PERSPECTIVE

History meets palaeoscience: Consilience and collaboration in studying past societal responses to environmental change

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Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved February 11, 2018 (received for review September 28, 2017)

History and archaeology have a well-established engagement with issues of premodern societal development and the interaction between physical and cultural environments; together, they offer a holistic view that can generate insights into the nature of cultural resilience and adaptation, as well as responses to catastrophe. Grasping the challenges that climate change presents and evolving appropriate policies that promote and support mitigation and adaptation requires not only an understanding of the science and the contemporary politics, but also an understanding of the history of the societies affected and in particular of their cultural logic. But whereas archaeologists have developed productive links with the paleosciences, historians have, on the whole, remained muted voices in the debate until recently. Here, we suggest several ways in which a consilience between the historical sciences and the natural sciences, including attention to even distant historical pasts, can deepen contemporary understanding of environmental change and its effects on human societies.

history | consilience | adaptation | resilience | collapse

The Problem

There is clearly a need to better understand interactions between past societies and their environments. Collaboration between the historical–archaeological and the paleoenvironmental sciences is essential to this effort, but it has been slow to materialize. While archaeology and history have always worked hand-in-hand, and while their research questions often overlap to a large degree, our concern here is with the fact that professional historians themselves rarely engage with recent developments in paleoscientific research, in part because history is a very fragmented discipline, one that is still figuring out how to open cross-field intra-history discourse. However, it has a crucial contribution to make to these interdisciplinary collaborations: besides corroborating or challenging paleoclimatic research findings, historians are able to warn against overhasty assumptions about the relationship between societal complexity and resilience toward environmental stressors.

Interactions within socio-environmental systems are hardly simple. Many societies, for example, have evolved precisely in locations where the environment was difficult to control: complex sedentary groups first arose in flood-prone river basins rather than more stable environmental contexts, suggesting that solving environmental problems contributed to the development of these societies. We focus here on the fact that states and societies have varied in their capacity to respond to environmental change; the complexity of a system and its ideology have always been key aspects in this respect, as our four case studies demonstrate. Societies need to be understood as existing within a specific socio-geographic environment upon which they impact (an aspect we do not directly address here) and with which they interact and adapt to, as part of a transformative feedback system, our main focus (1).

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Author contributions: J.H. designed research; J.H., L.M., T.P.N., A.F.C., A.I., P.G., I.L., and N.R. performed research; J.H., L.M., T.P.N., A.F.C., A.I., and P.G. wrote the paper; and I.L. and N.R. contributed to one section.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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Published online March 12, 2018.

www.pnas.org/cgi/doi/10.1073/pnas.1716912115

State of the Art. This paper is intended to open discussion and suggest ways to move forward rather than present a final statement about the ways history can contribute to the paleosciences. The historical record provides a conceptual laboratory in which hypotheses developed by both natural scientists and social scientists can be tested using parallel chronological and spatial comparisons (2). Former contributions have pointed out that it is all too easy to find some past environmental event, for example through proxy data, and link it to identifiable changes in the historical or archaeological record based on a few high-profile case studies (3–6), and that a more nuanced approach is required (7–11). The collapse of Bronze Age civilizations in the Mediterranean, the end of Classic Period Maya civilization, the fading away of Norse settlement in Greenland or of the Rapa Nui (Easter Island) peoples have all been ascribed to environmental stressors as much as to socio-environmental interactions (3, 6). Because correlation does not imply causation, many such interpretations are oversimplifications of a complex and interconnected system with multiple independent variables and feedback loops (7–10, 12, 13). However, an increasing awareness of the importance of environmental degradation and societal impacts on the environment has tended to popularize such a catastrophist perspective with regard to these historical examples and others (for literature critiques, see refs. 11, 14, and 15). Such interpretations not only tend to minimize the complexity of the causal relationships involved, as articulated in a previous PNAS special feature (e.g., see refs. 7 and 8), but also encourage a simplistic approach to contemporary problems and policy development.

Scholars have already recognized that what is needed is an approach that integrates societal and environmental factors through consilience: that is, using different disciplines to examine the same question (e.g., see refs. 7 and 8; for a recent example, see ref. 16). However, it remains the case that most studies of past human–environment interaction focus on comparing archaeological evidence with paleoenvironmental proxy and model data to make the case that the environment or society did or did not have the impacts they had generally been assumed to have (extensive literature is cited in refs. 17–20). While effectively establishing correlations between climate shifts and regional political and societal transformation and "collapse," for example, such work often ignores more detailed analyses of historical social-structural and institutional relationships, often allowing for a very wide chronological margin of error, even if statistically persuasive (21; for contrast see, for example, refs. 22–25).

