this macroscalar analytical bent ([12,13], see also [2]). Archeologists have certainly called out the poor resolution of some proxies, as opposed to records such as tree rings or speleothems, as well as the lack of people in many big environmental histories, the multiple and often incommensurate scales of practice that forged human–climate relationships and the nuanced, nonlinear realities of the impacts of droughts, floods or other phenomena on premodern life [13–15]. For the ancient Mediterranean, for example, we are increasingly more aware of modeling the effects of acute droughts of 2–3 years on rainfed agriculture, as opposed to the potential longer-term impacts of regional trends in aridity [16]. Often, attempts to integrate multiscalar investigations of human–environment relationships circle around the measure of social hierarchies and macropolitical change—ruling elites or state institutions, on one side, and masses of populations on the other [17,18]. It is more challenging, based on the available evidence and methods, to reach other scales of environmental and climatic histories: villages, communities, household networks and families [19].

Yet the household was the center of life in premodern and preindustrial sedentary societies throughout the Mediterranean, the regional focus of this paper. Indeed, up to the onset of industrialization, the household unit—typically defined as a kin-based, co-residential collective but not necessarily a nuclear family, given that their construction was historically and culturally contingent—was a crucially important site of production, consumption and the management of energy flows between people and larger collectives [20,21]. It is for this reason, for example, that archeologists turn to long-term comparative analyses of household size to study phenomena like inequality from the past to the present [22]. Beyond resource or wealth accumulation, where people lived and worked conditioned their understandings, perceptions and imaginations of landscapes, environments and senses of climate [12,23]. Even with Western industrialization during the 18th and 19th centuries CE, as recent work is showing, relationships between energy consumption and climate change can be traced to domestic needs around coal and the choices and decisions that changed daily life, directed economic strategies and redesigned the home [24]. It seems important to forward an archeology of the household-scale practices that mediated people's experiences of shifting conditions through their norms, ideas and decisions relating

to resources, landscapes, weather and climate. In other words, to think critically about how past people "domesticated" their environments, by examining how they established ideas and expectations of climate through everyday activities and understandings of social orders operating at shorter rhythms and place-based scales [1,25,26]. I argue this not to rebalance our macroscalar investigations by prioritizing only the microscale as a way to explain historical change, but to advocate the study of mundane and quotidian climates through the tempos and spatialities of domestic life. In the Mediterranean, households and dwelling structures comprise most of the spatial area of the sites we investigate, even if they remain woefully unexcavated in pursuit of larger, public or state-controlled structures in dense urban environments. Household archaeologies can thus offer important evidence of norms of subsistence or logics of production, particularly of women and others often elided from history.

This paper acts as a provocation to center ancient households as the point of inquiry. I begin by highlighting issues in the current field of (pre)historical climate studies and the importance of incorporating data and interpretive frameworks of smaller and shorter spatial and temporal scales. Multiscalar analyses are key to highlighting the diversity and complexity of human perceptions and experiences of environments and changing ecologies forged through everyday practice. They also expose the generalizations of the functionalist work that treats households as data points in larger arguments about land use or urbanization. I then turn to recent scholarship in the archeology of households and highlight insights on flows of materials, energy and labor: storage, consumption, foodways and gendered production. Examples from archeological contexts reveal how everyday practices conditioned how people experienced shifting environments and built up senses and norms of climate. Despite the inherent challenges of studying microscalar or daily practices in the ancient world, as well as the difficulties extending or connecting embodied, individual choices to a specific climatic change, I end with some concluding thoughts on how household archaeologies can contribute to pressing conversations on climate and sustainability. As I have argued elsewhere [27], I take climate to refer to the mediations between people and their perceptions and experiences, through bodily and material encounters, of weather, ecological conditions and natural phenomena. Households, then, should open us up to thinking of climate alongside and in dialog with statistics of regional meteorological data.

Instead of aiming for an exhaustive coverage of one or two case studies, I sample from a range of recent scholarship to articulate broader lines of inquiry and to provoke further discussions. I focus on the ancient Mediterranean for a few reasons (Figure 1). First, there is a wealth of data from differentiated household contexts as well as, for many historical periods, textual sources that can help contextualize and compare patterns of domestic activity [28]. Household studies have increasingly exposed the heterogeneity of ancient domestic built environments, reminding us that we cannot assume the functionality or makeup of households nor the transhistorical concepts of public/private. Second, advances in paleoenvironmental and paleoclimatic research have made the ancient Mediterranean a particularly robust place to explore premodern human–environment relationships. As a result, there is also a growing literature on ancient climate change in Mediterranean archeology and ancient history and available data from which to draw insights (e.g., [29–31]). And finally, the varied environmental and climatic conditions of Mediterranean regions, with millennia-long histories of resource use and landscape manipulation, offer compelling contexts in which to explore the relationality between households and changing ecosystems [32].

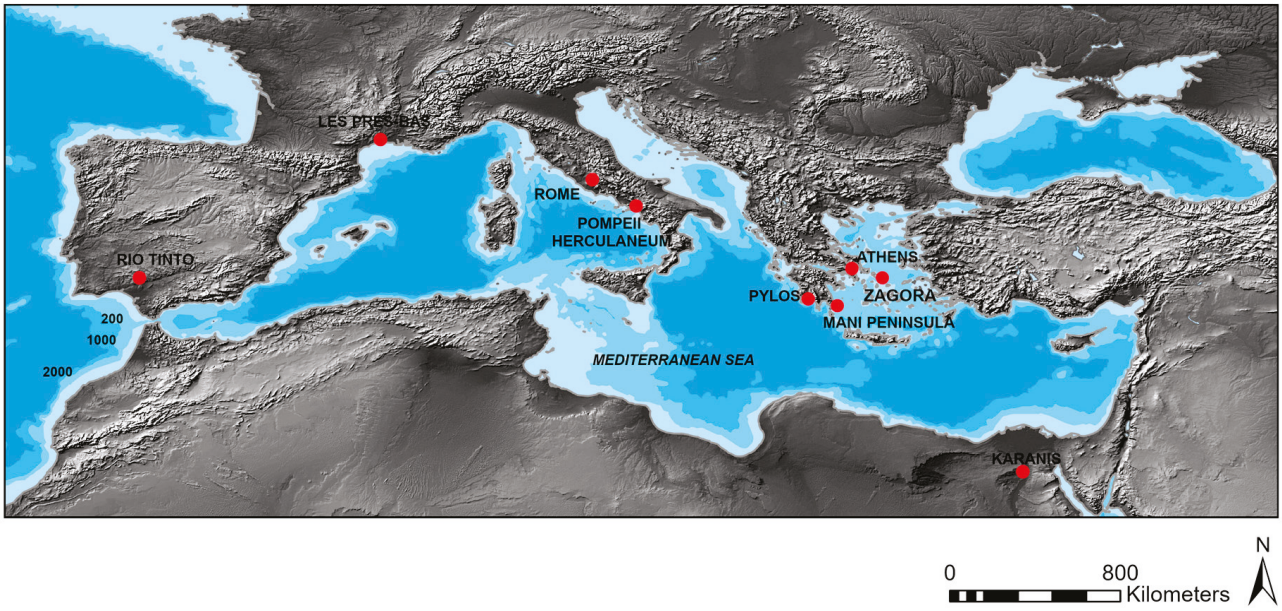


Figure 1. Sites mentioned in text. Map created by author.

2. Going Smaller

The influx of more data and more highly resolved natural archives, like speleothems, sediment cores and tree rings, has ramped up scholarly (and public) interest in past climates and environments. Consequently, the field has turned to self-reflexively consider its methodological and interpretive frameworks ([14,33] and other articles in this issue). Among these is the issue of scale, both analytical and of past practices. The Anthropocene, once proposed as a geological epoch meant to capture humanity's geophysical capacity to intervene in Earth systems [34] but recently voted against by the International Commission on Stratigraphy Subcommission on Quaternary Stratigraphy [35,36], hovers over much of this discourse. If humanity, as a species, is now capable of manipulating and transforming the Earth's atmosphere and surfaces, we need interpretive tools that think along global and planetary lines. Archeologists have rightly critiqued the conceits and presumptions of the Anthropocene [37–39], but the turn to considering how past societies responded to or altered Earth systems has similarly privileged large-scale analyses. Take for example "collapse" studies of imperial decline due to aridification and demographic crises through the study of agricultural economic instability and "mega-droughts" [18,40–42].

As noted above, the wide aperture we use to analyze societal responses or adaptations to changing climates emerges in large part from the evidence we have at hand. In the Mediterranean, regions with abundant sources of accessible paleoenvironmental data, like caves, freshwater lakes and standing forests, have provided starting points for reconstructing past environments through proxies of temperature and moisture changes, but these proxies come with diverse methodological issues for chronological precision, and many still require expensive radiocarbon dating and statistical methods to improve their resolution [43]. These records might produce trends in oscillations in local or regional temperatures at annual, decadal or centennial scales. For other regions, there exist no or very few robust paleoenvironmental studies, forcing scholars to rely on interregional data or hemispheric records, like arctic ice cores [44]. The dependency on non-local histories of ecological or climatic change thus also contributes to macroscalar spatial generalizations based on correlation and synchronization rather than direct evidence of causation. In addition, the use of survey evidence to chart changing regional settlement patterns, while capable of revealing diachronic trends in responses to broader landscape changes, typically

relies on surface collections without systematic stratigraphic testing, further coarsening interpretations.

More recent applications of systems theory in archeology, in the form of resilience and sustainability studies, attempt to overcome these issues by studying societal interactions with triggering climatic and environmental events or processes through examinations of persistence and disruption, often at landscape scales ([45–49]; see also [9–11]). Indeed, in a recent bibliometric synthesis of publications using resilience and/or sustainability concepts or frameworks, Jacobson [11] found two papers out of dozens that analyzed resilient practices at the scale of the household, in distinction from regional communities, states or empires. Most studies of resilient societal adaptations to climate change are quantitative more than qualitative, using numbers of households or sites as proxy evidence for the stability and coherence of state or institutional structures, like food supply [29]. Envisioning externalized forces like climate change primarily as impacts on society, scholars can then measure whether human groups or sociopolitical structures were "more" or "less" resilient to stresses. These studies can often remain essentializing by inferring or assuming pre-existing social conditions that determine who is vulnerable and who is not along coarse models of political or economic status. Resilience discourse can also mystify the causes or material habits of vulnerability, masking over differentiated social responses or encounters with environmental change, and can downplay the structural determinants of those changes in favor of reactionary outcomes [50,51]. In addition, relying on systems frameworks or larger analytical scales can obscure how societal well-being was created primarily through the smaller-scale, everyday household practices of resource accumulation. As Bowes [52], p. 32 has argued, "We need to keep the urgency to tell big stories, but use thick, small-scale data to tell them, returning to a place we actually know quite well—the household—and exploiting both well-known and new datasets in the context of lives lived—not trends already assumed."

Archeologists and historians have increasingly turned to advocating for smaller and shorter scales of analysis and the interpretation of integrated scalar relationships, given that looping, incremental or gradual changes are the mediations through which past people experienced and made sense of climate [53–55]. But as with paleoenvironmental data, the evidence available for Mediterranean households can make those moves tricky, especially in regions that lack the kinds of robust records of excavated or surveyed households and smaller social units. The majority of our evidence comes from urban residential areas, with fewer rural or non-urban domestic residences available to study [56]. While household or domestic archaeologies have been on the rise over the last few decades, providing variable and cross-cultural records, even within the Mediterranean there remain areas without commensurate data with which to compare household sizes, material histories and associated assemblages. Furthermore, the intersections between household studies and environmental and climatic histories are only beginning to gain attention. Conceptions of households and the "home" are often embedded in modern, bourgeois juxtapositions of the outside world of nature with the interior, private spaces of social life, conditioning us to keep environmental histories outside the domestic [57].

And yet as argued above, households were a key venue for the conjoining of human–environment interactions through lived experiences, "vital sites for the production and reproduction of nature. . .they also articulate with technologies of power while engaging in flows of matter, energy, capital, and knowledge" [58], p. 174. In past Mediterranean societies based on agricultural economies, significant amounts of production and consumption happened within households and estates of varying sizes, and people built their social worlds through dwelling and working with their families and local kinship networks, with diversely constructed ties to other scales of communities, states and regions [51].

Households were co-constituted through the micropolitics of daily life and the macrolevel structures and decision-making of larger forces, like tribes, ethnic formations or states and empires. Studying domestic realms of production, storage, consumption and social networks can therefore reveal important patterns of lived experience from bottom-up perspectives that privilege interconnections between people and their environments, not just external or exogenous triggers or shocks to the system [59–61]. Such frameworks can center social actors themselves, rather than abstract entities that adapt or react as parts of larger sub-systems. While archaeologies of individuals and their embodied experiences remain incredibly difficult to interpret, households offer a way to study the lives of underrepresented people, especially those who existed outside our available textual records [62]. Through household material assemblages and the remains of built environments, we can start to identify decision-making that shaped and was shaped by environments, as well as how these efforts and practices changed over time ([63]; see also [21]). In other words, we can investigate how households were not just passive and self-contained spaces but were instrumental to the making of nature [64].

But what is a household? The field of archeology has worked over the last few decades, especially since the provocation to study domestic contexts by Wilk and Rathje [65], to refine archeological and conceptual definitions borne from highly diverse, heterogeneous material records [66]. We can think of households as groupings of co-resident people, and their nonhuman networks, engaged in meaningful relationships and similar tasks, acting together socioeconomically [67,68]. Or, we might call them archeologically identifiable through physical structures that combine interior and exterior spaces for tasks and dwelling [65]. Importantly, households do not equate universally to the nuclear family, given the wide-ranging evidence for the co-residence of multiple constructed groups, and extend beyond the walls of built structures to include spaces like compounds and courtyards, refuse dumps and work areas like gardens, fields, pens and threshing floors. But equally important are self-reflexive attempts to interrogate relations of people, as a unit called a household, *and* the material residues of their actions in what we define as archeological contexts of households. Scholars have used household records to create comparative analyses across space and time or to follow material evidence to examine thematic issues, such as domestic scales of craft and food production, consumption and even identity [69–71]. Others confront households as a cultural trait, social historical practice or category of built environment in specific periods and regions ([72], see also [28]). For many, households are important indices of socioeconomic change due to a presumed conservatism in their material constraints and resistance to innovation [73]. As the field of household archeology has developed, the attention to the ecological contexts of household activities has also grown, particularly through the study of micromorphology, discard practices of botanical and faunal remains and resource management or capture, for example, in the form of water storage [74].

When considered conceptually as social groups whose activities mediated relationships between families, communities and social structures, households are additionally important for grounding studies of everyday and daily life [55,75]. Building on the ideas of practice theory as well as geographies of domesticity and micropolitics, archeologists have turned to household scales to explore the routines, habits and decisions that become interrelated with the social production of space [76–78]. A focus on everyday tempos can further connect to experiences of seasonality and weather, which were critical to developing norms and values associated with understandings of climates and their effects on local or regional surroundings [79]. It is important to remain attentive, however, to how the quotidian rhythms of household life were not separated from larger processes and structures, nor determined by ecological or climatic concerns. As Foxhall reminds [21], p.

417, households were dialectically intertwined with these forces at varying constructed scales, which together shaped homes and landscapes through the demands of practical needs, cultural ideals, as well as more coordinated and regulated expectations of political formations, through institutions like property and inheritance or taxation and tribute: "to what extent were household decisions shaped by constraints emanating from, on the one hand, other members of the communities in which they lived and worked, and on the other hand by political and economic forces extending beyond the local community?" (see also [80]). These interconnections between the household and society make it critical to situate studies of domestic climates against historically contingent forms of power and authority, from prehistoric villages to the empires of the Roman period and late antiquity. The diversity of household remains across the Mediterranean attests to the manifold ways that household collectives, from the so-called peasant or smallholder to landowning elites, thought about stability and persistence, the precarity and availability of preferred resources, among a myriad of other concerns.

What might an archeology of household climates look like? At one empirical level, we can draw from domestic records and household assemblages to reconstruct localized climatic and environmental conditions especially through the recovery and analysis of botanical, faunal, geomorphological, topographical and other kinds of evidence, like the residue analysis of imported materials. Additionally, such contexts can shed light on how groups responded to possible impacts or adaptations to local weather and seasonal environmental changes, such as strengthening or fortifying food reserves, mitigating climatic changes like flooding or siltation or adopting architectural choices for modulating temperature and ventilation [81]. In a recent example, Davoli [82] shows how windbreak walls in the buildings of Karanis and other arid-region settlements in Mediterranean Egypt during the Roman period worked not just to regulate flows of people, but to prevent sand accumulation. Archeologists can also consider how households modified local climates. Building on historical ecological studies, for example, to explore how humans engineer their own selective environments, archeologists can use empirical datasets to examine how households adapted microregional conditions to access preferred resources and maintained landscape practices that altered ecosystems and variables like soil conditions, water availability and vegetation cover over time [48,83].

But equally compelling are insights from political ecology that move beyond typologies of household traits to access the mediations between social actors and changing conditions, especially taking into account uneven perceptions of crisis, risk, productivity and scarcity depending on fault lines of social difference [39,84,85]. Political ecological approaches to past environments are elucidating how diverse groups within a society responded to or experienced certain changes unequally, creating multiple forms of adaptations, responses or practices of continuity. We might focus, for example, on the ways the consumption and discard of materials and nonhumans, like animals, made domestic worlds work and seem stable for different kinds of households; how property rights secured some households to particular kinds of landscapes; or how elements like fuel or crafting supplies were willingly or unwillingly brought into homes through forms of economic, social or ritual relations [86]. Some aspects of domestic human–environment relationships remain less challenging to identify and analyze than others, particularly those related to the storage, production and consumption of crafts or foodstuffs and flows of fuel and energy sources, given the durability of things like storage containers and manufacturing equipment. At the heart of these questions, however, is the recognition that within and outside households extend networks of humans and nonhuman constituents, like animals, plants and biota, entwined in complex and uneven systems of formation and exchange [58].

3. Household Climates

This section suggests three key topics, among many, where studies of households can instigate research opportunities for smaller-scale archaeologies of climate: the storage of surplus, practices of consumption and discard and engendered modalities of household management. As argued above, in the spirit of provocation rather than straightforward historical argumentation, I use a capacious rendering of the term household to refer both to the structured collective of people, generically related to social groupings through family or kinship formations, as well as to the analytical concept recovered through the material remains of domestic features of the built environment in their landscape settings. I privilege the household contexts of sedentary societies of the ancient Mediterranean, rather than attempt to synthesize all kinds of domestic or dwelling features of nomadic or semimobile configurations, although it is important to recognize that dwelling practices could be intermittent and extend beyond the single built structure into activity areas in the landscape. Although the permanent or semi-permanent structures of premodern home-making share many similarities across Mediterranean regions, they offer a starting point for challenging assumed stereotypes of human–environment relationships in historical research. Indeed, as Gillespie [87], p. 41 has noted, the recognition that households are not easily isolated or turned into proxies "means that the outcomes of their members' actions *make* history, including unintended consequences." I extend these ideas below to argue that these actions also make environmental history.

3.1. Storage

The storage of foods and harvested or extracted goods, as well as fuels, resources like water and other forms of energy capture, can show how households thought about what they needed and how they wanted to keep it as well as how they observed and managed the conditioning and preservation of their livelihoods. Archeologists can distinguish between the physical components and requirements of storage, the material apparatus through which people accumulate things, and the more abstract idea of surplus, typically defined as the accumulation beyond levels of basic subsistence needs. As Van Oyen [88] has recently put it, "'surplus' denotes that extra bit that allows some people to be released from the relentless need to cultivate their own foods." For many working in archeological contexts, surplus acts as a signifier of a kind of rational activity associated with sedentism or with hierarchical societies and the ability to keep or preserve more than what a person or family requires for eating, drinking, clothing and sheltering and to control what happens to it—often for sociopolitical motivations [89]. Taking things out of circulation and storing them for future use could take numerous forms of varying archeological visibility: caches, underground pits, portable container and aboveground structures. This storage could then be converted in ways that reveal differentiated social relations, such as communal feasts, as well as diverse senses of time and need: in the realm of the storage of foodstuffs to sustain households in agricultural economies, for example, archeologists can explore how much social groups might have needed to counter risks of poor harvests, as well as how people responded to unpredictably productive harvests or bumper crops [16,90].

While concepts of "normal" surplus can often be rendered quantitatively, as numbers of calories or volumes of commodities, archeologists have increasingly recognized the social and political dimensions that turn accumulated things into a surplus with differently weighted effects: who makes decisions about what to store, how much, where and in what manner and how those production and consumption practices are dependent on surplus reproduced or generated forms of social inequality [91]. Many of these practices of accumulation operate at small scales, such as decisions to store certain foods during wet or dry seasons, adaptations of storage containers to mitigate the threat of weather events or

pests, moving goods between kinds of storage at different points of the working calendar or the placing of stored things in particular areas to control accessibility [81]. Because storage and surplus have been seen as critical innovations in the development of human social complexity, the material traces of certain kinds of semi-permanent or permanent storage—which often survive in archeological records due to their durability, technologies and size—have become entryways for political ecologies of human–environment mediations [89–92]. As such, archeologists have sought to understand how storage practices, and ideas of surplus, conditioned responses and negotiations to problems like scarcity, precarity, abundance or environmental risk and unpredictability [93].

Because of the obvious material propensities of things stored and kept, like grains, wine, water or cut wood, we can turn to the diverse practices of storage that people created to account for issues of accessibility, preservation and the creation of value over time, as well as ideas and expectations of climatic norms. Recent studies in the storage of surplus grains in the ancient Mediterranean, for example, have shown how people considered the challenges of degradation and spoiling, pests and contamination and weather conditions to extend their longevity or to ensure adequate and efficient forms of food supply and trade. Cheung [94] has studied storage practices in the Roman empire, from scales of households to the state, to argue for the flexible technologies of storage and transport that brought bulk foods around and across regional territories in a world without refrigeration. Within Roman households, grain accumulations took the form of large ceramic *pithoi* containers, often placed into underground pits to regulate moisture and temperature, e.g., [95]. The material characteristics of different grains led to varying styles and modes of storage: threshed wheat, for example, could be more vulnerable to pests and insects if not stored in sealed containers. Controlling access to air could preserve wheats and grains like hulled barley, while sealing off other kinds of harvest, like fruits or oils, could delay ripening or spoiling. Material choices in storage, then, enacted diverse ideas of the management of weather conditions as well as expectations of value. This type of multiscalar synthesis points to ways that household decisions on prolonging the quality of foods could be entwined with state and imperial interests, particularly in the extraction of surplus from agricultural territories for wider networks of dependent populations.

Recent work on Roman economies of grain and wine storage further attests to how acts of storage and surplus accumulation mediated household–environment relationships [96–98]. In her study of rural practices in southern France during the Roman period, Van Oyen [94] examined evidence for continuities of viticulture and wine production at varying scales, especially in the establishment of wine fermentation using large ceramic *dolia*. Signs of more intensified production facilities in large agricultural estates, so-called villas like that of Les Prés-Bas (France), suggest practices of foresight, extending expectations of productive harvests into multi-year projections with associated labor and technical demands. And alongside evidence for the specialized production of wine in these large estates, archeologists have revealed many small farms in this region of southern France with wine-making infrastructure [97]. Given the typical subsistence focus presumed for rural inhabitants of the empire, especially agricultural workers or smaller-scale property owners embedded in and reliant on seasonal cycles of cultivation, economic historians have traditionally considered them conservative, risk-averse and identified through, if not innately attuned to, weather and climate (see [79]). This scholarship shows, however, that choices in how to store wine for months or years to increase its quality of taste, color and smell, among other added value traits, made rural winemakers of varying socioeconomic classes more ambitious and innovative [98]. Such evidence of taking risks for returns on the energy expended in intensive grape and wine production points to how people thought more open-endedly about expected climatic conditions, their

standing and future economic stability, as well as their norms of environmental time: "in particular, storage's rhythm of material change does not just tell us that the future was reckoned with, but what particular kind of future was envisaged" [96], p. 197.

Archeologists can also question how households navigated the spatial needs of storage and surplus in special containers, permanent structures like cisterns or granaries or more mobile kinds of vessels. Domestic built environments, while not easy to always identify as sites of dwelling or residence, often include areas where things were kept for varying periods of time, sometimes within or near living spaces and sometimes located closer to land use activities like farming, animal husbandry or the extraction of resources. Traces within domestic structures can include benches and shelves, sunken storage vessels or semi-subterranean pits or basins. In Foxhall's [21] diachronic study of households in the Bronze and Iron Age Aegean, she argues that choices in how much food or water to store seem to have been made by individual households, even in periods with signs of the centralized authority of state interests in surplus production. Despite the regularity of the shape and sizes of excavated houses—typically rectilinear, one-room structures with attached or associated courtyards—there was diversity in where people built houses and storage facilities during the Late Bronze Age period, when states like Pylos would have governed the flow of certain commodities and materials like wool and semi-luxuries like wine. After this period, sites like Nichoria in the southwest Peloponnese transitioned to a settlement with only one seemingly "big" house: a single-room structure in which the inhabitants created extra storage space through an apsidal addition to one end of the building. While not enough of the settlement remains to understand specific power relations during the nineth and eighth centuries BCE, the evidence suggests that households were capable of regulating flows of goods and resource management alongside the strategies of powerful social actors or elites. Similarly, Seifried's [99] recent work on later medieval and early-modern households and their water cisterns in the Mani peninsula of Greece shows how social, political and economic practices and concerns shaped water storage in this arid region, which became entwined with responses to climatic conditions. While in earlier periods, households appear to have constructed independent cisterns in a variety of techniques to keep enough water to sustain daily life during the hot dry summers, later periods saw the increasing placement of larger built cisterns in certain family compounds, suggesting the control of the access to communal or collective water. The diversity of the sizes, shapes and built features of cisterns, like compound walls, indicate that household and community senses of weather, water storage and sustaining livelihoods were constructed through social relations.

3.2. Consumption and Discard

Archeologists have long thought about consumption, using household assemblages to reconstruct socioeconomic norms, the accessibility to goods, the social and cultural logics of choice or markets or signs of wealth or social inequality as a means to examine society and its structural conditions [100,101]. Beyond viewing the house as the smallest functional economic unit of society, archeologists have sought to understand internal variations in patterns of consumption and deposition, as well as to situate households within wider networks of social groups, such as villages or urban neighborhoods, rural and productive landscapes and local or regional ecologies [102]. In this vein, attempts to analyze the household choices and control over what comes in and out of homes and what types of things are consumed are particularly salient to studies of climatic and environmental history: how and what to collect, which substitutes for fuel or resources work and which do not, how to manage food waste or spoilage or confront precarity or how to navigate unexpected windfalls.

Foodways, or the intersecting cultural, political and economic modes through which people acquired, made and consumed food, constitute an important part of household constructions of environments and nature. Equally notable to recent archaeologies of climate change in the Mediterranean are assumptions around the subsistence-based household. Closely aligned economic concepts like self-sufficiency, by which these groups were not reliant on the trade or exchange of supplies, further construct scholarly ideas of the convergence of environmental conditions, economic action and household stability [79,103]. Recent interrogations of constructs of subsistence and self-sufficiency have increasingly contested their universalisms and thrown doubt on their historical realities, particularly in the more marginal or unstable of Mediterranean ecologies [104]. Paying attention to flows of food within and beyond households can therefore be an important step to nuancing long-held assumptions about Mediterranean agricultural populations, the "peasant" and the premodern working classes of food producers, as well as to expanding our study of the cultural and social practices behind household food consumption. In addition, archaeologies of food consumption have shown how meals, from the everyday to the feast, reproduced social and political structures through the choices, display and rituals of eating and drinking [105]. They also mediated household relationships to the environment and climate. To take one example of these ideas, Halstead [106] has argued that during the transition between the Neolithic and Bronze Age periods in the Aegean, special meals were created from more highly valued harvested foods and scarce ingredients, as opposed to the more available options for everyday eating, to mark social differentiation amongst households. At Bronze Age centers like Pylos, those with greater status were able to overproduce staple grains, turn them into more elaborate meals or feed them to livestock and thereby mobilize labor while also conspicuously consuming goods, despite risks of shortages due to poor harvests. Through the work of formal "feasts" and the cleaving of high-value foods and fodder, people used food to reinforce links between their control over agricultural production and labor and commensal politics.

Consuming landscapes also structured fuel use. Wood was a critical energy source in the Mediterranean world, and recent estimates suggest that wood fuel supported half the functioning of ancient economies. Yet fuel, as an increasingly important topic of long-term environmental and energy history, is often studied at the scale of urban needs, such as supplying a Roman city with enough charcoal to heat its baths, or abstracted as quantities of wood charcoal required for industrial uses, such as metallurgy [107]. Households were also important consumers of fuel, particularly for the maintenance and firing of hearths for dwelling and food production as well as for domestic craft production, in the form of kilns or furnaces. Steps in acquiring, managing, storing and using wood brought people into wider networks of trees, forests and states, with attendant choices on what fuel types and which heating sources to combine. Societies around the Mediterranean engaged with multiple kinds of wood sources, such as lowland maquis or montane forests, and often chose certain kinds of wood for selected purposes. For many people, collecting wood was likely an important part of everyday life and was necessarily mediated by these local or regional conditions, whether foraging or gathering branches and twigs or maintaining groves or orchards of trees to prune for a systematic supply. For others, options to use wood or charcoal, a denser energy source, were likely shaped not just by household desires or the capability to produce charcoal, but through their access to markets or interregional exchange, particularly for charcoal commodified for domestic use [108]. Additionally, scholars have shown how woods differed in their propensities to ignite quickly, let off less smoke and yield more heat and for longer amounts of time, creating a complex field of practical and cultural knowledge for choosing certain fuel sources [109]. These practices of the acquisition, use and even re-use of wood would have put pressure on local

resources as well as been impacted by shifting climatic conditions that shaped vegetation and forestry areas.

Mediterranean households also incorporated other "secondary" matter derived from their practices and environments to use as fuel, such as animal dung, peat and olive oil pressings, or pomace, the latter of which is archeologically recoverable as fragments after carbonization. As a byproduct of olive oil production, olive cakes or pomace would have been efficient sources to burn in domestic ovens and hearths in lieu of, or in preference over, wood charcoal despite its lower calorific value [110]. In a recent study of archeological traces of carbonized olive stones throughout the Roman empire, for example, Rowan [110] has shown that households at Herculaneum and Pompeii, in southern Italy, used pomace as a fuel. In one excavated sewer tunnel at Herculaneum, the paleobotanical findings show an overwhelming signature of pomace, deposited as waste after its service for domestic fuel needs. Differentiating the evidence at these sites between the olive seeds discarded after cooking from olive stones, crushed and carbonized after pressing, reveals important trends in household consumption practices mediated through temporal and economic engagements with olives: as an oil, fruit and fuel. This evidence also points to the contingent decisions households made in consuming energy; despite available wood charcoal sources, some inhabitants at Pompeii and Herculaneum chose pomace for its easier and efficient handling, especially for cooking.

Archaeologies of discard, waste and re-use, like turning pomace into fuel, have opened up important avenues for understanding household practices as they constructed and responded to climatic and environmental conditions. As others have noted, the question of what to do with "waste" is social and political, even cultural, and not just economic [111]. Archeologists have turned to thinking about circular economies beyond single-use and disposal or discard practices, including the re-use and recycling of materials in systems of craft production or the continued value of things over time, despite their loss of their original function (e.g., [112]). Household studies have also thought about the varying tempos and perceptions of discard, from the everyday cleaning of accumulated things to the more abrupt, singular events of removal "that disrupt the equilibrium of everyday life" [74], p. 9 and [113]. As argued above, the flows of things and "waste" through and around households can reveal insights into the relationships people forged between their home-making practices and wider environments, senses of place and expectations of future change. Studies of landscape and environmental change surrounding the industrial scales of mining in the Iberian peninsula, across the second century BCE and second century CE, provide traces of working households living amongst mining waste. Gosner [114] has argued that as the Roman extractivist economy of mining took over the region, it required new kinds of settlements that supported thousands of working people, especially smaller and more easily controllable villages that the state equipped with public services, like schools and baths, to maintain high levels of labor productivity. At Corta Lago at Rio Tinto, one of the largest scale mining enterprises in southwestern Spain, archeologists uncovered the remains of one of these small towns buried under tons of slag deposits, a byproduct of smelting, with several buildings still visible [115]. Homes here of the first century BCE were physically constructed from industrial waste, re-using large slag fragments for architectural support. While it remains challenging to interpret these choices in built construction due to the fragmentary recovery of the site, as Gosner argues, it is clear that the expansion and intensification of mining in Iberia deeply impacted the everyday nature-making of local people in uneven ways.

3.3. Gender, Women's Work and Generational Time

Household studies are additionally important for their ability to recover engendered experiences in past communities, a key structuring force of social difference that can often escape notice at larger scales of analysis. Decades of attention to gender and sexuality in archeological scholarship have emphasized the mutability of gender expressions and identities in the ancient Mediterranean, the false transhistorical idea of rigid gender and sex binaries as well as the historically constructed logics structuring divisions of labor across categories of age, gender, ethnicity or disability [116–118]. For the sake of space, I focus here on environmental archaeologies of women, although we should advocate the intersectional study of the plurality of gendered experiences and embodied practices in ancient households and landscapes. Despite the lopsided nature of available textual sources, such as the *Oikonomikos* of Xenophon or Hesiod's poem *Works and Days* for the Greek world, which privilege the concerns of men, we understand that women were often the ones making household decisions around the management of flows of resources, labor and production, making them consequential for the production of household space and human–nature relationships. As Beaudry notes, "the shift of emphasis on household as productive unit to that of an often highly differentiated and complex system of both fixed and shifting relationships has led to a strong focus on the gendered nature of household activities—for instance, on women's work both in terms of tasks and chores and often as arbiters of taste, morality, and behavior" ([74], pp. 3–4). The themes of domestic production and traditional knowledge are therefore pertinent to studying how household practices, norms and decision-making reproduced larger-scale economic and political processes as well as relationships with climates and environments. They can also further reveal how climatic or environmental changes could have uneven impacts for different gendered groups as well as amplify gendered inequalities.

Building on feminist archaeologies and geographies of domesticity, scholars have increasingly sought to analyze the spaces and gendered dynamics of domestic labor, production and consumption as flexible and constructed at different scales. Women likely engaged in many tasks, like agricultural and horticultural work, resource gathering, food processing, animal husbandry and childrearing, not to mention what we learn from sources about their roles in home-making, labor mobilization and household ritual activity [117]. In certain societies and periods women also owned property. These activities of provisioning and tending the home enmeshed actors in wider environments and produced gendered experiences of the weather, environment and climate (e.g., [119]). In the Greek world, for example, iconographic and textual evidence suggests that women handled the provisioning of water for households through trips to springs, fountains or other sources [120]. Encountering changes moreover, especially in the times of scarcity or intensifying vulnerability, would have put pressure on women to find additional resources and manage increased workloads, particularly through processes of provisioning [for data on recent global climate change and gender, see [121]. These encounters also produced ideas of the landscape and climate through embodied forms of traditional knowledge that could be passed on to others. More broadly, these domestic practices shaped local forms of knowledge about the seasons, weather and environmental changes, which led to the creation of place-based imaginations within and beyond the household [122]. While it is important not to essentialize gendered categories via particular material traits or practices, household assemblages can reveal how these forms of environmental knowledge shaped everyday decisions around productivity and flows of materials.

Another example of the intersections between domestic craft production and gendered knowledge in the ancient Mediterranean relates to textile and cloth production, one of the more archeologically visible ways to ascertain "women's work" in premodern households.

Archeologists have regularly analyzed textile production through the ubiquitous presence of tools and equipment such as loom weights and spindle whorls as well as iconographic evidence in excavated contexts [123]. While studies have often focused on the craftsmanship of textile work itself, or on the equipment or finished products, the *chaîne opératoire* of production required a knowledge of plants and animals and the seasonal availability of local resources. Through work, women and other actors made decisions on sources of materials and their qualities, the equipment needed to achieve diverse scales of production and the design of finished products in relation to domestic, community and often state interests. In recent research on the production of sail cloths for Greek warships during the Classical period, for example, Dimova et al. [124] follow the technological steps of making large wind sails to argue that in times of war, the state pressed existing domestic labor into service, scaling up household work to produce military goods. Navigating these abruptly shifting scales, women and free or enslaved laborers were forced to confront new flows of supplies of materials, like flax, through their households.

Attending to gendered and embodied experiences of home-making can shed light on the formation of knowledge around ecologies, nature and landscapes as well as to senses of household temporality. In the absence of data on land tenure and property rights, more attention to the duration of households at particular locations can reveal how their inhabitants built permanence and longevity through ties to the land and the creation of worked and meaningful places [27]. In many ancient Mediterranean state-based societies, claims to land with "good" soils or valued resources became operationalized as forms of property and ownership, which could generate new concerns over inheritance and succession, materialized through wealth in marriage and dowry rituals. Thus women's role in the reproduction of families and kinship groups often led to investments in cross-generational connections and to ancestors, rooted in household and landscape practices and rituals of commemoration as well as to claims of belonging to families, kin groups, ethnic identities or otherwise. Granular studies of household assemblages and features are also a helpful direction for assessing tempos of occupation and abandonment, for example, in the reconfiguration of spaces to accommodate changing needs and working conditions at seasonal or generational scales. In a recent example, Mann [125] has analyzed microhistories of abandonment among the excavated households of the Early Iron Age settlement of Zagora, on the Greek island of Andros. Recording the practices of the cleaning and discard of this site reveals patterns of what households valued and how senses of time structured what could be left behind for ongoing but less visibly permanent use. At Zagora, large food storage vessels and loom weights appear to have been taken while leaving the site, perhaps as markers of inherited traditions or economic value, while some basic cooking equipment was left behind in some houses. It appears that deliberate planning and anticipatory conditions structured the more intermittent, and potentially less rooted, forms of household living after the eighth century BCE.

4. Conclusions: Toward an Archeology of Everyday Climate Change

The work drawn from the Mediterranean studies summarized above illustrates the importance of archeological research on the intersections of household life and environments in the making of history. Attending to practices of storage and surplus production, consumption and discard and domestic work highlights the interpretive potential of household contexts in archaeologies of climate and environmental change. Other topics could equally bring the domestic to bear on current interests in past environments: taking care, living with and exploiting animals, mobility and seasonal dwelling practices, processes of household abandonment, landscape engineering or ideational and affective relationships to materials. In choosing to sample from diverse periods and places, I have withdrawn from

an attempt to make a singular methodological or historical argument and rather aimed to build up comparative and multiscalar questions of household–environment histories for future research. Choosing to examine smaller spatial scales and shorter temporal scales of past practice can complement existing work in archaeologies of climate that operate at the level of landscapes, societies and regional systems. It is important then for future analyses to turn to creating robust quantitative and qualitative studies of household assemblages that can produce effective arguments and modes of explanation about how people in the past experienced climates through everyday, domestic activities [126]. Studies that produce highly resolved spatial and temporal distributions of materials within and alongside household features, as well as the systematic recovery of information on production and consumption practices, are a clear next direction.

We should not reduce the domestic only to the small scale but refocus our inquiry to the dialectics between scales and their co-constitution, between the particular and general, the short term and long term, the small scale of weather and the big scale of climate. But equally, I have argued that households were sites of practices, often mundane or quotidian, which mediated past people's understandings and experiences of environments and climates, and they should also be studied on their own terms. A "domestic" lens to environmental history is therefore valuable inasmuch as it reminds us that the small scale is typically where we begin, as humans, to become embedded in material environments and webs of life. Household archaeologies, moreover, remain some of our prime vantage points for the environmental history-making of people beyond the ruling class.

These are important analytical and interpretive moves to consider in light of recent, twenty-first century attempts to refocus conversations on environmental policy and regulation around the home and household [58,85,127]. Our contemporary moment is also one of a crisis in housing and climate migration, concerns that have led some to argue for deregulations on policies of home-building and civic and technological infrastructure through metaphors of abundance, particularly in places in the Global North [128,129]. These shifts are part of broader neoliberal concerns to promote markets and to push concepts of responsibility for environmental sustainability onto individuals through operational logics like recycling, green living and ecofriendly consumer goods, as well as to constrain mounting anxieties about scarcity and environmental degradation within structures of growing inequality. We should therefore be aware of the current politics of a focus on homes and housing, but equally use archeology, and the broader strengths of the humanities and social sciences, to contribute to these conversations by exposing deeper histories of small-scale engagement with and management of changing environments, as well as the political and social dimensions that shaped those lived realities. We can articulate how the household was a critical site of environmental construction, experience and history-making by investigating how the more readily conceivable, and comprehensible, modes of everyday practice relate to the big scales of climate.

5. Captions

Sites mentioned in text. Map created by author.

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Climate and the Ancient World: Beyond Present Concerns to Complications, Where Details Matter

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Abstract: Current modern attention and concern about (human-driven) climate change has prompted much focus on the historical/archaeological relevance and role of (natural) climate change in the past. The topic is both relevant and important—and especially those short(er)-term events that perhaps helped trigger historically substantive change episodes. But, at the same time, initial, somewhat naïve enthusiasm has now run headlong into the limitations of the available data sources before the early modern era, and the many complications of establishing actual causal associations. These need to be, first, closely defined in terms of timing and effects, and then also, second, established as relevant to the specific human societies/civilizations and contexts in question. This paper seeks to highlight the need for appropriate care and rigorous method when seeking to associate climate and environmental events with the available ancient historical and archaeological evidence, and investigates three illustrative, problematic, cases from the Classical Mediterranean world.

Keywords: climate and history; black box determinism; suck-in and smear; low frequency; high frequency; Aristotle; Cyrene; Okmok

1. Introduction: Avoiding "Black-Box Determinism" and "Suck-In and Smear"—Details Matter

Many studies which attempt to bring climate to bear as explanation or causal agent in history or archaeology struggle to avoid the fundamental challenge of first establishing that the climatic or environmental evidence they seek to associate with some historical/archaeological process or change is in fact (i) closely (temporally especially, and spatially) associated, and (since mere correlation is not causation) (ii) that there are plausible and relevant causal connections (e.g., [1]). As we move back into the past, this usually becomes more challenging: we must be very careful not to be tempted to try to associate different approximately dated events and evidence with something that is precisely dated (suck-in), while also being on our guard against the problems of the smearing of approximately dated evidence over a period of time (whether from the ranges from radiocarbon dating or from history) such that either we lose actual single, separate, specific events, or we end up creating false periods of change from what are really unconnected elements [2]. The further necessary step is to avoid what might be termed "black-box determinism". A chain of plausible causality needs to be investigated and established. Human societies and their political structures (e.g., cities, states, empires) are highly complex and usually resilient within and among their several dimensions [3]. Demonstration that climate or environmental episodes caused "collapse" are often problematic when critically examined [3–5]. As Butzer [3] (p. 3638) observes with reference to western Europe since ca. 1200 CE, "This

more recent historical experience . . . suggests that environmental or economic disasters do not necessarily lead to social breakdown or collapse".