From the perspective of a historical analysis, the causal mechanics of the relationship between society and environment remain obscure or at best hypothetical. A truly integrated approach thus remains elusive. Complex historical societies were often resilient to adverse climate change and feedback loops between climate and society occurred under very specific conditions (e.g., refs. 18, 20, 22, and 23). To elucidate such relationships, a thorough and nuanced examination of the effects of environmental pressures and climate forcing within any given society and context is thus needed. This in turn requires consilience not just between archaeology and the paleosciences, each with its own set of narratives and methodological tools, but also—and crucially—with history (8).

There is an established tradition of human–environmental science engaging with historical–archaeological themes, in which archaeologists and anthropologists, as well as ecologists and geographers, have largely been at the forefront (see refs. 26 and 27 for discussion and ref. 28 for an example). However, this approach still remains marginal to both the sciences and the social sciences (14, 15, 29, 30). While several historians have recently attempted to bridge this gap (e.g., refs. 31 and 32), it remains the case that historians do not collaborate enough and in a multidisciplinary-team environment sufficiently to resolve issues of method and approach.

The need to incorporate the complex interactions and feedback mechanisms within a historical cultural system alongside the impacts of a range of environmental and climate-related factors with their own dynamics has been recognized (33, 34). However, it has rarely been followed through with a grounded historical analysis. Furthermore, it is not only the physical or social–institutional impact of changing environmental circumstances or sudden catastrophes that are fundamental, but also the perceptions of such events upon the "cultural logic" of a society: how people understand what happens in their world directly determines how they respond and how they transform their environment. Historical analysis is crucial to such study. These points were underlined by Butzer and Endfield (8), who set out a powerful agenda for the integration of "insider history" based on historical records with the archaeological and natural science paradigms that have dominated the field, in this case in terms of both collapse and resilience to environmental challenges (for examples, see refs. 33, 35, and 36).

Key research questions for this shared agenda include identifying the severity, abruptness, and duration of climatic events and changes that had the potential to influence history (37); reconstructing past environmental conditions in selected regions, as well as the physical means available to society to respond to environmental change; deploying an archaeological–historical approach that utilizes environmental data to address societal linkages to climatic and environmental change and associated episodes of crisis and adaptation; and integrating the study of both human agency and cultural perceptions or "world-view" into societal responses (17, 38–42).

Issues of Integration. Integrating instrumental, documentary, paleoenvironmental proxy model results and archaeological records to produce socio-environmental narratives is key. The three disciplines we focus on here have different training emphases and research methodologies, as shown in Table 1. This variance leads to challenges: historians and archaeologists, trained with a particular approach to their data and the results they generate, can misuse environmental data, generalizing from limited datasets or misappropriating low-resolution data insensitivity. Paleoclimate scientists can misconstrue the nature of societal complexity and draw deterministic or simplistic conclusions about causal relationships. None of these groups is in a position by themselves to integrate all of the data necessary for a multicausal analysis that explains rather than simply describes. It is relatively easy to generalize at a global level, but integrated local and regional studies are needed to test methodologies, collect multidisciplinary data, and ultimately derive holistic interpretations (39, 40).

Because of differences in the quantity and scope of the available evidence, the study of the societal effects of climate change differs considerably between regions and periods. For some there is a considerable amount of written evidence, whereas in others historical data are insufficient to infer specific reactions and ways of coping with, for example, the extreme weather events sometimes associated with climate fluctuations. Insufficient high-quality paleoclimatic and archaeological data complicate attempts to establish firm links between climate and societies and foster more hypothetical/simplistic analyses, which in turn draw attention away from more robust case studies (43–45; for similar criticisms, see refs. 38–40 and 46). Elucidating the potential causal relationships and assessing socio-economic political resilience thus requires a collaborative consilient research program, sharing data, and developing common interpretive strategies. Examining the microregional level in

Table 1. Data sources and characteristics

Approaches	Historical (written)	Archaeological	Paleoenvironmental
Subject	Details of specific events, phenomena, and processes	Quantitative/qualitative data on long-term socio-economic/cultural transformations; demographic estimations	Reconstructions of environmental and climatic change via proxy evidence (e.g., pollen for past vegetation)
Training	Focuses on a specific social group and period (e.g., Athens in the fifth century BCE)	Focuses on a specific group and period, often through a single site or group of sites	Wider scope of technical methodologies applicable to multiple spatial and chronological cases
Collaboration standards	Heavily biased toward individual work; vast majority of publications are single-authored	A mix of individual and collaborative work, reflected by both single-author and multiauthored publications	Work is inherently collaborative, very few single-author publications
Origin of data	Manuscripts, documents, inscriptions; seals	Excavations, surface surveys, or studies of standing monuments	Sediment cores, dendro data, speleothems, ice cores, other natural archives
Preparation for interpretation	Editing; source criticism; translation	Artifact or monument analysis, statistical processing of data	Laboratory processing, analysis, statistical calibration
Dating precision	Subweekly to subannual	Decadal to centurial (rarely annual)	Annual to centurial
Duration and continuity	Typically discontinuous/short (<50 y) duration	Semicontinuous and normally multicentury duration	Continuous and long duration
Customary ways of interpretation	Reconstruction of events, historical model-building	Identifying periods with stable socio-economic and cultural-material characteristics; reconstructing changing settlement pressure	Identifying periods of different environmental and climatic conditions
Climate–society causality	Can offer explanatory mechanisms	Inferential; normally site- or area-specific (e.g., from excavated or surface materials)	Inferential; nearly always achieved by temporal correlation