This essay seeks to do three things:

1. Discuss some of the issues involved with bringing current climate change concerns into studies of the past;
2. Address what types of climate changes are plausibly relevant to historically forcing episodes (inherently short-term), versus those that may form the general background varying from longer-term historical trajectory to evolutionary context (important but an entirely distinct category);
3. Investigate three Classical cases wherein claims have been made for the relevance of climate or environmental effects (affecting climate) but where, upon examination, the actual details do not support the claim or raise questions about causal primacy and the relevant complexity involved.

2. From the Present to Past and a Necessary Separation

Increasingly modern politics and the world of the earlier 21st century CE, even in democratic countries, is divided/polarized and noisy (e.g., [6,7]), with the USA, formerly perceived as the "leader of the free world" post-WWII (e.g., [8]), now an exemplum of the challenge (e.g., [9]). This division spills over into, is reflected in, and shapes, approaches and academic responses across many fields from literature (e.g., [10]) through—and even centrally involving—climate change and any effective responses thereto (e.g., [11–13]), and again particularly in the USA (e.g., [14–17]). We have plenty of noise but relatively little clear signal on most big topics, and, in particular, on how to address current climate change.

Today, unless a climate-denier, the threat to lives and livelihoods from substantial and rapid climate change around the globe is regularly observed and stated—this modern climate change is, according to the vast majority (>99%) of scientists, primarily human-caused [18]. It is the collateral damage from the massive human transformation of the Earth since the beginning of the Holocene and especially agriculture [19], and, notably, the dramatically increased human activities and their discharges into the planet's atmosphere, oceans, and total landscape following the mature Industrial Revolution (e.g., from ca. 1850 CE, as illustrated by greenhouse gas emissions [20]). It is in turn matched by an exponential increase in human population associated with this same technology-driven era of human change across recent centuries [21], and the associated and now widespread human presence/pressure (>65–75% of the planet already in two 2016 reviews [22,23]), habitat fragmentation (e.g., [24]), and endemic pollution from human-created materials like (micro-)plastics, everywhere ([25] frighteningly, the vast amount of micro-plastics actually attested on the seabed are but the tip of the iceberg [26]), including within our own bodies [27].

We are well into the fourth decade since the Intergovernmental Panel on Climate Change (IPCC) (https://www.ipcc.ch, accessed on 30 March 2025) was created in 1988, and, starting with the First IPCC Assessment Report of 1990, there have now been six IPCC Assessment Reports through 2023. Across the history of these increasingly sophisticated reports backed by more and more data and the work of a large international scientific community, the picture is grim (e.g., [28]). Guzman [29] reviews and provides numerous examples of the major threats to the world: for instance, in Asia, more than a billion people "face the risk of severe water shortages" (p. 117) because of impending climate change (i.e., more than 12% of the total world population)—and by 2016 it could be estimated that water scarcity affected 58% of global population in the 2000s [30]. Wallace-Wells [31] articulates the existential threat we all face. Climate change is and should be a focus of serious attention (irrespective of any politics) as a common threat to humanity's future. One could go on and

on. And this almost appears to be a fundamental problem itself. As in "the Boy who cried wolf" (one of Aesop's Fables [32]), the repetition and dramatic scare-mongering around climate seems to inure. Thus, the "U.N. climate chief says two years to save the planet" (10 April 2024, Reuters: https://www.reuters.com/world/un-climate-chief-says-two-years-save-planet-2024-04-10/, accessed on 30 March 2025) becomes almost self-defeating, as for many people climate change seems detached from fundamental quotidian concerns. Climate change only ranks 11th of top problems facing the nation (USA) in a 23 May 2024 Pew Research center study (https://www.pewresearch.org/politics/2024/05/23/top-problems-facing-the-u-s/, accessed on 30 March 2025).

But, despite the impressive inability of the contemporary world as a whole to grasp these problems and to coordinate seriously effective responses to all our modern human-driven climate change and associated pollution and increasingly existential threats, there has been a marked "climate turn" in historical and archaeological scholarship. Is this reassuring or desperate—does this scholarship bring signal or sometimes more "noise"? From a relatively niche concern started in modern times by scholars like Lamb [33,34], in recent decades numerous academics writing about the past have increasingly focused on climate change as the lens or explanation for changes observed in the historical or archaeological records (e.g., [35–45]). Of course, this is not surprising: prehistory/history is always really about the present and is inherently political. Political and intellectual fashions in the present have shaped and continue to shape our interpretations of the past (e.g., [46–49]). In the present case, we may even observe the rapidly changing climate of academic fashion, noting how, for example, climate moved to become a/the key factor between the first (2014) and updated and revised (2021) editions of Eric Cline's *1177 B.C.: The Year Civilization Collapsed* [50,51] mirroring the increased attention on climate change as we have moved so far through the 2010s to the early 2020s. The cover of the 2021 revised and updated edition quotes Adam Gopnik: "Astonishing . . . with eerie relevance"—very much seeking to draw the present–past, past–present connection. However, the concern remains as described and critiqued by Butzer [3] (p. 3633): "Current research in historical collapse suggests a primary fascination with climatic change and environmental degradation as primary agents of change, but at the cost of less attention to the necessary cross-disciplinary integration. Indeed, the recent return to environmentalism is not about a fresh interest in the environment–society interface, but a continuing failure to appreciate the complexity of such inter-relationships".

3. "The Past Is a Foreign Country" [52] (p. 7)—Issues and Questions for Climate History

There are important differences as we combine present and past. Modern climate change and the globally polluted and over-populated world is primarily a human-caused crisis. The vast majority of scientists, at least, more or less know what the causes and vectors comprise, and we have increasingly good records that characterize current changes and circumstances globally versus those of the past several centuries back at least a millennium or two (e.g., [53]). We can, for example, quantify 2023 CE as the hottest year globally over the past 2000 years [54]. Strategic action and resilience/sustainable planning ought to be possible. However, once we move back more than a few centuries, climate and history associations are predominantly about how natural climate changes affected and sometimes shaped human history. In contrast to the present, the people of these times were largely unaware of the processes driving their climate context. At best we have the summary observations of a great thinker, Aristotle, who highlights that rainfall across Greece is diverse, potentially varying greatly from place to place:

> "And sometimes drought or rain is widespread and covers a large area of country, sometimes it is only local; for often in the country at large the seasonal rainfall is

> normal or even above the normal, while in some districts of it there is a drought; at other times, on the other hand, the rainfall in the country at large is meagre, or there is even a tendency to drought, while in a single district the rainfall is abundant in quantity" (Aristotle, *Meteorologica* 360b5-13, translation of Lee [55]).

But his explanations for why this is so, in terms of the different exhalations (see [56] (pp. 35–50)), fall well short of modern meteorological theory.

In reality, most pre-modern people could only know and use the recent and known past history of their area to construct strategies of resilience; changes beyond those reasonably anticipated from past experience could thus form potential but largely unknown threats (until they occurred). Thus, while past episodes of climate change may offer examples or laboratories of possible scenarios and human responses of relevance as potential analogues for the present and future (e.g., [57]), they are also different.

3.1. Lower to Low Frequency Climate Variations

The telescope of history brings one other key distinction into focus: in broad terms there are two fundamentally distinct forms of climate relevance or effects on history. The first is the lower to low frequency (that is, longer to long-term) cycles and shifts in climate regimes that have shaped the Earth over its history. These longer-term fluctuations range from the centennial scale (argued by some to be associated primarily with solar irradiance cycles [58,59] but cf., e.g., [60]), to the millennial-scale variations like the Dansgaard–Oeschger cycle associated with ocean circulation systems [61]. In addition, there are glacial–interglacial cycles linked with 100,000-year (eccentricity) and 41,000-year (obliquity) orbital forcing cycles (e.g., [62,63]) observed in long ice-core records back over 800,000 years (e.g., [64]—on-going exploration suggests the potential eventually to recover records reaching back beyond 2 million years [65]) and (with less resolution) back many millions of years from isotope records from deep-sea benthic foraminifera recovered from ocean-floor cores (e.g., [66,67]). All these categories of climate variations occur over time periods from much longer than, to vastly beyond, human generations to lifespans. The history of human adaptation and evolution, and human culture, was at least partly driven by these and earlier lower-to-low-frequency climate cycles and changes (e.g., [35,68–70]). This type of climate change was background context: humans were not immediately confronted with, or aware of, dramatically changing and challenging circumstances where decisions and strategies were straightaway necessary. Indeed, some such lower-frequency shifts could be to more benign/stable periods that generally favored growth in human societies (like the overall Roman era, e.g., [71]). Altogether, there were merely constant on-going adaptational processes which (with successes and failures) led to longer/long-term evolutionary outcomes.

Here, it is important to mention phenomena such as so-called "mega-droughts" (or similar)—the idea of extraordinary negative episodes lasting many decades, even centuries, and blamed in a very generalizing, reductionist, "black-box" logic for a variety of cases of collapses of civilizations/societies (see, e.g., [44,51,72]—and generally contrast with the critiques of such overly simplistic black-box thinking by, e.g., [3,4]). Yes, paleoclimate archives indicate variations over multi-decade to centennial-type scales. However, such longer-term variations—if not sudden and extreme—that become a new normal for a sustained period, are what humans are very adept at adapting to and, indeed, where climate may enhance/decrease effective environmental circumscription, such patterns of longer-term sustained shifts may play an important background role in driving economic, and sociopolitical evolution or devolution. Egypt offers a case wherein a reasonable argument can be made that periods (multi-decadal to centennial scale) of sustained climate conditions, shifts to periods of more extremes of higher/lower Nile floods versus periods

of more stable (non-extreme) conditions, can either encourage or discourage the effective level of environmental circumscription of the agricultural population (and so the basis via resource mobilization, e.g., tax, to socioeconomic and political organization structures), and hence can be associated with the longer-term evolution or devolution of political stability and so economic and socio-political structures [73]. The 4.2 kya episode overall may offer another case with a range of outcomes depending on the local contexts and pressures [74,75]. Furthermore, it is also important to observe that cases of longer-term variations covering a few centuries, like the Little Ice Age, do not represent consistent "bad years", rather a shift, usually in fact relatively modest, in average conditions. Despite the name and the impression of cold winters and frozen conditions, Lockwood et al. [76] have shown that, during the Little Ice Age period, there were in fact many warm summers and not all winters were especially cold (just cooler winters were more common), and overall, the Little Ice Age represents a climate shift (downturn) that was within the manageable range of many societies. Even in those areas of northern Europe that were most strongly affected, many societies carried on, and indeed some—notably the Dutch Republic—with its more open and inventive social, economic, and political structure found and took advantage of new opportunities managing or benefitting from the different climatic sub-phases from the mid-16th to mid-17th centuries CE (e.g., [77]). Obviously entirely marginal areas may become unsuitable for existing use frameworks over time during such a climate shift (e.g., a swing to much drier conditions making cereal agriculture problematic, or wetter and cooler conditions leading to a change from wheat to more tolerant crops like barley, oats, or rye), and, if too difficult, one adaptive response could be migration (habitat-tracking), while others include alterations in resource emphasis; for example, a move more to pastoralism or other strategies (e.g., [78]).

3.2. Higher to High-Frequency Climate Variations

The second type of climate variations are higher to high frequency over relatively short (decadal) to short, interannual, timescales, often associated with observed climate patterns like the North Atlantic Oscillation [79], the El-Niño-Southern Oscillation [80], the Pacific Decadal Oscillation [81], or Atlantic Multi-decadal Variability [82]. Many of the types of climate anomaly associated with such short-term variations are just that: short, in particular one-year, and not necessarily especially extreme in the longer-term, historically forcing, sense. Let us consider three examples:

(i) Western Anatolia where Köse et al. [83] reconstruct precipitation from a network of tree-ring (*Pinus nigra*) sites from 1632 to 1929 CE covering 298 years. While there are 85 years (or 28.5% of years) that exceeded 1 standard deviation (SD) from the mean (43 dry, 42 wet), only 12 years exceeded 2SD from the mean (6 very dry, 6 very wet). Furthermore, most (31 of 43) of the dry or very dry events were just one year, only two cases of very dry events lasted 2 consecutive years, and one case lasted 4 consecutive years. Similarly, the wet events were mostly one year (31 of 42) and only two of the very wet events comprised 2 consecutive years. Thus, in total, consecutive multi-year extremes occurred over just 4% of years.

(ii) In Medieval Egypt, the available Nile flood records indicate longer and short-term variations (Hassan [84]) (Figure 1A–C)—thus, indicating fairly commonly occurring changes/challenges that people were well aware of. But, looking at the 289 years from 944 to 1232 CE, there were just 22 years where a $\geq$2 consecutive years of abnormal Nile flooding occurred associated with evidence of catastrophic impacts [85] (Table 2); thus, in about 7.6% of years. Alternatively, assessing flood data more generally from the 7th to 15th centuries CE, Grins [86] (p. 109) observed of 820 floods that just over a quarter (27%) of years saw floods that would *not* have been recognized

as good/propitious, but only up to about 12% of floods would have caused serious alarm (5% destructively high, 7% too low for cultivation). Looking across 7 centuries in the pre-modern second millennium CE, Morris [87] (pp. 6–8) notes six periods of multi-year famines (variously 3–7 years) in Egypt associated with Nile flood irregularities (either too low or too high). Thus, here we see challenges with a frequency of around once a decade (ca. 8–12% of years), but with disaster and especially multi-year crises that were infrequent-to-rare in general (some periods saw heightened risks associated with major explosive volcanism, e.g., [88,89]). Nonetheless, the unusual singular annual dependency of Egypt on the Nile flood made this risk and occasional disaster both severe enough, and it reoccurred sufficiently regularly over time, to form a haunting fear that became ingrained into long-term social memory and practice in Egypt [86,87].

(iii) India, where from 1871 to 2002 CE Ó Gradá [90] (Table 2) identifies, from examination of, respectively, India, or East Rajasthan, or West Rajasthan, that 20, 21, and 14 extreme droughts occurred and 18, 20, and 17 extreme floods. That is occurrences in between 11% and 16% of the years covered in the respective regions. However, 2-year consecutive droughts (back-to-back as [90] characterizes) are very rare, just once for India and once for West Rajasthan; thus, in 1.5% of the years covered for the respective region. Floods in 2 consecutive years are also much less common, occurring for India just twice, in East Rajasthan five times, and West Rajasthan four times, or in between 3% and 4% of the years covered.

The relevance is that, in many areas of the world, occasional negative-to-extreme 1-year weather events occur and people living in any particular region will expect these with some sort of approximate frequency according to their lived local experience (and that of parents, grand-parents, family, and friends). Events that occur above about once a decade (so around or $\geq$10% probability per year) were undoubtedly frequent enough that anyone surviving to adulthood likely would have experienced such an event at least once, and those surviving to become parents and those reaching their later 20s to 30s, or older, probably two or more times. Parents, grandparents, family, and friends would add more to such an experience base and collective social memory. Thus, some adaptations to try to be prepared for such known possible challenges may be expected as well as other social strategies to address such anticipated challenges (e.g., [91,92]). For such reasons, across the pre-modern Mediterranean, Halstead [92] (p. 162) reports the aspiration of recent traditional Mediterranean farmers to store enough grain for a second year "so they could ride one total crop failure" (citing, e.g., [93]), while noting that this was not always achieved. And on a wider global basis, we may observe various traditional/ancient strategies to try to adapt to survive "bad years" as relevant to region and society (e.g., [91–97]).

3.3. Back-to-Back, or Consecutive, Multi-Year Climatic Extremes

In contrast to the anticipated, if feared, known challenges of a "bad year", the instances of two or more consecutive years of such climatic extremes are much less common in most cases. As in the three cases noted above, two or more such consecutive, or "back-to-back", extreme bad years only typically occur in a small percentage of years. And rather than once or more a decade, it is perhaps more often once a generation or even less, and only a few times a century, or even less. Such relatively rare events—even if known and feared in social memory (e.g., [86,87]) (and Egypt with its critical annual flood, long-recognized as central to life, and the state, is an unusual case and so the focus of rare early bureaucratic attention—Nilometer records, e.g., [98]; see in general [99] (pp. 26–35))—are much less likely to be anticipated in an everyday practical way, and were unlikely the focus of any regular strategy: they are not really expected (until too late), and are less likely to be

part of routine individual or collective adaptation strategies and resilience models for any particular society.

With reference to the ancient Greek world, Garnsey [100] identified this important bifurcation of risk and of human risk adaptation. The comparison of mid-20th century data from 1931–1960 CE for Attica against the approximate plant moisture thresholds for wheat (300 mm per annum), barley (200–250 mm per annum), and dry legumes (350–400 mm per annum), indicated that, in any one year, there was a 71% probability of dry legume failure, a 28% probability of the wheat harvest failing, and a 5.5% probability for barley failure [100] (p. 10). Thus, there was a fairly regular likelihood of some form of annual food insecurity or scarcity and a review of ancient evidence confirms this. Hence, Garnsey [100] (p. 17) observes that "Subsistence crises were common in antiquity". This was something to expect and to try to plan for—the one bad year strategy. However, [100] (p. 17) then asks how often does such an expected, relatively frequent, instance of food shortage to subsistence crisis "assume the proportions of famine?" This means a subsistence crisis that is not just 1 year but occurs over consecutive years and so overwhelms the adaptative efforts towards resilience via "bad year" economic practices through plausible storage or social strategies. As in the examples above Garnsey [100], (p. 17, Table 3) finds that 2 or more consecutive "bad years" with harvest failures are much less common to rare. In Athens, for wheat, the 1-year probability of 28% becomes only a 7.8% probability for 2 successive years, and for barley the 1-year probability of 9.7% drops for 2 successive years to just 0.3%—thus, less than even once a century. Data from Larisa in northern Greece are similar: for wheat, 28.5% (1 year) to 8.1% (2 years), and for barley 9.7% to 0.9%. Garnsey also looks at Odessa in the Black Sea: wheat 46% (1-year probability of failure) to 21.1% (2-consecutive years probability of failure) and barley 15.6% (1 year) to 2.4% (2 years). Thus, even here where the failure probabilities are higher, a fall back to barley means that a no-cereal situation occurs only maybe 2–3 times a century. "Thus, where drought is an important precipitating cause of food crisis, genuine famines are much rarer than mere shortages" [100] (p. 17).

The end result, compounded by the many difficulties in pre-modern times of storing staple foodstuffs, even the less-perishable, for periods beyond 1–2 years (such as (i) practicalities of suitable space and climate except where very dry, as perhaps Egypt (see [101]), or special one-off oxygen-free cases like storage pits, (ii) unwanted germination, (iii) issues of pests, and (iv) mold and other microorganisms) (e.g., [92] (pp. 162–163), [102,103]), is that, while many ancient and traditional societies had strategies or intentions to attempt to try to cope with anticipated single "bad years", they did not usually have adaptative mechanisms in place for rare and thus effectively unexpected occurrences of 2 or more consecutive "bad years" and thus famine. Raphael [104] (p. 56) provides an example from the medieval Levant writing that "even well-organized regimes found it hard to cope with long periods (*more than two years* [my italics]) of food shortage", and, after a review of granaries and storage [104] (p. 66) concludes that "the medieval Middle East was ill equipped to battle long-term droughts and famines". Ó Gradá [90] provides other examples where "back-to-back" bad years of extreme weather led to genuine crisis and famine (and this is leaving out the roles of warfare and other forms of human agency in causing or exacerbating famines [105] and the increasing evidence of a general association between climate changes/extremes and conflict, e.g., see discussion in [106]).

One other major difference comparing modern circumstances with those in the past revolves around communication (and so information) and infrastructure. Rapid long-distance communication was a considerably greater challenge in the pre-modern world; typically only the elite and especially the ruling structures of states and especially empires could invest in and support forms of relatively rapid (and, even then, sometimes seasonally or geographically limited or fairly slow—e.g., Middle Bronze Age Assyrian contacts with

Anatolia were not possible in the winter when roads were closed for about 4 months: [107] (p. 75)) communications structures (e.g., [108,109]). For most in society, long-distance communication or access (and so information) was limited at best or impossible. Moving large quantities of bulk goods was also a challenge. Transport by water, and especially since sailing ships became available, made bulk transport possible [110,111], but over land this was considerably more challenging until the Industrial Revolution and railways. In what has become the orthodox assessment, Finley [112] (pp. 126–127) argued that the available bulk land transport options (ox power principally) were limited by possible distances and thus costs/practicalities, except for a few state-level efforts (such as using large numbers, e.g., 30, oxen for each marble column drum for a major temple construction), and referred to the passage of Pliny the Younger (*Epistles* 10.41.2) where, in his letter to the emperor Trajan, Pliny explains that, in contrast with water, transport by cart requires much labor and considerable expense. Finley [112] (p. 126) therefore argued that "towns could not safely outgrow the food production of their own immediate hinterlands unless they had direct access to waterways". But, as Laurence [113] discusses, it is clear, despite this orthodox view, that roads became key infrastructure in the Roman world notwithstanding the higher terrestrial/road costs (see also [114]). Recent modelling from the distribution of materials recovered from Roman period archaeological sites in lowland Britain by [115] further questions some of this orthodoxy based on literary evidence and Diocletian's *Edict on Maximum Prices* [116]. Wiseman et al. [115] find overall that transport by road was (best-fit values) about 1.6–3 times as costly as by river and about four times as costly as by sea, which as an overall heuristic they turn into an approximate 1:3:4 ratio (with 95% confidence intervals of river 1:1-5 and sea 1:1-9).

All this leaves any specific area in the pre-modern world vulnerable if it is hit by an unexpected and rare two or more "bad years". If a port locus then, with communication, grain, and other transportable food products could potentially be sought, or bought and brought, from elsewhere (and various requests for such relief are known in ancient text sources, e.g., [117] (Table 2)), and might be shipped in if these other areas were not also afflicted (noting the limitation that cereals are much easier to harvest and transport on a larger scale compared with pulse crops: [92] (pp. 103, 105, 114)). An inscription from Cyrene discussed below offers such an illustration of grain from North Africa being provided to cities in Greece at a time of grain shortage (*Supplementum epigraphicum Graecum*, *SEG* ix 2, [118] (inscription no. 96), [119]), and such trade—largely maritime—in key staples became central to the support of major urban centers, like Athens and Rome, and a source of considerable profit and state focus [100,120], [121] (pp. 206–257). But addressing the terrestrial settlement landscape more widely, many cities, towns, and regions in the pre-modern period lacked such potential communication and bulk-transport potentials and thus rare to very rare instances of consecutive to even multiple "bad years" likely could or would have overwhelmed storage and resilience practices and led to famine and potential disaster. Here, as discussed by Garnsey [100] (pp. 22–23), although human factors like profiteering often came into play, the limitations of land transport are attested in ancient sources as creating real challenges for inland cities with food crises. In turn, these cases of real crisis, reaching upwards, would subsequently seriously affect regional and inter-regional tax revenues, economic structures, and so on (but by the time communication and information from these became systemically known, highlighting the problem, the original cause was already critical, and likely no effective remedy was immediately possible). In this way, occasional instances of what form effectively extraordinary episodes may prove historically forcing where no help is at hand. An example are three consecutive very dry years in central Anatolia ca. 1198–1196 BCE recognized from tree-ring growth information, within what appears from stable isotope information to be a longer-term shift (centennial-

scale) to somewhat drier conditions. This rare confluence not attested for centuries before or after, since coincident, might therefore form a substantive part of an explanation for the apparently sudden end of centuries of the Hittite Empire and its administrative system [122] (and see now further in [123]). Another similar recently investigated case is the role of an unusual three-consecutive years of severe drought 364-366 CE and consequent harvest failures as a likely driving factor behind the massive rebellion known as the "Barbarian Conspiracy" in Roman Britain around 367 CE [106].

4. History, Climate, and Environmental Changes: It's Complicated

Confronted with data, problems and questions, the usual human (or AI) response is to try to simplify: to reduce "noise" to patterns or signal and then to offer some form of assessment. In general terms, simplification forms a basic cognitive strategy to address an endlessly complex world given limited mental resources (brain or processing power) and available time. And, with a complementary logic, the principle of parsimony (Ockham's Razor) is regarded as a basic of Philosophy, holding that simpler explanations are superior (and likely to be true) compared with those that are more complex [124]. The identification of (or reducing data to) the simplest pattern(s) or elements—by various means—is regarded as a fundamental of the *Gestalt* school of psychology and cognition and related approaches, through modern applications in, for example, image analysis, and other complex topics (e.g., [125–128]). But, despite its central role in all human dealings with the world, and while never perfect, to be robust, simplification must be appropriate. It must, in particular, take into account all the relevant parameters and data—not just (subjectively) selecting out a few observations or impressions and then using these and so creating a biased or even entirely flawed analysis (an obvious example is political debate where various simplifications from the pool of information and misinformation available often offer differing, different, and even contradictory outcomes).

Efforts to associate climate or environmental changes with history are very much a case where over-simplification can often seem enticing, but care is necessary to establish whether this is robust. Fundamentally, it is key to remember that correlation is not causation. Coincidence in timing and place may make an association possible, but that is all (and of course failure to securely document such real propinquity undermines any claims for a climate–history association). Establishing whether there is an actual plausible causal association requires detailed investigation and substantive articulation—a point made in various ways and in various contexts several times (e.g., [1,3–5,129]).

Both the science side (climate and environmental data and the processes that drive, affect, and propagate these), and the human side (history, politics, society, culture), are inherently hugely complex. Furthermore, from the human side, decisions and actions by individuals and groups will often derive from and involve many different factors, some of which may be largely independent, and some of which may interact. The topic of the relationship between climate and history is a case wherein we must guard carefully against easy but inappropriate simplification, especially as we usually lack much relevant direct testimony. This is not a new statement. Ingram et al. [130,131] provide a critical review of historical climatology up to that point (now more than four decades ago) and they noted then the issue—looking at existing work—of needing much greater critical attention to the sources of information employed in order to build reliable data from which climatic reconstructions are plausible and then whether associations may (or may not) be drawn with human history. But, while in many ways the modern and critical field of climate history begins with the critique of Ingram et al., it remains very much the case that a focus on efforts to robustly link climate with history can often receive insufficient attention.

The idea that climate (and climate change) could be relevant to history is far from new. When Thucydides 1.23 reviews the factors leading to the Peloponnesian war—which he regards as unparalleled in Greek history (as 1.1)—he concludes pointing principally to the rise of Athens to greatness and the associated fear of the Lacedaimonians (1.23.6). En route, however, in 1.23.3, Thucydides refers to various natural events and disasters (a recurring reality in the Mediterranean [132] (pp. 298–341)), finishing with mention of great droughts in some areas with famines and in particular the plague. While ending up identifying a central human agency, the recognition of the potential relevance of an environmental/climate/disease context is striking. But this example also nicely highlights the challenges of moving from noting some disasters or events and speculation to clear and specific historical causality.

In the final part of this essay, I therefore wish to investigate three Mediterranean Classical World examples from recent work which serve to draw out some of the complexities in trying to tie history and climate together without a careful and critical review, both of the evidence used, and how this evidence relates to the relevant history to which a climate association is claimed.

4.1. An Inscription and a Major Drought 330–328 BCE?

In an article usefully reviewing sources, topics, and the limitations of current evidence for environmental–climate history of Classical and Hellenistic Greece, Ruben Post [133] (p. 6 of 12) notes that a high-resolution climate record from dendrochronology:

> "would be particularly useful for the study of the Classical and Hellenistic periods given the existence of well-dated written evidence for climatic anomalies, such as an inscription recording a major drought throughout Greece 330–328 BCE" ([133] (p. 6 of 12) citing [118] (inscription no. 96)) (my underlining emphasis).

This "well-dated written evidence … an inscription recording a major drought throughout Greece 330–328 BCE" appears to be important evidence. The inscription in question is from Cyrene in Libya, North Africa, on one face (of four, two others have the sacred Law of Cyrene) of a large white marble stele later reused in Byzantine baths ([118] (no. 96), [119], [134] (pp. 205–207), *SEG*, ix 2). Investigation proves salutary. Reading the presentation of Rhodes and Osborne [118] (no. 96), the date for the inscription is only estimated and as "c.330–326" (p. 486) and they further qualify the dating of the information in the text by stating "We do not know whether the grain was sent in a single year or more than one year. We do not know in which year or years the grain was sent". For example, Garnsey [100] (p.159) observes the inscription is "normally placed in the period 330–323 (although 332/1 …recently … suggested by an ingenious argument)". Thus, the date is not given in the text, and could cover almost a decade and not necessarily the fairly specific date of 330–328 BCE suggested by [133]—although a date likely ca. 330 BCE to the beginning of the 320s BCE seems probable (as [119]).

However, rather more fundamental: where in the text is information allowing the description of an "inscription recording a major drought throughout Greece"? In fact, the text only records:

"Priest: Sosias son of Kallias. These are those to whom the city gave grain during the grain shortage (*sitodeia*) in Greece. To the Athenians 100,000, to Olympias 60,000 … [and to another 49 (eight repeated) names of cities and two individuals]" [118] (pp. 486–489). Rhodes and Osborne [118] (Figure 2) show a map with all the locations mentioned covering much, but notably not all, of mainland Greece (also [119] (Figure 4.2), Horden and Purcell [132] (p. 73 Map 8))—in particular, most of the Peloponnesian poleis are absent bar those in the northeast (and Elis—which however receives only a modest allotment). While it has been suggested that absences may reflect politics around Macedon (for or against) and/or Cyrene's

network of partners/allies [119] (pp. 73–74), it seems more likely that the majority of the Peloponnese—relatively fertile in agricultural terms—did not require grain [134] (p. 205). The absence of many northern Greek poleis and many in Asia Minor is difficult to explain if there was truly an Aegean region major drought (and in more recent times major basin-wide droughts encompass more or less all of the Aegean (including north Aegean) and western Anatolia: [135] (Figure 5), [122] (Figure 3)). Bresson [119] (p. 74) speculates that perhaps Pontus was responsible for "feeding northern Greece", but there is no positive evidence for this.

The text enumerates in all 805,000 (we can assume *medimnoi*) of grain. It mentions a "grain shortage in Greece". Nowhere does it actually mention the cause and specifically there is no mention of a "major drought". As Rhodes and Osborne [118] (p. 488) observe, "...this apparently straightforward text is in almost all respects obscure"—much though Bresson [119] seeks to add likely interpretation and context. We do not know whose *medimnos* measure was used (the Aeginetan/Laconian one was 50% larger than the Attic), which type of grain was sent (e.g., wheat or barley), nor whether this was all sent in one year or over several years. On the last, Bresson [119] (pp. 85–92) makes a reasonable case from linked observations that the sending of the grain did perhaps occur in a single year, and based on parallels, we might assume that Cyrene both gave (allocated) grain to some of the cities or people on the list, but also likely made available (i.e., sold) grain to the *sitōnai* (public grain commissioners) seeking grain for their cities. The productive potentials of Cyrene and its territory and early harvest date are outlined by [132] (pp. 65–72). But no actual date is given. And no actual reason is stated. As Rhodes and Osborne [118] (pp. 489–490) then observe, the mentions of Olympias, likely the mother of Alexander the Great, and Cleopatra, likely Philip II's daughter/Alexander the Great's sister, are both the best dating evidence and indicate a probable political motivation (whether or not any climate or environmentally related factor may have also been involved). Carney [136] (p. 51) makes the case that Olympias and Cleopatra are named because they "were functioning here as heads of state". For Cleopatra this could either be as regent from 334 BCE when her husband and uncle (Alexander I of Epirus) went to fight in Italy, or perhaps best from her period as regent and ruler following his death in 331 BCE. Hence, widest likely dates are between ca. 335 (after Cleopatra's marriage) and probably 334 BCE to 324/323 BCE (with the political conflict in Cyrene from 324 BCE leading to its takeover by Ptolemy I in 321 BCE [137] (pp. 92–93), and/or death of Alexander the Great in 323 BCE, setting a *terminus ante quem*), and more likely, since Cleopatra is named, ca. 330 BCE or a few years later.

It may be noted that some other sources indicate grain shortages and/or grain gifts 330/329 and 328/327 BCE, and these may have climatic associations, although as Rhodes and Osborne [118] (p. 490) further observe, it seems likely that warfare and other strife at these times may have also contributed (and, as the study of Manning et al. [88] illustrates looking at Egypt 305–30 BCE—a very little later—with higher resolution historical and climate-proxy data series, both issues are often intertwined and thus co-correlated). For example, we hear of production deficits and restrictions on grain exports in Egypt, and profiteering by its governor, Kleomenes, at the beginning of the 320s BCE [119] (p. 77, 84). Such actions may well have affected wider grain supplies also. Indeed, more generally, given the timeframe involved, it might be suspected that an obvious elephant in the room is being missed in considerations, since we may assume that Alexander the Great's (and associated allies' including Alexander I) many and enormous military activities across the region and then beyond 336–323 BCE both created many upheavals across the entire eastern Mediterranean region and their own major provisioning–supply needs (as Duncan-Jones [138] (p. 104) highlights in his review of [100]; for detailed analysis of feeding and

supply of Alexander's army, and the implications for local crops and hence massive local to regional disruptions, see [139]). As a slightly later example, considering the grain shortage in the Peloponnese ca. 191–188 BCE, Post [134] (pp. 200–202) considers the possible relevance of various military activities and the requirements to provision armies, and, having reviewed the evidence, observes for example that "The period from 191–189 BC was thus one in which the Roman state's demand for provisions was exceptional, evidently straining its grain supply system". Likely much greater mobilizations and regional demands applied in the late 330s to early 320s BCE.

Returning to the Cyrene inscription itself, there is no actual evidence to relate the Cyrene gifts to any of these other events—but the mentions of Olympias and Cleopatra do point to the relevance of Macedonia. In all, reduced grain supplies which, among other factors could be because of drought or other environmental causes, enormous and many military activities in this period, allied with political considerations—and particularly relations with the ascendant Macedonians—may singly or together be behind this inscription, but we really can only guess, and the actual date is simply not known. Thus, despite the frequent mention of this inscription as supporting a period of famine (already extrapolating from a *sitodeia*) ca. 330 BCE (e.g., [140] (p. 99)), the cause of this *sitodeia*, and whether there was in fact a drought (or other environmental issue), and the exact date, are unknown.

While we at present lack high-resolution climatic data for the Aegean for this time period, more recent evidence from the last millennium raises two further and somewhat contradictory issues. Analyzing annually resolved tree-ring evidence for drought in the Mediterranean over the last 900 years, [135] (p. 2065) observe that their "Figures 5 and 6 . . . show evidence for antiphasing behavior in the eastern end of the basin, where there is a tendency for Libya, Egypt, and the southern Levant to be wet or near normal when Greece and Anatolia are in drought". They relate this circumstance possibly to the North Atlantic Oscillation (NAO) [135] (pp. 2063, 2066, Figures 3 and 7). This observation could be used to argue that, as stated in the inscription, Cyrene was able to supply grain at a time Greece experienced drought because the area around Cyrene did not. But, there is also an obvious complication! Egypt (at least northern Egypt) and Cyrene (north Libya) appear usually to experience typically similar conditions probably as linked with the NAO [135] (pp. 2063–2066, Figures 3–7). Hence, when part of the Cyrene discussion links to stated problems with grain supply in Egypt 330/329 and 328/327 BCE, this seems less plausible since typically Egypt should have shared the Cyrene climatic circumstance (both positive or both negative regarding likely precipitation and grain harvest). As in all aspects of a review of this notable but difficult inscription, therefore, the totality of the available evidence is less than clear-cut regarding the cause or causes of the *sitodeia* mentioned and the exact date of these circumstances.

4.2. Aristotle and a Mycenaean Drought?

Discussing the period around 1200 BCE and the topic of societal collapse, Kaniewski et al. [141] (pp. 370–371) write:

> "There are no written sources with direct information on climate for this period except Aristotle's statement about the Mycenaean drought around 1200 BCE". (my underling emphasis).

The name Aristotle of course draws immediate attention. The above quoted sentence ends with a footnote in [141] (footnote 25). This refers the reader not to Aristotle directly but to an article of 30 years earlier by Neumann [142]. Moving to this article, [142] (p. 441) begins by noting that:

> "Aristotle's pronouncement has a measure of relevance to the 'Mycenaean drought (1200 B.C.)' problem which led to an interdisciplinary controversy among some

> classical archaeologists and historians as well as meteorologists. In fact, it was this problem that aroused part of the stimulus to undertake the literature search".

Neumann [142] (p. 445) addresses the text of Aristotle (*Meteorologica* 1.14) using the Loeb translation of Lee [55] (dated 1952—[142] gives the date as 1962). He introduces the argument of Aristotle that slow changes—well beyond any one human lifetime—in landscape (relating to wetness/dryness) occur such that (352a7–16):

> "... places that formerly enjoyed a good climate deteriorate and grow too dry. This has happened in Greece to the land about Argos and Mycenae. In the time of the Trojan War Argos was marshy and able to support few inhabitants only, while Mycenae was good land and therefore the more famous. Now the opposite is the case for the reason given above: for Mycenae has become unproductive and completely dry, while the Argive land that was once marshy and unproductive is now under cultivation".

Aristotle is talking in 1.14 about land–sea changes and the role of rivers. Hence, Aristotle states "The same parts of the earth are not always moist or dry, but change their character according to the appearance or failure of rivers" (351a19-20). As [56] (p. 172) summarizes: "According to Aristotle, districts of the earth undergo periodic senescence and rejuvenation according to the amount of wet exhalation present in the ground. A district in its youth is moist and rich in vapors". Aristotle in particular sees a progression that starts from new land that is too wet. Egypt is his example of this, writing: "But this [too wet] land changes in its turn and in time becomes thriving. For as places dry they improve, and places that formerly enjoyed a good climate deteriorate and grow too dry" (352a6-8). Aristotle observes that these processes and the changes take place slowly over long time periods, much longer than human lives, and given that people die in wars, because of pestilence or plague, etc., there is thus no record of these changes preserved by humans, and people thus forget (351b8-22).

Aristotle employs rivers as the linking element in a complex argument, and one against his opponents (the Ionian "entropists" as [56] characterizes them), in which he contrasts but seems causally to associate changes in wet/dry areas:

> "The various species of the genus of moisture need not in their own right have a causal connection among themselves. Rather, the compelling reason for positing a causal connection between vapor, rivers, and the sea is the polemic against the entropists. The apparently paradoxical, but clearly intended, result of Aristotle's scheme is that one district by becoming wet can make a neighboring district dry. In two distinct dynamics the presence of one opposite in one place causes the other opposite to appear elsewhere" [56] (p. 173).

It is in this context of slow and effectively unobserved (by humans) long-term change that Aristotle comes to the Greek case when he tells us the information quoted above from his *Meteorologica* 352a7-16 comparing Argos and Mycenae contrasting the past with the present stating that in his own time "Now the opposite is the case for the reason given above: for Mycenae has become unproductive and completely dry, while the Argive land that was once marshy and unproductive is now under cultivation".. (my underling emphasis)

On the question of the specific reason, see the text emphasized (underlined) above, Aristotle is not in fact explicit. The implication appears to be that the relevant local river, the Inachus, is the cause of the change (also [56] (p. 174)). On the question of the timing the text is clear. Aristotle is saying that, between the time of the Trojan War and his own time (so classical period and in particular the 4th century BCE), formerly moist Mycenae has become dry and the formerly swampy Argos has become arable (352a9-14). Yes, the

majority of classical sources place the Trojan War somewhere around 1200 BCE, give or take a margin of a century or two. For example, the first historical source available to us, Herodotos (2.145), although demonstrably poorly informed on historical events and dates before about 700 BCE [143], nonetheless indicates a date for the Trojan War somewhat more than 800 years before his own time (mid-later 5th century BCE), but less than 900 years earlier (placed earlier and linked with Heracles instead), and so perhaps a date somewhere ca. 1300 BCE to mid-13th century BCE. Subsequent more detailed chronographic efforts, such as Eratosthenes especially and his date of 1184/1183 BCE, and others (see [143] (pp. 142–143), [144] (esp. pp. 246, 249–250)) led to dates mainly between the 14th and the 12th centuries BCE. Thus, Aristotle (384–322 BCE: [145]) does indeed tell us that, between ca. 1200 $\pm$ 100 BCE (give or take) and the mid-later 4th century BCE, a period of ca. 750–950 or so years, formerly moist Mycenae became dry and the formerly swampy Argos became arable. But this was, according to the theory he expounds in *Meteorologica* 1.14, a gradual change imperceptible to people at the time. Therefore, there is absolutely no evidence or statement by Aristotle about a "Mycenaean drought around 1200 BCE" as claimed by Kaniewski et al. [141] from Neumann [142].

Neumann [142] (p. 445) comments that "Aristotle's . . . important statement appears to have passed unnoticed by those who participated in the controversy over the 'Mycenaean drought' problem". An obvious response and explanation is that Aristotle says nothing about any Mycenaean drought at all. And when Neumann [142] (p. 446) then goes on to write "that Aristotle's statement concerning Mycenae 'confirms' our picture that the period from about 1200 was relatively warm and dry in Greece. . ." we entirely leave Aristotle's actual text behind. Aristotle specifically states that, around the time of the Trojan War, Mycenae was good land—he does not say warm and dry. It only became (too) dry *later* sometime across the 750–950 or so years between the Trojan War and Aristotle's time (and the reverse for Argive territory).

4.3. Okmok Volcanic Eruption in 43 BCE and the "Fall" of the Roman Republic

McConnell et al. [146] argue that the climatic effects of the massive Okmok volcanic eruption in Alaska in 43 BCE, during what was already a cooler period, created substantial effects (very cold years in 43 and 42 BCE) that played a part—the authors note accounts of unusual climate, crop failures, famine, disease, and unrest—in what they describe as the "fall" of the Roman Republic, and, not satisfied with just this, they include also the end of Ptolemaic Egypt (last ruler Cleopatra VII). The abstract of the article ends stating:

> "While it is difficult to establish direct causal linkages to thinly documented historical events, the wet and very cold conditions from this massive eruption on the opposite side of Earth probably resulted in crop failures, famine, and disease, exacerbating social unrest and contributing to political realignments throughout the Mediterranean region at this critical juncture of Western civilization. [146] (p. 15443)"

This study is the product of 20 authors in total, including several major figures in ice-core and climate science as well as some well-known ancient historians. The idea of a volcanic association is not entirely new. Mention in ancient sources of an eruption of Etna in Sicily at this time had already prompted suggestions that some of the unusual occurrences noted and linked with the assassination of Julius Caesar had a possible volcanic association [147]. However, this new work identifies Okmok as a dramatically larger, and thus much more climatically effective, volcanic eruption and main would-be culprit, and the new ice-core data are high-resolution, with the events identified dated accurately to the year. In order to further interpret scale and effects, the Okmok eruption ice-core signal is linked also with absolutely dated tree-ring evidence as well as speleothem data, and climate impacts are estimated via computer modelling employing the Community Earth

System Model ([148], and subsequent versions, see: https://www.cesm.ucar.edu, accessed on 30 March 2025). This is a state-of-the-art fully coupled global climate model. The data and modelling show that the Okmok eruption likely caused substantial cooling with the authors stating: "The CESM simulations suggest that the Okmok II eruption in early 43 BCE resulted in 0.7 to 7.4 °C seasonal cooling in specific regions of southern Europe and northern Africa, with cooling especially pronounced during summer and autumn" [146] (p. 15447). The authors on the same page note a variety of ancient sources that mention cold or stormy weather, issues with agriculture, and instances of famine, and so on. The challenge is whether a connection can be drawn with wider Roman history and all the issues noted by the various historical sources.

To begin, the scale of the effects postulated and their spatial reference both need care—if we examine the reconstruction in [146] (Figure 4A,B). The reconstructed temperature anomalies affecting most of Italy (including around Rome) and several of the main grain supply areas are in the more modest −2.0 to −2.5 °C range and only some in the −3.0 to −2.5 °C range and few in the more dramatic change ranges. The authors caution on the challenges of accurate precipitation reconstructions, but, nonetheless, the more strongly affected areas are the very west Mediterranean and parts of the Aegean, Anatolia, and the northeast Mediterranean, whereas much of Libya and Egypt and almost all of Italy and Sicily are in the smaller two categories of positive precipitation increase (0–3 mm and 3–6 mm per month).

Given the paper's title and dramatic claims, and the not surprising substantial media coverage, it attracted criticism from some quarters. Strunz and Braeckel [149] (p. 32207) complain that McConnell et al. [146] does not provide the "detailed analysis of integrated socioenvironmental mechanisms [that] would be indispensable to overcome 'black-box determinism.'" They conclude that "a superficial correlation between climatic and social events cannot substantiate the purported effects", noting Butzer's [3] (p. 3633) critique of the "continuing failure to appreciate the complexity of [human–nature] interrelationships". McConnell et al. [150] (p. 32209) respond to the criticism and point to the large climate episode they document and model arguing that:

> "It is only logical to conclude that such an extreme climate event—including the second- and eighth-coldest years of the past 2500 y at the start of the fourth-coldest decade—had a significant effect on food production and society during this already tumultuous, critical juncture of antiquity".

However, it is also true that this is a classic case where one needs to carefully investigate whether correlation is actually causation. Indeed, if we consider some of the historical events that [146] (Figure 2A) and [150] (Figure 1) identify and propose to associate with the Okmok eruption, then there are complications. Let us examine:

1. McConnell et al. [146] (Figure 2A) and the improved McConnell et al. [150] (Figure 1)—see https://www.pnas.org/doi/full/10.1073/pnas.2019906117, accessed on 30 March 2025—note "food scarcity in Rome" as starting specifically from 43 BCE—more than implying that it was caused by the eruption at the same time. However, if we examine the ancient source material, there are indications of shortages of food in Rome 49–43 BCE (e.g., [100] (pp. 201–202)), i.e., before the Okmok eruption in 43 BCE, and these are stated as caused by military and political threats. And these military and political threats and food shortages continue through to 36 BCE. Garnsey summarizes from statements in several contemporary ancient sources ([100] (p. 202 n. 15) taking evidence and quoted text from, respectively, Cicero, *Epistulae ad Atticum*, 7.9.2 and 4; 9.9.4; *Epistulae ad familiars* 14.7.3; Appian, *Bella civilia* 2.48; Cassius Dio 41.16.1):

> "The civil war that broke out in 49 between Caesar and Pompey put the inhabitants of Rome at risk. Blockade of the city was more or less inevitable, as Cicero had hinted in a letter of December 50. In March 49 Cicero reported to Atticus Pompey's 'first plan': it was 'to throttle Rome and Italy and starve them, then to lay waste and burn the country, and not to keep hands off the riches of the wealthy'. A few days later Cicero was gloomily predicting a terrible war, 'ushered in by famine'. He was aware that a large fleet was being prepared 'to cut off the supplies of Italy and blockade the grain-producing provinces'. In June he advised Terentia and Julia to head for the family estate at Arpinum if grain became more expensive. When Caesar arrived back in the city from Spain, he found the people 'starving'. He had grain brought in from the islands and distributed".

Thus, Okmok perhaps exacerbated a situation ongoing for some years, but did not start it nor necessarily form the prime cause.

2. In the more elaborated work by McConnell et al. [150] (Figure 1—https://www.pnas.org/doi/full/10.1073/pnas.2019906117, accessed on 30 March 2025), perhaps aware of some such complications, McConnell et al. add underneath the "Food scarcity in Rome" red bar a second red bar from 40 to 36 BCE labelled "Sextus Pompeius blockaded Italian Peninsula, limiting grain imports". This is placed a few (three) years after the Okmok-43 BCE start shown by them for the "Food scarcity in Rome". However, in fact, Sextus Pompeius controlled the relevant seaways and started a blockade of Rome in 43 BCE!—i.e., this, rather than Okmok, may specifically explain or cause the "Food scarcity in Rome"—even if the Okmok climate impact worsened the effects. To quote Garnsey [100] (p. 202): "From late in 43 to 36 Sextus Pompeius was entrenched in Sicily (and his lieutenants in Sardinia and Africa), and able to exploit his naval superiority to cut off shipments of grain to Rome. By 42 many were dying in the city". Thus, Sextus Pompeius caused "Food scarcity in Rome" and not just from 40 BCE but from 43 BCE. Key to this continuing from 43 BCE onwards and to beyond 38 BCE was first a victory by Sextus Pompeius over the Octavianic fleet off the promontory of Scyllaeum in 42 BCE (Cassius Dio 48.18-19; Appian *Bella civilia* 4.85) and second a storm and effective victory in the same area in 38 BCE (Cassius Dio 48.47-48; Appian, *Bella civilia* 5.88). Neither of these circumstances and events can be regarded as caused by Okmok, nor the intervening short-lived pact of Misenum. More generally, this overlooking of the critical challenge posed by Sextus Pompeius conforms to the pattern in ancient history of rather down-grading what was a major and almost central/critical role of Sextus Pompeius. This is all very much an historical outcome of the eventual success of Octavian/Augustus in largely writing Sextus Pompeius out of history (after the eventual victory in 36 BCE by Octavian and Anthony), and hence the usual scholarly treatment of Sextus Pompeius as a sideline and relatively minor figure. In fact: Sextus Pompeius was likely a key part of the existential threat to the Triumvirs as they sought to establish control of the Roman World over a number of years (e.g., [151]), and much more of a threat to Rome and its food supply and much else than the Okmok volcanic eruption. If indeed there was a "fall" of the Roman Republic, it was a relatively long and highly complex set of processes and protagonists, with a prolonged denouement 49–31 BCE, but beginning in earnest well before, at least in the contest between Marius and Sulla in the 80s BCE. It is difficult to detect any actual, let alone significant, role for the Okmok volcanic eruption in these human affairs spread across an empire (e.g., [152]).
3. Overall, the work of McConnell et al. [146,150] provides an impressive assembly of high-resolution data. But, even so, some of the fundamental historically associating, and historical-narrative forcing, information that they list and invoke as explained

by and so linking with the Okmok volcanic eruption involve significant question marks over the relevant exact temporal placements and causative associations. It is also good to remember Garnsey's [100] (p. 205) conclusion from a review of later Republican Roman history: "Flood, pestilence and harvest failure play minor roles in the 'famine narratives' of late Republican Rome". Although he was thinking about Etna 44–42 BCE and possible short-term effects (and not yet Okmok), Sallares [153] (p. 20) nonetheless captures the bigger picture historical canvas when he concluded: "However volcanoes did not have major long-term effects on the climate or the economy in classical antiquity".

5. Conclusions

The relationships between changing climate and human history are complex and numerous depending on timescales, contexts, and the many interconnections between human and ecological factors. The object of the investigation also requires care: what often is characterized as "collapse"—and which then needs a cause (and is this climate?)—can instead better be interpreted as resilience via transformation. The Late Bronze Age to Iron Age transition is a case in point. Although some specific cases of rapid historical change may relate to dramatic immediate multi-year climate shocks in potentially vulnerable regions (e.g., [122]), other areas of the East Mediterranean experienced differing climate contexts and were situated in differing geographic/ecological, economic, social, and political contexts, and this overall regional transition occurred across a considerable time-span [117]. Hence, Broodbank [154] (pp. 460–461) argues that "climate played no significant part. . .This transformation began and ended with human actions". As in this case, rarely is there a binary situation, rather shades of nuance and difference at many scales.

Two general categories for analysis emerge. There are (i) general longer-term climate variations and plausible associations of these with human history entwined with other social, economic, political, and ideational issues, but also (ii) some circumstances wherein immediate shock episodes of back-to-back or multi-year years of climate extremes can trigger crisis and thus force potential disaster or change. In both cases, the specifics of a climate association beyond general background factor need close argument. However, this is especially pressing for the second category. If we wish to try to establish a particular causal association between a climate episode and potentially historically forcing event, like famine—and so move climate forward from one of several elements of the context for human decision-making to the primary concern—then it is critical to establish a tight temporal, spatial, and causal connection, not just allege a general approximate coincidence. As reviewed in some cases above, all too often the lack of careful focus on details is a weakness in work trying to propose climate as explaining history.

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A Cross-Comparative Framework to Explore Land Use Histories of the Northeastern Peloponnese, Greece

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Abstract

Calls for an "archaeology of climate change" highlight the interest in integrating human land use histories with the paleoenvironmental record. Shifts in land use patterns, observed via regional archaeological surveys, have been used in studies exploring the relationships between human and environmental systems, often via the Adaptive Cycle (AC). Recent work has combined datasets from separate surveys to examine macroregional patterns, which can then be integrated with environmental proxy data. However, efforts at aggregating archaeological data are often problematized due to projects' differing collection methods and periodizations. This study ascribes the formal constructs of the AC to survey data to minimize data aggregation issues and maintain local integrity. Aoristic sum functions were performed individually on data from four projects in the northeastern Peloponnese to identify local patterns. These data were then aggregated, allowing for changes in land use to be observed at the macro and regional levels. Further measurements relating to land use abandonment, continuity, expansion, and potential serve as proxy data to identify the AC constructs of organization, exploitation, conservation, and release. The approach allows for cross-comparative regional analysis and the creation of an aggregated dataset that describes macroregional trends, essential to integrating human and paleoenvironmental narratives over time.

Keywords: Adaptive Cycle; archaeology; paleoclimate; aoristic sum

1. Introduction

The ways human and environmental systems change over time, how and why changes occur, and the lessons they may impart to our condition have received significant interest. This has led to a call for an "archaeology of climate change", which seeks not only to understand past relationships between climate and human systems, but to elucidate potential solutions to our current condition [1]. In the last 20 years, and the previous 10 years in particular, theoretical constructs and methodological approaches have turned towards thinking of the interplay between social and environmental changes, eroding what

had become a dualist approach to studying ecological and human evolution [2]. Many of these studies (e.g., Refs. [1–9]) point to the need for developing integrated approaches to analyzing human and environmental datasets.

This work is often at broad geographical and/or temporal scales, with an interest in assessing landscape use within a quantitative framework [3,8,10], in some part owing to the desire to integrate human and environmental data using theoretical models drawn from ecology [3–5]. Often, central to these studies are three processes: the amalgamation of archaeological data from various projects; the synthesis and interpolation of paleoenvironmental data; and the placement of these data within theoretical constructs that can associate both human and environmental processes, allowing the exploration of causal relationships without the overt imposition of deterministic paradigms. Thus, two things need to happen to investigate the long-term relationship between humans and the environment substantively.

1. A means of aggregation that obviates or mitigates the methodological barriers between survey projects needs to be developed.
2. Once configured, the data must be implemented within an interpretative framework that can couple human and environmental information.

This paper presents a method by which legacy archaeological survey data from multiple projects can be assessed within a common framework, enabling cross-comparisons of human activity across the longue durée. Placed within a framework that has been applied to both human and environmental systems, this approach can provide a means of integration with paleoenvironmental records to discuss possible responses to climatic fluctuations.

1.1. Prior Approaches

In the Aegean, aggregating survey data has been considered important yet problematic. In this region, archaeological surveys are limited to comparatively small areas (often between 10 and 40 km^2) and occur in relatively short time frames (3–5 years). This observation scale is small compared to other places, such as Mesoamerica (e.g., the Oaxaca survey, which took place over nine years and covered 2150 km^2) [11]. If a goal of landscape studies is to develop a broad understanding of how societies engage with their environment and explore the reasons for regional differences and broad similarities [12], it is necessary to develop interpretative frameworks that reach across multiple projects [13,14]. This matter was brought to the fore via the publications of the POPULUS project [15,16] and the subsequent publication of an edited volume exploring the efficacy of intra-project syntheses [17]. Reviews on the efficacy of combining survey data have identified difficulties such as the lack of consistent methods related to data collection, chronological periodization, and descriptions/definitions of discrete areas of activity [7,14,18–22]. Beyond methodological considerations, the permanence of past activity can be difficult to measure; a concentration of Late Roman sherds, for example, does not imply constant ongoing activity over the entirety of the 200 (or 400) year extent of time [7,23–26]. An additional consideration lies in geographic and temporal interest. While a significant amount of energy has been expended studying a given region or period (e.g., the Late Bronze Age Argolid), the lack of similar focus in other areas and periods leaves disparities in resolution across time and space, complicating data comparison [21]. These considerations have confounded attempts at integrating data, leading some to view the process as highly problematic or untenable [21,27,28]. Recent reviews of landscape archaeology in the Mediterranean point towards data interoperability as an area requiring development [6,29,30].

The issues with data interoperability have not prevented the generation of significant works synthesizing survey and other data to explore such topics as Roman Greece [31], the Late Bronze Age to Early Iron Age economy [32], or cultural evolution in central

Greece [13], but researchers are careful to discuss the limitations of the data caused by differing collection methods and research foci that generated the data. More recently, Attema et al. have proposed a set of 'good practices' to encourage consistency [33] and developed a means by which three major surveys in Latium could be brought into a condition of interoperability [14]. De Haas and van Leusen produced data publishing protocols according to FAIR (Findable, Accessible, Interoperable, and Reusable) principles [22]. While these initiatives may assist in developing future datasets (but also noting concerns about a defined set of 'best practices' [18,34]), outside of the expense of great energy exemplified by the Roman Hinterland Project, legacy datasets remain problematic yet significant sources of information.

Considering work integrating patterns of human activity from multiple survey datasets with environmental information [3,5,6], Izdebski, Pickett, et al. [10] sought to review settlement and environmental changes in southern Anatolia and the Levant between the third and ninth centuries using archaeological surveys and paleoenvironmental evidence, as did Roberts et al. for sixth- to ninth-century Anatolia [8]. Similarly, contemporaneous work in the Aegean on pre-classical and classical periods sought to integrate archaeological and paleoenvironmental data [35–39]. Within these works was a desire to engage human and environmental data to develop a broad understanding of how human and ecological systems engage to impact the configuration of the other and how such changes affect the socio-environmental system (SES) at multiple scales of time and space, from the local (e.g., Ref. [40]) to global [41].

In compiling land use data across multiple projects, these efforts used aoristic sum analysis (e.g., Refs. [42–44]), which divides an observation (e.g., the presence of a feature) by the extent of time during which that observation could have occurred. This transformation distributes the probability of an archaeological site uniformly over a given archaeological phase [35], yielding patterns that account for the varying lengths of archaeological periods (compare bar graphs a and b in Figure 1).

Using this approach, Weiberg, Bevan, et al. investigated the differences between northern and southern Greece between the Neolithic and Roman periods and the possible correlations to climate fluctuations [35]. Within this study, survey data were combined by period to derive aoristic sum values, which were used to track the increase/decrease in the number of features (i.e., sites) over time. The study employed a uniform periodization. When considering variability at such a scale, temporal and spatial resolutions can withstand coarseness. This is possible given the desire to incorporate human with environmental data, the collection of which is idiosyncratic and correlated more to areas where such data can be retrieved rather than where archaeologists choose to conduct investigations. However, the comparison of northern and southern Greece potentially masked subregional variations. This was justifiable given the spatiotemporal resolution under study, and the authors were cautious to note that "variations within these subregions are likely to be non-trivial" [35] (p. 29). Indeed, while a coarse resolution provides an appearance of uniformity, closer scrutiny might reveal localized differences based on local environmental and social conditions. In periods of human history where locally specific conditions were important to the evolution of social systems, an approach at the scale of the local region is required.

A similar situation is found in the exploration of sixth- to ninth-century Anatolia, where survey data from central, southern, and northern Anatolia were combined with paleoenvironmental data to discuss patterns of resilience [8]. While the study identified coincidences and potential correlations in human and environmental shifts, these results were complemented by interrogation of the survey data [7], identifying inconsistencies brought on by vagaries in data collection, periodizations, and other methodological dif-

ferences. Further interrogation of the aggregated data from northern Anatolia suggested that within that regional pattern, localized human land use patterns differed despite uniformity when the data were combined [25]. The work indicates a need for an approach capable of observing broad patterns of land use while simultaneously preserving regional idiosyncrasies that suggest localized adaptations that inform our broader perspectives of cultural evolution.

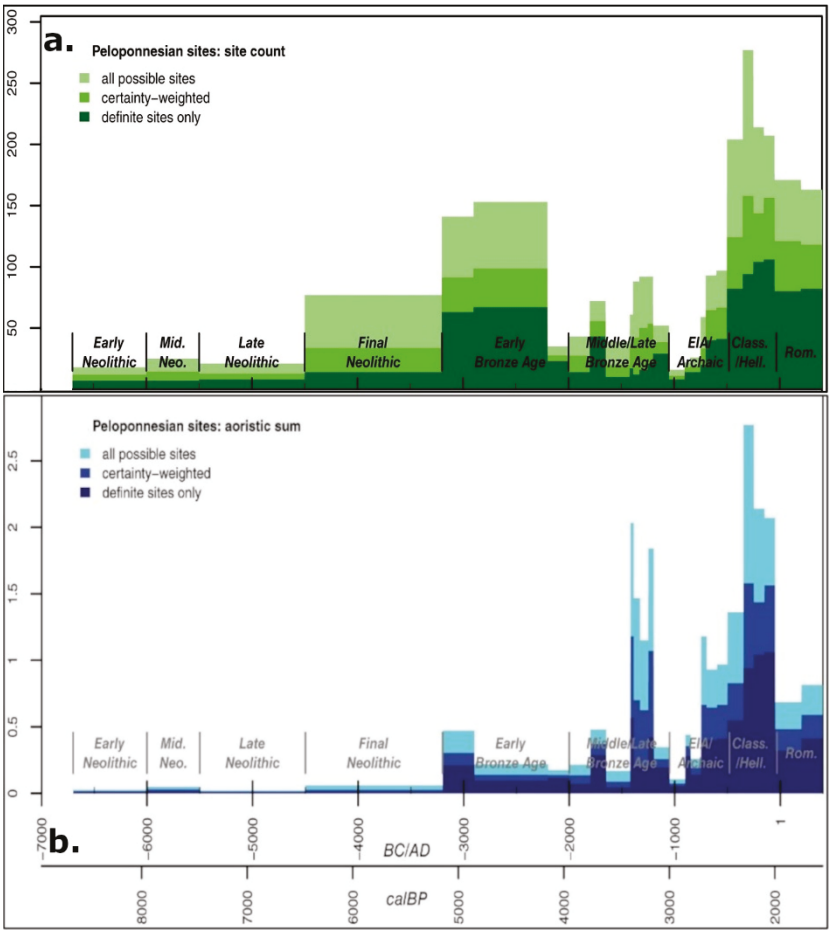


Figure 1. Aoristic sum of sites, adapted from Weiberg et al. [35], Figure 5. The *x*-axis represents years, the *y*-axis in (**a**) indicates counts, and the *y*-axis in (**b**) indicates aoristic sum values.

Despite these attempts to integrate data from multiple regions, the approaches do not fully assist in modeling regional or macroregional changes in human society. The analysis of landscape use is more than measuring the quantity of land use over time. Equally, if not more important, is how perceptions of the use of the landscape change over time. Reviewing the extent to which land use of a space **continues** from one period to another suggests persistance of activity. The extent to which spaces are **abandoned** from one period to the next also implies differing interactions with the land. Adding new spaces of activity implies the **expansion** of land use or activities that may stand as proxies for increased population or changes to subsistence strategies.

We propose a framework for collating, interpreting, and discussing regional and methodologically variable survey data. This process renders the data comparable across time and space, yielding more holistic interpretations while identifying opportunities for future study. Instead of aggregating land use data from projects, the approach develops an analytical framework that is first applied to the individual projects before aggregation. Instead of a broad regional narrative, the approach thus develops local narratives that are both cross-comparative and capable of broader syntheses [6].

1.2. Theoretical Considerations

Those studying complexity, change, and adaptability have been drawn to the constructs of resilience—how a system meets the demands of changing conditions and how those systems adapt and reconfigure [45,46]. A key framework within this construct is the Adaptive Cycle (AC) [47], which holds several assumptions:

- A system consists of human and environmental components; the two are interdependent, often termed a 'social-environmental system' (SES).
- An SES moves through the organization (α), expansion (r), conservation (K), and release (Ω) phases.
- Each phase consists of a combination of forces, termed 'potential' and 'connectedness'. 'Potential' refers to the range of opportunities available to an SES to engage. For example, an SES in an organization phase would have several future permutations; a system in expansion, in contrast, having established set systems, has fewer options to respond to changing conditions. 'Connectedness' describes the level of engagement and interdependence between an SES and other entities.

Each of the four phases is characterized by the extent to which these elements are found (Figure 2). Thus,

- α: high potential, low connectedness. An SES is in the process of developing new structures and innovations. The SES is localized and experimental.
- r: low potential, low connectedness. The SES experiences growth—technological, demographic, or both—social structures become more complex and integrated.
- K: high potential, high connectedness. The SES is in stasis, with established social structures that reify the status quo. Practices solidify and become resistant to changing circumstances, either internal or external.
- Ω: low potential, high connectedness. Internal or external pressures become so prevalent that the SES cannot successfully respond, causing a need to reorganize/reconstruct effective structures.

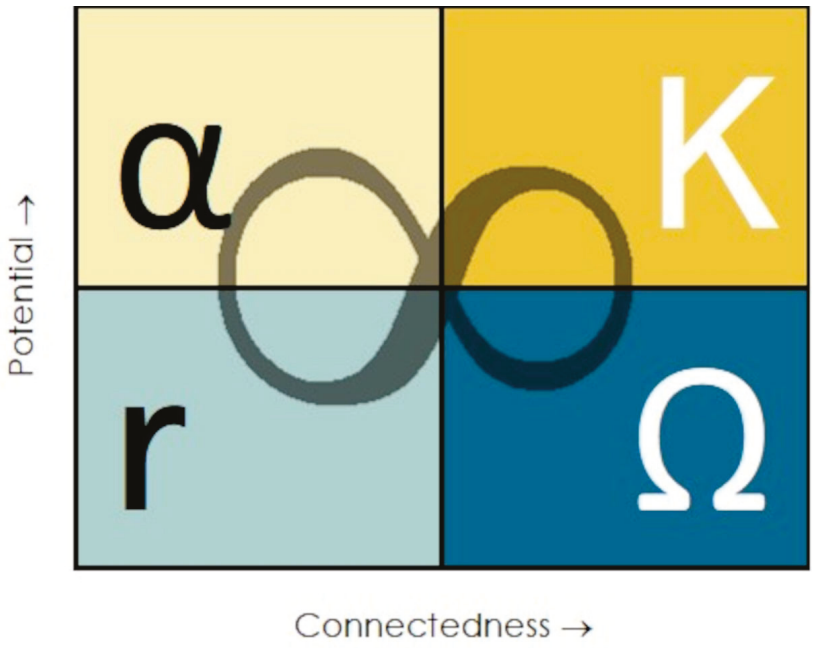


Figure 2. The Adaptive Cycle. Derived from Holling and Gunderson [33], Figures 1–7.

These four phases can be discussed as a serial development (α → r → K → Ω), operating in a continuous loop [48]. The early proponents emphasized that an SES would

not necessarily progress through the phases in the order given; indeed, the strength of the framework was that it offered a way to observe and then interrogate how and why SESs fluctuated between the various phases [49,50]. It is this fluctuation that provides the ability to examine a system's overall trajectory of adaptation and development [47].

2. Materials and Methods

This study's approach consists of developing aoristic sum functions (ASFs) for each selected regional project. These local ASFs (LASFs) provide a probabilistic measure of human occupation in the landscape according to localized periodizations. Tied to a timescale, these LASFs were aggregated to form a regional ASF (RASF). The process thus provides a measure of broad trends over time while maintaining regional idiosyncrasies. LASF development involved investigating each project's dataset in terms of the resolution at which each project reported its data within the context of each project's periodization.

Four projects in the northeastern Peloponnese were selected for analysis (Figure 3): the Southern Argolid Survey (AEP) [51], the Berbati-Limnes Survey [52], the Methana Survey [53], and the Eastern Korinthia Archaeological Survey (EKAS) [54,55]. The projects were selected based on their geographical proximity, publication status, and breadth of time during which the surveys were conducted. Projects near each other were sought, given that one of the ideas to be tested was the extent of regional variability. Projects in relative proximity would have the best opportunity for similarity. When combined, the projects cover the northeastern part of the Peloponnese. While significant gaps in territory remain (notably, the Epidauria to the north of the AEP and the areas surrounding the Argive Plain), the selected projects provide a geographical range of the area in question. The four projects have been published to such a degree that data related to long-term land use for all periods were available. Other projects, notably the Nemea Valley Archaeological Project [56], the Western Argolid Regional Project [24], and the Saronic Harbors Archaeological Project [57], still await complete data publication at the time of writing, although several publications exist that provide data for some projects for some periods (e.g., Refs. [58,59]). The four projects selected also offered a range of methods representing the new wave of projects in the 1980s and 1990s and their immediate descendants [6]. While integrating data with this range of approaches invites questions about data comparability, the span of methods found in these legacy datasets provides a helpful test case.

Since the interest is on observing shifts is primarily demographic, data were cleansed of features identified as solely mortuary, religious, or defensive. The intent was to remove features that, while providing evidence for activity, may skew the data to exaggerate a region's RASF for a given period. While this may raise concerns about periods where archaeological evidence is scarce except for cemetery data (such as the Early Iron Age), mortuary data (consisting of cemeteries, sarcophagi, and tombs) consisted of 2.1% (N = 13) of the overall sample. Of the total number of features (619), an additional 53 (consisting of such things as chapels/churches, aqueducts, fortification walls) were removed from tabulation (8.7%). Given that the projects vary widely in areal coverage, the data were divided by the area covered for each survey. Although this does not account for the total variance caused by differing levels of intensity in data recovery [60,61], it mitigates against skewing the data in favor of projects with large areal coverage.

To maintain local integrity, LASFs were applied to each project using each project's chronological phasing (Figure 4; see Supplementary Materials, periodizations.xlsx). Periodization is viewed as a regional consideration, derived from a process of large-scale understanding of material and historical shifts and specific regional knowledge. In most areas, prehistoric phases are based on relatively dated typological sequences, while later historical divisions are often made based on historical events. Professional opinions on

the beginnings and ends of several periods may have shifted between the earliest (AEP) and latest (EKAS) surveys in the study. Given the local knowledge embedded within those frameworks, the best approach was to hold to local periodizations to create regional narratives. On a grand scale, there is general consistency, although there are some significant points of departure. For example, the Early Helladic Period (Early Bronze Age) is undivided in the Methana periodization but subdivided in the others. The period between 1190 and 675 BCE is noted as a single phase (EKAS, Berbati-Limnes) or subdivided into as many as five (AEP). The "Hellenistic" period lasts either 100 years (Berbati-Limnes) or 292 (EKAS), starting close to the ascent of Alexander (EKAS, Methana) or 50 years later in the mid-3rd century BCE (AEP, Berbati-Limnes). The Roman period begins at different times over 119 years (150—31 BCE). Likewise, the assignment of the beginning, end, and divisions within the Late Antique and Medieval periods can vary based on local understandings and historical events. In the context of developing ASFs, conditions where there are more chronological divisions and highly diagnostic pottery will develop higher ASF values.

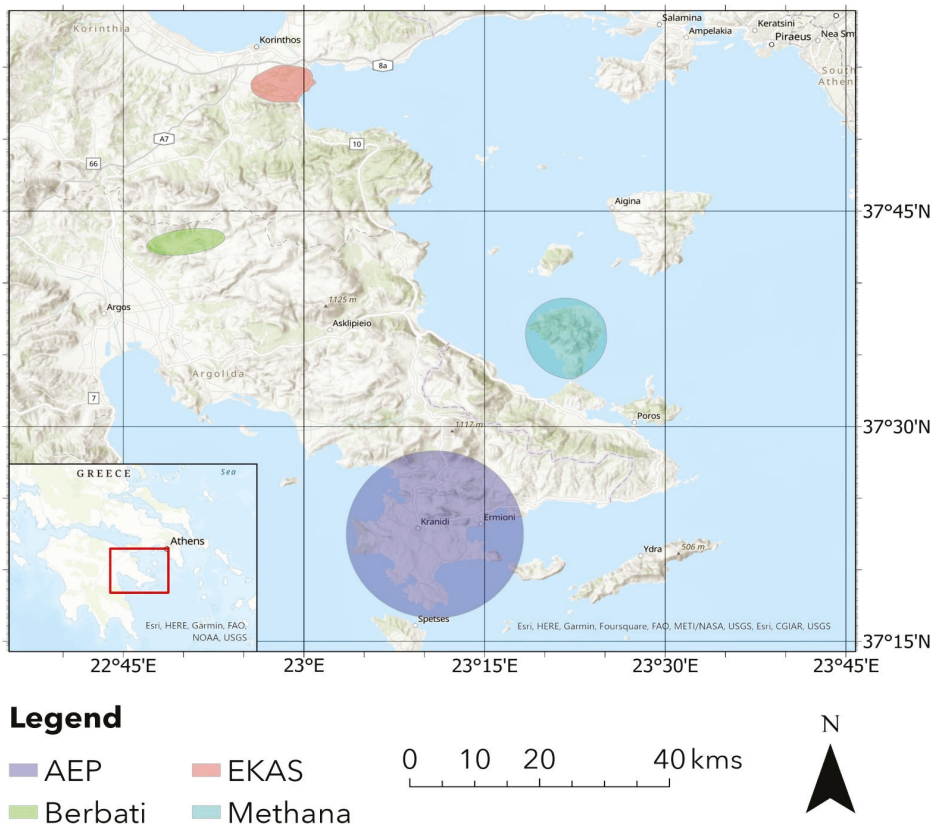


Figure 3. Approximate locations of archaeological projects used in the study.

The Eastern Korinthia Archaeological Survey (EKAS) is the most recently completed project in the study. Conducted between 1997 and 2003, the project data have been archived via OpenContext and are available for free download [54], in addition to a formal publication discussing the impressions and considerations of the data's integrity and interpretation [55]. The ready availability of data allowed for individual feature (Localized Cultural Anomaly (LOCA),[1] in EKAS terminology) review. LOCA and artifact tables were downloaded [62,63]; the former provided a functional and chronological assessment of the LOCA and listed each LOCA's discovery unit(s). The artifact table, consisting of artifact counts grouped by chronotype and discovery unit, was parsed for each feature, providing a summary count of artifacts for each period. Based on these data, three separate methods

for deriving aoristic sum functions could be constructed, which proved informative and helpful in understanding ASFs derived from the data of the other projects. These methods are discussed in Appendix A. The method that measured the presence/absence of activity for a period was deemed most suitable for the study. If evidence was observed at a feature for a given period, regardless of quantity, a value of 1 was recorded. This was then divided by the number of years in the period (Equation (A2)) to obtain a feature's aoristic value (AV) for the range of years in which the feature indicated activity. The AVs were then summed by year. The resulting ASF removed bias for artifact quantity while preserving a probabilistic measurement based on the length of a given period. While still accentuating periods of short chronological duration, the function presents probabilities of activity for a given year. Thus, it represents the presence and a probabilistic measure of activity.

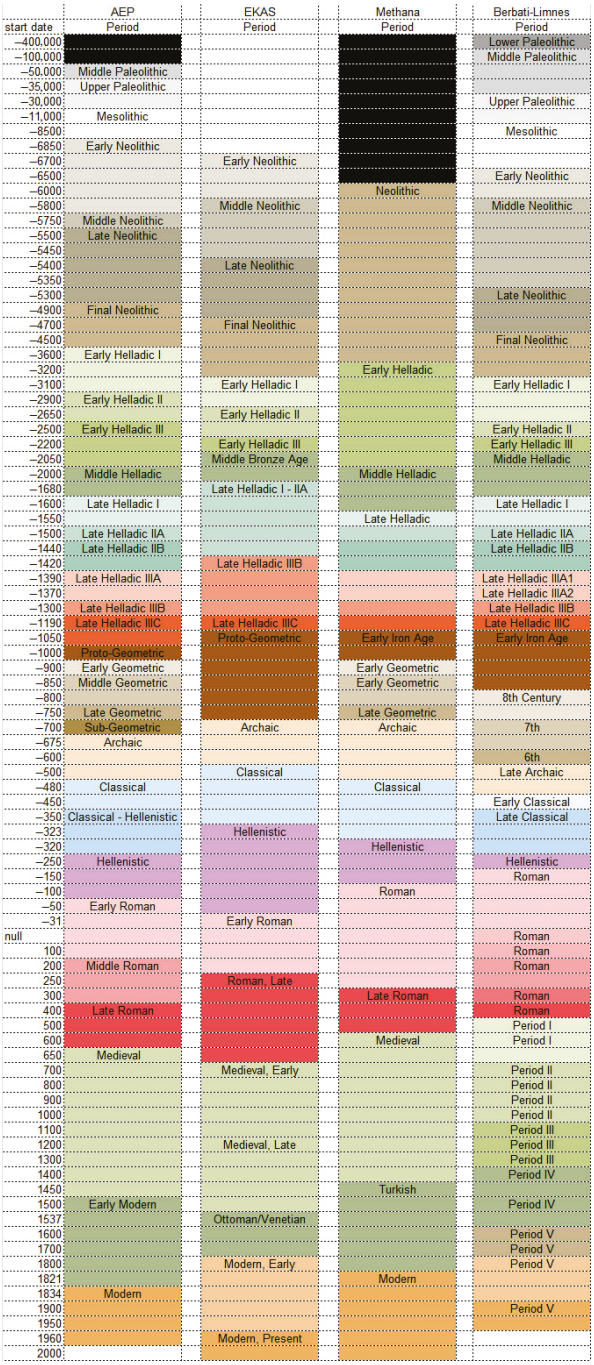


Figure 4. Side-by-side comparison of the periodizations for the four regional surveys.

The LASF for EKAS (Figure 5, see Supplementary Materials, EKAS.xlsx) indicates four decreases in activity, at the transitions between Early and Middle Bronze Age (2050 BCE), Late Bronze and Early Iron Age (1050 BCE), the Classical and Hellenistic (323 BCE), and the Roman and Late Roman (250 CE). The ASV increased in the Early Bronze Age and decreased at that period's end. Aoristic sum values rise throughout the Late Bronze Age, with a decline in the latter half of that phase leading into the Protogeometric (1050 BCE). Aoristic sum values then rise dramatically, brought on by both an increase in the number of identified features and the presence of diagnostic artifacts with high chronological resolution. There is a dramatic decrease in ASV at 323 BC, followed by an increase beginning in the early Roman Period (31 BCE). This increase in ASV continued throughout the Roman period until a dramatic decrease in 400 CE. Further reduction in ASV at 700 CE suggests a region in collapse, which slowly emerges in the Late Medieval (1200 CE).

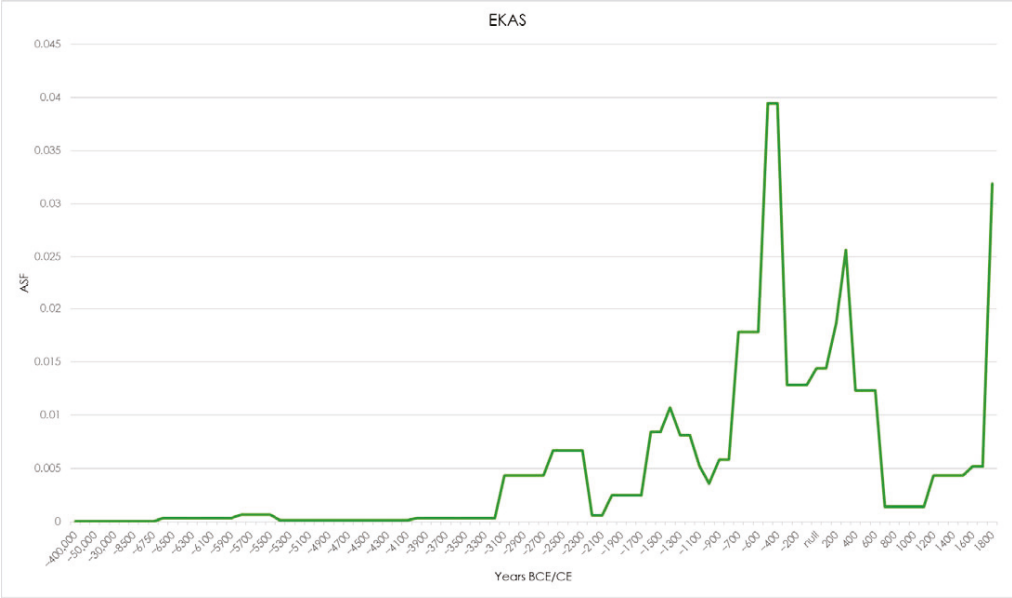


Figure 5. LASF for the Eastern Korinthia.

The Southern Argolid Survey (also known as the Argolid Exploration Project, or AEP) was conducted in 1972 and between 1979 and 1982. Started as a survey around Franchthi Cave, its later iteration included methods of spaced intensive fieldwalking (variable between 5 and 15 m), with subsequent revisits to delineate feature boundaries and recover data related to chronology and function. Data recovery varied between non-random grab samples, "dog leash" sampling (establishing two perpendicular lines within a feature and collecting samples at regular intervals in 1 m radius circles), and gridded collections. The range of methods employed makes internal comparability difficult beyond a regional understanding of the presence of human activity and approximating where such occurrences happened over time.

In compiling the LASF for the AEP, the site catalog was reviewed in Jameson et al. [51]. The published artifact catalog for prehistoric phases was consulted to verify the information provided in the site catalog. Site descriptions provided periods of activity. When a range of prehistoric periods was noted, the artifact catalog [64] was reviewed to determine if the designation implied activity that could not be ascribed to greater chronological resolution. The LASF (Figure 6; see Supplementary Materials, AEP.xlsx) presents an increase in AS values beginning in the Early Bronze Age, with a decrease at the end of that period. AS values rise throughout the Late Bronze Age, with a decline in the latter half of that phase leading to a near absence of AS values in the Protogeometric (1000 BCE). AS values then

rise dramatically, brought on by both an increase in the number of identified features and the presence of diagnostic artifacts with high chronological resolution. AS values first decreased significantly in the Hellenistic phase (250 BCE), then more gradually, followed by a significant rise at the onset of the Late Roman (400 CE). The Medieval phase (650—1500) shows moderate but sustained AS values before leveling off in the Early Modern (after 1500 CE).

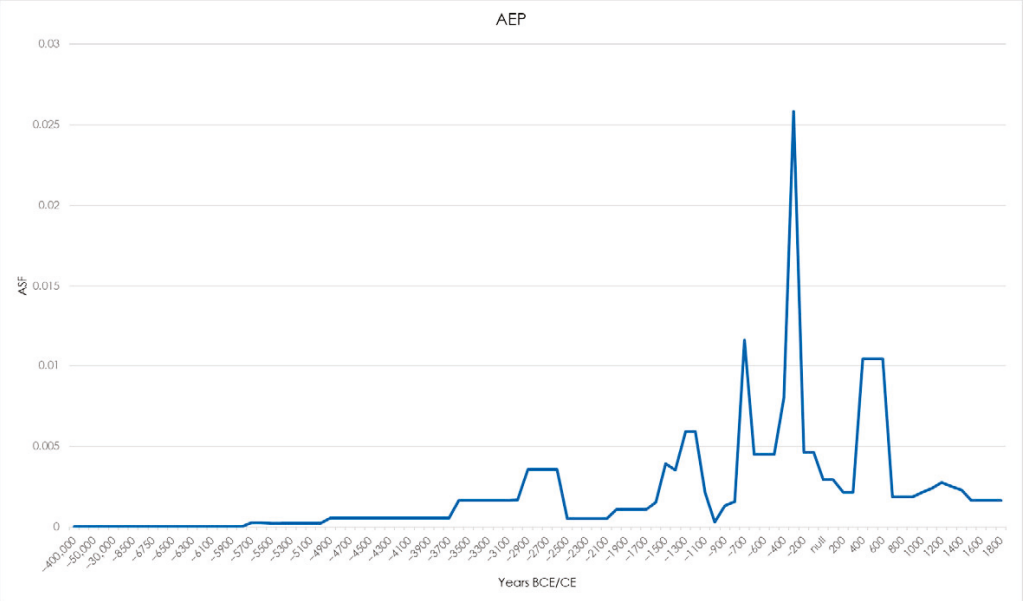


Figure 6. LASF for the Southern Argolid.

The Berbati-Limnes Survey [52], conducted between 1988 and 1990, surveyed 25 km^2 [65] in the territory within the spheres of the villages of Berbati and Limnes in the northern Argolid (Figure 3). Field reconnaissance consisted of dividing the survey area into observation units (tracts) followed by a pedestrian survey at 10 and 15 m intervals, depending on the landscape and vegetation cover. Feature (findspot) delineation was empirically derived in the field based on artifact concentration and other geographical considerations. Site data were presented via chapters organized by period and authored by specialists, resulting in some variety when discussing human activities and their chronological range. The Berbati region is known for an LBA pottery production site, resulting in a highly refined chronological framework for the Late Bronze Age [66]. This feature of the region's history has ramifications in terms of ASF, given that the ability to ascribe artifacts to narrowly defined periods inflates the aoristic values for those periods.