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particular can generate in-depth analyses of specific historical–environmental conjunctures to analyze local impacts and responses.

Improving Integration. Research needs thus to prioritize micro-region case studies where the various classes of data are available in sufficient quantity to permit correlation and cross-checking across disciplines and data types. This minimizes the range of interpretive options in understanding the mechanics and nature of the interaction between "anthropogenic" and "natural" complex systems, disentangling the causal association between them (38, 40).

We describe the results of some recent and ongoing research that is informed by this integrative approach below, and that reinforce the message imparted by some other case studies (e.g., see refs. 9 and 47). Four broad outcomes demonstrate the potential contribution of history to paleoscience research: integrative research generates innovative questions and new insights; it reveals more complex sets of causal interrelationships than hitherto understood; it challenges existing interpretations of historical processes; and it provides more detail and nuance of tipping points in historical socio-environmental systems.

Properly integrating paleoenvironmental data and research into historical and archaeological scholarship allows both natural and social scientists to work together in multidisciplinary teams and generate and answer new questions. The case study of Sicily and the southern Levant illustrates the interaction within a socio-environmental system through a feedback loop, where environmental change generated political–economical changes, facilitating the rise and subsequent decline of formerly marginal regions.

The Carolingian case study reveals the deficiencies of depending on one source of information. Moving away from simple climate determinism, it shows that reported years of subsistence crisis are not always associated with identifiable environmental triggers and vice versa. It suggests that resilience or vulnerability to detrimental environmental stressors was not constant even on a semidecadal scale, signaling the extent to which premodern societies could mitigate these conditions.

Paleoenvironmental research can revise existing historical narratives. The case of Caracol, a Maya city in Central America, uses better climate reconstructions to change the interpretations of the causes of its decline and collapse, revealing that societal conflict, rather than drought, caused the city's abandonment.

Finally, the consilient approach uncovers tipping points in historical socio-environmental systems in greater detail. The case of early modern Poland illustrates how a resilient society appears able to mitigate a given set of unforeseen environmental challenges for decades, as long as the stress factors do not interact with contemporary shifting political and societal vulnerabilities. The impacts of the Little Ice Age on the country were easily weathered in times of peace. The context of increased warfare and its accompanying socio-economic stressors, however, pushed the system beyond a threshold, bringing about swift and unexpected economic collapse and political breakdown.

In all of these examples, we would repeat the key point that simple correlation does not imply causation. Through multidisciplinary collaboration, historians, archaeologists, and natural scientists can better determine societal response to environmental change and therefore rewrite and replace well-worn narratives of collapse.

Sicily and the Inland Levant in the Early Middle Ages: What conditions do climate–society feedback loops require? Sicily and the Southern Levant (modern Israel, Jordan, and southern Syria) in the Early Middle Ages (ca. 600–900) offer rare examples of climate–society interactions in the form of feedback loops. Both regions played a key role in the empires to which they belonged before experiencing a shift to aridity as well as agricultural, economic, and political decline. In both cases, there are grounds to suggest that contemporary conditions generated feedback loops that made it possible for climate change to undermine the economic regime of each of the two regions. During the preceding period (ca. 300–600) the eastern half of the Roman Empire had flourished, with economic, agricultural, and demographic expansion (e.g., refs. 48–51). This process coincided with an increase in winter precipitation, as indicated in Fig. 1, in the Eastern Mediterranean. Precipitation was at its highest in the sixth century, when the settlement expansion trend culminated. Rural society flourished in "marginal" regions with less than enough rainfall for regular