The LASF for Berbati-Limnes (Figure 7; see Supplementary Materials, Berbati_Limnes.xlsx) presents a region with several boom-and-bust phases, with no AS values recorded for several periods. Such examples include the Middle Helladic to LH IIB (2000—1440 BCE) and the LH IIIC middle to last quarter of the Early Iron Age (1150—850 BCE) phases. Another near loss of AS values is found at 100 BCE, at the beginning of the early Roman phase, which slowly began to increase at the start of the Common Era. Significant drops in AS values occurred in Period II of the Medieval (700 CE), followed by a sharp increase in Period III (1100 CE), with another slow decline in AS values beginning at 1300 CE before a sharp rise in the Modern phase.

The Methana Survey [53] was conducted between 1984 and 1986 and surveyed 21% (11 km^2) of the Methana peninsula [53,65]. As with the Berbati-Limnes survey, methods of fieldwalking were adapted from the AEP for the steep terrain of the peninsula. Feature (site) identification and delineation were empirically derived while in the field. Feature

sampling consisted of laying out perpendicular lines, typically in the cardinal directions, from the feature center and collecting artifacts from 1 m "dog leash" sample units until the artifact count fell below two per square meter. Further collection consisted of random grab samples for diagnostic sherds and lithics across the entirety of the feature. The space was set to a grid of 10 × 10 m units for large features, which were collected at 50 m intervals. All artifacts were collected within the 10 m unit.

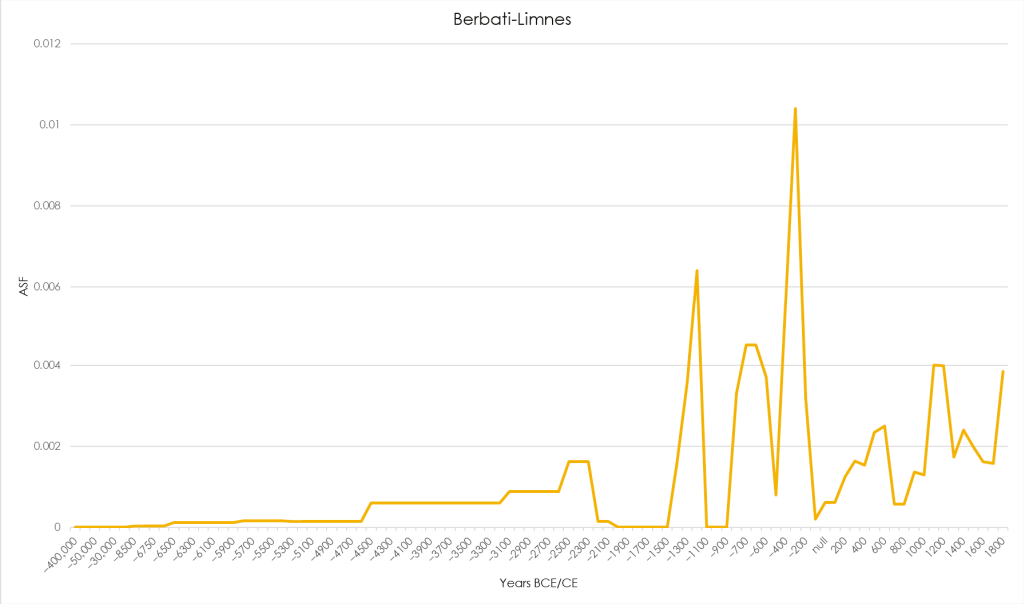


Figure 7. LASF for the Berbati-Limnes Survey.

The LASF for Methana (Figure 8; see Supplementary Materials, Methana.xlsx) shows a rise in AS values beginning with the Early Helladic, with a decrease at the end of that phase leading into the Middle Helladic. At this point, a steady increase in AS values occurs through the Late Bronze and early Iron Ages until a dramatic rise in the Classical and Hellenistic periods (480–150 BCE). Following an equally steep decline at the beginning of the Roman period, the peninsula saw a steady rise in AS values from 300 to 600 CE. AS values were largely stable between the Medieval and Ottoman phases (600—1821 CE) before an increase at the beginning of the 19th century.

Once these LASFs were calculated, the four survey datasets were aggregated (Figure 9). The trend closely resembled the pattern generated by Weiberg et al. ([38], see Figure 1). Comparing the RASF against the constituent LASFs suggests significant influence from projects in more densely occupied regions and periods where greater chronological resolution developed larger aoristic values.

The RASF and four LASFs provide a probabilistic measure of activity over time. However, these data are not without issues. The aoristic values are impacted by the underlying factors of survey intensity, feature delineation, collection strategy, and reported chronological resolution of the recovered artifacts. When considering the fundamental equation (N of observations/N of years), the first three conditions affect a feature's identification for a given period (the numerator). The fourth (chronological resolution) impacts the denominator. Given these considerations, the aoristic sum functions hold greater interpretative value at the local level, where intensity, periodization, feature delineation, and collection methods are more consistent. The process has value in a larger regional context as a point of comparison when discussing potential activity, although the underlying determinants can compromise such comparisons.

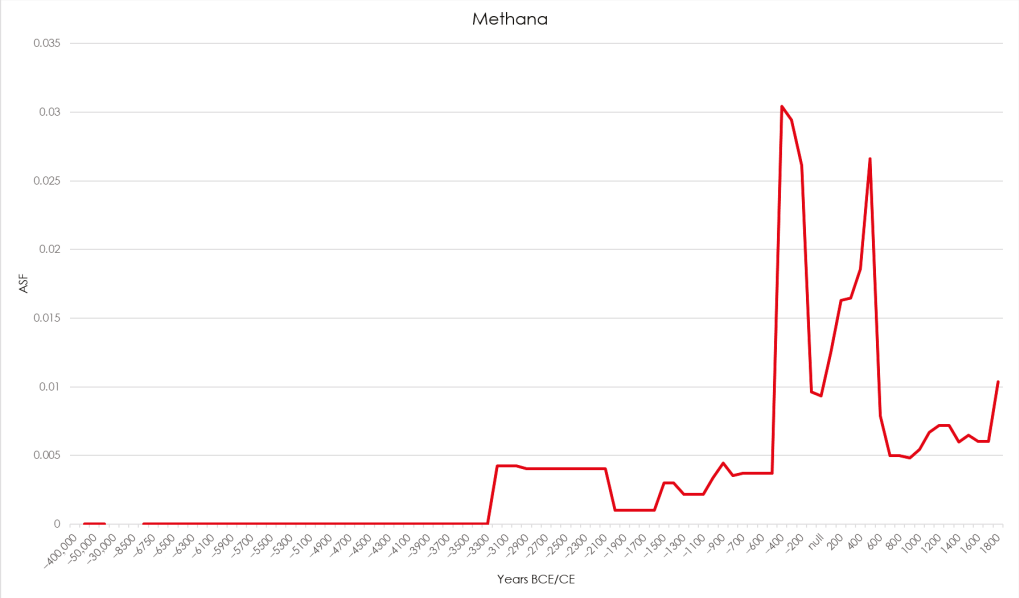


Figure 8. LASF for Methana.

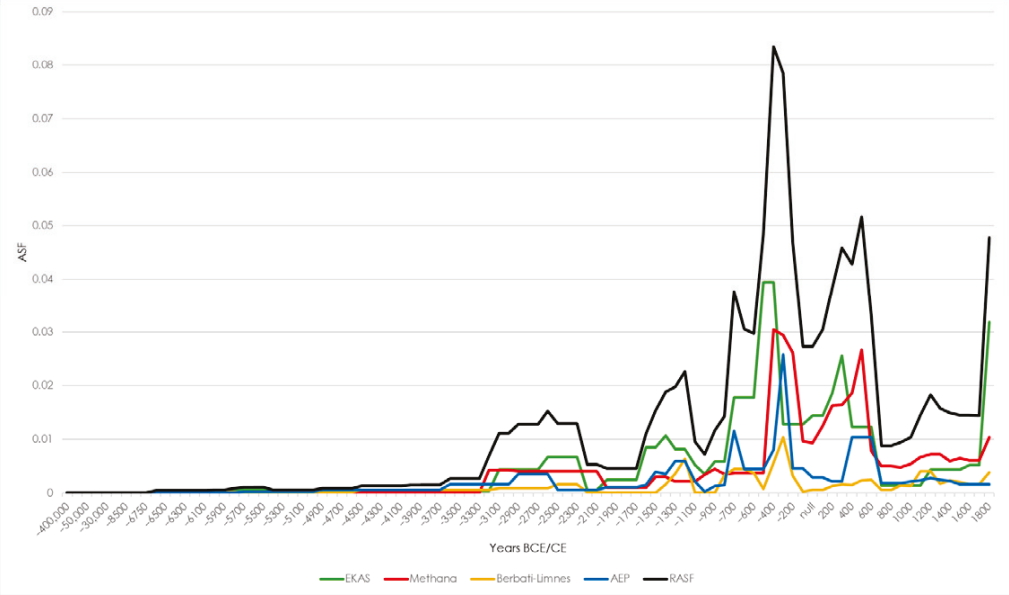


Figure 9. Graph showing the fluctuations in aoristic sum values over time for the four surveys.

Furthermore, the ASF is a probabilistic measurement of activity but speaks little to the nature of shifts in that activity over time. Beyond generating a probabilistic measure of activity, ASFs do not assist in understanding the extent to which potential activity from one phase to the next occurs at the same place (continuity), includes new areas of activity (expansion), or discontinues activity at a place (abandonment). Such data would provide potential proxy data to suggest shifts in local dynamics, which can, in turn, be ascribed to phases within the Adaptive Cycle [25].

Each project dataset was therefore assessed for abandonment, expansion, and continuity. The aoristic value (AV) was used to develop these indices. The AV is the probabilistic value each feature holds at a given period, contributing to the region's aoristic sum (AS) for a given period. Some features, for example, may have a low chronological resolution (generally dating to the Medieval period); others may have diagnostic material that would place activity in the 9th–11th and 14th centuries. The contributions of each site towards a

conceptualization of abandonment, expansion, and continuity, therefore, differ in weight. In developing these indices, the focus was not on counting the number of features but calculating their AV contributions. In considering **Abandonment,** the intent was to gain a measurement of the proportion of total activity that ceased from one period to the next. For each feature *i* that disappears between period P_t and P_{t+1}, its weighted contribution to abandonment is given by

$$\delta_{i,t} = \frac{AV_{i,t}}{AS_t}$$

Summing over all abandoned features gives the total abandonment index:

$$\delta_t = \sum_{i \in abandonedsites} \delta_{i,t} \quad (1)$$

This measure accounts for different chronological resolutions by weighting sites proportionally to their aoristic contributions. **Expansion** measured the proportion of new activity appearing in a period relative to total activity. For each feature appearing in P_{t+1} but absent in P_t, its weighted contribution to expansion is

$$\eta_{i,t+1} = \frac{AV_{i,t+1}}{AS_{t+1}}$$

Summing over all newly appearing features gives the total expansion index:

$$\eta_{t+1} = \sum_{i \in newsites} \delta_{i,t+1} \quad (2)$$

This measure adjusts for different chronological resolutions of the constituent features. Subtracting abandonment (Equation (1)) from expansion (Equation (2)) provides a measurement of expressing positive or negative **Potential**, where 1 (expressing positive potential energy) represents the absence of abandonment, and -1 represents the absence of expansion (expressing negative potential energy). Expressions of energy (positive or negative) align with the low potential AC phases (r and Ω). A value of zero represents no expression of energy, either because there is neither abandonment nor expansion, or because the quantity of abandonment and expansion are equal. This corresponds to the AC high potential characteristics identified for phases of α and K. **Continuity** was assessed by measuring the contribution of AV to the overall ASV for features persisting between adjacent periods, accounting for different resolutions. For each feature Si that appears in both periods P_t, and P_{t+1}, its contribution to continuity is

$$\alpha_{i,t} = \frac{AV_{i,t}}{AS_t} + \frac{AV_{i,t+1}}{AS_{t+1}}$$

Dividing a feature's AV by the AS value for a given time yields a percentage contribution of that feature to a given period. The average contribution of the feature across the two periods is, therefore,

$$\beta_{i,t} = \frac{\alpha_{i,t}}{2}$$

Summing overall continuing features and multiplying them by the percentage of sites continuing from one period to the next gives the total continuity index:

$$\frac{\gamma_t = \sum_{i \in continuingsites} \beta_{i,t} \times Totalcontinuingsites P_t P_{t+1}}{Totalsites \in P_t} \quad (3)$$

This formulation ensures that features with low chronological resolution contribute less to continuity. In addition, the index is adjusted for the probabilistic presence of

features rather than raw counts. Thus, the continuity index represents the AV moving from one period to the next, considering the chronological resolution of the initial features and the overall percentage of features persisting from one period to the next. High values will be generated from many features that continue to provide evidence for presence between the two periods.

Given that the indices were products of assessing a portion of the AV against the total AS, the indices were presented as percentages. This allowed for the evaluation of the distribution of values using quantitative methods. Employing Jenks Natural Breaks Optimization, each value for abandonment, expansion, and continuity was classified as exhibiting a high, medium, or low value (Table 1). The classification method was applied in two ways: one in which the values were classified for each project independently, and a second iteration, in which the values were classified using all values for a given index from all four projects. To demonstrate the approach, this study will employ the second classification method.

Table 1. Classification of abandonment, expansion, and continuity according to Jenks Natural Breaks Optimization.

Abandonment			
class	lower	upper	count
low	0	0.18391	83
medium	0.19786	0.53433	49
high	0.59375	1	37
GVF	1.56649	16.8539	0.90705

Expansion			
class	lower	upper	count
low	0	0.19939	73
medium	0.21612	0.5502	46
high	0.57503	1	51
GVF	1.80452	17.5175	0.89699

Continuity			
class	lower	upper	count
low	0	0.32591	56
medium	0.34325	0.69741	53
high	0.71094	1	60
GVF	1.58955	17.6292	0.90983

Along with potential, these values were applied to the phases of the AC (Table 2). A region entering a reorganization phase (α) will be in the process of re-establishing organizational structures. These systems could be somewhat different than prior organizations. One would anticipate new settlement or land use activities elsewhere than in the preceding period. Therefore, we would expect a low continuity index and a high number of new features (expansion). Abandonment will also be of medium-to-high value. Entering exploitation (**r**), a region will capitalize on a successfully organized system. Therefore, we would expect to see high continuity values and a relatively high number of new features, representing a continuation and expansion of the previously established system. Since exploitation is viewed as capitalizing on a previously established process, abandonment

will be low, and potential values will be high. A region experiencing conservation (**K**) will be in a state of stasis—continuity indices will be relatively high, and expansion and abandonment indices will be moderate to low. Alternatively, a system may see a consistent, moderate measurement in expansion and abandonment with moderate to high indices in continuity. Potential values will be near zero, either from slight expansion or abandonment, or from those activities canceling each other out. Regions experiencing a release phase (**Ω**) will have significant disruption from a prior period. The system is dismantling the previous structures but has not yet fully developed a new set of processes. Land use/settlement would exhibit low values for continuity and expansion and high values for abandonment. Potential values would be significantly below zero.

Table 2. Values of abandonment, expansion, continuity, and potential as applied to the Adaptive Cycle.

	α	**r**	**K**	**Ω**
Abandonment	Medium to High	Low	Low to Medium	High
Expansion	Medium to High	Medium to High	Low to Medium	Low
Continuity	Low	Medium to High	Medium to High	Low to Medium
Potential	0	1	0	−1

3. Results

Figure 10 presents the data from each survey as they correspond with the phases of the Adaptive Cycle (see Supplementary Materials, periodizations.xlsx). This study places the datasets within a standard quantitative frame of reference that allows for a measure of cross-comparison. While the results present disparities in local AC phasing, some broader trends exist. After 300 CE, periods of conservation predominate. Except for Methana, all other areas present a canonical Adaptive Cycle pattern in the Late Bronze Age. For all but Berbati-Limnes, the release phase at the end of the Bronze Age is relatively short, leading to processes of reorganization and expansion. All areas entered a release phase between 2500 and 2100 BCE, at the interface between the Early Helladic II and Early Helladic III periods (i.e., the latter third of the Early Bronze Age). In only one period, between 1300 and 1100 BCE, there is a consistent phase (K) across all four regional datasets.

The eastern Korinthia expressed long periods of alternating reorganization and expansion, punctuated by periods of release at the Late/Final Neolithic (5400–4000 BCE), EH III (2200–2150 BCE), and LH IIIC (1190–1050 BCE). Though the other regions displayed considerable changes, it is thought that the proximity to a larger city allowed for more stability [67]. It is noteworthy that the results of this study reinforce a landscape of relative stability in the Late Roman phase, consistent with Pettegrew's re-analysis [68]. The ensuing period (700–1200 CE) is identified as a phase of reorganization, consistent with larger socio-economic changes to the Korinthia [69].

As seen also from the LASF, data from Berbati-Limnes express periods of release in the EH III—early Late Helladic (2200–1440 BCE) and Early Iron Age (1150–850 BCE). The period from 850 BCE to 1200 CE presents several classic AC cycles of organization, exploitation, conservation, and release phases at 850–500 CE and 800–1200 CE, after which the region is observed to be in a condition of conservation until the 19th century. The condition between these periods (500 BCE–800 CE) is characterized by alternating α and K phases, a condition where the systems have high potential (potential indices near zero), but alternate between phases of high and low connectedness (high to low values for abandonment, expansion, and continuity). The boom-and-bust activity in the area, as indicated by the LASF, is supported by continuity, expansion, and abandonment indices. Like the eastern Korinthia,

the project directors ascribe this feature of the landscape to external relationships, in this case with the nearby Argive Plain [52].

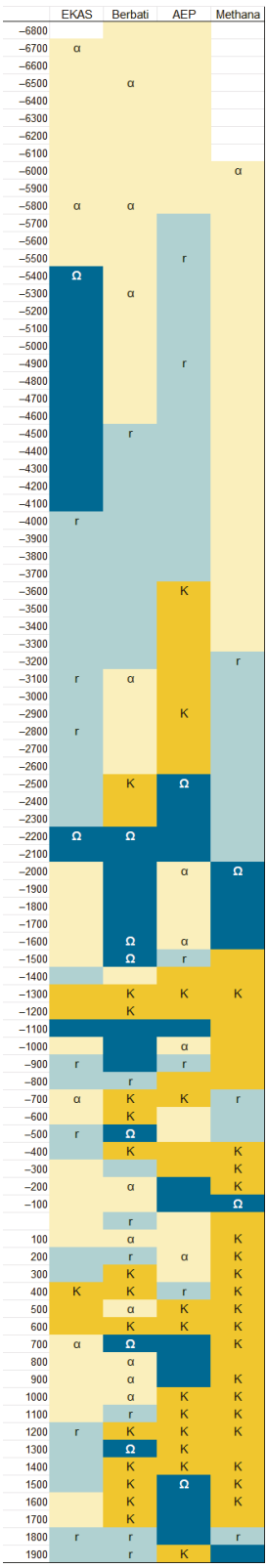


Figure 10. The phases of the Adaptive Cycle from 6800 BCE to 1900 CE at 100-year intervals for four regions in the northeastern Peloponnese. AC phases are marked at the points in time where indices were measured. Colors represent the phases of the Adaptive Cycle (see Figure 2).

After experiencing a release phase in the Middle Helladic (2000–1550 BCE), the Methana peninsula experienced a conservation period until a period of expansion in the Archaic/Early Classical (700–450 BCE). With minor phases of release at the beginning of the Roman (100–50 BCE) and Turkish (1450–1500 CE) periods, the region maintained a conservation phase for most of the historical periods. Notably, the "collapse" of the Late Bronze Age (c. 1100 BCE) is not observed here, which parallels other regions such as Achaea [70,71], the Euboean Gulf [72], and parts of Boeotia [13,73].

The southern Argolid experienced several Adaptive Cycles, beginning with the Early Neolithic through EH III (6850–2000 BCE) and the Middle through Late Helladic (2000–1000 BCE). The Protogeometric through Early Roman (1000–100 BCE) period presents as a series of reorganization, exploitation, and conservation phases before a release phase that began in the Hellenistic (250–50 BCE) period. The Roman and Medieval phases alternate between conservation and release before a reorganization beginning in the 19th century.

4. Discussion

The way in which the patterns expressed within the survey data map onto climatic events is thought-provoking. These events (the 4.2 ka event, the 3.2 ka crisis, and the Roman Climatic Optimum) are often mentioned when discussing human-environmental history in the eastern Mediterranean.

While there is debate on its global and regional uniformity and impact [74–76], evidence exists for a series of oscillations for the eastern Mediterranean Basin between 4.3 and 3.8 ka [74,77]. Although the chronological resolution of the survey data is coarser than for other periods,[2] each of the four regions records a release phase between 2500 and 2100 BCE, which aligns with prior work that presents this period as a time of cultural change (e.g., Refs. [79–81]). Given the debates over the climatological record and several culturally focused explanations to describe the shifts in the human record, establishing a causal relationship between environment and society in this instance is tenuous.

A second potential shift in regional climate patterns potentially occurred in the late second to early first millennium BCE [36,82,83], known often as the 3.2 ka crisis [84]. This shift appears to have been an extended period of drier weather [83]. This phase coincides with a series of cultural transformations in the Mediterranean, often discussed as a collapse event at the end of the Late Bronze Age. During this period, historical and archaeological evidence points towards widespread stresses in social and political institutions [32,85–88]. While the hyper-connective nature of societies could likely have caused a cascading effect at the scale of the wider eastern Mediterranean [89], localized impacts were more varied [13,32,48,71,90,91]. While climate has been argued as a significant determinant [92], other stresses (such as economic or political, e.g., Refs. [86,93]) or a combination of circumstances [85] have been suggested. Three regions under study experienced a period of release circa 1100 BCE. In the Berbati-Limnes survey area, the release phase lasted several hundred years, whereas the phase was much shorter in the southern Argolid and eastern Korinthia. Methana stands out as experiencing a conservation phase throughout this time frame. Methana's situation falls in line with patterns observed elsewhere in Greece, often interpreted as the result of decreased authority of the centralized palatial systems [70,72]. It could be suggested that the key to Methana's resilience, as in the larger regions of Achaea or Euboea, was attributed to its relative peripherality to the palatial systems.

Europe and the Mediterranean generally experienced a period of warming temperatures between the third century BCE and fourth century CE (approximately 250 BCE–400 CE), referred to as the Roman Climatic Optimum, also known as the Roman Warm period (e.g., Ref. [75]). The period presents a series of phases of organizations, exploitation, and

conservation for the areas within this study. No consistent, broad pattern emerges across the region. Methana, again notably, except for a release phase circa 100 BCE (shared with the southern Argolid), exhibits a continuous conservation phase. If there is a benefit to the Roman Climatic Optimum, the survey data would suggest that it is incorporated within localized adaptations and subsumed by other socio-political factors.

The approach has its caveats. As opposed to an authoritative assessment, the results guide future interrogation. As in any synthetic approach, the "narratives are limited by the rules that govern their construction" [4] (p. 8). Dramatic increases or decreases in AS values may be responses more often to shifts in periodizations than to an immediate change in human activity. Bayesian approaches [94], which provide a Gaussian smoothing to these abrupt shifts, may provide possible solutions. The method focuses on the presence/absence of features. Other aspects, such as data expressing complexity or internal/external connectivity (e.g., measures of standardization/skill, local/non-local production and exchange of ceramics, signaling territoriality as per Ref. [11]) or hierarchy (as per Ref. [13]) were not considered. Other variables related to size and similarity of features at different periods (as suggested by Ref. [21]) could not be applied, given the variety of methods in recording across the four projects. Not all projects reported these variables, and those that did often provided areal data for a single feature, even though it cannot be guaranteed that a feature remained the same size over time in multi-component contexts. Previous approaches using data with this information employed similarity indices to provide additional nuance to continuity, abandonment, and expansion [25]. Survey practices may have disadvantaged specific periods of activity, such as early prehistoric phases and the Medieval, which are increasingly viewed as having different approaches to the landscape and/or issues with visibility [68,95–99].

Survey data from the Aegean are highly localized in scale and divergent in method. While local narratives are critical and essential to understanding a geographically fragmented landscape, formulating approaches that establish a common framework moves us towards the broader goals of landscape studies as a cross-comparative tool [32]. Aoristic sums and other similar metrics used to measure quantity are helpful and provide a degree of cross-comparability. Employing metrics derived from aoristic sums to contextualize further the activity provides measurements that not only mitigate some of the weaknesses of the aoristic sum approach but bring us closer to a vocabulary that allows engagement between human and environmental data. The study proposes a way to synthesize information from projects conducted under different methodological frameworks. Using aoristic values derived from a feature's activity for a given period, aoristic sum values for a region are obtained, which can then be used to derive indices of abandonment, continuity, expansion, and potential. These metrics are then combined to express the phases of the Adaptive Cycle. Since each region's aoristic sums are calculated individually but according to the same process, a level of comparison is possible.

The approach leads us forward to developing a systemized process of analysis that allows for local variations to be observed and interrogated within a broader structure. Employing legacy data limited the study to using aoristic values based on presence/absence. While this may be disappointing, it raises the possibility of incorporating data collected from non-intensive methods to increase areal coverage. Given that survey boundaries are themselves problematic and rarely fully encompass a complete socio-economic system [21,60,61], incorporating non-intensive data would allow boundaries of analysis to become more easily amended and altered for a given period. Harnessing datasets such as those developed by Attema et al. [14] or curated by Consoli [100] to investigate chronologically and/or geographically discrete spaces provides interesting paths that move beyond the scope of this paper.

5. Conclusions

Humans do not directly respond to climate change. Instead, they are more reactive to local conditions, be they environmental or social [101]. While possibly influenced by climate change, these local conditions are often the driving factors in human adaptation. Identifying past strategies to mitigate the current effects of climate change is presentist, influenced in part by our modern condition of a highly globalized and hyper-networked world system in which the scientific evidence for a warming planet is undeniable. Seeking solutions via past corollaries requires recognizing that the most appropriate examples may lie in local systems of organization, where human and environmental conditions are most inherently intertwined, and identifying instances where chronological and spatial conditions for both human and environmental data are well defined [102]. When studying the ancient Aegean, variability across regions should be anticipated, as suggested by the results of this study, regional narratives detailed elsewhere (e.g., Refs. [13,90,91]), and recent paleoenvironmental studies [103]. Resilience involves the study of socio-environmental condition, a construct that views human and environmental elements as agents within an interdependent system. Understanding long-term changes in the human element, framed within a theoretical construct that can enable comparisons with paleoenvironmental conditions, is a critical step in developing a region's combined human and environmental history. Developing a process that can conceptualize macroregional trends while preserving the ability to engage in regional cross-comparative analyses enables us to discuss broad trends in human history and local responses to microregional variation.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/heritage8080298/s1, AEP.xlsx; Berbati_Limnes.xlsx; EKAS.xlsx; Methana.xlsx; periodizations.xlsx.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Adaptive Cycle
ASF	Aoristic Sum Function
ASV	Aoristic Sum Value
AV	Aoristic Value
LASF	Local Aoristic Sum Function
RASF	Regional Aoristic Sum Function

Appendix A

Appendix A.1 Deriving Aoristic Sum Functions

The Eastern Korinthia Archaeological Survey (EKAS) is the most recently completed project in the study. As noted, the project data has been archived via OpenContext and is available for free download [54]. The data allowed for individual feature (Localized Cultural Anomaly (LOCA), in EKAS terminology) review at a more intensive level of analysis than other projects, allowing the researchers to review different means of developing aoristic sum functions. The analysis used the LOCA and artifact tables [62,63]. The former provided a functional and chronological assessment of each LOCA and a listing of the LOCA's discovery unit(s). The artifact table, consisting of artifact counts grouped by chronotype and discovery unit, was parsed for each feature, providing a summary count of artifacts for each period (see Supplementary Materials, EKAS.xlsx). Based on these data, three separate aoristic sum functions could be constructed, which proved informative and helpful in understanding how different ASFs can be derived from survey data, their implications for future applications, and how to best apply the approach given the varied extent to which the four projects have collected and published their data.

The first ASF (ASF_1) consisted of taking each summary count for each period and deriving an aoristic value using Equation (A1). For an artifact i with a temporal range $\left[t_i^{start}, t_i^{end}\right]$, its contribution to the year t is given by

$$C_i(t) = \begin{cases} \frac{1}{t_i^{end} - t_i^{start}}, if\, t \in \left[t_i^{start}, t_i^{end}\right], \\ 0, otherwise. \end{cases}$$

where:

- t_i^{start}: Start year of the artifact's temporal range.
- t_i^{end}: End year of the artifact's temporal range.

The aoristic sum function (ASF) for a given year t is calculated by summing the contributions from all n artifacts:

$$A(t) = \sum_{i=0}^{n} C_i(t) = \sum_{i=0}^{n} \begin{cases} \frac{1}{t_i^{end} - t_i^{start}}, if\, t \in \left[t_i^{start}, t_i^{end}\right], \\ 0, otherwise. \end{cases} \quad \text{(A1)}$$

This equation is applied to all artifacts, including those with broad or imprecise chronological ranges (e.g., ceramic age, spanning 6700 BCE–2000 CE), ensuring the resulting aoristic sum function (ASF) incorporates all data, even those with poor chronological resolution (Figure A1).

The second ASF (ASF_2) focused on discrete phases of activity. By looking at the most chronologically constrained artifact types, a date range when activity at a LOCA would have most likely occurred was derived, consistent with principles for multicomponent activities [104]. ASF_2 consisted of only those aoristic values for periods of defined activity

(see Figure A1). It must be noted that Equation (A1) accentuates the values for periods that contain large numbers of artifacts and/or are of short duration. Thus, a single sherd from the Early Helladic Period (1600 years) results in an extremely low aoristic value, whereas five sherds dated to the Archaic (200 years) result in a significantly higher value. Therefore, the aoristic sums capture as much of a given period's visibility as its human activity.

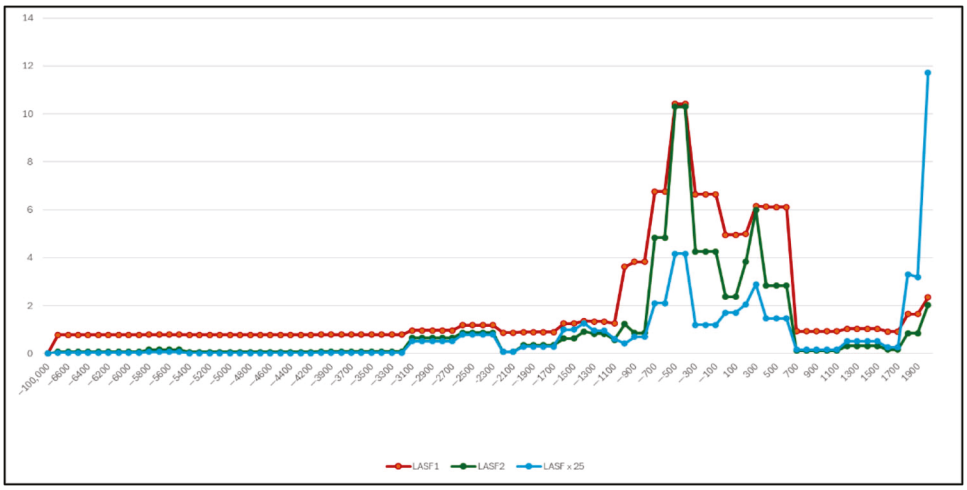


Figure A1. LASFs for EKAS. LASF 3 is multiplied by 25 to show patterns relative to LASF1 and LASF2.

The third ASF measured the presence/absence of activity for a period. If evidence was observed, regardless of quantity, a value of 1 was recorded, which was then divided by the number of years for the period.

$$1 \div No of years \in period \quad \text{(A2)}$$

The resulting ASF removed bias for artifact quantity while preserving a probabilistic measurement based on the length of a given period (see Figure A1). While still accentuating periods of short chronological duration, the function presents probabilities of activity for a given year. Thus, it represents the presence and a probabilistic measure of activity.

The three derived ASFs for each LOCA were summed to form three versions of a region's LASF (Figure A1). In general, all three computations present similar patterns apart from three instances: the Late Bronze Age–Early Iron Age (LBA-EIA; 1100–900 BCE), the Hellenistic–Early Roman (100 BCE–100 CE), and the Early Modern–Modern (1800–2000 CE) transitions. In the first instance (LBA-EIA transition), $LASF_1$ and $LASF_2$ increase, whereas $LASF_3$ decreases. This can be explained by the number of artifacts with poor chronological resolution beyond such designations as "historic." Given that values in $LASF_3$ are determined by the presence or absence of pottery with distinct chronological ranges, the aoristic value is lower. In the case of the Early Modern-Modern transition, the increase in aoristic sum values (AS) results from the short duration of the periods, which inflates the aoristic values (AV) for features.

The third formulation represents the computation most amenable to the work at hand. While limiting the impact of data with poor chronological resolution and accentuating data with high resolution, it provides some normalization by removing the quantity of diagnostic artifacts for a period from the equation. It thus mitigates against accentuating ASFs for periods where artifacts are highly diagnostic. The most compelling reason, however, came from data accessibility. All artifacts analyzed by EKAS were fully published and made available; this was not replicable for all projects. Of the three approaches, the third computation could be replicated across all projects in the study.

Notes

[1] The term for an area of interest, consisting of a concentration of artifacts or other signs of human activity is known by many terms—site, feature, locus, POSI, LOCA, etc. This paper will employ the term 'feature' to refer generally to this element. When speaking about individual project findings, the project-specific term will be used.

[2] It should be noted that this study employs the relative chronology originally used by the surveys in the study, with the exception of the Late Bronze Age (see Ref. [78]). See Weiberg and Finné [37] on the impact of relative chronologies in discussing connections between human and environmental events.

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Risk, Uncertainty, and Resiliency in the Face of Ancient Climate Change: The Case for Legumes

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Abstract

Continuing improvements in our understanding of ancient climate change renders it necessary to expand our toolkit for exploring human responses to climatic shifts. Currently, archaeological methods for exploring the resilience of ancient human agricultural systems—in addition to strategies for managing risk and/or uncertainty—are frustratingly limited in comparison to the rich ethnographic record of how humans have navigated climatic stressors. This article proposes that legumes might provide a new, albeit woefully understudied, vector for potential analyses, especially given their central role in traditional agricultural systems as a buffer against environmental stress. The peculiar agronomic character of legumes, especially among the widely cultivated varieties that are toxic in their unrefined state, could allow for robust hypotheses about agricultural strategies to be tested against our paleoclimate record. Importantly, these hypotheses could be tested against a wide variety of models of human–plant and human–environment interaction, as they could be based on labor costs rather than assumptions of ancient cultural preference. Legumes, however, present particular difficulties as objects of analyses, and therefore some methodological cautions are in order. Consequently, instead of proposing and testing hypotheses, this article seeks instead to inspire future research in relation to our constantly improving data.

Keywords: paleoethnobotany; archaeobotany; resilience; risk; uncertainty; sustainability; labor cost; legumes; legume toxicity; ancient agriculture

1. Introduction

Past decades have seen dramatic improvement in our knowledge of ancient climate change (see articles in this special edition), though archaeological tools for identifying past human responses to climate change remain frustratingly limited in comparison to the ethnographic record for human adaptations to climatic stress. Archaeological studies have looked for correlation between climatic disruption and the disaggregation, dispersal, or general movement of populations as direct indicia for human abandonment of unfavorable environments and/or socioeconomic arrangements [1], though timing and causal relationships often remain hotly debated [2]. Other studies have focused on water management strategies [3], but the difficulty of dating water systems renders this proxy highly specific in application. Given improvements in archaeobotanical data, it has, however, recently become possible to assess regional and local impacts of climate change through the exploration of agricultural strategies that may have been employed to mitigate risk and/or uncertainty. This mode of analysis presents a potentially rich toolkit for studying human response to climatic stressors, though current methods are confined predominantly to comparing patterns in cereal agriculture and/or the relative exploitation of fodder versus

pasture among agropastoralists [4–6]. To enrich our toolkit, I propose that legumes—and especially toxic legumes—provide a highly useful, albeit woefully understudied, proxy for identifying agricultural strategies that ensure yield under less-than-ideal circumstances. While we must always recognize that a farmer's selection of crops is subject to manifold cultural, agronomic, and ecological considerations, the peculiar character of many leguminous species means that they offer unique potential for hypotheses that are testable against our paleoclimate record.

For this article, I will focus on leguminous crops associated with the core group of domesticates that originated in southwest Asia, species that were eventually utilized in agricultural systems across Africa, Europe, and Asia. Despite long-standing recognition of the centrality of legumes within early farming systems [7], they have received only a fraction of the attention granted to cereals. Partially, this stems from overemphasis on classic concepts like the so-called "Mediterranean Triad" [8], but at another level there are intrinsic difficulties in the archaeobotany of legumes that render other crop species more straightforward as objects of inquiry (see Section 3). Legumes, however, possess many characteristics of great interest to archaeologists exploring how ancient food production might have been adapted to the challenges posed by climate change. The ethnographic record of traditional farming practices is replete with evidence for the special role of legumes in resilient farming strategies, including how multiple species might be planted simultaneously to exploit their individual strengths as a buffer against environmental stress (see Section 4). Furthermore, ancient and traditional agricultural systems have simultaneously exploited legumes that range in levels of toxicity, wherein the higher labor required to process toxic species safely was counterbalanced by their general hardiness vis-à-vis other, less toxic variants. This is of special interest in relation to past human responses to climate change, as such species might provide insight into how food producers managed risk through crop diversity.

Legume toxicity is central to this article, as it does not necessarily prevent exploitation, but rather requires special knowledge and/or additional processing requirements to provide critical nutrition for both humans and livestock. For those in possession of such knowledge and the wherewithal to undertake more laborious processing, these toxic species can form a cornerstone of strategies for mitigating both short-term uncertainties alongside providing longer-term insulation against the effects of macroscale forces like climate change. Importantly, by focusing on labor requirements rather than modern assumptions that certain species were more or less desirable to an ancient individual—information which we generally lack and often rests instead on the faulty projection of our own etic sensory assumptions as normative [9]—this method has the potential to be more testable against a wider variety of models for human–environment and human–plant interaction.

While both our paleoclimate and archaeobotanical knowledge are constantly improving, if the desire is to conduct large-scale regional and cross-regional assessments of how factors like climate change might impact human–plant interactions, or even if we wish to explore at a local scale how individuals might strategize on the basis of crops available within their given milieu, a great deal of methodological care is required in relation to known gaps or biases in our current data. Legumes present particular difficulties in this respect (see Section 3). Consequently, this article predominantly seeks to highlight their potential and inspire future hypothesis generation such that we might consider new avenues for identifying risk and uncertainty management strategies, alongside long-term agricultural resiliency in relation to climatic conditions. The potential for legumes—toxic or otherwise—to provide proxy evidence for ancient adaptive agricultures intrinsically lies at the intersection of several distinct models for exploring human–plant interaction, some of which are often considered to be incommensurate. To elucidate such a framework, this

article is structured as follows. First, I will discuss general issues related to resiliency in food production systems, risk management, and the decision-making processes behind the selection of cultivars (Section 2). I transition to the difficulties inherent to leguminous species as archaeobotanical data and their subsequent neglect within the literature (Section 3), which is followed by a discussion of their agricultural benefits in risk management (Section 4) and a characterization of legume toxicity among the species affiliated with the southwest Asian family of domesticates (Section 5). Finally, I offer some preliminary comments on potential ways to employ legumes in an exploration of our evolving dataset (Section 6). Additionally, the Supplementary File S1 supplies a glossary of terms that may be of use for the reader. While the focus here is on leguminous species from the orbit of southwest Asian domesticates, the framework presented here might prove transferrable to other species or regions.

2. Climatic Fluctuation, Resiliency, and Risk Management

At a certain level, exploring the role of legumes within food production—whether they served as food or fodder—requires a degree of theoretical pluralism. Indeed, even if the stated objective of this article is to inspire hypotheses for future testing against the ever-improving archaeobotanical data, the theoretical pluralism employed here merely indicates the frameworks within which such hypotheses might be tested. The usage of concepts like "risk management" and "resilience" already implies certain modes of thought; thus, it is prudent to pause and provide definitional clarity. Risk management, as employed here, operates predominantly within the understanding developed within Human Behavioral Ecology (HBE), wherein risk is understood as probabilistic variance in returns [4]. This is to be separated from uncertainty, which is to be understood as incomplete knowledge and therefore unpredictability of outcome probabilities. The two can, especially within archaeological application, be difficult to separate in practice, though the key distinction for risk management lies in the decision-maker's knowledgeable tailoring of strategies on the basis of known past outcomes [10]. Both concepts are intrinsically short-term in their interpretive object (i.e., the strategic efforts of individual food producers), though this does not necessarily detract from their centrality in exploring how food production systems were used to mitigate the impact of climate change—one need only contemplate how long-term climatic cycles might have been experienced within individual lifespans as so-called "creeping normalcy" [11]. Resilience, in contrast, provides the more macroscale framing through which to understand how ecological, social, and social–ecological adaptive systems linked to food production might change in relation to *longue durée* forces like climate change, though it is necessary to separate resilience from a teleological approach that simply renders it as a contrasting state to collapse [5,12]. Applying the above language to the case of especially toxic legumes, such species might form a part of short-term risk management strategies among farmers, whereas their presence/absence within broader regional agricultures might play a key role in the resiliency of said system in the face of ecological processes derived from anthropogenic or non-anthropogenic causes [13].

While the language above is clearly indebted to fields like HBE, theoretical pluralism here requires engagement with approaches often treated as contradictory to the core models of HBE. For instance, there has been ongoing dispute over the utility of tools derived from HBE for the evaluation of food production, with Optimal Foraging Theory (OFT) receiving the greatest degree of attention [14–17]. This has coalesced around Niche Construction Theory (NCT) as a potentially stronger explanation for the adoption and elaboration of systems of human food production [18]. While the issue is more acute in debates about the origins of agriculture [13], the ready integration of NCT into resilience thinking makes it of special interest here. For instance, the role of legumes in nitrogen fixation and cover

cropping—regardless of if farmers fully understood the benefits as such—can be viewed in light of the constructed niche wherein soil fertility becomes part of the ecological inheritance for subsequent users of agricultural land. While legume toxicity certainly can factor into both HBE- and NCT-based approaches, especially with respect to the interplay between nutritive returns and diversification as a method of risk management, other elements require attention—namely the material affordances of legume species, the transmission of practices related to their effective exploitation, and even their affective qualities (sensory or otherwise).

I have argued that theories of practice, materiality, and sensory archaeology form viable tools for exploring why individuals might or might not exploit toxic legume species—or any plant species for that matter [19]. While it has been repeatedly noted that OFT provides a hypothesis against which the data can be tested—thereby highlighting deviations from the expectations of the model—rather than a rigid explanatory covering law [14], to my knowledge there have been no proposed mechanisms to grapple with how OFT might highlight plant exploitation strategies that were potentially unconcerned with nutritive value and, instead, were concerned with some other quality of the plant-based comestible—e.g., how staples like cereals could have been emphasized for their affective qualities as a fermented drink, as discussed recently by Paulette [20]. In short, emic values might result in outcomes predictable via OFT, though the actual causal structure leading to the outcome might be fully independent of the assumptions of OFT. In such cases, should archaeologists desire highlighting something other than the prime mover of basic evolutionary fitness, it is incumbent to employ more malleable—though less intrinsically testable—tools from the broader suite of social theories concerned with reciprocal construction of agents and their sociocultural and material worlds [13]. Certainly, aspects of each aforementioned framework shed some light on why farmers employed certain legume species over time. Importantly, however, the use of legumes to better understand past agricultural strategies would be testable in some capacity within the confines of all the above frameworks.

3. The Problem of Legumes

Despite the fact that the domestication of various leguminous species seems to have been roughly coeval with that of cereals in the so-called "Fertile Crescent" [21,22], the adoption, spread, and elaboration of legume cultivation remains poorly understood. Though the discipline has largely abandoned concepts like the "Neolithic package," "founder crops," or the "Neolithic revolution" as oversimplifying and rendering teleological the diverse species, regions, timelines, and processes that characterize the development of food production [23–26], the cultivation of legumes—including toxic varieties—seems to have formed a key component of the diverse modes of food production that spread from southwest Asia to regions as far afield as Iberia and northwest Africa [27]. While the importance of legumes is evident, the general lack of attention given to them is not casual neglect. Rather, it stems from complications derived from a confluence of factors, namely leguminous botanical characteristics, the interplay between ancient agricultural and culinary practices with site formation processes, and biases introduced through archaeological recovery. Collectively, within the region of interest, this renders legumes difficult to study, difficult to recover, and—from a paleoethnobotanical standpoint—difficult to interpret.

For early periods especially, a major issue is that it is nearly impossible to differentiate domesticated legumes from their wild predecessors. The characteristics commonly associated with legume domestication—indehiscence (i.e., resistance to separation of the seed/pod from the plant), free-germination (i.e., lack of seed dormancy), and a smooth testa—are typically not observable in archaeologically recovered legumes [26,28]. This contrasts with the well-known signifiers of domestication in archaeologically recovered

cereals [25]. Consequently, within the region of interest, early legume cultivation is often only identified via higher densities of legumes in association with clearly domesticated cereals or, alternatively, the presence of legumes outside of their ancient wild range [26]. The former intrinsically renders the study of legumes subsidiary to that of cereals, whereas the latter is stymied by the fact that legumes—including domesticated types—can also appear as weeds of cultivation in relation to other crops, as is the case with bitter vetch in modern-day Egypt [29,30]. Consequently, our capacity to discern why food producers might adopt legume cultivation remains poorly articulated. This pertains not just to their initial adoption by the earliest food producers but also why later food producers might—or might not—include foreign legumes among their cultivars as part of a resilience strategy. The issue is rendered more acute by anthropogenic and species-specific issues that suppress archaeological recovery of legumes.

Given the ancient culinary techniques for processing dried legumes—namely soaking, boiling, and/or pulverization—there is relatively little opportunity for their preservation via common vectors like charring [31]. Additionally, the oft-forgotten possibility that certain varieties—wild or domesticated—were simply consumed fresh as a green vegetable would also lower probabilities of preservation [32]. Consequently, it is typically only the rare instances of sudden preservation that allow for substantive legume remains to enter the archaeological record in ways visible to the most historically common collection strategies. The issue is exacerbated by foddering since the whole plant is valuable as livestock feed [33], thereby reducing the probability that portions of leguminous plants will enter the archaeological record as crop processing waste. Similarly, experiments have shown that legumes contribute little to the phytolith record [34], further reducing their archaeological visibility. Bioarchaeological evidence, either in the form of isotopic data [35] or studies of dental calculus [36], can demonstrate the human consumption of legumes, but neither possesses sufficient resolution to explore what species were consumed beyond the level of genus. Other microbotanical evidence, such as that derived from starch and palynological analyses, presents similar difficulties [37]. The formation of the archaeobotanical record is already a highly reductive process, and legumes are more susceptible to pre-depositional loss compared to other seed-bearing species from the pool of southwest Asian domesticates. They are also resistant to archaeological recovery, as charred legumes are prone to post-excavation loss even with high-resolution recovery techniques like flotation. Given past tendencies to only sample densely visible organic deposits preserved in situ within features like silos, taxa like cereals and their accompanying weeds are typically over-represented compared to legumes [19]. Indeed, it has recently been demonstrated that high numbers of soil samples directly correlate with larger and more taxonomically diverse legume assemblages [38]; therefore, it is only with relatively recent systematic archaeobotanical sampling that we could begin to appreciate the role of legumes within food production systems. Hence, it seems most appropriate that we develop hypotheses to be tested, rather than prematurely testing them against highly dynamic data.

4. The Benefits of Legume Exploitation

Legumes have become a central theme of modern agronomic literature, wherein the hardiness and nutritive value of many leguminous species has been noted as key to future resilience and sustainability in the face of modern climate change [39]. While exact characteristics vary by species, it is possible to generalize about their resistance to even extreme fluctuations in temperature, moisture, and soil conditions, such that legumes are often a failsafe within traditional farming systems wherein their performance vis-à-vis other crops—including other legumes—grants them the flexible status of food, fodder, or

both [4,28,33,38]. Moreover, toxicities present in various legume species, the subject of Section 5, also lend resistance to pests—e.g., as with L-canavanine [40]. Substantial work has also been conducted on the nutritive complementarity of legumes and cereals and the capacity for legumes to improve soil nitrogen stocks—either through fixing atmospheric nitrogen or as a component of green manure [41]. Collectively, the above mark legumes as a cornerstone of many traditional and ancient food production systems, lending them a special place within risk management strategies and ecosystem engineering practices irrespective of the degree to which an individual farmer or farming culture employs direct knowledge of the underlying causative principles for these benefits [19]. Despite these generalizations, however, certain legume species exhibit variable performance under different environmental conditions, wherein the co-cultivation of multiple types might indicate agronomic strategies grappling with the effects of climate change.

The characteristics of individual species that are relevant to their viability in the face of changing and/or volatile climatic conditions stem predominantly from plant morphology, growth habit, seed size/composition, and phytochemistry. In food production systems favoring monocropping, these differences allow for strategies of temporal diversification, where each species is planted sequentially according to the seasonal conditions to which it is best adapted, with a general progression in traditional agriculture systems being from those species that better tolerate dryer conditions, such as the lentil (*Lens culinaris* Medik.), bitter vetch (*Vicia ervilia* L.), grass pea (*Lathyrus sativus* L.), and common vetch (*Vicia sativa* L.), to those which are more temperature- and moisture-sensitive, like the garden pea (*Pisum sativum* L.), chickpea (*Cicer arietinum* L.), and fava bean (*Vicia faba* L.) [28,33]. Notably, the ethnographic literature from southwest Asia, the Mediterranean basin, and north/northeast Africa also provides alternative legume diversification strategies based on mixed cropping, including methods like relay planting (i.e., broadcasting the seed of one species into beds filled with another, already-mature species), intersowing (i.e., planting different species at the same time but harvesting separately), or broadcast mixed sowing (i.e., maslins wherein the resulting mixture of species can be harvested simultaneously or separately depending on growing conditions and maturation rates). In these cases, the individual character of each species means that the farmer has insurance against less predictable weather conditions, an especially desirable strategy during periods of climatic transformation. The conditions that manifest within a given growth season and, therefore, the subsequent differential success of each sown species can provide a flexible crop of food, fodder, or both, depending on the surviving quantity and desirability of each harvested species. In difficult seasons, hardier legumes produced in such mixed fields that are considered less desirable and therefore typically grown as fodder might become an important failsafe in human diets [4,28,33]. Indeed, the ethnographic literature on traditional food production in Ethiopia revealed that informants intentionally cultivated the less desirable grass pea in legume co-agricultures specifically due to its resilience in the face of conditions deleterious to other legumes [42,43]. Consequently, archaeologists should pay close attention to evidence for legume co-cultivation in relation to known instances of climatic events, as it may be possible to see how food producers responded to changing environmental affordances. This may be especially relevant in relation to farmers who chose to include in their repertoire toxic legume species that require additional steps to exploit effectively, as these are among the hardiest legumes cultivated regularly.

5. Legume Toxicity

Archaeologists have a tendency to treat toxic legumes as highly dangerous, with their consumption potentially resulting in permanent disability or death [44]. A literary survey of paleoethnobotanical studies shows frequent statements that certain legume species—

especially of the genera *Vicia* or *Lathyrus*—are unfit for human consumption, relegated either to famine food or fodder [32]. Multiple authors have, however, noted that legume toxicity has been overstated across species and, importantly, that toxins can be mitigated using a variety of techniques—indeed, many such species are dietary staples among modern populations who exhibit no ill effect from their frequent consumption [45–50]. The situation has been further aggravated by the recycling of references, including a rather confusing history of the epidemiological literature wherein Greek and Roman texts were often uncritically paired with preliminary—and often flawed—phytochemical analyses [19]. Importantly, nearly every leguminous species contains deleterious compounds, more commonly known as anti-nutritional factors (ANFs), with the relevant difference among them simply being the required mitigation techniques and consequences of unmodified consumption.

Regarding commonly exploited legumes, this article will focus on the six species most often recovered archaeologically within the regions that adapted food production from the southwest Asian pool of domesticates: lentil, garden pea, chickpea, fava bean, grass pea, and bitter vetch. Of these, the ANF content of the first four is predominantly composed of protease inhibitors (especially trypsin inhibitors), phenols, tannins, phytic acid, lectins, saponins, and oligosaccharides. While the bioactivity of each is different, the effects largely range from the inhibition of nutrient uptake to moderate gastrointestinal discomfort [51]. More importantly, however, even in an unprocessed state, the collective post-consumptive impact—either from a nutritive or health/wellbeing standpoint—is minimal, and even the most basic cooking techniques (e.g., exposure to heat and water) are more than sufficient to neutralize bulk ANF content across all four species [51–57]. In short, the agronomic and nutritive benefits of these four species can be realized with little additional labor input—simply cooking them was more than sufficient, and, therefore, they should occupy a separate conceptual category from more toxic legume species. The only possible exception is the fava bean, which has been subject to grave, albeit misplaced, archaeological anxieties about its association with favism—a genetic disorder wherein consumption of fava beans (or even exposure to fava pollen) leads to hemolytic anemia [37]. It should, however, be noted that favism has been overstated in the literature, as attested not only by the commonness of fava beans in modern foodways but also because the compounds in fava beans connected with favism—vicine and convicine (as precursors to divicine and isouramil)—can be dramatically reduced by the simple act of cooking [58,59]. Consequently, these four species can be regarded as relatively straightforward additions to food production and/or strategies of crop diversification, possibly even as interchangeable elements wherein we should expect relatively little resistance to their adoption as foreign cultivars provided another similar leguminous species was already familiar to the farmer in question. As such, they are unsurprisingly some of the most commonly recovered legume species in regions that adopted crops derived from the pool of southwest Asian domesticates.

The situation, however, changes dramatically with respect to the other two species of interest—the grass pea and bitter vetch. While both largely exhibit the same ANF content of the four species discussed above, they contain additional compounds of greater toxicity. Notably, these compounds do not allow for the casual use of these species as fodder plants, as is commonly assumed [60], but rather, they can be lethal in relatively small concentrations to monogastric livestock species and, furthermore, must be proportionally controlled in the diets of more resilient ruminants in order to avoid negative outcomes [47,61–63]. Consequently, special knowledge is required regardless of whether the crop in question is destined for human or animal food. Sustained consumption—or rather overconsumption—of grass pea has been associated with a condition variably known as lathyrism or neurolathyrism, a toxic myelopathy resulting in paralysis and death that stems from the presence of BOAA (β-N-oxalyl amino-L-alanine)—analogously ODAP

(β-oxalyl-α,β-diaminopropionic acid). While the exact mechanisms of the disorder are not fully clear, the manifestation of the disease in modern populations that regularly consume grass pea is not nearly as severe as has been previously assumed in either the epidemiological or archaeological literature—the disease predominantly manifests under circumstances of sustained, elevated, and often near-exclusive consumption of grass pea [64–66]. That so many cultures around the world continue to consume grass pea safely or—as noted in some ethnographic investigation, cautiously—is because many groups exercise either conscious dietary balancing (e.g., mixing grass pea with other legumes or foodstuffs) or more rigorous processing that dramatically reduces the offending neurotoxin—e.g., varying combinations of soaking, heating (both dry and wet), grinding, dehulling, and even fermentation [42,43,67–69].

Bitter vetch was, for a long time, erroneously associated with lathyrism [19], though more recent phytochemistry has demonstrated that negative health outcomes in bitter vetch consumption—human or animal—are instead related to the presence of a different toxic compound, L-canavanine [40,47]. For humans and livestock, elevated consumption of L-canavanine—specifically via legumes of the genus *Vicia*—has been associated with inhibited nutrient uptake, fetal malformation, neurotoxic disturbances, hallucinogenic effects, hair loss, diarrhea, paralysis, cirrhosis of the liver, hypoglycemia, and arrythmia [46,68]. Much like the case with the grass pea, the chemical properties of L-canavanine and its variable presence in different portions of the bitter vetch seed mean that its reduction is only possible through a combination of processing methods that might variably include grinding, dehulling, soaking, heating, drying, and, potentially, fermentation [19,31,40,60,70,71]. Importantly, despite these phytochemical issues in both bitter vetch and the grass pea, as well as the additional labor required in rectifying them, ethnographic evidence has demonstrated that both legumes are valued within food production systems specifically for their hardiness in relation to a wide variety of extreme agricultural conditions, such that—while they may not always be the preferred food source—their cultivation as part of a diverse repertoire of legumes and grains serves to manage risk and insulate from uncertainty [42,47]. Consequently, it is inappropriate to dismiss these species as low-quality famine foods, but rather, we should explore them as potential indicia for strategies in relation to navigating various stressors of ancient agricultural systems—including but not limited to climate change.

6. Future Directions in the Archaeology of Toxic Legumes

Considering the difficulties for recovering legumes archaeologically (see Section 3), the treatment of legume cultivation over the *longue durée* in relation to any research question is difficult beyond discussions of presence/absence. Notably, however, we cannot always extrapolate from instances of presence whether the legume was wild, a weed of cultivation, or intensively exploited. Similarly, it remains difficult to assess whether absence is genuinely meaningful or if it is simply a consequence of the myriad biases outlined in Section 3. For instance, despite earlier arguments that bitter vetch cultivation likely never occurred west of Anatolia in during the Neolithic [72], subsequent data collection has demonstrated a near-continuous arc of early Neolithic cultivation of bitter vetch across southern Europe, into the Danube River Valley, and connecting Iberia with northwest Africa [27,73]. For this reason, it has been argued—especially for regions like Neolithic northeast Africa where archaeobotanical studies remain relatively rare—that we must exhibit extreme caution in relation to the "lack of balance between data and theories" [74]. It is necessary, therefore, to consider how we might meaningfully engage with the available data, even as it improves.

Fundamentally, the question relates to the presence/absence of a given leguminous species within the regional assemblage. The intrinsic issues with botanical data, however,

mean that rather than simple presence/absence, we must try to understand the degree to which we can assume that an absence from a botanical assemblage represents a genuine condition of antiquity (i.e., total absence from the agricultural system) or whether it is an artifact of something else—site formation processes, collection bias, etc. Conversely, there remains the problem of whether presence indicates intentional exploitation or if, instead, it signifies some other possibility on the spectrum of human–plant relations (weed of cultivation, wild species, etc.). The presence of large caches of cleaned seeds are, at one level, the only definitive indicator of exploitation. No equivalent certainty can be assumed in relation to the absence of a taxon within an assemblage. Instead, both absence and low levels of presence within an assemblage must be treated cautiously with respect to their significance.

We therefore need to ask whether meaningful analyses must be quantitative, semi-quantitative, or purely qualitative in character. The direct quantitative comparison of macrobotanical remains within and across regions implies that each assemblage within the overall dataset constitutes an accurate reflection of human–plant interactions in antiquity. Notably, the considerations described in Section 3 indicate that, for legumes especially, this assumption is untenable, and furthermore, the irregular character of the data discourages immediate leaps to tests of statistical significance. Instead, we must consider the target population about which we would like to draw conclusions based on our samples. Archaeologists do not directly sample the sum total of all plants that were in use at a site in antiquity, but rather we sample a volume of space for which the preserved macrobotanical remains are statistics of a sample element rather than the sample itself [75]. Importantly, this means that our target population can only be specified relative to space within a defined volume of sediment, not in relation to some hypothetical (and currently unknown) ancient population of plants [76]. Consequently, each sample within our dataset is a volumetric fraction of a constrained spatial population, thereby requiring both qualitative and quantitative characterization to assess the degree to which that sample might reflect broader agricultural strategies at a site or regional level. Put more plainly, the presence and absence any species within an assemblage does not directly correlate with patterns of human–plant interaction in antiquity but rather is a consequence of what survived pre- and post-depositional processes, what is present within the given volume of sediment accessible to archaeologists, and—in turn—what was actually sampled and subsequently not lost to various processes post-excavation.

Multiple strategies have been proposed to cautiously account for these issues in cross-regional datasets, thereby allowing us to draw larger conclusions about human–plant interaction over the *longue durée*. While quantitative studies via direct statistical analyses have been conducted, these have had greatest efficacy when applied to smaller regions [77]. More often, either in intra- or interregional discussions, more exploratory techniques have been applied. This has included visual, semiquantitative geographic representations wherein ranges in the number of identified specimens (NISP) of a given taxon are represented by abstract symbols [78], semiquantitative analyses employing the Representativeness Index (RI) [79], as well as semiquantitative applications to characterize regional patterns of presence–absence that combine qualitative sample characterization and distributional data (ubiquity) with diversity indices like the Shannon–Weaver Index and Index of Heterogeneity [19], to name but a few. Regardless of the approach taken, any hypothesis testing related to leguminous crops within and across agricultural systems, toxic or otherwise, will require some degree of accounting for the issues discussed in Section 3. This could take the form of constraining analyses to sites wherein systematic collection procedures were employed, but, ideally, any proposed method would possess the ability to engage meaningfully with less-than-ideal datasets from earlier periods of scholarship.

7. Conclusions

While this discussion is clearly preliminary, it is hoped that it will offer a potentially useful avenue for future inquiries. Collectively, only a few paleoethnobotanical tools have thus far been proposed for the identification of strategies related to the management of risk and/or uncertainty or the degree of resiliency that existed within ancient agricultural systems. Though legumes present problems still in need of resolution, they provide an additional, novel possibility for identifying how food producers strategized in relation to dynamic environmental conditions. Rapid improvements in the quality and quantity of archaeobotanical data offer increasing hope for higher resolution interrogation of ancient agricultural strategies in relation to shorter- and longer-term stressors, especially those related to climate. Given that our climatic data is also consistently improving, the types of legumes exploited—and the combinations in which they were exploited—could conceivably form a powerful piece of proxy evidence to be tested diachronically against regional and local climatic swings. Similarly, they provide promise in exploring how food producers navigated more localized landscape affordances. Certainly, the variables dictating an individual agent's selection of a given cultivar are myriad, but by focusing those species requiring higher labor requirements and/or specialized knowledge for their effective exploitation, it will be possible to test our modern assumptions within a diverse array of frameworks for understanding human–environment and human–plant interaction.

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Interpreting Collapse in Norse Greenland: Why Similar Data Produces Different Conclusions

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Abstract

This paper examines interpretations of depopulation in Norse Greenland between the 14th and 15th centuries CE. Using in-depth interviews with 13 experts working on the environmental, social and economic dimensions of settlement and depopulation in Norse Greenland, we examine the different interpretations of decline by experts using the same data. Our analysis reveals a geographical and disciplinary pattern of interpretation that reflects the institutional and disciplinary cultures, successive paradigms, and placed ideas about human–environment interaction. We examine the interplay between data and interpretation to uncover key developments in knowledge of the past and ideas about both the role of climate, ecology and social, economic and political processes in the end of the Norse settlement in Greenland, as well as their wider persistence in the North Atlantic region. In particular, we emphasise the importance of active reflection on disciplinary training, schools of thought, and national narratives in both the interpretation and perceived relevance of the past.

Keywords: research culture; knowledge production; archaeological interpretation; analogy

1. Introduction

This paper examines narratives of settlement decline in Medieval Norse Greenland during the conjuncture of climatic fluctuations of the Little Ice Age, European political economic changes and cultural contact with the Inuit in the 14th and 15th centuries. Using a comparative analysis of interviews with academic researchers working on the disappearance of the Norse in the 15th century, we assess the different interpretations of decline by experts using the same data. The Norse settled southwest Greenland in the late-10th century CE, following expansion from Scandinavia and occupation of parts of Ireland, the British Isles and the Low Countries, and the establishment of permanent settlements on the Faroe Islands and Iceland (Figure 1). This Norse diaspora spanned the 8th to 15th centuries CE, starting with the outward movement from West Norway in search of new opportunities [1] most likely by young enterprising groups in search of land for settlement [2], and ended in the 15th century with the unrecorded end of settlement in Greenland [3–5].

Climate change, environmental degradation, political economic changes and cultural contact with the Inuit have been argued to play a key role in the ultimate fate of Norse Greenland (e.g., [6–8]), although each of these explanations are disputed (e.g., [3,4,9]). It is not our intention to identify the most convincing explanation for the end of Norse Greenland, but rather to examine how researchers with access to the same evidence arrive at

different conclusions. To understand the relationship between "evidence" and "reasoning" in these narratives, we build upon recent knowledge production debates in archaeological theory together with a geography of science perspective. In so doing, we focus on how interviewees articulate their narratives—using a combination of data, method and theory—and what influence geographical context (situated knowledge), discipline and research traditions have on interpretation and thus the production of knowledge of the past. Our overall aim is to understand how thought processes operating in the present produce multiple different knowledges of the past, and particularly the articulation of social, environmental and climatic determinants of the disappearance of the Norse.

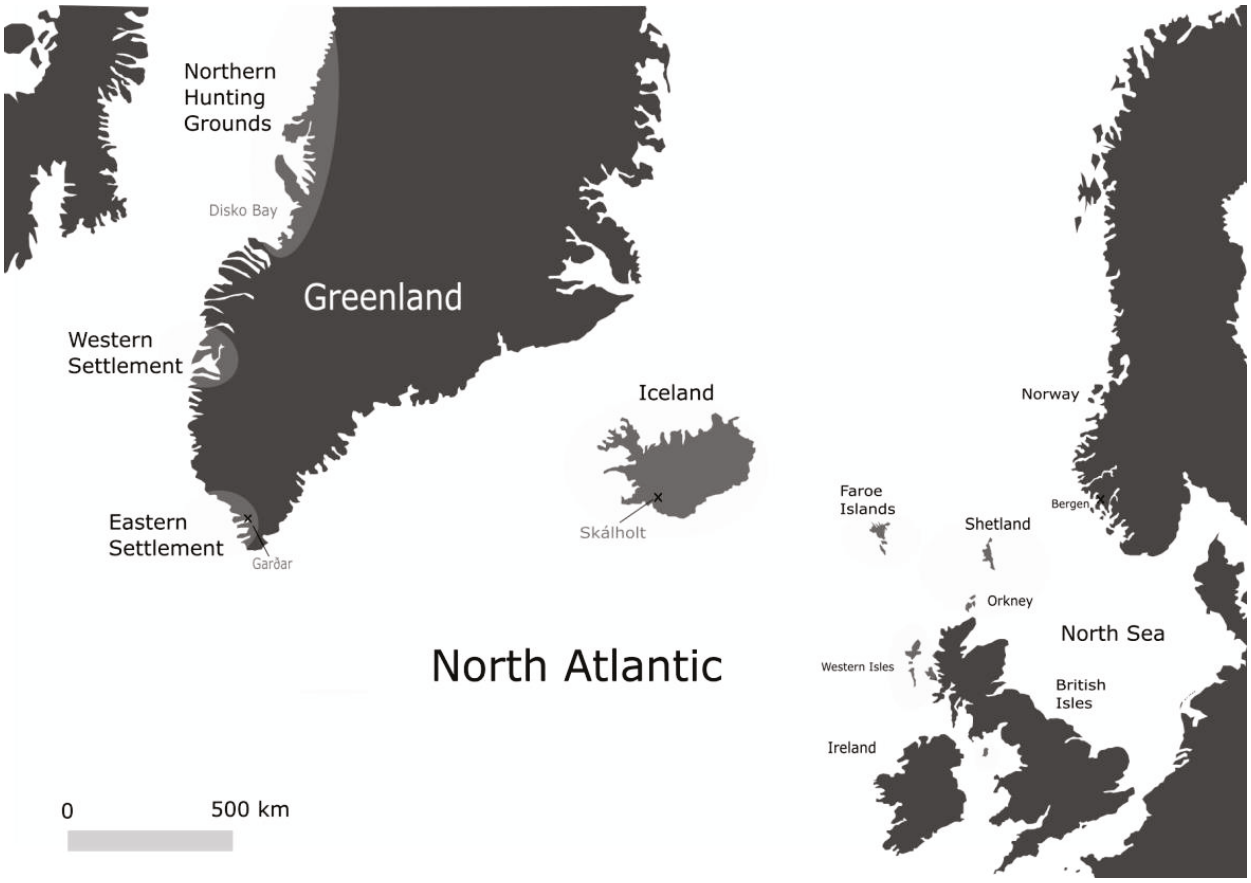


Figure 1. North Atlantic islands, showing Norse settlement areas in grey, including church farms in Greenland (Garðar) and Iceland (Skálholt). Map the authors own and produced in Inkscape v1.4.

1.1. Context: The Decline of Norse Greenland

Feature articles in scientific magazines and the wider media often draw attention to different explanations of the "mystery" surrounding the fate of the Norse settlers in Greenland (e.g., [10–12]). Various theories are proposed—often depending on their correspondence with academics who study the North Atlantic—including climate variability, environmental degradation, economic and political changes in Europe, or conflict with the Inuit [13,14]. What was changing in the late medieval period? And what impacts can be connected with the end of settlement in Greenland? These are questions taken up in academic research, focusing primarily on the relationship between impacts, adaptation and vulnerability [3,4,15–18]. But although it is known that settlement came to an end and there is significant evidence for changes to subsistence, trade, climate variability, how this evidence should be interpreted remains less clear and is largely unresolved in the literature [5]. Multiple different explanations have been provided between the 18th century and present day, explaining the disappearance of the Norse in the 15th or 16th centuries.

Such explanations have ranged from socio-cultural factors, such as conflict with pirates and the Inuit, and political-economic shifts, like declining trade links with Europe causing isolation, to a more recent proposals that environmental factors, including the decline of the subsistence system causing the end of the settlement [4,19,20]. There are two important points to distinguish regarding the interpretation of the late settlement period in Norse Greenland: first, the interpretation of different types of evidence (i.e., historical sources, archaeological materials or ecological and climatic records), and second, the weighting of this evidence—how it is articulated or 'cabled' as Chapman and Wylie [21] have put it—in reasoning about different causes of depopulation.

In Arneborg's (2015) review of evidence for Norse "abandonment" of the eastern settlement, she builds her argument on a publication by Dugmore and co-authors [3]. As Arneborg proposes, "it has been argued (Dugmore et al., 2012) that *abandonment* should be explained by a combination of external factors (climate changes; changes in European trade systems)." ([22]: 257 [emphasis added]). Whilst this publication attributes external factors (i.e., climate change and political-economic change in Europe) to the end of Norse settlement in Greenland, not all the co-authors adhere to a single narrative in previous or subsequent publications. Clearly, ideas evolve and there are circumstances when quite different interpretations can diverge or intersect in terms of both substance and emphasis. To illustrate this point, the co-authors of Dugmore et al. [3] can be divided into separate groups based their publication history. In an earlier work by Dugmore, McGovern and Keller [23], climate change, trade and hostilities with the Thule [Inuit] culture are reasoned to be responsible for "social collapse" caused by a failure of communal provisioning, followed by subsistence crisis and starvation. Arneborg in 2008 and 2015, and Vésteinsson writing in 2009, argue, conversely, that there is limited evidence that communal provisioning was stressed in the final years of settlement. Their argument rests on the assumption that cultural and economic isolation from the rest of Medieval Europe was responsible for the abandonment of a comparatively "poor" quality of life "irrespective of how much could be put on the tables" ([24]: 149). Lynnerup, writing in 2011, provides a similar narrative, arguing that evidence of church-building at the end of settlement should be interpreted as a symbolic attempt to create unity at a time of crisis and decline [25] and that there is little evidence to suggest the Norse starved to death [26].

While a broad consensus exists about the processes driving the end of settlement—including evidence of social inequality, subsistence adaptation strategies and eventual cultural limits to adaptation—there is no consensus about the fate of the Norse settlers themselves [3,15,16,18,27]. Notable is the lack of analysis and debate within the literature about the ways the evidence for the end of settlement is interpreted. Within the published literature, there is little evaluation of the reasoning as to why famine or abandonment occurred and little discussion between the proponents of these hypotheses about why ideas may be mutually inconsistent, intersect or change. Some authors appear on papers that apparently contradict their existing hypothesis, and though interpretations may change, differences in hypothesis and interpretation can be lost in multi-authored articles or lack clarity on how and why interpretations have changed—for example, owing to new evidence or applications of different forms of theory and method. Interviews with active scholars working in the field (see Section 3) show this variation in interpretation, with some participants advocated "famine" and "extinction" of settlement, but the same participants contribute to publications suggesting that depopulation was the result of abandonment [16,28]. Hence, while a broad consensus that the Norse settlements ended *because* of the impacts of climate variability and economic change in, and isolation from, Europe, *how*—by way of interpretation of evidence—Greenland came to be depopulated in the late-14th and early-15th centuries CE remains unclear.

Interpretations based on variably detailed, partial and incomplete evidence from a range of environmental and cultural sources are clearly evolving, diverging or converging, with shifting emphasis on overarching drivers of change. Hence, this analysis sheds important light on the role of interpretation and reasoning with data within the process of knowledge production of the past. We argue this has a potentially crucial role in understanding archaeological and environmental records in the final phases of Norse settlement, including interpretation of limits and barriers to adaptation.

1.2. Environment and Archaeology in the North Atlantic

A major research theme in Medieval Greenland and the wider North Atlantic has been to understand human–environment interaction through the theoretical and disciplinary frames of human ecodynamics, historical ecology and environmental archaeology [29–31]. The North Atlantic Biocultural Organisation (NABO) was founded in 1992 to improve communication and collaboration between the growing community of scholars studying the archaeology and palaeoecology of the region. Regular research meetings organised between active researchers in the region facilitated an increasing number of interdisciplinary projects spanning the humanities (including archaeology and history) and natural sciences and multiple academic institutes across Europe and North America [30,32]. Such collaborations came together under the assumption that human activities in the North Atlantic have been inextricably interwoven with their environments [33]. These studies have focused specifically on human response to environmental changes using a range of analytic tools from the social sciences, humanities and geosciences with significant success in the last 40 years—improving our understanding of the impacts, perceptions and responses to environmental change across the North Atlantic [32].

Because the Norse settlement of Greenland occurs at the northern limit of agriculture, and the five centuries of occupation extend from the warm conditions of the Medieval Climate Anomaly (~950–1250 CE) to the profound climate changes of the Little Ice Age (~1250–1860 CE), human interactions with the changing environment has become the dominant research theme [5]. Since the 1970s and 1980s, archaeological research has moved away from historical sources towards the consilience of archaeology and the environmental sciences [22,33]. For some, this has created a bias towards environmental drivers for the end of settlement, but at the same time the emphasis on environmental determinism and maladaptation of the 1980s and 1990s has been replaced with an increasing consensus that adaptive flexibility and cultural limits were responsible for the end of settlement [3,22,27]. This accumulation of evidence has coincided with an expansion of multidisciplinary and interdisciplinary research of human ecodynamics across the North Atlantic and Greenland especially [32]. However, the increasing size of the epistemic community, the accumulation of archaeological data and access to new methodologies does not guarantee consensus among researchers. It is necessary, therefore, to examine how different interpretations of this evidence are created and to investigate what processes create this difference.

2. Methodology

A qualitative research design is adopted here to examine the relationship between evidence—what forms of materials, observations, interpretation, analysis and models—and reasoning—argument/dialogue, rhetoric and narrative—were used to articulate stories about the past [34–36]. As we are interested in the articulation of evidence in its written form, interview transcripts (texts) formed the basic unit of analysis. Theory from archaeology and sociology of science provided an essential framework for the interpretation of interview texts.

A series of semi-structured interviews were organised with researchers of the Medieval Norse settlements in Greenland. Interviewees were selected using publication frequency analysis to target prominent researchers and snowballing to target other researchers [37]. The semi-structured format covered six broad questions (Box 1) about the processes driving the end of settlement in Greenland. The flexible interview format allowed a narrative approach to be adopted where interviewees were encouraged to articulate storylines [38,39]. This extended format was particularly important for encouraging more expansive explanations of evidence and reasoning for a chosen hypothesis. Interviewer reflexivity was also necessary to prevent knowledge bias but also expansion on key themes raised by participants [38,40,41]. This required self-reflection on potential knowledge-bias associated with interview questions and maintaining space for open dialogue with the research participant [41].

Box 1. Interview Questions

Q1.	What processes do you consider the primary drivers of the end of Norse set-tlement in Greenland?
Q2.	What were the causes of population decline in Norse Greenland after the peak in the mid-13th century?
Q3.	What happened to the Norse population at the end of settlement in the 15th century?
Q4.	What evidence do you use to support your hypothesis?
Q5.	With what certainty do you consider your hypothesis to be true?
Q6.	What is your appraisal of other existing hypotheses for the end of settlement and how do you repudiate these claims?

Researchers were recruited by email and sent an outline of the discussion format and question in advance of the interview. In total, twelve one-hour in-person, online and phone interviews and one email correspondence were conducted. Interviews were then transcribed for analysis in QSR NVivo 12 data analysis software. This software was used to organise interview data into categorical (descriptive) and analytic (thematic) codes [38,42]. These qualitative codes allowed an inductive grounded theory method to be utilised to generate themes from the interview transcripts [43,44]. These categories and themes were then used to structure further analysis of participant discourse.

Critical discourse analysis (CDA) was used to compare texts and examine the underlying semantics of the interview text. CDA is a method of eliciting the meaning, beliefs and the underlying social context of a discourse through analysis of the content and structure of a text [45–48]. CDA focuses on power through work association, emphasis and metaphor within vocabulary, as well as structural organisation of the narrative to build specific storylines [48]. Identifying how evidence was structured and reasoned within participant interviews was essential to understanding how disciplinary training, geographical and social context, and analogies were used to interpret and reason about the past [49]. This is an essential step to interpreting the articulation of interview participants' arguments. Arguments, according to Lucas (2019: 118–124), are constitutive of two elements: premise and conclusion. The premise, which includes evidence and reasoning, is used to justify the conclusions. CDA can be used to examine how such evidence is articulated by examining the semantic language choice used when justifying one's conclusions (Mayr and Machin 2012). An example in academic research is the use of theory to make sense of data. For example, systems perspective articulates social and ecological data through a framework and keywords that should be consistent with the existing systems literature [50].

The choice of theory invites a further step of analysis: the situated context of the research participant. The local and national context of researchers often influences their choice of research tradition and disciplinary orientations [51]. For example, environmental

archaeologists from the United States may emphasise environmental variables but downplay social and cultural mechanisms leading to the end of settlement in Greenland. The situational context of the interviewee would therein be seen as essential to the interpretation of archaeological and environmental data and structure the relationship between evidence and reasoning in the narrative.

3. Results

In the first step of analysis, we focus on the relationship between the hypotheses and drivers of decline. Figure 2 shows a summary of narrative themes, starting with the drivers of change and ending with the end-time scenario(s). A detailed table shows the narrative connections between driver, capacities to respond, population impacts, and processes and outcomes of settlement decline by each interview participant (see Table S1 in Supplementary Materials). This shows a broad consensus between researchers about the exogenous drivers of decline and the evidence of the adaptive strategies adopted by Norse settlers to mitigate such impacts. The subsequent impacts of these processes, at the end of the settlement period, differed between interview discussions. The most common hypothesis, adopted by nine interview participants, was the total abandonment of settlement by the mid-15th century. Eight of these scenarios involved the return to Scandinavian ancestral homelands and the North Atlantic islands and one explored the possibility of extension onto North America. Famine, loss at sea and cultural conflict were also discussed as end-time scenarios, where a remaining population died in situ as a result of climate impacts, economic (and social) isolation and/or hostility with the in-coming Inuit culture.

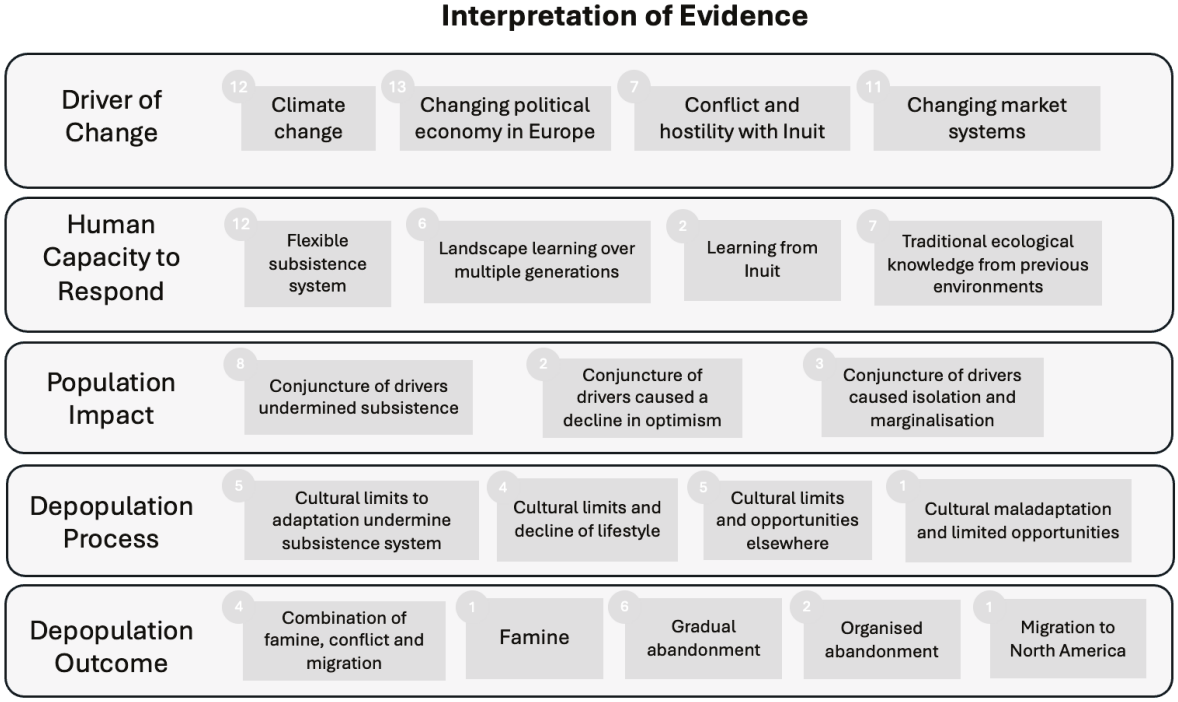


Figure 2. Organisation of descriptive themes into drivers of change, human capacity to respond (to change), population impacts, depopulation process and depopulation outcome. A number is provided on each descriptive theme (or code) denoting the number of participants referring to the theme.

It is notable that participants stressed similar drivers of decline and adaptive strategies in response to these drivers but diverge in their hypotheses about what happened at the end of settlement. Evidence of declining returns from farming, political and economic

isolation from Europe and to a lesser extent, hostility with the Inuit culture were cited in almost all interviews as drivers of the end of settlement. But why, if there is broad agreement about the processes driving the end of settlement, is there a divergence in the end-time hypotheses? To answer this question, interview narratives were examined for links between the evidence and theory used by participants to interpret, infer and articulate their hypothesis. This was essential to construct an idea of how participants draw multiple lines of evidence together using theory and reasoned judgement of evidence (to justify what is included and excluded) in the articulate a given narrative.

3.1. Evidence and Absence

Interview participants can be divided into two primary categories: those who argue the Norse abandoned the settlement areas for opportunities elsewhere and those who believe the Norse succumbed to a combination of starvation/famine, loss of life in hunting or boating accidents or conflict with the Inuit. We will examine in turn the evidence and reasoning used to articulate these positions. All interviewees qualified their responses with an acknowledgement that the level of certainty is limited by the availability of data and what can be inferred from reliable evidence. Most interviewees focused on the interplay between the chronologies of farm abandonment and modelled demographic changes in Greenland from the 13th and 14th centuries onwards. Participant 1 and Participant 2 cited evidence of reduced vegetation disturbance and household occupation using a combination of pollen and survey data and radiocarbon dates (Box 2). The abandonment of marginal land in the Eastern Settlement in the 14th century and the absence of new farms in core areas would suggest a declining population. However, the abandonment of these sites does not infer depopulation—as acknowledged by both researchers. This is a point raised by Participant 3 and Participant 4, who were sceptical of this interpretation of abandonment (Box 3). As they explained, farm abandonment does not necessarily mean a decline in population, as the population could reorganise or reoccupy different parts of the landscape. Comparative evidence of abandonment and settlement reoccupation in Iceland was cited in support of this scenario. This scenario is also considered by Participant 5, who explains that population movement between farms is a key question still to be resolved, as the interplay of between abandonment and occupation of sites produces multiple different scenarios.