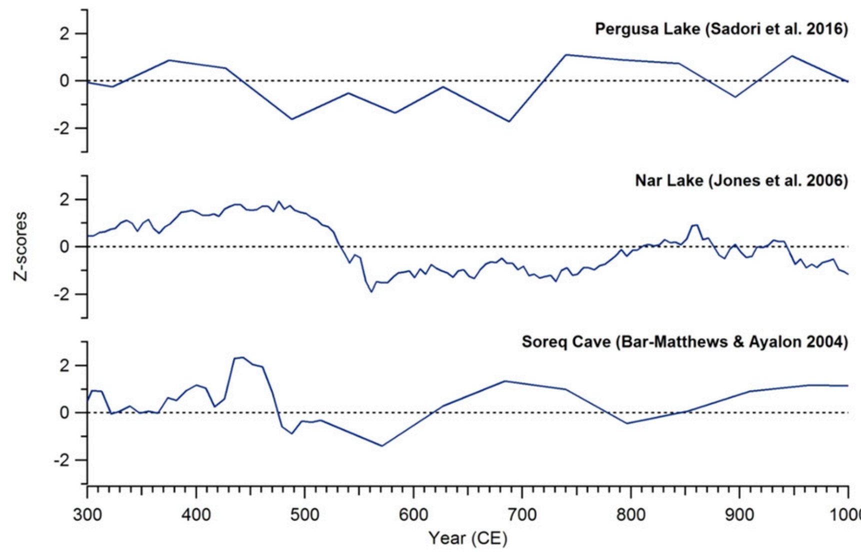

Fig. 1. Eastern Mediterranean hydro-climate reconstructions based on carbonate δ18O records. (*Top*) Pergusa Lake sediments (51). (*Middle*) Nar Lake sediments (108). (*Bottom*) Soreq Cave speleothem (109). All records have been converted to *z*-scores. Upward values represent dry conditions.

agriculture under average climatic conditions, and it is probable that the wetter conditions contributed to this agricultural boom (22). But in the seventh century the flourishing Eastern Mediterranean was transformed as a result of the Arab conquests: the secure world of an imperial state and well-integrated markets disappeared.

In this context Sicily and the Southern Levant assumed special economic and political significance. Both had been peripheral to the booming economy of the Eastern Roman Empire in the sixth and early seventh centuries, but with the breakdown of the old order (48, 49) they became "islands of continuity" where the old intensive agricultural economies survived. Sicily, safe in its peripheral insular location, remained an important source of grain for the Eastern Roman Empire in the seventh century, as well as a key base for imperial power in the central Mediterranean, supplying much of the produce for the imperial armies and for the capital at Constantinople (e.g., refs. 25 and 52). The inland Levant became the major source of food supply for the new Arab Umayyad Caliphate in Damascus. Indeed, given the territorial extent of the Caliphate and the difficulty of moving fiscal resources from the more distant provinces to the center, it became a key region for the power and authority of the new rulers.

However, as both regions assumed their new economic–political roles, they also experienced a shift to drier conditions (22, 51). This climatic change undermined local agricultural regimes. For Sicily, cereal pollen data suggest that large-scale grain cultivation declined as drier conditions set in; rural population density and interregional trade also decreased (51). In the Inland Levant, a shift in local hydrological conditions led to the disappearance of intensive cereal farming in northwestern Jordan between the 7th and the 10th centuries (53). Both regions lost their political significance: the importance of Sicily declined in the eighth century, and the Arab conquest of the now-impoverished island began in 827. In the Levant, a new dynasty, the Abbasids, replaced the Umayyads in 750 and moved their capital to Baghdad, in the fertile river-fed agricultural lands of Iraq.

In both cases, converging lines of evidence suggest that the interaction between climate and society took the shape of a feedback loop. Intensively cultivated regions, pushed to their ecological limits under advantageous climatic conditions, assumed unique economic and political significance in a transforming world, but declined when climate no longer supported their fragile ecological balance. Vulnerability to climatic change was inherent to the social–ecological system that developed at a specific time.

Environmental stress in Carolingian Europe: Crisis and mitigation. Historians have traditionally planted the seeds of Europe's medieval demographic and economic expansion in the Carolingian period (broadly ca. 750–950). The so-called barbarian migrations had ended and recurrent bouts of plague had fizzled out, it seems, by 750 (54; cf. ref. 55). The markedly cool summer temperatures that spanned the sixth to seventh centuries as well had given way in the eighth or ninth century to a climate more advantageous for agriculture (5, 56).

Before Verhulst (57, 58), the people of Carolingian Europe were thought to be technologically backward, sustained on subsistence agriculture, penurious, and starved (59, 60). More robust agrarian lives are imagined now and most historians believe Europe's population grew noticeably in this period (61–65). Growth, however, appears inconsistent and punctuated by periods of crisis. Recent studies integrating the written record with paleoclimate data help to explain some of these setbacks, showing that the Carolingians did not enjoy natural conditions consistently more benign than their predecessors and that they remained vulnerable to environmental stressors (43, 66–68).

Historical sources reveal that Europeans endured more than 20 subsistence crises across these two centuries (67). Whether dearth occurred as often earlier we do not know, as there is more written evidence for Europe north of the Alps in the Carolingian period than before; in later medieval centuries, Europeans may have suffered dearth as often (69). Although more complete, the record of food crises after 750 is still fragmentary: for no dearth do we possess anything approximating a full geography or chronology, and some crises may have escaped the written record altogether.

What triggered these crises? Textual and paleoenvironmental evidence for environmental stressors—extreme weather and short periods of abrupt climate change in particular—routinely, but not universally, correlate with reported food shortage (Fig. 2). Long winters, severe droughts, and relentless precipitation regularly, it appears, resulted in dearth and multiyear sequences of famine and excess mortality. Years when such correlations cannot be made require close scrutiny. Did Carolingians then successfully absorb or deflect adverse conditions?

For example, textual and paleoclimate data reveal severe conditions at the turn of the ninth century associated with a volcanic eruption. Reconstructions of summer temperatures, both European (Alpine and Scandinavian) and Northern Hemispheric, identify the summer of 800 as the coldest from the mid-6th century to the early 11th (70–73). Carolingian annalists mention spring and summer frosts (74), the only instances of their kind recorded across the centuries considered. However, there is no record of poor harvests or dearth. It is possible that the recent experience of famine in the 790s and the legislation issued to curb hoarding and profiteering, and encourage charity, made Carolingians more resilient against a crisis in 800–801. If so, we must explain why drought appears to have triggered famine 5 y later (805–807). Perhaps the record temperatures of 800 heightened Carolingian vulnerability to drought in the years afterward or drought was simply a more capable trigger of dearth at the time. As Fig. 2 shows, famines, those sandwiching 800 and several others, correspond to droughts. Alternatively, contemporary annalists could have thought a crisis would have tarnished Charlemagne's achievements in 800, chiefly his crowning as emperor by the pope, and deliberately omitted a famine from the sources.

Establishing moments of resilience in the distant past is not easy, as this example demonstrates, but the fact that not all episodes of extreme weather or short periods of abrupt climate change correspond to reported crises raises the very real possibility that susceptibility to anomalous conditions was not constant, even on a semidecadal scale. It serves also to remind us that correlation is not causation and that it is a coalescence of external and internal factors that generates crises (75). The Carolingians neither experienced overwhelmingly better conditions than their predecessors nor were they perpetually destitute and starved. Although the expansion and intensification of arable farming and the wider application of valuable agrarian technology (three-course rotation, heavy plow, weather-resistant crops such as spelt), did not save the Carolingians from dearth, mid-8th through mid-10th century sources nevertheless suggest that the Carolingians could mitigate, at least on occasion, the harsh conditions they periodically faced.

The ancient Maya, climate change, and Caracol, Belize. The ancient Maya of Central America occupied a series of different environmental zones and successfully adapted to their landscapes for well over 2,000 y (76). Scholars use a combination of archaeological records, hieroglyphic histories, and scientific data to learn about this past civilization.

The ancient Maya stopped carving hieroglyphic texts around 900, a trend that correlates with the abandonment of their large Classic Period centers and the subsequent depopulation of much of the Maya area. In popular literature this is referred to as the "Classic Maya Collapse." Scholars have debated the reasons for this collapse for more than two centuries (e.g., ref. 77). Recently, the idea that the Classic Period Maya came to a disastrous end as a result of severe drought has gained serious traction (3). The modern-day focus on and political arguments over climate change have also driven a drought-based explanation for the Classic Maya Collapse. However, archaeological data suggest that the explanation for the collapse is far more complex and that a direct correlation with the climatic record is premature and at best only tentative.

Past climate records are being deduced from multiple proxies (e.g., ref. 78), but there are issues with each of these records. Many of the known lake-cores across the Maya area provide different assessments of when droughts occurred (79, 80) and the records from the central part of the Maya area—precisely where