Box 2. Abandonment

> What we would do to pollen analytically is, when we start to see the restoration of shrub (willow, birch, etc.) in our records and the amount of grass is going down and the other weeds indicates that the agricultural activity is perhaps on the decline. When all that is happening, you're getting a threshold crossing event. You can assume, with a severe reduction, that it has been abandoned. But of course, they might have just moved another 500 yards away, but we're not getting that. We're getting the vegetation point of view and we have to make inferences that explain that. Its then a step change from the pollen evidence to explain that people are leaving because farming is becoming difficult. [. . .] But we don't see that, so you have to connect this data with the economic context and associated demographic factors. These factors are raised in the background but obviously the pollen doesn't say that. (Participant 1)
>
> Is it because there are less people [in a slow decline] or are there more and more people concentrated in the core areas? I don't think so because all of the farms that we do have in the core areas, they are mostly traced back to Landnam. So, you don't really see new farms, but you do see a few new churches in the core areas. And that could of course be because you have more people coming in, so you need more churches—two churches, I think, are new and built after 1250 AD. So that might indicate that you have more population coming into the core area, but I think you basically have fewer and fewer people. I think that Lynnerup is right. (Participant 2)

Box 3. Alternative interpretation of abandonment

> I suspect there weren't that many of them left, but one of the things we do know is that people have a remarkable attachment to particular places. [. . .] although the story in Greenland is so enigmatic, it's what we know about people and also that there are changes and there are times when people will get up and go (leave) but the difference between abandoning the valley, and moving down valley, about abandoning the uplands for the lowlands – that sort of movement. (Participant 4)
>
> One thing to realise is that we can see abandoned settlements, but we don't really know about the population. We're assuming that an abandoned farm means one family less, but that is not really the case because we know in Iceland for example that there are lots of abandoned farms, but they are just going somewhere else. Usually what is happening is that they are just becoming ten-ants or landless labourers. (Participant 3)

Resolving uncertainty of where people went following the abandonment of marginal areas required inference or abstraction to explain social processes that are not evident in the archaeological record. Because the evidence is not sufficiently resolved to explain the outcome of farm abandonment (cause and effect), this becomes a matter of inference from inductive or deductive reasoning. Participant 6, for example, deduces an abandonment scenario because of limited evidence for excessive violence or economic decline in the 14th century. They also interpret the evidence of household abandonment in the wider historical context of Europe and the North Atlantic—a decline in optimism in Greenland and opportunities for livelihood elsewhere. For this reason, they argue that the elites in society would organise a departure because of a decline in relative prosperity. For Participant 4 and Participant 3, the inverse of this scenario is true. They argued that there was little incentive for elite groups to move to Iceland because they would become "penniless refugees" by moving to Iceland or Norway. So, this argument goes, if the purpose of occupying Greenland was to claim land and establish a following, a return to Iceland or Norway would have meant submitting to feudal lords.

Because interview participants drew upon multiple lines of evidence, they explained that evidence from the settlement areas required contextualization in light of broader environmental, economic and social context. The challenge of articulating social change from limited evidence is discussed in Participant 1's interview.

> It's then a step change from the pollen evidence to explain that people are leaving because farming is becoming difficult. You can think of this as either a determination of climate or prolongation of the little ice age. But we don't see that, so you have to connect this data with the economic context and associated demographic factors. These factors are raised in the background but obviously the pollen doesn't say that.

The conclusions that are derived from pollen evidence are combined with the economic and demographic context. This articulation of evidence resembles Wylie's [52] "cabling" metaphor; evidence does not speak for itself but is inferred by combining multiple strands of evidence.

3.2. Absence and Inference

With evidence so limited at the end of settlement, a significant sticking point between researchers was the use of absence as evidence. How absence is interpreted and combined with other evidence can produce multiple different scenarios [53]. In this case, different expectations of what should be found in the archaeological record and historical accounts led to different interpretations of absence. The absence of evidence for subsistence crisis and conflict was cited in several interviews as a case for abandonment. However, absence

of evidence was also questioned as a "weak" or "partial" interpretation of human and environmental records in Norse Greenland. Here, we focus on the absence of boats, bodies and elite material culture as evidence for different depopulation scenarios.

One issue raised by several interviewees with the abandonment hypothesis was the absence of ocean-going boats and the absence of local wood and iron resources for construction of sea-worthy vessels.

> Leaving Greenland is a problem. To me, the problem is that they can't build big ocean-going boats in Greenland. They don't have the wood and there is no evidence that they ever maintained ocean-going vessels. (Participant 4)

> Where did they get the boats? [...] Even so, if you think about the carrying capacity of the boats, and a bit of back of the envelope calculations you're talking about at least a hundred round trips between Iceland and Greenland. And that just doesn't seem to be something happening without someone noticing. (Participant 3)

> I don't think they had any ocean-going boats. They were really dependent on Norwegian boats. So, they depended on what was going on in Norway. (Participant 2)

The absence of evidence for ocean-going boats in historical and archaeological records suggests that the Norse did not have the capacity to leave Greenland. Historical sources do mention that 6-oared boats and toy boats of the same design have been recovered from the Western Settlement [54,55], but these boats were not ocean-worthy.

But whereas Participant 3 and Participant 4 suggest that this infers a limited capacity for abandonment, Participant 2 does not consider this adequate evidence that the Norse could not leave. As they argued, "many boats were blown off-course and there must have been unacknowledged voyages between Iceland and Greenland." Participant 6 takes this point further explaining that there would not be historical evidence for the abandonment because it would limit their legal claim to Greenland if they were to return.

> "I think there was never an acknowledgement that nobody was there. Either they thought that there were still people there, or they chose to believe that it was easier politically and economically and they wanted to maintain rights to property."

This raises a significant question about the nature of absence in the archaeological and historical records to which we will return in the discussion: can a complex sociopolitical rationale, such as this, be inferred from the absence of historical evidence? The relative absence of boats was also countered with the argument that an absence of bodies found in homes provides further evidence that the Norse did not stay. However, an absence of bodies is difficult to establish when very few building from the very last

Phase of occupation in the core areas of the main settlement areas have actually been excavated.

The absence of bodies lying in houses and any osteological evidence of starvation is a sticking point for the famine hypothesis. Lynnerup's [56] analysis of Norse skeletal remains revealed no evidence of starvation nor diseases associated with excessive hunger. Furthermore, the absence of bodies in households has often been considered a case in point that the Norse did not succumb to starvation [22,26]. Table 1 provides a summary of hypotheses explaining the absence of evidence for famine and bodies in houses. Participant 8, Participant 2 and Participant 7 all acknowledge that there would probably have been casualties during the decline, but the absence of "skeletons in the houses" is considered evidence that food shortages were not widespread. Participant 7 explains that abandon-

ment could have, in theory, taken place over multiple centuries with a small, vulnerable population remaining that could not support subsistence.

Table 1. Reasoning from interviewees to dismiss starvation as a drivers of Norse settlement termination.

Starvation
There must have been casualties along the way but it's silly to say that they all died standing there because there would be skeletons all over the place. People starving to death in their houses couldn't possibly bury their dead. (Participant 8)
I don't think we have any evidence of hunger. We have all those bones. There are lots of seals and lots of fish, so I don't think that was necessary. . . we are talking about the Eastern Settlement where you have seals, and you have some reindeer. And there were not that many people. How many seals do we need to support that many people? I'm not a statistics person so I don't really know. . . I mean, I don't think it takes too many seals to feed a population of that size, does it? (Participant 2)

However, Participant 3 and Participant 4 argue that the absence of bodies still provides little evidence that they did leave. Three significant points are raised here: the lack of preservation, lack of representative archaeological evidence and the possibility of mass death at sea. Participant 3 and Participant 4 cautioned against the suggestion that absent bodies infers the abandonment of settlement and therefore that the Norse did not succumb to famine. Their argument rests on the point that the absence of bodies from the limited number of sites that have been excavated is not adequate evidence to infer a lack of evidence for the in situ deaths of the last Norse Greenlanders. Participant 4 makes direct reference to Pompeii, arguing that the absence of bodies could suggest a whole array of possible scenarios, including poor preservation or the consumption of human remains by animals. Participant 3 also explains the importance of Christian burial in Norse society, explaining that it was an essential duty for the dead to be inhumed soon after death. Such arguments about the representation of archaeological evidence were also applied to the analysis of material culture.

Excavations in the Eastern and Western Settlement have recovered a limited array of status finds—or elite material culture—even on high-ranking manor farms (Arneborg 2000). The absence of elite material culture was discussed in several interviews as evidence of organised abandonment of the settlement. As Participant 7 explained, the lack of elite material culture at significant sites such as Gardar and other church farms suggests that precious metals and holy objects were removed before the Eastern Settlement was abandoned in the 15th century (Table 2). Participant 4 and Participant 3 queried the extent to which the Norse Greenlanders ever had great quantities of elite material culture. As Participant 3 explains, "sampling error" from archaeological excavations can also overrepresent the relative level of elite objects from each site. A further issue for archaeologists in Greenland would has been the lack of systematic excavation carried out on major farms in the late 19th and early 20th century. This, Participant 3 suggested, could have caused the loss of great quantities of material culture. Furthermore, Participant 3 questions the extent to which the Norse ever had status goods as we would expect from these sites (Table 2).

Table 2. Interviewees reflecting on the lack of known bodies.

Christian Burial Rites	Preservation & Sampling Error	Loss at Sea
That is of course also a counter argument because someone buried those people. There would be very strong cultural reasons to bury people. For one thing, it's a Christian duty, another thing is that if you don't bury them, they're going to walk. From our standpoint, people would go to extreme lengths to get people buried. So, I agree that this would be a lot more persuasive if we do see loads of bodies lying around inside houses. (Participant 3)	In Pompeii, there has even been a bit of trouble finding the bodies there. I know that many of course may have run down and died by the beaches. . . And again, if the bodies lay where they fell? And how they may have been consumed or disappeared? We know that in GUS, they ate the dog. If people died and they haven't eaten the dog, then no prizes for guessing what the dog then eats. So, there could be a variety of ways where the bodies left lying where they fell could fail to preserve. (Participant 4) . . . it is important to recognise that there are very few late-period excavations. We have a whole lot of unexcavated structures out there. (Participant 3)	A tidy way of disposing of everybody—though I recognise that this a type of special pleading—is that they all decide that they do want to get out and they all pile up in the boats, they all get halfway out into the fjord and a storm comes up and they are all drowned. So, there they are, all of the bodies are at the bottom of the ocean so you're not going to find them. (Participant 3) It's a pretty small population, and the capsizing of one boat, on the way back to Iceland or whatever, would have had massive consequences. (Participant 7)

3.3. Models, Comparison and Analogies

Theoretical models, ethnographic analogies and comparative methods were all used, in interviews, to overcome absence in the archaeological record. This section will cover each of these methods in turn. First, comparisons with other Norse archaeological contexts in the North Atlantic where contemporaneous historical records are available. Second, analogies with ethnographic processes used to explain the presence or absence of material culture or likely depopulation scenarios. And third, models and scenarios were used to construct hypotheses and to provide evidence of likely social changes and environmental limits. As we will argue, direct and indirect analogies were used as "paramorphic models" to overcome absence at the end of Norse settlement in Greenland [36]. However, the use of different analogies to explain social processes in Greenland can produce contrasting models and scenarios depending on how evidence is triangulated.

The common cultural heritage of Norse Greenland and Iceland has provided a strong basis for comparison of the settlements in Greenland—without any direct, contemporary historical record—and the historical records and legal texts in Iceland [57]. Because there is a clear cultural link between these settlements, it has long been used as a basis for direct ethnographic comparison and particularly to explain social and economic organisation of the Norse settlement areas in Greenland [15,23,27,58,59]. However, the differences in geographical contexts do limit this comparison because of the relative isolation of the Greenland settlement and the different resource systems that led to different styles of

sustenance, trade, clothing and settlement structure [60,61]. However, the extent to which this can indicate anything about the end of settlement is unclear.

Indirect analogies from different cultural and geographical contexts were used throughout all interviews to explain the absent Norse population at the end of settlement in Greenland. Table 3 provides a list of the analogies and their geographical contexts. Contemporary experiences of intra- and inter-continental migration were highlighted significantly as evidence of "ordinary human behaviour."

Table 3. Indirect analogies invoked to explain key characteristics of the ending of Norse Settlement.

Indirect Analogies	
Geographical Location	**Description**
19th century Australia	British colonists in Australia
Denmark	Decline of adolescent demographic from rural towns and villages in rural Denmark
England	Decline of adolescent demographic from rural towns and villages in Northern England
France (Dunkirk)	Allied expeditionary force rear guard at Dunkirk (1940)
Iceland	20th century abandonment of isolated communities in Iceland
Middle East	Youth migration to Europe from Afghanistan, Iraq and Syria
North Africa	Youth migration from North Africa
Norway	20th century island life
Scotland	21st century inequality in Edinburgh and Glasgow
	19th century abandonment of the island of St Kilda
16th century North America	European colonisation of North America (Virginia)

> I like to ask 'what adds up as ordinary human behaviour?' and that's why I keep putting in what we know today because today there are young people moving from North Africa because they want to earn money and get a new life, so it is young people moving in search of opportunity, and I think that is a very, very old story. And I think that's what makes it fit because the pieces of the puzzle come together. There is a push and pull factor over two-hundred years, and people could easily go back into the bigger Norse society. (Participant 7)

> Well, look around and see who is moving away from North Africa and Afghanistan. It's all the people from 16–18 years of age, all of the young people are leaving. They have the strength to leave and to build up a new life somewhere else. (Participant 2)

> "In the news, we see cases of people migrating away from the Middle East and Iraq because they cannot sustain themselves." (Participant 8)

The analogies used here reflect no common cultural or environmental driver to leave, but instead what Participant 6 has described as the "evaporation of [relative] optimism" among young demographic groups. As Participant 7 explains, this analogy fits the puzzle and what would be considered key motivations to leave—pushing and pulling young groups away from Greenland and back to Iceland and Scandinavia. Their argument is that this fits what normal human behavioural traits, as an adaptation strategy to survive and as an opportunity afforded by social networks across the North Atlantic.

Analogies were used in both theoretical and mathematic models of end-time scenarios. The demographic analogues of migration in Europe, North African and the Middle East provided a basis for Participant 7's demographic model scenarios.

> I did some research on demographics, and we can actually model a small number of people leaving on average each year. And this will draw the population below sustainable levels. [. . .] We're seeing it in the Mediterranean everyday now. Its young people who feel that they can make a better living elsewhere. So, I think that being the number two or number three son in a reasonable farm, in the 13th century, in Greenland—well, who is going to inherit? Even though Greenland is huge, the arable land available for getting fodder is after all only of a certain size. So, what can you do if you are son number three? And you need to get some cattle going to get married. And again, to get married with the population of only 2–3000 the selection might not be that huge.

The scenarios explored in Participant 7 demographic model, as he explained, were developed from his experience of Danish migration patterns, with young groups moving from rural towns into urban areas. In this model, Participant 7 explored the impact of population decline on population size and reproductive rates. Key variables in this model were developed from a combination of input data from Norse Greenland church burials, ethnographic data from contemporary Iceland and assumptions based on historical texts and assumptions of stable population size.

3.4. Geography, Discipline and Nationality

Two major themes arising from all interviews was the influence of local and national research traditions and field experience on the interpretation of evidence. Because interview participants spanned four different disciplines (archaeology, anthropology, history and geography) and several research traditions (environmental, social, medieval (pre-historic) and historical archaeology, biological anthropology, palynology, soil science, environmental geography, and history), this also had a significant bearing on the articulation of evidence. Table 4 provides a summary of the nationality and discipline of each interview participant.

Table 4. Disciplinary and national backgrounds of the participants.

Name	Discipline	Nationality
Participant 1	Geography (Palynology)	British
Participant 2	Historical Archaeology	Danish
Participant 3	Zooarchaeology	United States
Participant 4	Geography (environmental, interdisciplinary)	British
Participant 5	Medieval Archaeology	Danish
Participant 6	Historical Archaeology	Icelandic
Participant 7	Biological Anthropology	Danish
Participant 8	Social Archaeology	Canadian, United States
Participant 9	Geography (Soil Micromorphology)	British
Participant 10	Historian	Norwegian/United States
Participant 11	Geographer (interdisciplinary)	United States
Participant 12	Geography (palynology)	British
Participant 13	Social Archaeology	French

Geographical and disciplinary differences were expressed in multiple interviews. Participant 8 explained that the way archaeologists, in particular, interpret evidence is

influenced by research traditions associated with different regions. For example, North American archaeology is intimately coupled with anthropology, drawing a great deal of theory especially from ethnology and the observations of cultural material practices [62,63]. In Box 4 they refer directly to the use of ethnographic analogy in North American archaeology. Participant 8 also discussed the influence of contemporary concerns, such as climate change, on research in Greenland. In particular, the influence of national research agendas is highlighted as a vehicle for funding but also understanding the relationship between human adaptation in the past and what it can tell us in the present. Participant 2 was more cautious about the influence of national research traditions on interpretations of human–environment interaction (Box 4). For Participant 2, Anglo-American researchers studying Medieval Greenland have been influenced by trends in academic discourse and paradigms in archaeology and geography, including environmental determinism in the 1980s and 1990s and climate change research from the 2000s. Anglo-American research in Greenland has been heavily influenced by environmental archaeology since the 1970s, whereas Scandinavian archaeology, by contrast remains within continental German research traditions that use historical sources to contextualise archaeological evidence.

Nationality and the "baggage" associated with research training in and experience of "temperate" environments was also discussed in multiple interviews. This theme was most evident in Participant 10's discussions of American and Danish archaeology and history.

> "[Participant 3] is not an historian, he doesn't know any of the histories from Norway, and he has never understood the basic Norse economy that was brought along to Iceland and Greenland. So much has been influenced by the Danes, who have nice fertile soil, and who find it very difficult to imagine a rural place without villages. Well, you can't have villages in a place where there are lots and lots of rocks…" (Participant 10)

For Participant 10, the lack of experience in hostile environments such as Arctic Norway have skewed the Danish (and Anglo-American) interpretations of Norse economies in Iceland and Greenland. But this failed to acknowledge the closer cultural and geographical connection between Iceland and Medieval Greenland. As Participant 2 argued, Icelandic cultural history has been an important ethno-historical analogy for understanding the organisation of Norse society in Greenland. Participant 2 went on to explain the historical context for national disputes over the North Atlantic islands:

> Because of the way they [the North Atlantic islands] were split up after the Napoleonic wars, the Norwegians never really forgave the Danes for that… Helge Ingstad wanted to say that the Danes don't really know their stuff because it isn't Danish culture… the Norwegians never really trusted the Danes to do a proper job because it was not their culture. (Participant 2)

This reflection on research history in Scandinavia provides an important insight into the disputed terrain of historical interpretation. The contested geopolitical and cultural history of the North Atlantic itself is a basis for contested knowledge claims, especially in the context of ethnographic analogy.

Box 4. Geography and Research Tradition

> Have you spoken to many North American archaeologists? Because North Americans are taught anthropology and you might find more of that in the North American audience. [. . .] I think [Participant 3] would be inclined to use ethnographic analogies. [. . .] a lot of the rea-son why there is the availability of money to do research in the Arctic is because climate change is (and was) a big research agenda. We wanted to understand how people in the past adapted to climate change and what sort of impacts this will have today. (Participant 8)
>
> I think that subjects such as climate studies, at least in the past and not so much now, had a bigger appeal to Anglo-American research. For instance, [Participant 3] and An-glo-Americans were more routed in what is happening in the time you're living in, so you try to bring that in. In the beginning it was over-utilisation, you were simply destroying the resources, which was of the time in the 1980s and 1990s. [Participant 3] was very much into that. And now comes the climate change phase and (their) very much into that. Whereas Scandinavians have more of a continental German research tradition where we go into the sources and we see what they can say and what we can deduce from them. [. . .] But when you have this very Anglo-American approach you go 'oh god!' because you can put it into a model and say this and this, but they forget that we have a source saying this. . . (Participant 2)

Demonstrable knowledge of "the field" was one-way researchers sought to overcome bias. Fieldwork and field experience were raised as important contexts for interpretation and contextualisation. In Participant 4's discussion of fieldwork and interpretation, he reflected on the specific importance of experience in the field together with an understanding of the broader regional dynamics.

> An understanding of the geographical differences between the North Atlantic islands and the broad political, economic and social context of the Middle Ages is essential if you are to contextualise archaeological finds in Greenland. It is sometimes possible to overread the importance of outliers from a single context. Contextualisation can suffer if materials are not understood in relation to the broader spatial, temporal and cultural dynamics. (Participant 4)

This quote reflects the importance of the contextualization of finds within the broader social and environmental dynamics of the North Atlantic. Knowledge not only of the field (local and regional environments), but also the cultural-historical context (historical texts and multiple archaeological contexts), were highlighted throughout interviews as essential grounding to interpretation. In this case, knowledge is not only placed in the field as location and expertise but results also from experience and accumulation of knowledge in one's field and through collaboration with other researchers.

A more direct reflection on the importance of the field as a space with which interpretation and knowledge production take place is reflected in Participant 5 and Participant 9's reflections on experience, deliberation and notetaking.

> . . . I didn't anticipate what an impact extended time in the field would have on my understanding and interpretation of life in Norse Greenland. (Participant 5)
>
> I'll have to get my notes to remember what we recorded and discussed in the field [. . .] a lot of this information on ruin groups and homefield management comes from discussions with Christian and Konrad in the field. (Participant 9)

In Participant 9's interview, he described the field as not only a site for observation but also discussion and deliberation between researchers with different forms of disciplinary expertise. He reflected on the scaling from soil profiles and samples that inform him of land-use and management practices, up to landscape and settlement scales of interaction

between sites. Discussion allowed his notes to be collected and contextualised in situ. For Participant 5, the extended experience of the field is essential to guiding the interpretation of such results and understanding the capacities and limitations on human activities in the Greenland environment. Historical and ethnographic information was important for the triangulation and contextualization of archaeological data (site location, use) about human–environment interaction, including historical hunting and stocking records and observations/experience of seasonal hunting and animal herding.

4. Discussion

It is clear from the interviews in this study that no granular consensus for the end of settlement exists within the active research community studying the end of the Medieval Norse settlements in Greenland. However, interviews and existing data show a broad consensus as to the drivers leading into the final stages of settlement in Greenland (see Table S1). All interviewees acknowledged the role of the deteriorating climate and increasing economic isolation from Europe, but the impact this had on the Norse population themselves remains contested. Interpretations of the same evidence produced different narrative of depopulation. This raises the question of how interpretation of the same evidence produces divergent conclusions. In the first instance, this question can be answered quite simply, as summarised in Participant 6's interview: "there is no longer any single-track hypothesis about why this place came to an end. We know enough to know there cannot be just one explanation." This is because there is a significant level of uncertainty raised by multiple lines of evidence and the simultaneous absence of clear archaeological evidence of famine or abandonment. In the section that follows, we will synthesise the key themes and theory discussed in this paper so far to explain the role of interpretation and how they are situated within distinct geographical and disciplinary networks.

4.1. Absence, Representation and Uncertainty

For participants in this study, absence was a significant point of departure. Disagreement about what can be inferred from the absence of ocean-going boats, skeletal remains in households and elite material culture revolved around questions of representation, preservation and significance. What can be inferred from the absence of elite material culture rests on expectations of what should be found in the archaeological context. The foundation of these arguments' rests on the interplay between evidence, absence and the use of theory and other resources to articulate the human activities.

Archaeologists and historians are always faced with absence. There are the absent subjects (or people), with which to animate the past, and the archaeological record is always partial, recoverable as traces of the full material assemblages of the past [53,64]. As Lucas [53] explains, archaeologists interpret and construct the past through the interplay between absent things and absent people. This leads to multiple different articulations of the past, using the fragments, or traces, of the past, to construct models or draw analogies with similar social phenomena from other spatial and temporal contexts.

4.2. Analogy and Models

Analogies and models have been used widely in research of Norse Greenland. Theoretical and quantitative models have been used to test the sensitivity of the Norse subsistence system and to consider different scenarios leading to subsistence crisis [56,65–67]. These models draw upon assumptions from analogies with Icelandic farming and ethnohistorical information from other societies in the North Atlantic. However, what such analogies can reveal about the past has been a persistent question in archaeology [68,69].

One criticism of ethnographic analogies is that they merely operate as a heuristic to ask "what if" questions [70,71]. For example, Participant 7's model of population decline uses population data from churchyard burials in Greenland but combines this with ethnographic assumptions from pre-modern Iceland and tests a constrained depopulation scenario that assumes the Norse emigrated from Greenland [56,72]. This model does, however, provide an essential building block in the debate about interpretation. By providing a scenario for decline it raises significant questions to be asked of the archaeological record: how do we corroborate evidence that the Norse emigrated using material remains in Norway or Iceland?

Another example of these "what-if" questions was raised in Participant 3 and Participant 4 interviews and two research publications featuring decline scenarios. Dugmore and colleagues [23] examined a range of scenario inputs and outcomes in their conceptual model of collapse, focusing on the interplay between resource availability and population size over time. The conclusion of this model and study was that the Norse succumbed to subsistence crisis and famine as "population decline forces a contraction in resource utilisation" [23]. This resulted in feedback loop forcing a continuing decline in both population and available resources [23]. However, population decline could also represent the same economic determinants that Lynnerup uses to explain the gradual depopulation [56,73].

In another model by Dugmore and colleagues [27] different population and subsistence scenarios are considered, using a comparison with the Inuit. Using an adaptive cycle diagram to frame different scenarios [74], they reason that different mixes of farming and hunting or a larger population may have delayed the decline of a mixed farming-hunting economy (possibly until economic contact with Europe was restored), but that hunting without farming represents an alternative social-ecological regime [27].

The use of analogical inferences in this study are highly varied and draw upon evidence from multiple different geographical and temporal contexts. Most analogies are based on what Currie [71] terms *indirect analogies*, where a group with no direct continuity with the group in question is used to explain social, economic and cultural dynamics. As Currie [70] has argued, such indirect or surrogate evidence can be likened to experimental interventions in scientific experiments—especially in biology. They operate to fill gaps as leverage points within the multiple strands of evidence that are used to assess hypotheses [69]. By actively discussing different models of decline, it would be possible for researchers to better understand the role of interpretation in different narratives. On these grounds, Currie [71] defends the use of indirect analogy to make the past empirically tractable.

4.3. Research Traditions and Geography

The flip side of this is the role that theory plays in articulating narratives. Choice of analogy and the models constructed from this are responsible for retroactively articulating strands of evidence into different configurations. For example, the relative influence of environment on subsistence depends on the way such environmental and social data is combined (e.g., systems theory), inferences used to articulate decision-making (e.g., decline of optimism, analogy with migration). Geography, discipline and research traditions play important roles in the interpretation of data—North American emphasis on environment and climate (environmental archaeology) and Scandinavian focus on continental German approaches to Norse (historical archaeology) [72,75,76].

Narrative plays an essential role in the production of knowledge claims insofar as it privileges certain evidence and articulates it into a clear storyline that "hides the discontinuities, ellipses and contradictory experiences that would undermine the intended meaning of its story." [34], pp.1349–1350. The narratives explored in this paper are pro-

duced through the articulation of different combinations of data, theory and social relations. Social and environmental information is articulated through the specific disciplinary and theoretical lenses through which evidence is organised, valued and interpreted in different ways [21,34].

But there is no single way of triangulating evidence and articulating narratives. The choice of theoretical framing and narrative structure in each of the interviews was based on a combination of discipline, or field of study, normalising standards of practice and prioritisation of certain forms of knowledge [51] and the situated context of the researcher and institution: nationality and institutional traditions [72,76]. The local specific conditions of knowledge production played a significant role in the way each researcher drew analogies between ethnohistorical and contemporary analogies with the past [51]. The situated context of knowledge production has been discussed widely in archaeological theory, and especially in debates about interpretation of the past [35]. As Julian Thomas [77] summarises, archaeologists must be self-aware when drawing analogies to reconstruct the past. Knowledge production is not a "view from nowhere" [78] but situated social practice [34]).

As discussed in the opening to this paper, there is much that is agreed upon in the narrative of Norse Greenland. However, subtle differences in interpretation can lead to drastically different hypotheses about decline. As Hodder [79] explains, the archaeological record does contain a reality that is independent of our own interpretation—a *guarded objectivity*. However, interpretation must remain critical and responsive to its own assumptions of objectivity and coherence [36].

Interpretations of sites, improved chronologies and increased resolution of environmental change in Norse Greenland make the interpretation of the past an ongoing cyclical and spiralling process of analysis and reanalysis. This hermeneutic circle (or spiral) requires an ongoing reflection on accumulated evidence and how we as researchers are interpreting it [80]. The North Atlantic is a highly interdisciplinary and interconnected research network where discussions of theory and interpretation are highly varied. Perhaps it is time to facilitate a more open dialogue on how researchers from multiple disciplines and research traditions are interpreting the past, and from there identify new research questions to ask and hypotheses to test in the future.

5. Conclusions

The range of depopulation scenarios for Norse Greenland demonstrates the complex task of interpreting past human–environmental interaction in general and the role of climate change in human affairs in particular. This paper has examined why and how Norse Greenland researchers interpret the same evidence for settlement depopulation in different ways. Two broad scenarios are still debated—mass death and abandonment—but both rely on the same evidence, albeit interpreted in different ways and articulated into particular narratives. Geographical and disciplinary factors play a significant role in the relative emphasis of environmental, climatic and social data, as well as biases in the use of analogy. Researchers tended to utilise familiar analogues to interpret human activities and triangulate archaeological and environmental datasets. Critically, the way narratives are articulated are situated in the place of production, whether such interpretations reflect national, institutional or disciplinary traditions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/heritage8080293/s1, Table S1: participants' contrasting views on why and how Norse Greenland settlement ended. TEK stands for Traditional Ecological Knowledge.

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The Evolving Landscape of Inquiry: Climate's Growing Importance in Reconstructing Ancient China

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Abstract: This paper examines the growth of climate change discussions in narratives concerning the development and evolution of human societies in Ancient China over the past two decades. This shift reflects climate's ascension from a marginal factor to a central player in reconstructions of past human actions and societies. We provide an overview of the expanding research on ancient human–climate interactions in China's prehistory and early history, emphasizing the increasing importance attached to climate as a major player in the rise and, significantly, the collapse of these societies. Through a meta-analysis of publication trends in the last two decades, we identify the chronological periods and topics where climate has come to be interpreted as having a notable impact.

Keywords: climate change; ancient China; bibliometrics; publication trends

1. Introduction

In recent years, human–climate relations have become a central research focus in many fields worldwide, including in China. Studies on contemporary periods and the recent past have examined how humans have affected their environments—either through taming natural forces on unprecedented scales, such as the Three Gorges Dam project on the Yangtze River, or, more commonly, by highlighting environmental degradation as populations extract more than the land can sustain and efforts to combat these effects [1–3]. Some scholars are extending this analysis into the deeper past by combining climate-modeling with historical and archaeological work [4–6]. In recent decades, such research on human–climate interaction in China's past has exploded, with hundreds of papers, books, and projects investigating the relationships between climatic shifts and milestones in human history. Climate change has emerged as a prominent explanation for political, social, and economic change, with some researchers finding correlations between climatic shifts and the rise and fall of Chinese dynasties [7–9], or earlier archaeological cultures [10–13].

Given the present climate crisis, it is not surprising that research into climate change past and present, and its impact on human societies, is at the forefront of research in many fields around the world. While archaeologists and historians have long recognized the impact of climate—as well as local environmental conditions—on human societies, direct collaboration with climate scientists, and vice versa, has been rare [14]. In some cases, this lack of collaboration has resulted in an inadvertent return to environmental determinism, a theoretical paradigm that archaeologists have largely rejected [15–18]. In a recent paper [14], our bibliometric analysis revealed that studies connecting climatic, environmental, and archaeological data in research on early China (i.e., prehistoric and early historic periods from the Paleolithic to the early states) predominantly appear in

Earth and planetary science journals and multidisciplinary publications, rather than in archaeological or anthropological periodicals, and that they tend to emphasize the natural science aspects of their research and spend less time and effort on the sociocultural context. This publication pattern appears shaped by several factors: journal ranking systems both within and beyond China, researchers' aims to emphasize natural science aspects of their work, and their desire to engage with diverse academic and public audiences.

The present paper builds on our previous work to analyze trends in English-language publications addressing human–climate interactions in China's past. While our forthcoming paper [14] focuses on the cultural, historical, and socio-cultural context of knowledge production, pointing out pressures created by publication the requirements, career progression demands, and expectations of funding agencies, as well as political frameworks and public discourse, here, we focus on the academic end of the matter. To better understand the main research questions that are being asked at the juncture of archaeology and climate sciences, the way research trends have developed over time, and to gain insights into the general state of the field, we focus on journals where articles at the intersection of archaeology and climate science are most often published, examining how researchers present their work and engage with the topic of human–climate interaction. Our analysis of published research, presented below, reveals characteristic patterns in how human–environment interactions have been conceptualized across different time periods. We examine these patterns and discuss major research trends in detail, first based on bibliometric data and then via an in-depth review of major research publications and their insights in a more traditional state-of-the-field assessment, before using this information to consider future directions at the intersection of these fields.

2. Research Methods and Bibliometric Analysis

In recent years, bibliometric studies have become popular, proving a useful tool for identifying research trends in various fields and tracing the underlying causes in an attempt to highlight potential issues and predict future developments. Such papers have identified biases in citation networks or funding allocation [19,20] and in the case of Chinese archaeology, they have tended to focus on the internationalization of the discipline [21,22] and general overviews on specific research topics. Our own forthcoming paper mentioned above [14] shows how publication trends in research linking archaeology and paleoclimate studies are connected to pressures on (especially young and mid-career) scholars to publish in high-impact journals, which are often natural-science focused. They are impacted by the ability to obtain research funding, which is more readily available for studies with a natural science component, especially when touching on pressing present-day issues, such as climate change and human adaptation to extreme environments.

Our present body of papers is the same as that compiled in [14], where we first used the bibliometric analysis websites Web of Science (WoS) and ScienceDirect to determine which journals were publishing significant numbers of articles at the intersection of archaeology and climate science and which journals were considered especially impactful. We used the following keywords in our searches, which included searches of article titles, keywords, and abstracts: archaeology, China, Neolithic, Paleolithic, Bronze Age, settlement, collapse, climate/climatic, environment(al), paleoclimate, paleoenvironment(al). We set our date range to 2000–2020. We found 14 journals that regularly published articles at the intersection of these topics. However, the total number of articles over the last 20 years for each journal varied significantly, from 10 to 200. Most of the journals with the lowest numbers of articles were in very high impact venues such as *Nature*, or were archaeology-specific, so we opted to keep these due to their potential impact generally and within archaeology, despite the lower number of publications.

For each article returned in our search, we recorded detailed information on the authorship, which is analyzed in detail in another publication [14]. We also collected information on the contents of the article based on the keywords, titles and abstracts, which we analyze here. Our comprehensive analysis of 405 English-language publications that engage with human–environment interaction in early China reveals nuanced patterns of research development from 2000 to 2020. Notable growth in scholarly publications can be seen over the past two decades (the output increased from 18 papers in the early 2000–2005 period to 205 papers by 2016–2020), with an increasing diversity of research themes and methodological approaches that reflect a more complex understanding of human–climate interactions in early China. To assess what these studies reported and the main research questions they were addressing, we tabulated and summarized the keywords and terms used in the paper titles and the keywords listed by the authors for their papers. Broad topics and terms, such as agriculture and periods (e.g., Neolithic, Paleolithic, etc.), were clearly observed. Additionally, we also searched for terms we expected to see on human–environment interaction, namely reliance, collapse, adaptation, and sustainably, but these, surprisingly, were not nearly as common (Figure 1, and see more below).

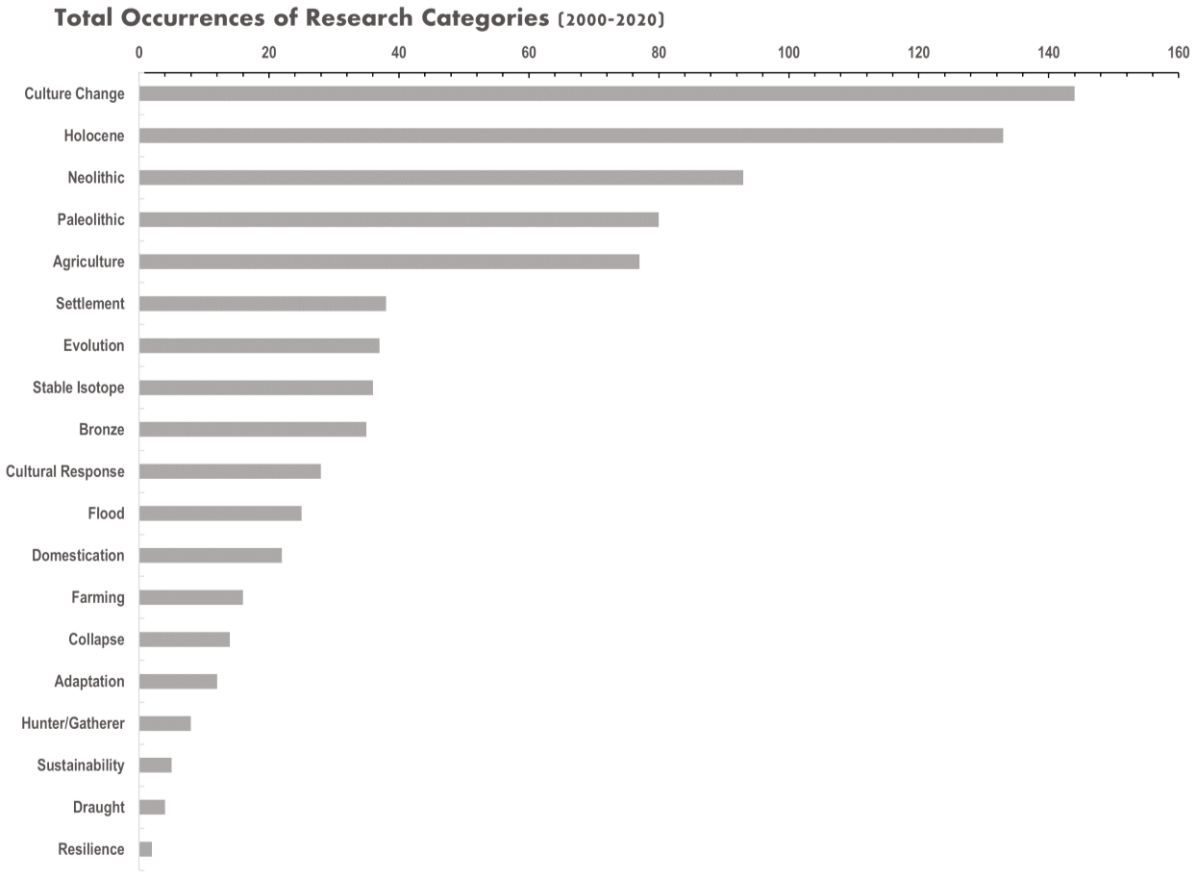


Figure 1. Total occurrences of selected research terms (2000–2020).

Looking at where archaeological papers (i.e., papers with a primary focus on archaeological data aiming to reconstruct past human behaviors, socio-historical developments, and sociocultural phenomena) were published and the topics and issues they inspect in relation to human–environment interaction, we can see a number of trends. Figure 1 shows the main terms and research categories discussed and their total number of cooccurrences over these years.

When we look at paper topics by publication venue (Table 1), a number of key trends emerge. The publication landscape in terms of research on human–climate dynamics

focusing on archaeological data is dominated by journals in the Quaternary sciences, with *Quaternary International* leading the way with 119 papers, followed by *The Holocene* with 70 publications. This is not so much a reflection of an interdisciplinary approach to understanding human–climate interactions in early Chinese contexts but rather a research thrust led by paleoclimatologist [14]. *Quaternary International* emerges as the most prolific publication venue, with 119 papers spanning a wide range of keywords. Its research breadth is particularly notable, with strong representations of culture change (51 papers), Holocene period studies (46 papers), and Paleolithic research (35 papers). This journal appears to provide the broadest coverage of archaeological research on early China. *The Holocene* journal takes a more focused approach, with a concentrated emphasis on culture change (37 papers), Holocene period studies (30 papers), and Neolithic research (24 papers). Its publications suggest a more targeted exploration of environmental and cultural dynamics during specific historical periods. In contrast, journals like *PLoS ONE* and *PNAS* show more specialized research profiles. *PLoS ONE* demonstrates a balanced approach with agriculture (11 papers), culture change (8 papers), and Paleolithic studies (6 papers). *PNAS* appears to have a more selective publication strategy, with fewer papers but a focus on critical themes like agriculture and domestication. *Nature* and *Science* have minimal representation, suggesting they publish only the most exceptional or groundbreaking research in this specific field of early Chinese archaeological research, however that may be defined. Considering the profile and aims of these two journals, this is not surprising.

Table 1. The publication venues investigated in this study and the top 3 research themes among papers focusing on archaeology and climate. Please note that some of the keywords co-occur, so the numbers add up to more than the total number of papers in each journal.

Journal	*Total Papers*	*Keywords*		
Quaternary International	119	Culture Change (57)	Holocene (46)	Paleolithic (35)
The Holocene	70	Culture Change (37)	Holocene (30)	Neolithic (24)
Quaternary Science Reviews	51	Holocene (30)	Culture Change (19)	Paleolithic (12)
PLOS ONE	40	Agriculture (11)	Culture Change (8)	Paleolithic (6)
Journal of Archaeological Science	30	Agriculture (8)	Neolithic (8)	Domestication (5)
Quaternary Research	21	Culture Change (11)	Holocene (11)	Neolithic (6)
Catena	24	Culture Change (6)	Holocene (7)	Stable Isotopes (3)
PNAS	17	Agriculture (5)	Culture Change (3)	Domestication (3)
Nature	6	Paleolithic (3)	Holocene (1)	Agriculture (1)
Antiquity	6	Neolithic (3)	Culture Change (2)	Agriculture (2)
Quaternary Geochronology	6	Paleolithic (3)	Neolithic (2)	Holocene (1)
Science	2	Holocene (1)	Culture Change (1)	Settlement (1)

When we look at developments from 2000 to 2020, the data reveal distinct patterns in how scholars have studied human–climate interactions in early China through English-language publications (2000–2020). Notably, while new theoretical frameworks and methods emerge, traditional research interests (e.g., culture change, chronology, emergence of agriculture, and general changes in subsistence practices) remain robust and even expand (Figure 2—composite figure).

Early publications (2000–2010) engaged in human–environment interactions are relatively sparse and focused primarily on basic culture change and chronology (particularly in papers published in the journal *The Holocene*). The papers are largely descriptive, focusing on period-specific studies rather than theoretical frameworks or specific environmental responses (see discussion below for a more detailed description of these research trends with specific references). From 2010 to 2015, there was a notable diversification in how human–climate interactions were studied. While "culture change" remained a dominant

focus, the integration of stable isotope analysis marked a shift toward more precise methods of climatic or environmental reconstruction. The increased attention to agriculture and settlement patterns might suggest a growing interest in understanding specific mechanisms of human–climate relationships rather than just their outcomes in terms of changes over time. This may have something to do with chronologies becoming increasingly fine and precise, freeing up research capacity to investigate new questions rather than focusing on establishing basic chronological foundations.