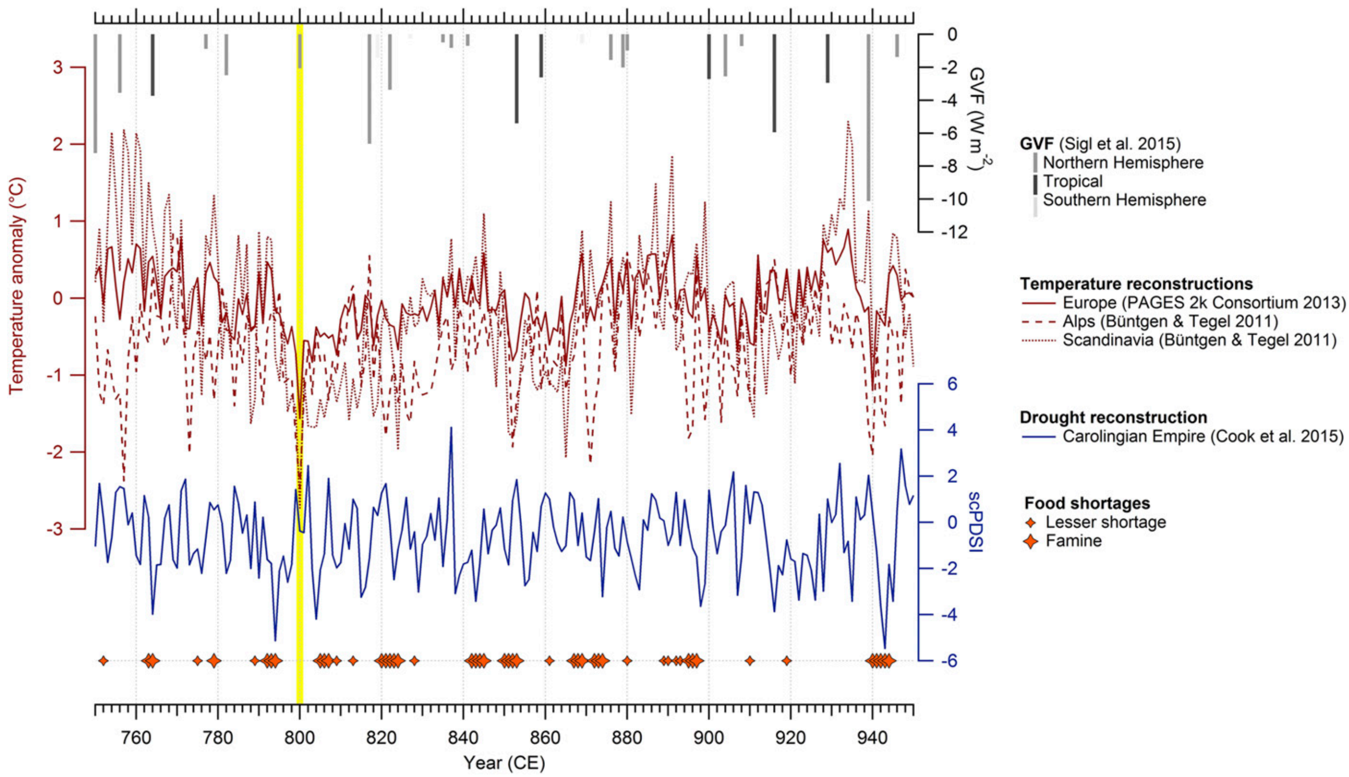

Fig. 2. Carolingian climate and dearth. Gray bars (*Top*) show a reconstruction of global volcanic forcing (GVF) (110). Red curves represent summer (June/July/August) temperatures for Europe (70), the Alps, and Scandinavia (71). Temperatures are expressed as anomalies compared with 1860–2004 (Alps and Scandinavia)/1961–1990 (Europe). Blue curve shows a reconstruction of the self-calibrating Palmer Drought Severity Index from the "Old World Drought Atlas" (111) averaged over the Carolingian Empire. Negative values indicate dry conditions. (*Bottom*) A depiction of food shortages (updated from ref. 67).

Maya civilization crystalized—show minor to no variability in rainfall in the 9th and 10th centuries [paleoclimate records based on stable isotope from lake records, speleothems (81 and 82)]. Although additional concerns with current paleoclimate data continue to be raised (e.g., ref. 83), these problematic records continue to be utilized for lack of better data (e.g., ref. 84).

Caracol, Belize is a large Classic Period Maya city that had 100,000 inhabitants at 650 (85). The city's overall settlement system was well-adapted to its environment for continued sustainability over the long term (86–88). Over 9,000 residential groups were embedded within an urban landscape that was integrated with agricultural terraces and reservoirs that supplied food and water, making the site largely self-sustaining. Due to its size, Caracol would have been affected by any long-term drought, but direct evidence for such an event is not found in its archaeological record. Correlating the archaeological data from Caracol with its hieroglyphic history and the projected drought cycles for the region suggests that the site expanded at the height of each such cycle (89). During the early part of the Late Classic Period (562–680), Caracol was a dominant force in the southern Maya Lowlands, but warfare disrupted its political sway for a century before it participated in regional politics again during the Terminal Classic (after 780). However, the city's latest elite modified social and economic policies that had previously led to Caracol's long-term success, creating a greater divide between them and commoners (85). The central part of Caracol was rapidly abandoned at ∼895. Archaeological evidence suggests that socio-political factors, accompanied by warfare, were responsible for the city's end during this phase of economic prosperity (90). This example indicates that climate change and drought likely strained the system but were not enough, by themselves, to cause the Maya collapse (see also refs. 78, 91, and 92).

Archaeological evidence from Caracol demonstrates that its inhabitants were well-adapted to survive in an environment rich in rainfall but lacking natural standing bodies of water. The inhabitants of Caracol had a long-term investment in their landscape, terraforming their environment over six centuries to control the flow of rainfall runoff for agriculture, while monumental and household reservoirs helped the population through years of low rainfall. Aggregated, the evidence suggests that the inhabitants of Caracol had adapted to environmental variability and climate change over time and were capable of mediating climatic fluctuations, but that disruptive short-term socio-political policies and events triggered the ultimate collapse of their society.

Poland and the Little Ice Age. An influential narrative of early modern Europe argues that the Little Ice Age dramatically affected the Polish–Lithuanian Commonwealth (4). The crisis peaked in 1655–1660, during the country's war with Sweden, when "the Polish–Lithuanian Commonwealth encountered all of the Four Horsemen of the Apocalypse—pestilence, war, famine and death—with catastrophic consequences" (4). This narrative, however, does not differentiate between the political and military factors that led to the crisis, and the impact of climatic change, even though recent work has produced much paleoclimate data for the region (93–96), which makes such a distinction possible. Using new data, we can show that Poland, politically and economically the stronger part of the Commonwealth, remained resilient to the adverse climate conditions of the Little Ice Age until a tipping point in the mid-17th century, when the country was invaded by most of its neighbors and its economy collapsed.

To evaluate the resilience to climatic change in the case of late medieval and early modern Poland, we use data covering the period ca. 1340–1700. Although many argue that the Little Ice Age commenced in Europe during this timeframe (94, 95, 97, 98), Polish historians unanimously describe most of these years as Poland's Golden Age in which the Polish economy expanded and the Old Polish cultural Renaissance bloomed despite marked weather instability (Fig. 3), which hampered agricultural productivity in the temperate climate of Central Europe.

Reconstructed population sizes through historical sources suggest a relatively constant rate of impressive premodern population growth of 0.3–0.38% in Poland from the late Middle Ages to the mid-17th century (99). This growth coincided with intensive internal colonization and a developing manorial economy. Local pollen data show a transformation of the landscape, with large-scale forest clearances and a notable growth in the cultivation of rye, a basic breadmaking cereal important in the internal market and as an export product (100). Land tax data support this interpretation: the amount of land under cultivation doubled between 1533 and 1578 (101). The second half of the 16th century also witnessed the growth of manorial farms.

Contemporary territorial expansion boosted commodity export, in particular grain, from Poland to other European countries (102). The most important traded grain was rye (102–105), whose export increased from the late 15th century, reaching its high watermark in 1619 (Fig. 3). Together with contemporary population growth, the burgeoning grain-based export economy was a key factor of Poland's economic growth in the 16th and early 17th centuries. Both incentives toward agricultural expansion were strong enough to sustain growth even during periods of significant late-spring cooling (Fig. 3).

After more than 200 y of continued growth, all population and economy parameters in Poland collapsed in the second half of the 17th century, a trajectory that suggests that Poland crossed a threshold as a socio-environmental system. Wars with Sweden, Transylvania, Russia, and Turkey reduced the population by at least 30% and cut drastically the amount of land under cultivation. This led to the collapse of grain exports and the integration of the economy with west-European markets, crippling the country's per capita gross domestic product (106).

The Little Ice Age, which did not impede Poland's economic and political development during the relatively peaceful 16th and early 17th centuries now functioned as a major detrimental factor in the context of the major mid-17th century wars. Adverse climate change resulted in poorer grain yields (107), which affected the gentry's manorial farms, whose development had been based on extensive rather than intensive farming. Seventeenth century wars brought plague, often accompanied by famine. This case therefore represents an otherwise resilient socio-environmental system overwhelmed by an accumulation of negative impacts on its basic infrastructure: while the Polish economy had been quite successful in dealing with just one of the Four Horsemen of the Apocalypse—the Little Ice Age—the coming of all four was too much for it to endure.

Conclusion

All four case studies reveal the potential synergy that collaborative work between historians, archaeologists, and paleoscientists has for illuminating the causal interactions between environment and premodern society. In this article we have demonstrated the unique contribution of history for untangling societal–environmental linkages. This consilient approach can generate new research questions and insights, challenge facile interpretations, revise existing narratives, and identify tipping points in socio-environmental systems.