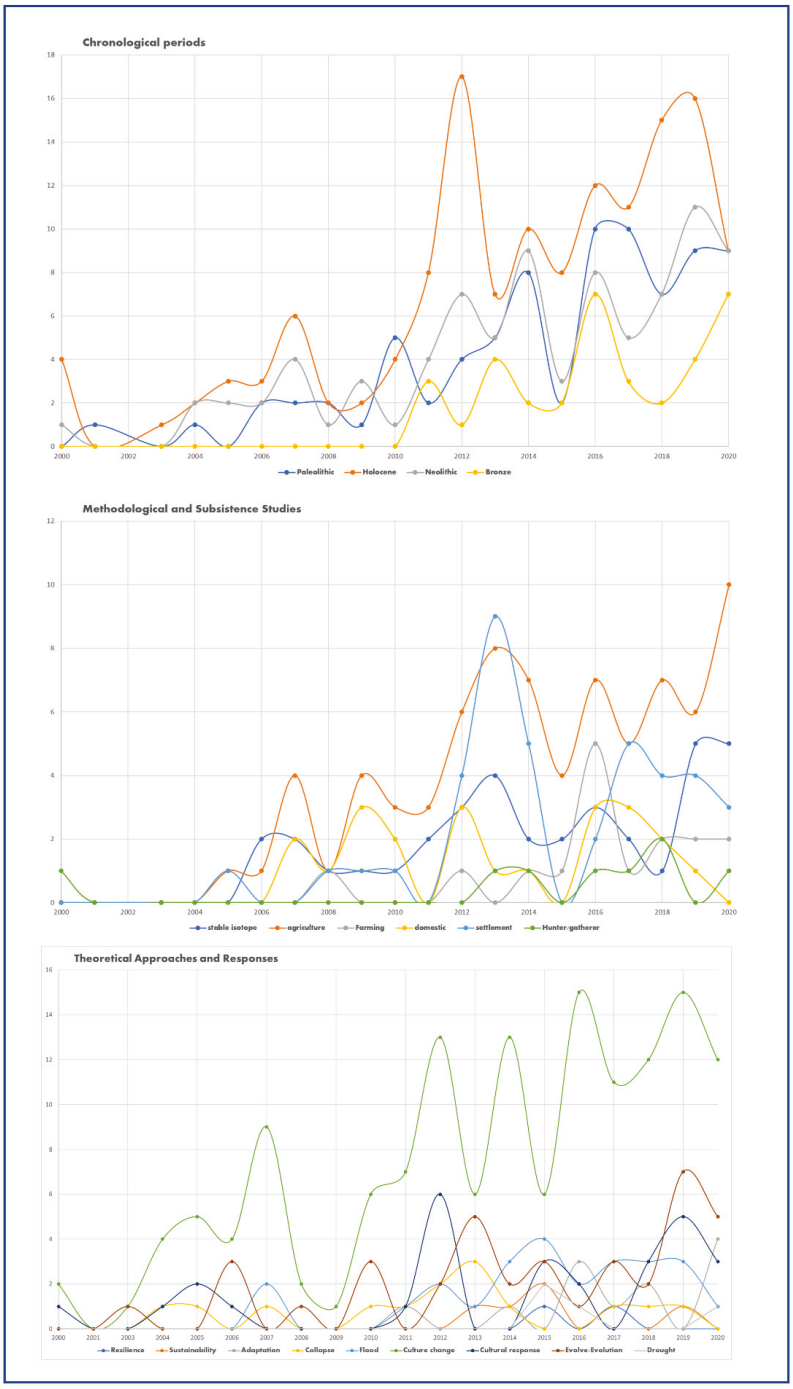


Figure 2. Research themes on human–climate interaction in Chinese archaeology by year (2000–2020), in English-language publications.

"Culture change" stands out as important and even shows growth over time, particularly after 2010. This suggests that rather than being replaced by newer theoretical

frameworks, broad culture change perspectives remain central to understanding human–climate relationships. Interestingly, "cultural response" appears less frequently than "culture change," perhaps indicating a distinction between general observations of change and specific responses to environmental pressures. When newer concepts, like adaptation, resilience, and sustainability, began appearing (post–2015), they did not replace culture change studies, even though during 2013 to 2015, there was a small dip in their prevalence when new themes were first introduced—instead, they seem to have complemented them. This suggests that these newer concepts are being integrated into existing frameworks rather than replacing them. The sustained and growing attention to agriculture and related subsistence practices alongside newer theoretical approaches is particularly telling. Rather than being superseded by newer frameworks, agricultural studies have been enhanced by them, integrating more sophisticated methods, like stable isotope analysis, while maintaining focus on fundamental questions of human–environment relationships.

Chronologically, Holocene studies dominate but show interesting patterns of co-occurrence with other periods. While Paleolithic research maintains a consistent presence, notably less attention is paid to hunter–gatherer adaptations despite their relevance to human–environment interactions. Bronze Age studies show periodic spikes rather than steady growth, often coinciding with peaks in agriculture and culture change studies, suggesting focused interest in this period's environmental transitions. The relationships between Bronze Age studies, theoretical frameworks, and methodological approaches reveal a complex pattern of scholarly development. Bronze Age research shows distinct intensification during periods of methodological innovation, particularly when stable isotope studies became more prevalent. The years 2016 and 2020, which saw the highest numbers of publications on the Bronze Age (7 each), coincided with significant agricultural studies and the application of new analytical methods.

Culture change has remained a dominant framework, but its relationship with specific approaches has evolved over time. While early peaks in culture change studies (2012–2014) correlate strongly with settlement pattern research, later peaks (2016–2020) show stronger relationships with stable isotope analysis and agricultural studies. Studies focusing on cultural responses to climate fluctuations follow a different pattern, reaching their heights in 2012 and 2019, periods when the application of various methodologies in a single study can be seen, along with a focus on Holocene studies. This suggests that cultural response might be conceptualized differently from general culture change, perhaps reflecting a more specific focus on human–environment relationships that benefits from multiple analytical approaches.

Finally, about two thirds of the papers combine multiple keywords listed among our search terms, and the publication trends reveal nuanced interconnections across multiple themes (Table 2). Notably, culture change emerges as the most interconnected keyword, strongly linked with the Holocene period (72 papers) and showing significant connections to the Neolithic period and agricultural research. This suggests cultural transformation is thought to be tied to climatic and technological shifts. The Holocene period has proven to be central to interdisciplinary research on human–climate interactions, with strong connections to culture change, the Neolithic period, and agricultural studies. Agricultural research itself is tightly linked with culture change and shows strong associations with the Holocene and Neolithic periods, indicating agriculture as a key driver of culture change. The Neolithic period particularly stands out, bridging culture change, agriculture, and climate research as a transformative era in human development. To better understand the correlation between these patterns and their impact on the field, we now delve into specific trends that we have identified via our bibliometric research.

Table 2. Research theme connections/top keyword co-occurrences.

Theme Pairs	Number of Co-Occurrences
Culture change—Holocene	72
Holocene—Neolithic	38
Culture change—Neolithic	35
Culture change—Agriculture	29
Agriculture—Holocene	27
Agriculture—Neolithic	27
Stable Isotopes—Paleolithic	10
Domestication—Neolithic	6
Adaptation—Paleolithic	3
Flood—Holocene	13

3. Discussion—Dominant Trends in Early China Human–Climate Scholarship: Climate Change, Agriculture, and Culture Change over Time

Based on the above analysis, we have identified several key trends within the research concerning the intersection of climate and archaeology in early China, with the most common focus on the topics of culture change and agriculture. Here, we look in more detail at the narratives within these trends, discussing specific approaches and results as observed, primarily from papers identified via our bibliometric analysis, before discussing how these foci may impact future research trajectories.

A dominant topic that emerged from our analysis above is agriculture, particularly in relation to the Holocene and to culture change. The origins of agriculture in China—as anywhere in the world—are intricately linked to various environmental factors, including climatic changes, geographic features, and ecological conditions [23,24]. These factors played a crucial role in shaping the agricultural practices that emerged in different parts of what is now China and neighboring regions. One of the primary environmental influences on the origins of agriculture in China were the climatic conditions during the Holocene, which explains the strong connection with this keyword.

The relationship between climate and humans is complex, and the archaeological record shows a gradual transition from foraging to farming over thousands of years in various parts of China [25–27]. This extended timeline suggests a more nuanced role for human agency in this process, one that consists of experiments with various strategies rather than abrupt and complete changes to subsistence practices and/or social organization in response to changing climate conditions [28–30]. Plant and animal domestication processes varied significantly across regions, shaped by local environmental and ecological conditions, as well as sociocultural factors [31]. In the Lower Yangtze region, the transition from wild to domesticated rice involved a complex interplay of ecological knowledge and experimentation. Millet, in the north, was likely domesticated across multiple centers, while pigs—generally adaptable creatures that excel at extracting food resources from various environments, except in hot and dry climates—may have been bred in a single northern Chinese region [32]. As communities transitioned to agriculture, they developed new technologies for managing water resources, including irrigation systems essential for sustaining agricultural productivity [33]. Periods of drought and changing rainfall patterns necessitated adaptations in farming techniques and crop selection to maintain viable subsistence practices in specific locations [34]. Subsequent climatic shifts allowed for

more growing days and optimal crop management periods, enabling human expansion into previously challenging zones [35].

Another major research trend is the focus on connecting climatic change to culture change, as demonstrated by culture change being one of the top keywords from 2010 to 2020, with particularly strong relations to the keywords Holocene and Neolithic. This may be connected to general concerns with establishing a strong chronological framework that traces change (in material culture and archaeological evidence, more broadly speaking) over time, but also with the perennial "why" question of archaeological and historical narratives. Why did societies change over time in terms of social structures, subsistence systems, beliefs, and other aspects of "culture" broadly conceived? Throughout the Holocene, multiple global climatic shifts have been identified, many of which have been considered as drivers behind major shifts in subsistence systems and/or sociopolitical organization in certain parts of China. The main events occurred around 8.2 kya, 4.2 kya, and 3.2/2.8 kya BP, with other significant events noted at 7.2/7.0, 6.0, and 5.5/5.0 kya BP [36–43]. In this context, it is crucial to note that in relation to climate, the term "event" can mean a variety of things and can extend over shorter or longer periods. It can be something short, such as a one-season draught or heatwave, however, the events mentioned most commonly in the context of debates on human–climate relations in the past are a lot longer in duration, have fluctuations within them, and vary tremendously in intensity and impact among different areas. This is rather different from the way that the term "event" is used for instance in history or other fields in the humanities or social sciences or in everyday speech, a fact that has led to significant misunderstandings in communication among archaeologists, historians, and climate scientists.

Among these events, the 4.2 kya or 4.0 kya cal BP cooling event is the most widely discussed period, with significant implications for culture change, especially shifts in social organization and settlement patterns [44]. Based on archaeological and climatic research, this period of climate change is believed by many to have triggered a widespread collapse of Neolithic cultures across China in the late 3rd millennium BCE, with previous sociopolitical structures giving way to the first Bronze Age states [36,45–56]. These changes are often seen to have instigated widespread cultural, dietary, and agricultural shifts, such as the adoption of hardier barley and millet crops, and the adoption of more mobile forms of pastoralism [57–62] for an overview of these topics). It is worth noting that the somewhat vague and general term "culture change" assumes a narrower definition in the context of the emergence of state societies, in this case, meaning major sociopolitical and socioeconomic shifts if not complete breaks with the past. This narrower view of "culture change" might be linked to the historiographic traditions that draw on textual accounts emerging from the Late Shang period onward (~1250–1050 BCE) but include some allusions to earlier periods. Indeed, several scholars have suggested that the establishment of the Xia Dynasty, often considered China's first dynasty (predating the Shang, dating anywhere from the late 3rd to the middle of the 2nd millennium BCE), is closely linked to climatic changes, citing narratives of great floods and their control by Yu, and forming the founding myth of the Xia Dynasty [63,64]. However, such hypotheses of wholesale collapse and change are not universally accepted. Critics point to the unequal impact of this and other climate events across China and mismatches of scale among paleoclimatic, archaeological, and historical datasets, which are often too coarse to establish connections, let alone causal relationships [15–18,60,65]. Both uneven impacts of these climate shifts and varied reactions to climate change are consistently demonstrated [66–70] while evidence of continuity and resilience appears across the ancient landscape [60,71–74]

Interestingly, based on our analysis, research papers focusing on the later Bronze Age and Iron Age (late 2nd and throughout the 1st millennium BCE), generally do not

see climate as an important catalyst for change. For example, only a few papers have attributed the fall of the Shang to climate change, and only a small number of studies have argued that climate change drove the Shang "over the edge" and led to their downfall by the Zhou [75–79]. These publications are rare and have yet to make their way into the wider archaeological discourse. In the current literature, standard explanations for the shift from the Shang to the Zhou dynasty focus on political and sociocultural factors. When scholars investigate relationships among environmental conditions, climate changes, and subsistence practices, they typically are not concerned with wholesale regime changes (such as the collapse of a dynasty). Instead, they examine how shifting environmental conditions required adaptations to continue flourishing, such as transitioning to hardier crops or animal husbandry [80–84]. Additionally, in these analyses, climate is usually not viewed as a determining factor, but rather as one aspect among many.

4. Conclusions

The research on publication trends at the intersection of archaeology and climate science reveals a clear evolution of the scholarly approach from 2000 to 2020. Beginning with a modest 18 papers in the first five-year interval, the field experienced exponential growth, culminating in 205 papers between 2016 and 2020. Throughout this period, a consistent set of keywords dominated the research landscape, with culture change and Holocene emerging as the most prominent themes. The early years showed a tentative, exploratory approach, with limited interdisciplinary connections. By 2006–2010, research began to diversify, introducing more complex relationships among concepts like agriculture, domestication, and culture change. The 2011–2015 period marked a significant turning point, characterized by more sophisticated, multi-dimensional research that deeply explored the interconnections between environmental and cultural themes. The final interval (2016–2020) represented the peak of interdisciplinary research, with intricate links between Holocene, culture change, Neolithic, Paleolithic, and agricultural themes.

Overall, scholars investigating human–climate interactions in early China have approached the topic through various lenses, examining the complex relationships among climatic changes, agricultural development, and cultural transformations. Researchers have explored how these environmental shifts have influenced human adaptation, utilizing diverse methodological approaches, including archaeological evidence, paleoclimatic reconstructions, and isotopic analyses. The scholarly discourse has centered on the gradual transition from foraging to farming, emphasizing regional variations in domestication processes and highlighting unique agricultural developments across different ecological zones, such as rice domestication in the Lower Yangtze and millet cultivation in northern China.

The general pattern indicates that the field has evolved through accumulation rather than replacement. Newer approaches and methods are being integrated into persistent research interests in culture change and agricultural development, while maintaining traditional period-based frameworks. The continuing dominance of culture change studies, alongside growing methodological sophistication and new theoretical frameworks, suggests that researchers are finding ways to combine broader interpretive frameworks with more precise analytical tools and contemporary theoretical perspectives. Each successive five-year period demonstrates increasingly nuanced approaches to understanding human–environment interactions in early Chinese societies. The research trajectory reflects a profound shift from isolated disciplinary investigations to a holistic, interconnected understanding of cultural evolution, environmental adaptation, and human development. This progression highlights the field's growing complexity, with researchers increasingly recognizing the intricate relationships between archaeological, climatic, and cultural phenomena.

Based on this trajectory to date, we expect that papers emphasizing the role of a changing climate in the adoption of new technologies, including agriculture, water management systems, and new forms of social organization in early China, will continue at pace. However, we also hope that scholars will continue to challenge simplistic narratives of climate and environmental determinism. The present analysis demonstrates that scholarship engaging with climatic and environmental factors maintains considerable ambiguity—while 'culture change' emerges as the predominant theme in our analysis, its extent, intensity, and impact remain open-ended. This framing reflects, we believe, a tension between acknowledging significant causal feedback mechanisms affecting human societies, while circumventing the methodological pitfall of positing overarching deterministic outcomes—a theoretical position now largely abandoned. What is needed are more nuanced interpretations of human–climate interactions and scrutinizing potential impacts while acknowledging the complexity of climatic influences on human societies. In this way, research on human–climate interaction can not only shed light on the development of complex societies and early states in ancient China but can also provide valuable information on human responses to climate change that are relevant for our present climate crisis.

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Climates of Change in Northern Kenya and Southern Ethiopia: From Scientific Data to Applied Knowledge

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Abstract

This paper outlines the implementation and core results of a combined archaeological, historical, and ethnographic study of the histories of well construction and water management among Boran, Gabra, and Rendille pastoralists in arid and semi-arid areas of Northern Kenya and Southern Ethiopia. Co-developed with representatives from different local communities from the outset, this project sought to document the spatial distribution of different types of hand-dug wells found across the study areas, their associated oral histories and, if possible, establish through archaeological means their likely date of initial construction. Concurrent with addressing these academic objectives, this project aimed to train a cohort of local heritage stewards in archaeological, historical, and ethnographic data collection and interpretation, equipping them with the necessary skills to monitor sites of heritage value and further record additional elements of the tangible and intangible heritage of the study areas. This paper discusses the archaeological work that the community trainees participated in, the strategies developed with them to create wider awareness of this heritage, and its implications for identifying ways to "weather" climate change in the future.

Keywords: Kenya; Ethiopia; hand-dug wells; stone cairns; community engagement; climate change; knowledge co-production

1. Introduction

The archaeological and cultural heritage sites found across the arid and semi-arid pastoral landscapes of Northern Kenya and Southern Ethiopia have survived multiple changing climatic and environmental conditions over several millennia. However, these environments are facing fresh, unprecedented challenges, including increased frequency and severity of floods and droughts likely due to changes to regional weather systems arising from current global heating [1–5]. These climate-driven threats are both direct and

indirect. Flash flooding and fierce winds causing severe erosion and deflation pose the most obvious direct threats to various categories of archaeological sites. Possible permanent displacement of resident populations and increased precarity of local livelihoods, largely reliant on mobile pastoralism, also have the potential to undermine cultural practices and belief systems associated with places and landscape features that have been accorded spiritual and heritage value. Resettlement of displaced families, whether permanently or temporarily, by relief agencies and government bodies may further lead to inadvertent damage to undocumented archaeological sites in those localities identified for use as temporary camps, feeding stations, and/or temporary health posts, especially given the current weak systems of development control in both countries.

In the past, protection of contemporary cultural sites was ensured through an ideology of communal identity and the authority of traditional institutional leadership; however, these safeguarding features had no bearing on the protection of older archaeological sites and monuments in these locations since local inhabitants typically do not identify with these remains and most are largely unaware of their notional scientific significance and importance. Moreover, even highly visible monuments, such as clusters of deep, hand-dug wells and the numerous stone cairns distributed across these arid and semi-arid landscapes, tend to be associated in oral traditions with earlier, semi-mythical peoples, despite the continued reliance by both people and livestock on water drawn from the hand-dug wells [6].

Surviving archaeological sites are important archives and sources of information on how populations in the past responded to previous episodes of marked climate change, the adaptive strategies they developed and how these may (or may not) have enhanced social, ecological, and cultural resilience that might be beneficial to efforts aimed at reducing societal vulnerability to current climate change [7–10]. Damage to and loss of archaeological records due to factors driven by current climate change thus have implications for present- and future-oriented research fields as well as for more historically oriented disciplines.

With such observations in mind, our ongoing research entails working with pastoral communities in Northern Kenya and Southern Ethiopia to strengthen the protection of archaeological and other cultural sites within these landscapes from direct and indirect negative effects of climate change and other escalating threats. This research also seeks to generate new information on past human responses to climate change that can inform efforts to enhance the current cultural and socio-ecological resilience of these same pastoralist communities. A fundamental principle guiding these actions was that creation of local public awareness of the importance of protecting heritage sites can be significantly enhanced through the direct involvement of community members in research activities as equal knowledge producers [11–13]. Additionally, ensuring longer-term continuity of community-driven heritage protection also requires equipping a cohort of community heritage stewards with the requisite skills in archaeological site recording and monitoring, oral history documentation, and related research skills for recording tangible and intangible cultural heritage, supported by various knowledge dissemination and public engagement strategies. This paper provides a summary of the approach we have adopted as an example of collaborative community archaeology involving a combination of knowledge co-production, capacity building, and advocacy suited to helping demonstrate to different stakeholders the wider relevance of archaeological research and heritage against a context of escalating climate change and socio-ecological challenges.

2. Project Goals and Objectives

The aims of our project encompass both the production of new knowledge about human–environment relations, including the history of water management and settlement

in our study regions, and the creation of a new community of citizen researchers trained and empowered to collect, interpret, and utilise archaeological, historical, and anthropological data for their own cultural and personal sense of wellbeing and community resilience. Integrating these dual elements is also envisaged as an ethically appropriate approach to raising wider public knowledge of the deep histories of our study areas and the nature and scale of current threats to tangible and intangible heritage in these localities, and to embedding community stakeholders in processes of archaeological heritage documentation, monitoring, and future management. A particular aspiration is to equip our collaborators with the appropriate skills and knowledge to empower them to lead the preparation of Biocultural Community Protocols [14] for protecting customary rights and cultural heritage in their home areas. It is hoped this will serve as a counterpoint to governmental approaches that have tended to overlook the rich tangible and intangible heritage of these localities.

More specifically, the project's objectives are to achieve the following:

(1) Document the spatial distribution of hand-dug wells across both areas through a combination of field survey, oral interviews, and remote-sensing mapping;

(2) Link these datasets to existing and newly collected archaeological, historical, and palaeoenvironmental records for the region;

(3) Undertake parallel ethnographic documentation of recent and current systems of water management;

(4) Empower the communities in our study areas through the transfer of various archaeological skills, including how to identify surface archaeological materials through surveys, the practical basics of archaeological excavations, and how to record archaeological and other cultural sites;

(5) Train community participants in ethnoarchaeological, historical, and cultural heritage data collection methods, promote awareness of different conservation actions, and enable competence and fluency in presenting defendable cultural demands to local and national government officials and other external actors.

3. Theoretical Framework

Both the research activities and the skills and knowledge transfer elements of th project are framed in terms of community-based landscape historical ecology, co-produced by a group of external research scientists and resident, mobile pastoralists with family and clan histories of extended occupancy of one or the other of our two study areas. Following foundational studies such as those by Carole Crumley [15,16] and William Balée [17], landscape historical ecology is defined here as a form of integrated landscape analysis that draws extensively on archaeological, palaeoecological, and historical records to reconstruct continuities in and changes to human–environment relations over extended periods of time (at least centennial and sometimes millennial scales), with the explicit purpose of generating knowledge about past system dynamics that can be used for informing current and future beneficial approaches to addressing environmental and climatic challenges [18–20]. Our approach to knowledge co-production seeks to emulate methods proposed for enhancing transdisciplinary research, e.g., [21,22], with a specific orientation toward generating knowledge "co-produced through the combination of scientific perspectives with other types of relevant perspectives and experience from real world practice including policy-making, administration, business and community life" [23] (p. 111). Emphasis is also placed on using this approach to identify and define forms of landscape biocultural heritage [24,25] of relevance to local community livelihoods and cultural affordances from the perspective of enabling sustainable futures [26].

4. Study Areas and Research Context

Located in the cultural landscapes of Northern Kenya and Southern Ethiopia, our research has focused on areas along the eastern side of the Chalbi Desert, around Marsabit mountain, the arid lands north of North Horr and Marsabit up to the Kenya–Ethiopia border, and the lands between Moyale and Yabello in Southern Ethiopia (Figure 1). Prior to the creation of the border in 1907, there was significant movement and interaction between the two localities, and while this has diminished since the creation of two distinct nation-states, unregulated movement across this border by kin-related groups and as part of the seasonal mobility of herders in search of grazing pastures remains common. Several different ethnic groups also occupy these areas, sharing similar livelihoods, cultural traditions, and histories of interaction. Ethnicities within Marsabit County (Kenya) include Gabra, Borana, Rendille, Daasanach, Elmolo, Somali, Samburu, and Turkana. In Yabello (Ethiopia), Borana are the primary ethnic group, although individuals identifying as Burji, Sakuye, Waayu, Konso, and Amhara are also present. Mobile pastoralism is the main livelihood strategy for the majority of these, although some communities—such as the Burji in Kenya—practice agropastoralism in the highlands. In Kenya, these include Mt. Marsabit, Mt. Kulal, and the Hurri Hills, while in Ethiopia, the main areas where crop cultivation and livestock herding are combined are the upland regions near Yabello. Around the shores of Lake Turkana, groups of Turkana, Elmolo, and Daasanach combine livestock herding and fishing.

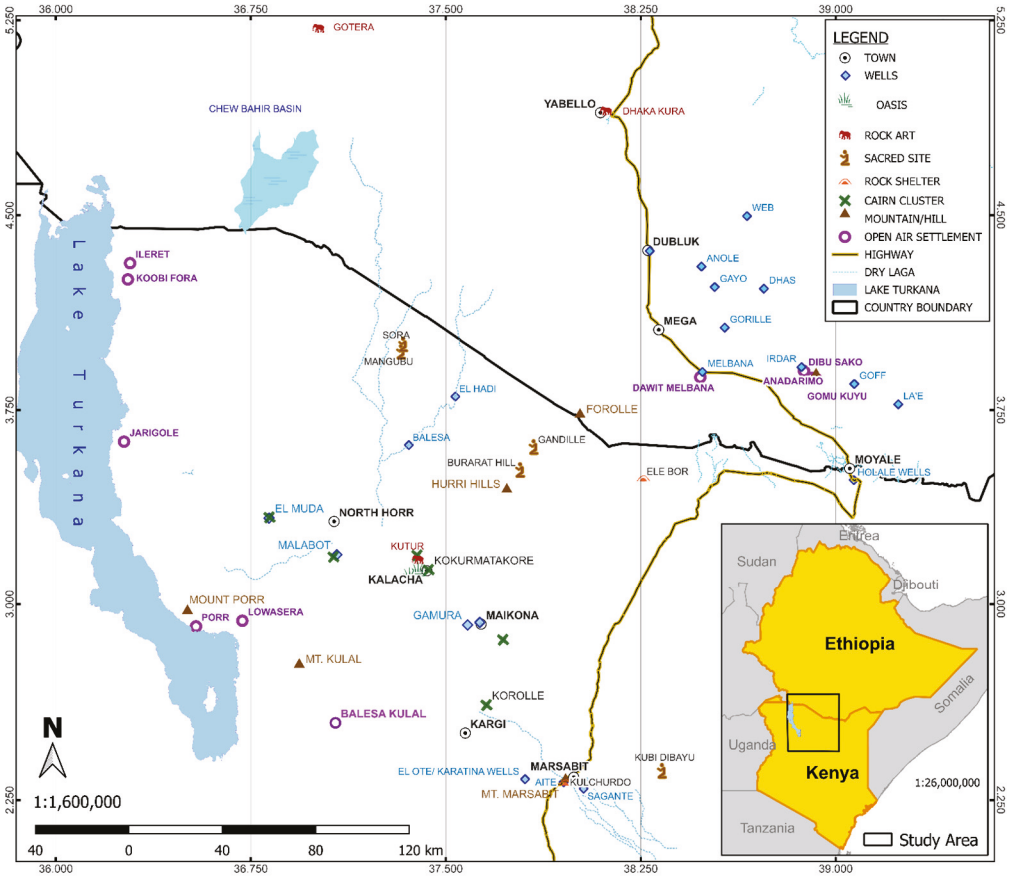


Figure 1. Location of main research areas in Northern Kenya and Southern Ethiopia.

Our field research on the Kenyan side of the border has tended to focus on areas currently occupied primarily by Gabra, and to a lesser extent Borana and Rendille peoples, while on the Ethiopian side, our research has concentrated on areas inhabited mostly by Borana. According to some scholars, Borana claim that all those currently inhabiting

Northern Kenya derive from the same ancestors with ”those who kept camels [becoming] Gabra; those who kept goats [becoming] Rendille”, and so on [27] (p. 191, fn. 10). Others argue that the history and processes of ethnogenesis have been more complex, entailing recurrent centripetal and centrifugal socio-economic processes [28]. This is reflected in the oral histories of different clans and phratries, which are best described as rhizomic in structure [29], with overlapping practices and customs (as an example, the Gabra follow the Borana system of custom and law (*aadaa seera*), whereas their personal ornamentation, calendar, and rituals are more similar to Rendille practices [27]).

Historically, access to water in both localities was through seasonal rivers, oases, springs, and ancient hand-dug wells (some of which are known as *Tula*—see below). Recently, these sources have been supplemented by modern boreholes, dams, and water pans. While there is considerable variation in their form, depth, and associated architectural features, the social systems of well management are quite similar. Available oral histories attest to the initial construction of the deeper wells in our study areas some 600 or more years ago [30–32]. The oral histories of the contemporary populations here often refer to a semi-mythical people called “Wardai” as the early inhabitants of these two regions and as the excavators of the oldest wells. These accounts also suggest the Wardai were pushed out of these landscapes by the current populations toward the Upper Tana valley, in what is now Kenya, where their Orma descendants now reside [33]. In some accounts, the stone cairns that are found across these landscapes are also attributed to the Wardai, who are considered in these traditions to have been giants due to their ability to use heavy stone tools to dig complex well systems.

5. Previous Archaeological Research

Previous archaeological research in the study areas has been unevenly distributed, with localities bordering Lake Turkana receiving most attention owing to the fossil-rich Pliocene and early Pleistocene deposits there [34–36]. The Holocene archaeology of the Turkana–Omo Basin is also rich, and as with the Plio-Pleistocene records, most research has concentrated around the Kenyan sections of Lake Turkana. Here, extensive traces of early-to-mid-Holocene remains associated with some of the earliest evidence in the region for the manufacture and use of ceramics by Late Stone Age (LSA) fisher–foragers (dating to between ca. 12,000 and 9000 BP) have been investigated [37–41]. These sites attest to the nature of activity in the region during the earlier phases of the African Humid Period and are related to the expansion of human settlement across the wider “Green Sahara” [42,43]. Many of these same localities have yielded evidence of initial “Neolithisation” processes associated with the introduction of domestic animals into Southern Ethiopia and Northern Kenya during the Pastoral Neolithic (PN) [44–48], and early manifestations of mortuary complexes and associated monumentalism [49–53] (note, not all of these sites are located on the east side of Lake Turkana in Marsabit County—several of the key sites are in Turkana County, on the west side of the lake; nonetheless, as they attest to the same archaeological phenomena, they are cited here). In contrast to the LSA forager–fisher sites, these PN sites are associated with the onset of drier conditions during the mid-Holocene from ca. 5000 years ago [54,55].

By contrast, other areas of Marsabit County east of Lake Turkana have received much less archaeological attention. Previous research around North Horr, ca. 90 km east of Lake Turkana and at the northern end of the Chalbi Desert, identified several, partially deflated scatters of lithics, pottery, faunal remains, ostrich eggshell beads, and other artefactual remains dating from ca. 5000 to 600 BP [56–58]. The very fragmentary faunal material includes a mix of cattle, ovicaprids, zebra, gazelle, and unidentified large wild bovids. Surveys around the margins of the Chalbi Desert have also identified dense clusters of

stone cairns of various types, with the most common types being simple cairns and ring cairns. A small sample of those on Kokurmatakore Hill on the outskirts of Kalacha have been excavated [59–61]. The available radiocarbon dates suggest that the cairns were built and used over several centuries between ca. 3500 BP and 125 BP, with the earliest type (simple mound) likely associated with PN communities. Dated material associated with the ring cairns yielded a range of dates from the fourteenth to nineteenth centuries CE, while the platform cairns appear to date to the late first- to early second millennium CE. The excavators thought these might relate to an early incursion of Oromo speakers into Northern Kenya, while the ring cairns were thought to have been erected by either Eastern Cushitic or Nilotic speakers [61].

On Mount Marsabit, excavations in a small rock shelter (Kulchurdo) yielded a large sample of lithics made on locally available lava and a faunal assemblage dominated by wildspecies. These likely date to the late fourteenth to early fifteenth century CE, indicating the continued presence of forager populations well after herding economies had been established [62]. Farther north, at least two rock shelters and numerous additional surface scatters have been documented at Ele Bor, ca. 12 km south of the Kenya–Ethiopia border. The two excavated sites indicate even longer, localised continuity of hunter–gatherer economies reliant on broad-based foraging from at least the seventh millennium BCE to the mid-first millennium CE, associated with generalised LSA lithic assemblages on quartz, lava, and obsidian. Ceramics, some similar to forager pottery from around Lake Turkana, first appear here in horizons dated to between the late sixth- to early fourth millennium BCE, while grinding equipment was in use by the third millennium BCE [63,64].

Less archaeological research has been conducted in our study area in Southern Ethiopia, with most research focused around Yabello, where Desmond Clark [65] investigated several small rock shelters containing Late Pleistocene and Holocene lithic assemblages, and in some cases, also rock paintings; and around Gotera, over 100 km to the east in the Chew Bahir Basin, where a complex of over nine open-air Middle Stone Age (MSA)–LSA sites have been investigated [66,67]. Some of the sites near Yabello were re-investigated in the 1990s by Hundie Girma [68], who confirmed the presence of horizons spanning the transition from LSA foraging to cattle, sheep, and goat herding and the adoption of pottery, including potential early PN material similar to Nderit wares found around Lake Turkana [47]. More recent work has also located a wider corpus of painted pastoral rock art in rock shelters and on more open rock faces [67,69]. One site, known as Dhaka Kura (or Crow's Rock; designated YAB6 by Girma) is especially rich, including "representations of humpless and humped cattle, wild animals (e.g., gazelle and warthog) and other subjects. . .alongside geometric patterns of different colours, sizes and styles" [69] (p. 216).

6. Methods

In common with other community archaeology aimed at knowledge co-production and landscape historical ecology projects [70–76], we employ a mixed-methods approach that combines standard archaeological field methods, ethnographic and oral historical research techniques, palaeoecological sampling, remote-sensing mapping, GIS analyses, and diverse forms of public engagement and empowerment strategies including exhibitions, photovoice methods, and the production of educational materials.

Our archaeological efforts seek to contextualise local oral histories through a programme of targeted archaeological foot survey, mapping, and recording of different types of wells to generate a basic typology and, if possible, recover in situ organic materials that might allow for radiocarbon dating of episodes of construction, repair, and abandonment. The surveys are accompanied by selective test–excavation of other archaeological remains (especially cairns and stone-walled enclosures) in the vicinity of well clusters. Those inves-

tigated so far were chosen based on assessments made in the field of their preservation and potential to yield datable materials, and in consultation with the participating community members. This work is supplemented by targeted ethnographic and historical research, remote-sensing mapping of potential archaeological sites, and the collation and digitisation of archaeological legacy data, including unpublished records of rock art [77]. Self-selected community members are involved in all these activities and are provided relevant training in the field in various survey, excavation, recording, and documentation techniques. As discussed below, our public engagement strategy has combined the preparation of public exhibitions, the provision of teaching materials for local schools, public talks and lectures, academic publications, and the use of social media and web-based platforms, also involving our community collaborators.

7. Preliminary Archaeological Results

This section provides a basic summary of the archaeological work undertaken thus far; fuller accounts will be published elsewhere in due course. In Kenya, our archaeological research has focused on the eastern side of the Chalbi Desert from Kalacha northward via North Horr, Balesa, and El Hadi to the Kenya–Ethiopia border. Over 100 individual wells, mostly found in dense clusters along seasonal rivers, were documented (Figure 2).

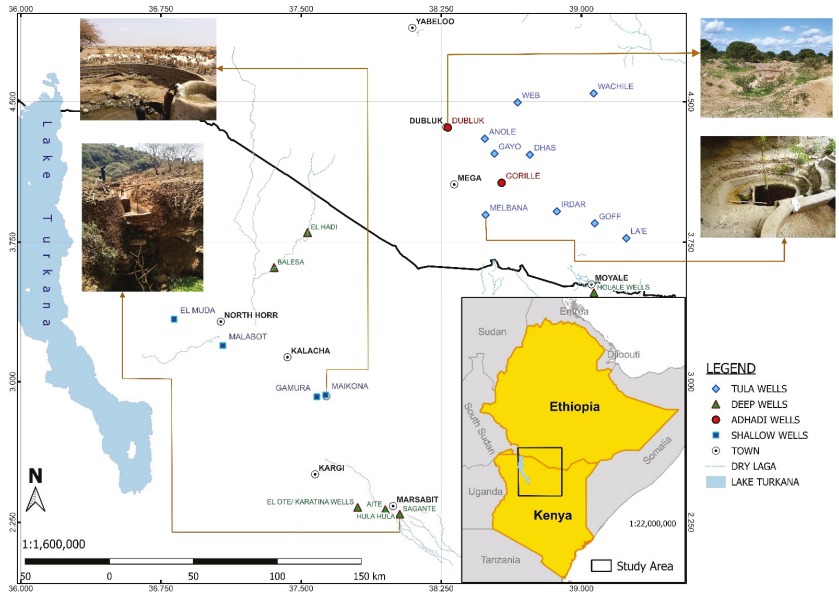


Figure 2. Location of traditional hand-dug wells of different types documented as part of the Wellbeing Project (map prepared by John Kanyingi, BIEA).

As noted above, numerous stone cairns of different forms (Figure 3) occur across this landscape, and the project has focused on detailed mapping of several of these concentrations through a combination of ground survey and remote sensing. Four examples (two ring cairns and two simple cairns) have been excavated thus far. The excavations exposed single inhumation burials in each of the cairns (Figure 4). Poor collagen and apatite preservation meant that none yielded viable samples for radiocarbon dating. Based on comparisons with the previously excavated cairns near Kalacha [61], these examples most likely date to between 3500 and 125 years ago, with the ring cairns potentially being the most recent. Additionally, numerous stone-walled enclosures also occur in the vicinity of the wells (Figure 5). Some mark the remains of recent seasonal encampments; others appear more substantial and may date to an era when annual rainfall was higher and more frequent than today. Artefact scatters were recorded at a sample of these enclosures,

although the finds were mostly undiagnostic, and test excavations at a large complex at El Hadi produced numerous shell beads and fragments in situ that returned erroneously old (>43,000 BP) radiocarbon dates.

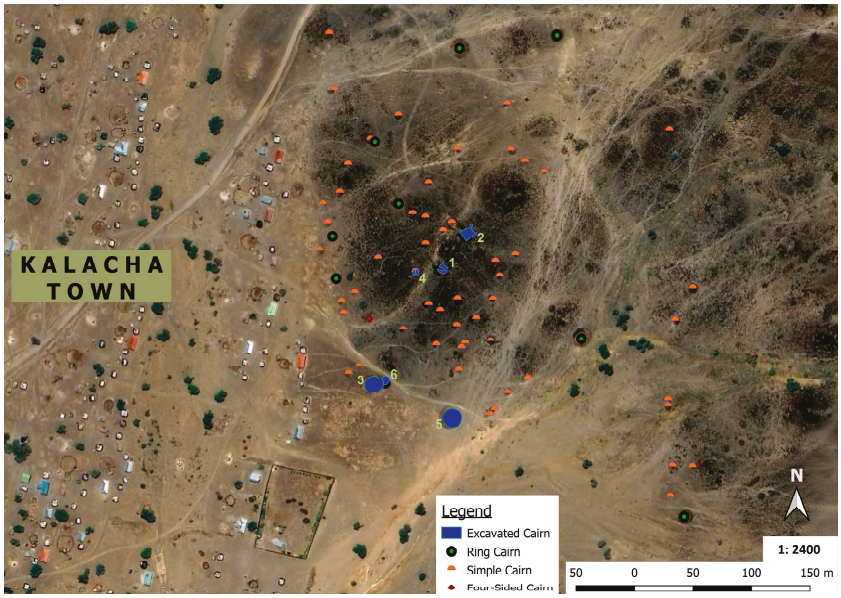


Figure 3. Location of cairns on Kokurmatakore Hill, Kalacha, excavated by Stiles and Munro-Hay (numbered cairns refer to their excavated cairns as per their numbering) in relation to other cairns on Google Earth™ (map prepared by John Kanyingi, BIEA).

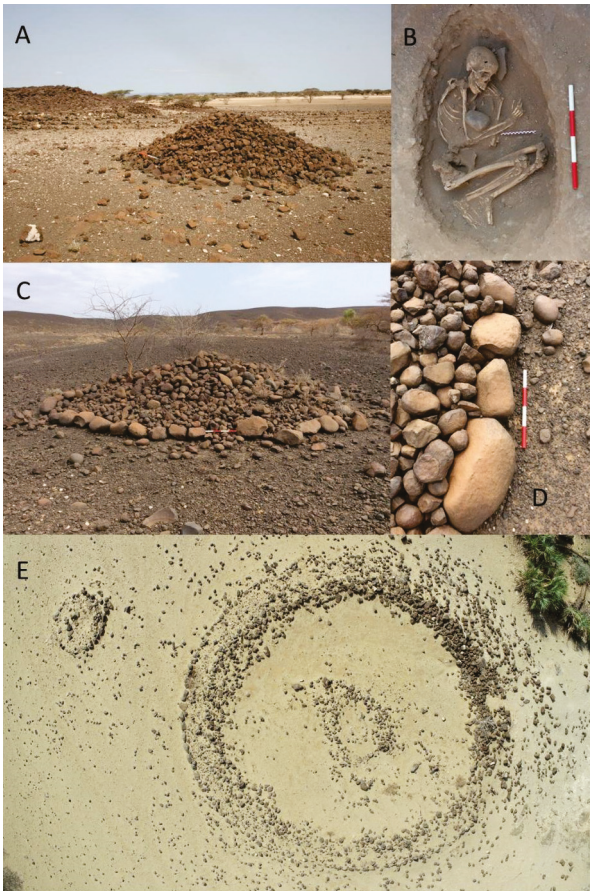


Figure 4. *Cont.*

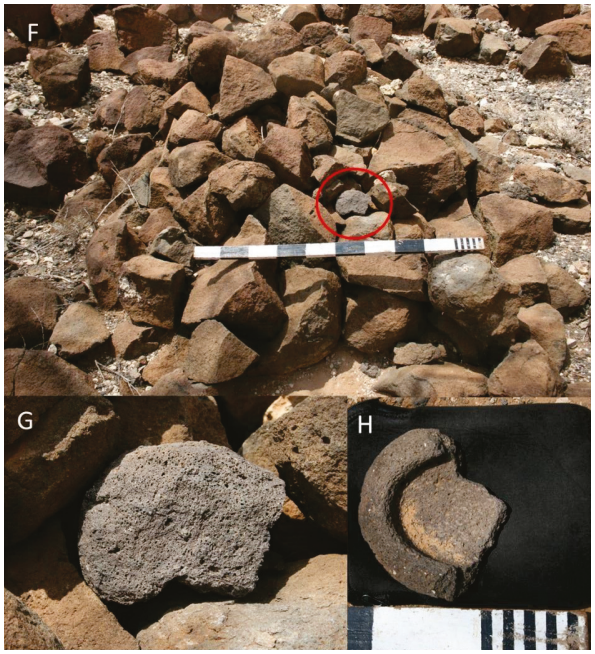


Figure 4. Examples of different types of stone cairn found around Kalacha and Korole, Marsabit County, Kenya: (**A**) Simple mound. (**B**) Excavated burial, El Muda, scale 40 cm. (**C**) Kerbed cairn, scale 40 cm. (**D**) Detail of stone kerb, scale 40 cm. (**E**) Drone photo of a ring cairn, Korole. (**F**) Small, simple cairn with broken Pastoral Neolithic stone bowl (circled), scale 50 cm. (**G**) Detail of a broken Pastoral Neolithic stone bowl on a simple cairn. (**H**) Pastoral Neolithic stone bowl from surface of a small, simple cairn, scale 20 cm. (Photos: Paul Lane; drone photo: John Kanyingi, BIEA).

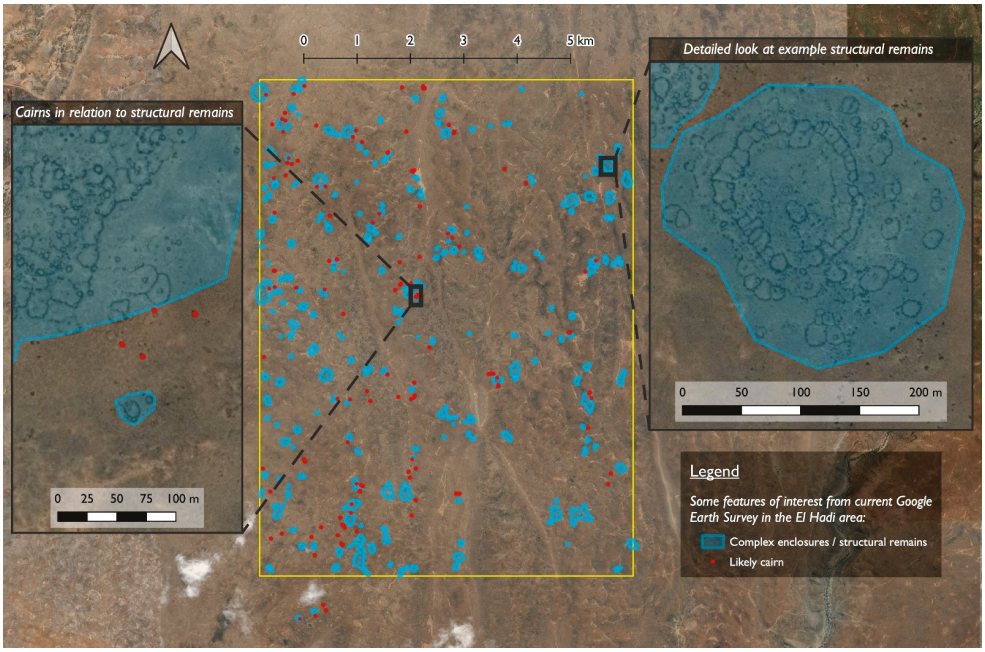


Figure 5. Illustration of stone-walled enclosures visible on Google Earth™ in proximity to a cluster of hand-dug wells near Balesa, Marsabit County, Kenya. Image prepared by Ed Burnett, MAEASaM Project, University of Cambridge.

To provide a sounder framework on which to infer human adaptations to changing environmental conditions around the Chalbi Desert, five sedimentary cores were recovered from different localities on the eastern side for palaeoecological analysis. The longest of these, from the Erenderi spring near Kalacha, extending c. 6.25 m, has been analysed. The

lowest sediments, dated to the mid-Holocene around 5200 cal. BP, indicate the presence of freshwater and saline lake habitats. Over the following millennia, these transitioned to terrestrial conditions with relatively abundant gallery tree species along perennial river courses and subsequent grassland expansion from c. 1200 to 515 cal. BP as the regional environment became drier [78].

Research in Ethiopia, undertaken in collaboration with community members and researchers from Borana University at Yabello and Addis Ababa University, was concentrated around the *Tula* well complex at Irdar. As in Northern Kenya, different types of stone cairns and stone-walled enclosures were recorded. These are noticeably different in terms of their style of construction and walling compared with the enclosures recorded on the Kenyan side of the border, as illustrated by the walling documented at Dawiti Melbana (Figure 6). Additionally, in one case (Gumuu Kuyyuu Hill), the hilltop settlement appears to have been ringed by numerous stone cairns—one of which was excavated, yielding remains of a child burial, radiocarbon-dated to c. 4000 BP. Excavation of two other cairns, at Dibu Sako/Guba Adi near Irdar, exposed well-preserved adult inhumations (Figure 6C). Radiocarbon dates on associated materials suggest these were in use between 900 and 600 years ago. While based at Irdar, the team worked with the users, owners, and managers of community wells in five localities (Melbana, Dubluq, Dhas, Irdar, and Gayo), documenting the physical characteristics of 65 individual wells, their associated histories, and current status.



Figure 6. Archaeological research in Southern Ethiopia in 2022: (**A**) Example of stone walling at Dawiti Melbana. (**B**) Excavations in progress at Dibu Sako. (**C**) Excavated burial at Dibu Sako. (Photos: John Kanyingi, BIEA).

From the data produced so far, there seems to have been an obvious relationship between the wells, cultural heritage, and other archaeological sites [6,79]. Many ancient burial cairns lie close to the wells, as do scatters of archaeological materials (that included MSA lithics, LSA microliths, ostrich eggshell beads, PN stone bowl fragments, and pottery sherds of various dates). Cairns also cluster around some of the contemporary cultural heritage sites. More research is need to resolve the many chronological uncertainties however, and to better link settlement, burial, and economic practices to the different episodes of regional environmental change, as documented in the Erenderi core and at other palaeoecological sampling localities around Lake Turkana and the Chew Bahir Basin, so as to better determine how societies responded in the past to climatic adversity. Despite such limitations, this project has been particularly successful in raising public awareness of the significance of the region's archaeological sites and monuments for understanding how pastoralist communities adapt to climate change and the kinds of insights for the future that can be drawn from such remains. The following sections describe how this has been achieved and the emerging role of community groups as local heritage stewards and champions in protecting these resources.

8. Implementing Awareness Strategies in Northern Kenya and Southern Ethiopia

Building on the findings and recommendations of archaeologists from around the world, e.g., [11–13], our project has endeavoured to raise awareness of the rich archaeology of our study areas at all levels of community membership and to create digital data that can be used for future site monitoring, adaptation, or development control. While formal, legal responsibilities for the protection of archaeological and other cultural sites in Kenya and Ethiopia rest with the relevant national and local government authorities (in Ethiopia, the main national authority with a legal mandate to protect archaeological sites is the Ethiopian Heritage Agency, while in Kenya, it is the Sites and Monuments Division of the National Museums of Kenya), the communities living around these sites also have a major role to play. Hence, the creation of awareness of the wider significance and heritage value of different sites and monuments is of critical importance for ensuring archaeological site protection and the promotion of heritage conservation goals through local advocacy and other actions.

While stone cairns, rock art sites, and contemporary cultural sites are often easy to recognise, other archaeological sites on these landscapes are not as obvious to members of the public unfamiliar with the concept of archaeology and its forms of practice. By providing basic training and participation in archaeological survey, excavation, recording techniques, and cognate fields such as ethnoarchaeology, oral history, and material ethnography, the project aspires to change this by establishing a cohort of local community members able to report finds and help keep the national authorities informed of fresh exposures, alert them to any site that may be under threat, and communicate information about the local archaeology and its significance to members of their own communities.

For impactful results, our collaboration with local inhabitants has focused on creating awareness about the aims of the project, the significance of archaeological sites (scientific, cultural, and economic) in the region, the imminent threats facing cultural sites (including those by climate change and external actors), and the role local communities can play in mitigating these threats. We have approached this by (i) hosting stakeholder meetings; (ii) delivering basic training in field archaeology; (iii) providing training in oral history and material ethnography; (iv) mounting exhibitions and producing popular books; (v) creating archaeological heritage clubs at local primary and secondary schools; and (vi) using different media to generate broader awareness.

8.1. Workshops for Stakeholder Engagement

Our initial goal of engaging the local communities as partners and heritage owners has guided us throughout our project. At the outset, we held three consultation workshops (in 2018–2019), two in Kenya and one in Ethiopia. The stakeholders at these workshops included elders, scholars, Community-Based Organisation (CBO) representatives, representatives from county government, and representatives from related government departments in both Kenya and Ethiopia, such as the Department of Tourism. The 3-day workshops were attended by 40 stakeholders (20 attendees in both Ethiopia and Kenya). These had been picked by our local project coordinators during the project scoping stage. Using PowerPoint presentations and group discussions, stakeholders were informed of the project's aims, the Holocene archaeology of the study areas, the potential contributions that archaeological and historical knowledge can make to planning for more sustainable futures, the possible future trajectories of current climate change, and potential end users of the project outcomes. A didactic approach was adopted, aimed at eliciting questions, suggestions, and opinions regarding the project goals and responding to these by incorporating stakeholder responses into the project design and implementation. One of the early outcomes was the creation of steering committees for both Northern Kenya and Southern Ethiopia, comprising six different stakeholders for each region who would be part of everyday project activities and decision-making.

In addition to hosting workshops, the team visited different decision-makers, including Cultural Heritage departmental heads, government officers in charge of water management, County Governors, Unit administrators, chiefs, and community leaders in the two study areas. With them, we discussed the importance of the sites in their localities and the imminent threats they are facing. Emphasis was placed on identifying possible benefits that might accrue from protecting these sites from the negative impacts of climate change and human activities. Interviewees were selected based on their standing in their community, regardless of whether they had participated in the workshops. Recapitulation of the project goals in these meetings helped generate more locally specific discussions on the archaeology and cultural materials in these localities.

At the end of the initial phase of project funding, a concluding workshop was held in Nairobi involving 30 invited stakeholders drawn from Kenya and Ethiopia. These included senior government officials, politicians, elders, CBO representatives, local administrators, academics, and members of the public with an interest in heritage management. During this workshop, we disseminated the results of our archaeological and ethnographic work, GIS mapping, and the results of the community training in archaeological field methods. For the latter, one of the newly trained members gave a presentation. This workshop served as a pathway to influence policy as the attendees were very engaged and were mostly interested in implementing changes regarding their cultural landscapes. Various ways of doing this were discussed and the positivity was encouraging. The roles of attendees in project activities aimed at enhancing public awareness were also discussed.

8.2. Creation of Awareness Through Practical Experience

The steering committees created after the initial workshops identified the individuals for archaeological training, selecting representatives from each of the areas targeted for field investigation. These areas were chosen based on the presence of ancient wells, stone cairns, and other biocultural sites and materials. Both regions (Yabello and Marsabit) nominated 15 members each for training in archaeological excavation methods, identification of surface archaeological materials, mapping of sites, and ethnoarchaeological and oral history data collection. The data collected during these field seasons were later used in the exhibitions

and discussed in a trilingual popular book (see below), summarising the findings of the first phase of research.

Surveys: Together with community archaeology trainees, community point persons (from the steering committees), and trained archaeologists in this project, archaeological surveys were conducted in both Northern Kenya (around Balesa, El Hadi, El Muda, Kalacha, Kargi, Maikona, and North Horr), and in Southern Ethiopia (around Dubluq, Mega, Irdar, Gayo, Wachille, Web, Borbor, Gorille, Dhas, and Anole). Some of these surveyed areas contain both ancient wells and burial cairns within the same vicinity. Of note were El Muda, Balesa, El Hadi, and Irdar. Others contained several cultural sites as well as ancient wells. Other archaeological sites in these areas include stone-built monuments (e.g., Borbor Site), and rock art sites (in Kalacha, El Muda, Mega, and a crocodile rock art site west of Dubluq). Several archaeological habitation sites flanked by burial cairns were found and surveyed in Southern Ethiopia (notably on top of Komu Kuyu Hill in Irdar) and on a series of low hills close to El Hadi town in Kenya. Participation in these activities provided community participants with basic archaeological training about how to identify different types of archaeological remains in their landscapes, how to identify different archaeological materials, and in various recording techniques and procedures.

Mapping: Mapping of wells, cultural sites, and archaeological sites was undertaken around the well clusters of Balesa, El Hadi, El Muda, Kalacha, Kargi, Maikona, and North Horr in Northern Kenya, and in Dubluq, Mega, Irdar, Gayo, Wachille, Web, Borbor, Gorille, Dhas, and Anole in Southern Ethiopia. Apart from taking coordinates, team members also documented the morphology, sizes, and depths of these wells, along with additional information on the surroundings, the well entrance, and the presence of additional elements such as tanks and water troughs for animals. Although some wells are still in use, others have fallen out of use owing to their collapse or abandonment, and team members interviewed local inhabitants to establish the causes at different locations.

As part of the mapping exercise, participants were trained in using handheld GPS devices to log the locations of surface finds whenever encountered during foot surveys. The activities served the dual purpose of training a cadre of community archaeologists on how to record sites and materials and in reporting these to research institutions, while also expanding the known archaeology of the two study areas.

Excavations: Excavations provided project participants with additional practical experience while also serving to establish what these physical traces can tell us about past human activities and populations. Nine sites that the team had identified during surveys as having potential were selected for test excavation. These comprised two cairns in Balesa; one in El Hadi; three sites (two cairns and one settlement) in El Muda in Marsabit County; and three sites in Yabello Administrative District around Irdar (two at Dhibu Sako and one at Komu Kuyu) (Figure 6).

These excavations exposed participants to excavation methods, and apart from answering the archaeological questions, the activity served to demonstrate the archaeological importance of the burial cairns in their landscapes, thus erasing the notion that they are places where Italians buried treasure (a common view in Ethiopia). Perhaps most significantly, by being witness to the excavation of stone cairns and the exposure of human burials, our community archaeologists are now able to inform others in their community that the cairns are burial places. For Borana and Gabra, it is a taboo to disturb the dead; hence, as knowledge of the true functions of the cairns spreads, this may help ensure protection of these archaeological sites. More generally, the excavations have helped demonstrate that these features are not mere piles of stones (*boralle*) but instead hold important records of their predecessors' settlement and burial practices. While working in the field gave them practical experience, daytime and evening discussions regarding the finds and possi-

ble interpretations gave them the opportunity to learn how to put evidence together for reporting purposes.

8.3. Ethnohistorical and Ethnoarchaeological Research

The teams were also involved in ethnohistorical and ethnoarchaeological research with community leaders, elders, and other community members aimed at collecting data about these cultural landscapes, water management practices, and the functioning of a pastoral economy (Figure 7). Community focus groups were held around each well cluster. In addition, individual members of the community and especially people who are directly involved in water management—the Abba Erega and Abba Konfi, including the retired ones—were interviewed. Other than the water managers, women, and individual elders, a sample of individuals respected by their communities as key heritage knowledge keepers were also interviewed. Our interviewees also provided information regarding their perceptions of archaeological sites, rock art, and monuments in the region. Their responses indicated a widespread lack of awareness about most of the archaeological sites in their localities and their historical significance. It was also clear that the contemporary cultural sites enjoy a degree of community protection, although, with the dwindling of the authority of traditional institutions and the growing influence of external actors in the form of governmental, non-governmental, and religious organisations, the maintenance of socio-ecological systems has been weakened. These interactions also served as avenues for talking with participants about climate change, the dangers it poses to these archaeological sites, and their potential roles as stewards of this heritage. While these interviews provided information for helping answer our research questions, they also gave our community trainees, who were mostly young or early middle-aged, the chance to learn more about their cultures and landscapes.



Figure 7. Oral history interview in progress at the Balesa wells (Photo: Paul Lane).

8.4. Trilingual/Bilingual Exhibitions and Publications

At the end of the initial phase of research, we installed a trilingual (Oromo, Kiswahili, and English) exhibition at the Kenya National Museum in Nairobi. This was opened by the Deputy Governor of Marsabit County (Northern Kenya) and the Member of Parliament of Saku Constituency in the same area, and attended by over 200 people (Figure 8). Other Kenyan dignitaries included the former mayor of Nairobi who is also a senior patron of the National Museums of Kenya (NMK) and officials from the Ministry of Water and Sanitation and the Ministry of Education. Attendees from Southern Ethiopia included the Provincial Commissioner of Yabello and the Administrator of Guchi District where we worked. Scholars, elders, and members of the general public from both countries also attended. This exhibition was an eye-opener for many attendees and for the public regarding the range of archaeological sites in their home areas, the threats they are facing, and their state of conservation, especially as this was the first exhibition the NMK had curated on the archaeology of these regions. During its four-month run, the exhibition was seen by over five thousand people, many of whom were school-age students and their teachers from around the country.



(**a**)



(**b**)

Figure 8. Project exhibitions: (**a**) The Marsabit Deputy Governor and other Ethiopian and Kenyan dignitaries attending the opening of the exhibition at the National Museum, Nairobi, September 2022. (**b**) Community archaeologist Ali Gufu Ibrae giving visitors a guided tour at the exhibition opening in Kalacha, October 2022. (Photos: (**a**) Paul Lane; (**b**) Katelo Abduba).

Due to public demand, for both dissemination and awareness, we duplicated and installed the trilingual exhibition at Kalacha, Marsabit County, where the opening was attended by about 300 people including school-going students. The exhibition has also been shown during cultural festivals in Marsabit, where it was viewed by hundreds of people, and it is now domiciled in the Marsabit County Office's cultural exhibition space. A bilingual (Oromo and English) exhibition was later installed in two localities in Southern Ethiopia (Yabello and Irdar), where we had undertaken fieldwork; this has been given a permanent home at Borana University in Yabello. It is our hope that this will serve as another pathway to the creation of awareness leading to policy change.

To promote more permanent respect and understanding for archaeological and cultural heritage among administrators and policy-makers, we produced a trilingual (Oromo, Kiswahili, and English) book (reproduced in a bilingual (Oromo and English) format for Ethiopian readership) aimed at a lay audience to accompany the exhibition (Figure 9). Copies were shared widely with different stakeholders and policy-makers. We envisage this as a tool that could help inform those policy-makers who make decisions about cultural heritage, education, and socio-economic development in our study locations and currently lack insights drawn from knowledge of long-term historical, archaeological, and palaeoecological data. These books were also distributed to relevant government ministries (especially those with responsibilities for land, water, the environment, and culture), development agencies, CBOs, and Non-Governmental Organisations (NGOs).

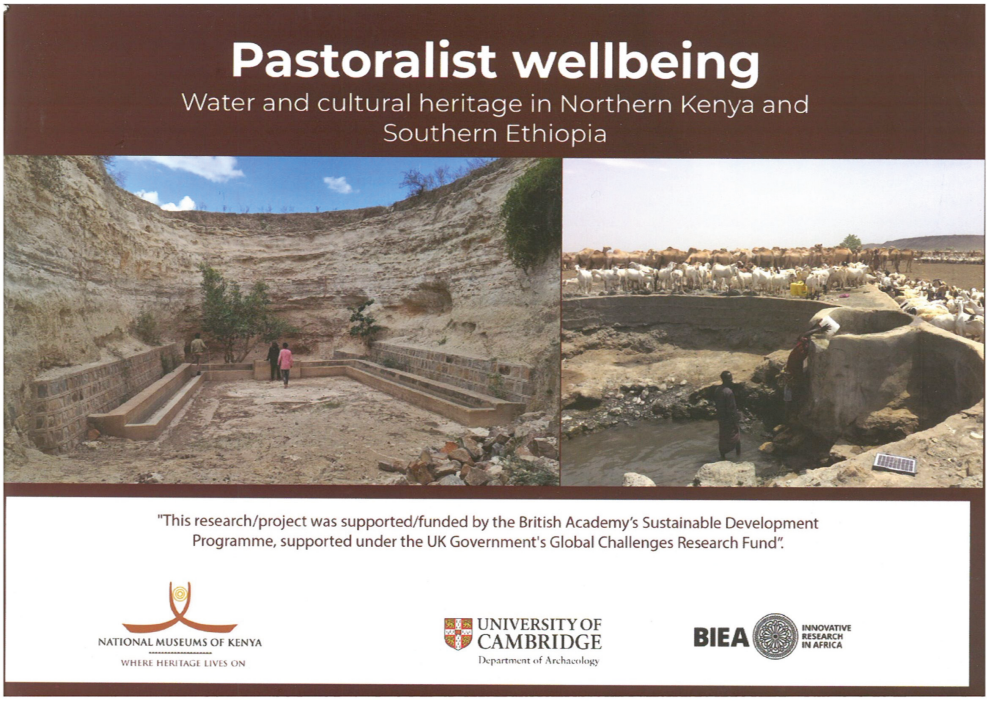


Figure 9. Cover page from the trilingual exhibition book.

8.5. School Archaeological Heritage Clubs

Heritage clubs have been set up in a sample of secondary and primary schools near Kalacha, Marsabit County, with the help of CBOs and our community archaeology researchers who had benefited from the initial archaeological training. The clubs' patrons, who are appointed by each school, also participated in a workshop and training organised by the project to discuss the project's results and identify learning tools and approaches that could prove effective for teaching school children about archaeology and the past in their area. As it transpired, the initial workshop on archaeology was as important for the club

patrons (since few of them had any prior understanding of the discipline), as it was for their students. Once informed about archaeological practice and how to identify archaeological remains, however, they quickly started devising practical exercises for their club members to implement (Figure 10). The project's team members also helped with these exercises and occasionally joined the students during their field projects. The students are now more aware of the archaeological sites and materials within their landscapes, and most learned that they had archaeological remains nearby (and in several cases on their school grounds) directly as a consequence of joining their school's Archaeological Heritage Club. The clubs have now expanded their activities to include discussions about climate change and its effects on archaeological sites, how the clubs can play a role in identifying and reporting any possible archaeological loss (in their opinion) because of adverse weather, and also how club members can help by informing their parents about the archaeological remains found in these landscapes.



Figure 10. Heritage Club activities in Kalacha: (**A**) Freda M'Mbogori explaining stone tool use to primary school students, Rage Primary School, Kalacha. (**B**) Katelo Abduba instructing Rage Primary School Heritage Club students in measuring a stone cairn within their school compound. (**C**) Ella V. Beaudoin working with students at Kalacha Girls Secondary School, August 2023. (Photos: (**A**,**C**) Paul Lane; (**B**) John Roba).

8.6. Media Engagements to Generate Broader Awareness

To sensitise external actors and the public on conservation issues and the negative effects of climate change in Northern Kenya and Southern Ethiopia, we engaged with international and local media and used social media to reach diverse audiences. The most widely circulated of these was an audio–visual article "*Tapping into deep history to manage water scarcity in Africa*," prepared in collaboration with the International Science Council (ISC) and BBC Storyworks for their Unlocking Science series in 2021–2022. This became the second most shared article in the series during the first two months of broadcast, and saw the highest average time spent on any page across the entire series. In our targeted locations, the article was viewed most by 25–34-year-old adults, with strong click rates from women across our target countries, which the ISC report pointed out was unusual. The

BBC further reported that they saw a very strong average click-through rate on our article of 1.97%; nearly double the Facebook industry benchmark of 1%. Twitter statistics for the same article saw the most views from an audience engaged in the "#UnlockingScience" series, as well as for key words "recycling," "anthropology," and "archaeology" hitting our chosen demographics mostly from Somalia, Ethiopia, Kenya, Uganda, and Tanzania, and with the highest overall engagement in the series (including retweets, clicks, and likes). The article also had the highest engagements from audience members following from global organisations such as the United Nations Development Programme ("@UNDP") and the United Nations Educational, Scientific, and Cultural Organization ("@UNESCO") [80]. Other broader awareness engagement included the project's website and social media accounts (YouTube, Facebook, and Twitter [as it was then]) as well as through the British Institute in Eastern Africa's, the National Museums of Kenya's, and the Mapping Africa's Endangered Archaeological Sites and Monuments (MAEASaM) Project's social media pages. We also reached many audiences through presentations at the British Academy, British Institute in Eastern Africa (seminars and annual lecture), University of Addis Ababa, University of Cambridge, and various international conferences including at the *Heritage in Crisis* conference in Tbilisi, Georgia, the 5th Shanghai Archaeological Forum meeting in Shanghai, and a keynote at the 29th European Archaeological Association held in Belfast, Northern Ireland, in 2023.

9. Climate Change Awareness, Threats, Adaptation, and Mitigation Strategies

"Climate change" as a phenomenon is not widely recognised by most pastoralist communities in Northern Kenya and Southern Ethiopia, and neither the drivers of current global heating nor fears of the potential negative effects of current climate change are topics of everyday, voiced concern. However, these communities are intimately familiar with adverse weather conditions that historically caused them severe hardship periodically, and which are now more frequent, extensive, and devastating. Historical and ethnographic data [32,81,82] suggest that communities were quite skilled at recognising signs of impending weather events and imminent floods or droughts, allowing them to take appropriate actions to protect their livelihoods.

Our own research suggests this indigenous knowledge is deeply woven into the fabric of Gabra and Borana communities in Southern Ethiopia and Northern Kenya, and often finds expression in rituals and ceremonies throughout life's stages. This knowledge is also transmitted to future generations, forming a strong foundation for their epistemologies and agency. Traditional leadership systems, such as the *Luba* among the Gabra and *Gada* among the Borana, play an important role by coordinating grazing committees and village meetings and directing routine monitoring of grazing and watering locations. Individual mitigation strategies include sustaining social exchange networks and stock-friendships that allow herds to be split between different localities during periods of drought, thereby spreading the risks of stock loss [82]. These institutions are reported to have contributed to maintaining socio-ecological resilience during previous ecological crises [32,83–86]. Likewise, oral histories document significant environmental events, like floods, droughts, and locust invasions, among others [84–86]. These records chronicle the devastation caused by these events and the measures taken for mitigation, adaptation, or recovery.

Whereas pastoral systems across Northern Kenya and Southern Ethiopia are well-adapted to the prevailing arid and semi-arid environments, the archaeological sites and monuments that provide material testimony to previous pastoralist adaptations are now facing escalating direct and indirect threats from climate change, as in other parts of Africa [87]. Violent desert winds driven by the Turkana Jet have become more frequent, and

aeolian erosion has increased owing to the loss of vegetation cover during years of extended drought. Surface scatters of material have long been susceptible to aeolian erosion, and many are already deflated and subject to stratigraphic mixing; however, they are also now exposed to additional threats from violent flash flooding when the rains return. Aeolian and fluvial erosion are also impacting elements of the built heritage, especially the stepped, wooden ramps that lead down into the deeper wells, while waterlogging of low-lying areas following flash floods may well be stimulating microbial decay of organic materials that had previously survived due to arid conditions.

Additionally, as well as causing direct damage to archaeological and cultural sites (Figures 11 and 12), archaeological remains are now at greater risk from being either destroyed or damaged due to changing adaptive strategies. For example, because droughts are typically now more prolonged and frequent than even in the recent past, some communities are becoming more nomadic and making greater use of temporary camps (*foora*) for their herds when searching for suitable grazing land, while still maintaining a permanent or semi-permanent settlement elsewhere. In *foora*, temporary dwellings are erected along with animal kraals. As documented through systematic mapping of enclosures visible on satellite imagery, the distribution and number of *foora* are intensifying as herd management systems are adapted to meet the challenges of a changing climate. Stones from archaeological burial cairns are sometimes used for building kraals, and the *foora* may also be built over archaeological remains and incorporate ancient stone walls and cairns, causing damage to sites (Figure 12). The damage caused by such actions is generally inadvertent rather than due to deliberate attempts at destruction, arising from a lack of awareness of the historical and archaeological value of what might appear to be no more than a convenient pile of stones (*boralle*). These losses largely go unreported, and thus no action is taken by the relevant heritage authorities to either protect the sites or to recover the materials which may otherwise be destroyed. It is likely that in the absence of heightened awareness of the local archaeology, this kind of threat will intensify.



Figure 11. (**A**) Abandoned modern borehole well, Gayo, Ethiopia, April 2022; (**B**) litter-strewn abandoned well at Wachille, Ethiopia, April 2024; (**C**) flooded well, Dubluq, Ethiopia, April 2024 (photo credit: Freda Nkirote M'Mbogori).

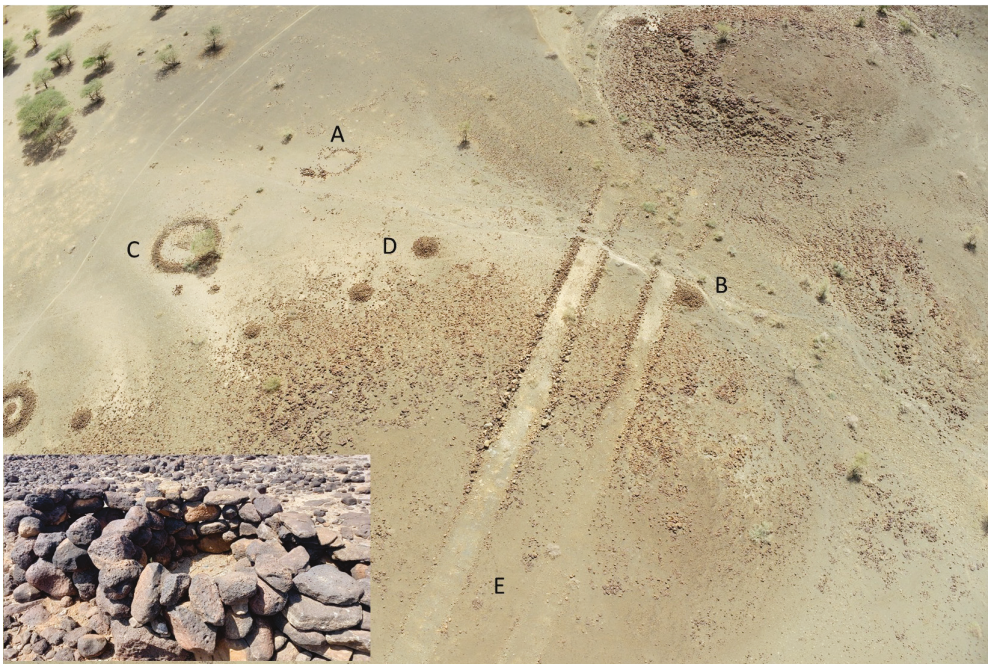


Figure 12. Drone image of cairns north of Kalacha, showing damage from recent *foora* construction (A) and geological exploration work (E linear bands), including partial damage to a cairn (B). C = ring cairn, D = simple kerbed cairns; inset—example of a *foora* goat pen, June 2022. Photo credits: John Kanyingi/BIEA.

The ancient wells that have been maintained and used for over five centuries are also now in danger of being lost because of collapsing walls and changes in attitudes toward them. The introduction of boreholes by government and non-government agencies appears to be contributing to this. Some boreholes are intended to make it easier for livestock to access water during droughts because the animals are usually weak and unable to descend the ramps leading down to the watering area found in many traditional hand-dug wells. Due to the ease of accessing water from the boreholes as opposed to the hand-dug wells, some families are now abandoning the latter (which require regular, routine maintenance) and embracing the use of boreholes and pans. Boreholes can be used throughout the year but, unfortunately, when drought sets in, they can quickly run dry. Likewise, pans may dry up rapidly within the first few months of a drought that might last several years. When this happens, the abandoned ancient wells cannot be rejuvenated because they require considerable investment of labour and firm leadership. Because of the impoverishment of community members during droughts, youth migration to urban centres, and decline in the authority of traditional institutions, the organisation of labour needed to revitalise the collapsed and neglected ancient wells is becoming increasingly untenable in many areas.

Droughts, which have caused great human suffering in Northern Kenya and Southern Ethiopia, also attract external actors to these regions who come to save lives through the provision of relief food and much-needed health care. This too can lead to inadvertent damage to undocumented archaeological remains. Feeding centres develop close to cultural sites, especially near ancient wells, a situation that attracts people in need of food, medical treatment, and other services. Given that many burial cairns are located in proximity to ancient wells, stones may be removed and used in various ways including to construct houses, boundaries, and small animal kraals. These feeding centres sometimes become areas of high population concentration, leading to land degradation and thereby causing further damage to nearby tangible heritage.

10. Impact of the Project in This Study, the Preservation and Protection of Heritage

Our efforts at the creation of archaeological awareness in Southern Ethiopia and Northern Kenya brought to the fore the scientific, economic, and social benefits that protection of these landscapes can bring, and the possible loss of much of what communities have held dear for many centuries if conservation plans are not put in place and other actions taken. As appreciation of the archaeological heritage took root among our community participants, a new sense of attachment to the wells and the deeper heritage emerged. Participants were proud to have been involved on an equal footing with the project scientists, and that the project had sought to communicate the deep history of the wells and other elements of their cultural landscapes to wider, public constituencies. At the outset of our work, local communities in both study areas tended to view archaeological research as a foreign, Western endeavour, with no relevance to their own lives or sense of history. Hence, there was little understanding of what archaeology entails or how it can be used to address societal issues and concerns in the present.

The willingness and enthusiasm shown by the local communities in the Marsabit and Yabello regions with whom we worked has begun to change these attitudes. The training of community archaeologists, for example, was intended originally for just five individuals in each region but that number tripled due to demand and interest. Moreover, although only fifteen from each region received formal training, several more expressed interest in participating but were unable to do so owing to time and financial constraints. This response was a clear indication that more public engagement is needed and that the local communities are willing to take leadership in the protection of their cultural heritage, whether archaeological, historical, or contemporary, if provided the appropriate tools and guidance. The main hindrance to their participation seems to derive from their lack of knowledge of relevant disciplines and the lack of opportunities to engage intelligently with visiting archaeological research teams.

Rapid mapping of several hundred archaeological and cultural sites in our areas of focus proved an effective means of raising awareness and stimulating participation. The mapped sites include ancient wells (both those in use and abandoned), stone cairns, rock art, monuments, and contemporary cultural sites where different clan ceremonies and rituals are performed (these data have been added to a cross-border database of archaeological sites and monuments currently being developed by the Mapping Africa's Endangered Archaeological Sites and Monuments Project, coordinated by P.J.L and hosted by the University of Cambridge [88,89], and which is continuing the use of remote sensing to map other sites and monuments in our study localities). The mapping work generated data for use by various stakeholders and introduced our trainees to various forms of archaeological and cultural sites, their locations, and their interconnections. During the mapping, participants gained new understanding of the cultural and archaeological makeup of their landscapes, and they began noticing similar archaeological features in their home areas that previously had not seemed important to them. Mapping and physical visits to these sites created a sense of ownership. We hope this will foster voluntary monitoring and reporting by the community members since they now understand and appreciate the research value of these sites.

Of note is that the archaeological and other cultural sites within Northern Kenya and Southern Ethiopia are interconnected and, therefore, conscious conservation or protection initiatives are likely to lead to the general protection of the cultural landscapes of these areas. For example, the ancient wells and their environments have been protected in some cases for over 500 years through community actions because of their importance for "weathering" [90] periodic climatic adversity. Specifically, in the past, settlement was

not allowed within several kilometres of the wells. Other land uses near the wells were also highly regulated, creating an environmental buffer zone around them. This helped to protect critical grazing areas that could be utilised during times of drought. At the same time, by virtue of being located close to some of the wells, many cairns and other archaeological features also benefitted, albeit inadvertently, from protection.

The exhibitions, stakeholder meetings, and the popular books have all helped to make the archaeological and cultural sites more readily visible to the wider public, thus adding to the number of knowledgeable people. The trained community archaeologists can now speak more fluently about archaeology, climate change, and the threats it poses to cultural landscapes, and so are better able to initiate discussion about cultural heritage conservation and protection. For instance, as a follow-up activity to the initial phase of data collection and after instruction in the Photovoice methodology [91,92], in 2023–2024, our core group of community collaborators designed a digital exhibition on the theme "*Water, Heritage, Sustainability*". For this, each member selected two photographs, from dozens they had taken on their mobile phones, to illustrate key ideas on this theme that are important to them as members of their community, and about which they provided a few lines of explanation. Some highlighted what they saw as problems, such as the build-up of litter in and around wells, or damage to wells, while others chose to highlight other issues with many focusing on the importance of water in rituals, ceremonies, and everyday life (the exhibition will go live on a revamped project website in 2026, and an article on the process and content is in preparation).

Many of the students and community researchers involved in this project have since become ambassadors for archaeology in their respective areas within the region. For example, one community researcher (who holds an MA in Education), from Marsabit county government, has enrolled for a Master's degree in Archaeology at a Kenyan university and, in his county government role, now informs members of the wider public in the county about the intersections between archaeology, climate change, and emerging threats to cultural heritage. Another community researcher joined the project as a student from Borana University, Yabello, and is now part of its teaching staff and has formed an "archaeology club" there, and voluntarily teaches others what he learnt during this project. Others have played coordinating and facilitating roles in follow-up activities including in a two-day workshop involving local government and NGO representatives from Marsabit county on integrating cultural heritage into future climate change adaptation scenarios, using the KESHO participatory modelling tool [93], and identifying locations for documenting indigenous knowledge concerning different kinds of traditional containers and the individuals skilled in their manufacture as part of a project to record endangered material knowledge in our study areas (both sets of activities will be reported on at a future date in more detail).

Perhaps the most important consequence arising from our awareness campaigns was in Southern Ethiopia, where we witnessed a new policy initiative. While undertaking fieldwork, the project team had frequent meetings with local policy-makers and community leaders to talk about the dangers facing *Tula* wells and their associated cultural heritage landscapes. Emphasis was placed on the range of current threats that could result in total loss of archaeological, cultural, and historical sites, and the loss of intergenerational knowledge and livelihood sustainability. In response, local government officials, in consultation with the national government, decided to delink the administration of two of the units (Irdar and Webb) from Guchi and Wachille, respectively, and to elevate them to become independent administrative units. Given this new status, they were renamed Tula Irdar and Tula Webb. The addition of the word "Tula" was a conscious policy decision intended to

promote the *Tula* wells and their landscapes for cultural heritage preservation and cultural tourism through sensitisation and creation of local pride and awareness.

11. Conclusions

In conclusion, by creating awareness among local communities, a sense of ownership is fostered that forms the basis for agency. In this way, the monitoring and protection of sites becomes a calling rather than an imposed responsibility. Although a community's reasons for conserving an archaeological site might differ from those of a professional heritage manager, they can still find a sense of purpose as the cultural, social, and economic benefits arising from protection are recognised and begin to accrue. For policy-makers and administrators, the benefits of archaeological and cultural sites' preservation and conservation in our region tend to be seen mostly in terms of the potential economic returns that might arise from increased cultural tourism. This is because both regions are marginalised economically and politically, and government officials see cultural tourism as a possible source of jobs and revenue for local communities that could offset such marginalisation.

Creation of awareness to instil agency in Northern Kenya and Southern Ethiopia communities for monitoring and conserving archaeological and other cultural sites, whether on the basis of economic benefits (in the case of cultural tourism) or their cultural beliefs about not disturbing the dead (in the case of ancient burial cairns), is also timely. As extended droughts have become more frequent and the flooding that typically follows their ending has become more severe (Figure 13), the region's diverse and varied mix of archaeological sites has become more vulnerable to both the direct and indirect threats these worsening climatic conditions have initiated.



Figure 13. Impacts of flash flooding in late 2022 on contemporary society: (**A**) Passers-by help push a loaded Land Cruiser through the flood waters. (**B**) Flood damage to a recently constructed bridge on the Kalacha–Marsabit highway. (**C**) A herd of sheep and goats drowned during a flash flood. (Photos: Hassan Godana).

There have been challenges, and several remain. As discussed above, most of the excavated sites remain poorly dated and settlement sites with well-preserved stratigraphic deposits that would allow for the recovery of faunal and botanical remains and other economic indicators that might demonstrate how previous inhabitants responded to past episodes of significant climate change have yet to be located. Similarly, it has not been possible to determine archaeologically when the practice of well digging first began, owing to the lack of surviving deposits or dateable structural evidence that might relate to these initial phases of construction. Both factors severely limit attempts to infer how resilient communities were to climate change in the past, and hence also the utility of the existing archaeological information for informing strategies aimed at enhancing the resilience of contemporary communities. While the chances of establishing archaeologically when well digging began seem remote, further archaeological survey and targeted excavation of habitation sites may generate the necessary datasets for better understanding how past societies responded to the cycles of environmental change documented in the Erenderi sediments and how resilient they really were in the face of severe climate change. In tandem, more research is needed on determining the social, economic, and political consequences of different episodes of population expansion and migration, such as the sixteenth and seventeenth southward expansion of Oromo peoples [94], and the timing and impacts of the spread of other Cushitic language speakers into the Ethiopia–Kenya borderlands [95].

This project has been far more successful in raising public consciousness of the rich archaeological and ethnographic heritage of our study areas and the growing threats to this heritage from current climate change and other factors. Nonetheless, despite widespread public support in the areas where this project has run for the creation of museums in these areas to showcase this rich heritage, there has been no movement yet on the part of the relevant local and national authorities to allocate resources needed to create these institutions. Likewise, local governments, NGOs, and development agencies continue to pay scant heed to integrating heritage promotion and protection into their activities aimed at addressing the UN's Sustainable Development Goals, despite the recognised value of doing so and the existence of relevant guidelines, e.g., [96–98].

Hopefully, the willingness with which the leaders responded to our programmes and the urgency they adopted in crafting their own programmes for awareness creation and policy change do signal a better future for archaeological and other cultural sites in these two regions. To be effective over the long term, however, requires recognition of local communities as the first point of call for heritage site protection efforts. This can be achieved through advocacy and targeted community empowerment programmes. As we hope to have shown, when designed and undertaken in this manner, archaeological research, site conservation, and protection initiatives are likely to be well-received by communities who are eager to be knowledge co-producers, especially if they understand the project. Finally, this style of research can generate practical and realistic actions for site protection and ways to involve a wide range of stakeholders in climate change mitigation measures for archaeological and other cultural heritage sites.

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Data Availability Statement: Our data have been added to a cross-border database of archaeological sites and monuments currently being developed by the Mapping Africa's Endangered Archaeological Sites and Monuments Project, coordinated by P.J.L., and hosted by the University of Cambridge [88,89], which is continuing the use of remote sensing to map other sites and monuments in our study localities. See the following: https://maeasam.org/.

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Abbreviations

The following abbreviations are used in this manuscript:

BBC	British Broadcasting Corporation
BIEA	British Institute in Eastern Africa
CBO	Community-Based Organisation
ISC	International Science Council
LSA	Late Stone Age
MA	Master of Arts
MAEASaM	Mapping Africa's Endangered Archaeological Sites and Monuments
MSA	Middle Stone Age
NGO	Non-Governmental Organisation
NMK	National Museums of Kenya
PN	Pastoral Neolithic
UNDP	United Nations Development Programme
UN	United Nations
UNESCO	United Nations Educational, Scientific, and Cultural Organization

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