The Sicilian and Levantine case study considered the same timeframe but from the perspective of two formerly marginal regions. Both managed, within very demanding political and economic situations, to respond to climate change and develop their

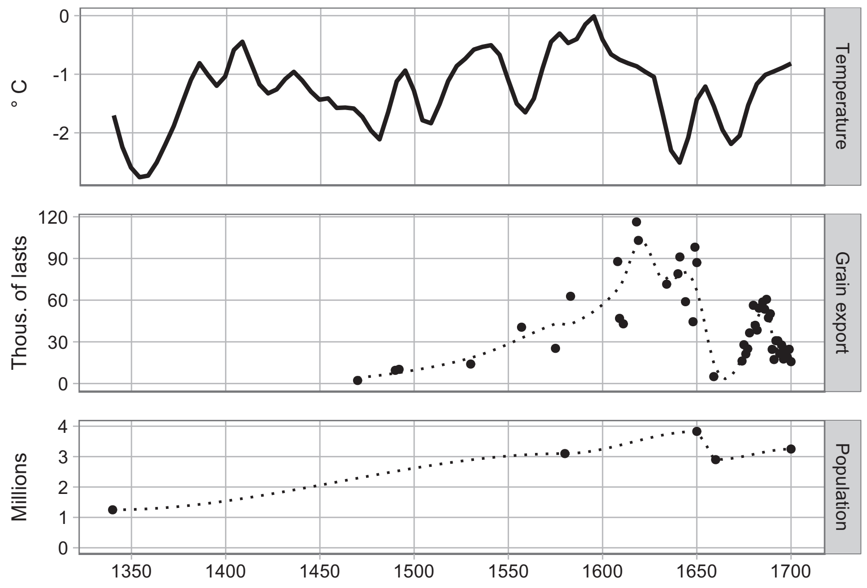

Fig. 3. (*Top*) Temperature reconstructions for southeastern Poland (Loess regression with 0.1 span); May–June, larch, Tatra Mountains, 1961–1990 reference period (94). (*Middle*) Poland's grain exports from Gdańsk (1 last = 2.2 tones) (103–105). (*Bottom*) Population of three major Polish regions (99).

agrarian output, in effect creating and maintaining for a time climate–society feedback loops.

The Carolingian survey highlighted the fallacy that adverse climate events universally triggered dearth and death in premodernity. By focusing on an occasion in which detrimental weather does not coincide with dearth in the surviving historical evidence, this case study moved away from environmental determinism and instead suggested ways in which past societies could demonstrate resilience by mitigating environmental effects.

The case study of Caracol built upon scientific and interdisciplinary scholarship to revise existing narratives. Earlier work covering the broader regions containing the premodern metropolis argued that Caracol society declined and collapsed as a direct result of environmental stressors, namely droughts. Recent work has integrated new paleoenvironmental data and scientific approaches toward human–environmental interaction to argue that this society successfully attenuated environmental stressors and eventually collapsed as a result of internal factors. Because the external socio-economic infrastructure of the Maya never fully recovered, the collapse resulted in the permanent depopulation of Caracol.

Finally, the case of Poland in the 16th–17th centuries illustrates how societal context can determine the impact and effects of environmental stress factors. Human conflict, its mediation through particular ideologies, and the ways in which it interacted with the physical environment, rather than an all-powerful deleterious environment, brought the system to its tipping point and transformed contemporary urban centers and economic systems.

All case studies examined historical periods and places in which existing paleoclimate, archaeological, and historical data sources overlap. We have argued that a consilient approach, which exploits this convergence, is critical to establishing more robust and nuanced causal interpretations about the links between human societies and their environment, while taking account of the interactions and feedback mechanisms between both. This approach moves away from studies that analyze broader chronological and spatial ranges with less available historical and archaeological data yet still equate causality with correlation and argue for environmentally triggered societal collapse. Although the supposedly clear chain of cause and effect in these studies is attractive, it is rarely robust.

We argue that future research on premodern human–environmental linkages should prioritize cases on which social and natural scientists can work in multidisciplinary teams. Such cases would contain richer data over a more limited spatial and chronological scope and, where possible, offer historical documentation that can link social action more broadly to aspects of a cultural belief system. Where such data are not available, space needs to be left within the explanatory framework to permit theorization of the possible roles this played (e.g., ref. 35).

The above examples make it clear that societal decline or collapse is never monocausal and never predetermined. Rather, the environment is a continuous factor with which human societies interact. While it can adversely affect these societies, the causal relationship between them is complex, malleable, and has a differential impact within a given society.

The contribution of scholarly historical analysis to the study of the interaction between past societies and the environment is directly relevant for 21st century debates about climate change and its effects. Using a consilient perspective to interpret the intricate causal relationships underlying how past societies mitigated their challenges, contemporary policy-makers can develop more resilient and robust strategies to tackle the challenges of our own changing environment. Holistic interpretations, nuanced arguments, and careful causal analyses are the potential contribution of the discipline of history to these discussions.

Acknowledgments

The research for this article was supported by the Princeton Institute for International and Regional Studies Climate Change and History Research Initiative (https://cchri.princeton.edu/); Poland's National Programme for the Development of the Humanities; and the Georgetown Environmental Initiative.

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