Review

Towards a rigorous understanding of societal responses to climate change

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A large scholarship currently holds that before the onset of anthropogenic global warming, natural climatic changes long provoked subsistence crises and, occasionally, civilizational collapses among human societies. This scholarship, which we term the 'history of climate and society' (HCS), is pursued by researchers from a wide range of disciplines, including archaeologists, economists, geneticists, geographers, historians, linguists and palaeoclimatologists. We argue that, despite the wide interest in HCS, the field suffers from numerous biases, and often does not account for the local effects and spatiotemporal heterogeneity of past climate changes or the challenges of interpreting historical sources. Here we propose an interdisciplinary framework for uncovering climate–society interactions that emphasizes the mechanics by which climate change has influenced human history, and the uncertainties inherent in discerning that influence across different spatiotemporal scales. Although we acknowledge that climate change has sometimes had destructive effects on past societies, the application of our framework to numerous case studies uncovers five pathways by which populations survived—and often thrived—in the face of climatic pressures.

HCS comprises a large, multidisciplinary scholarship that considers how pre-industrial climate changes influenced human history[1–4]. HCS has focused on hydroclimatic anomalies or periods of prolonged cooling, which allegedly disrupted growing seasons and thereby provoked famines, migrations and ultimately conflict within or between polities[5–13]. Controversial arguments hold that, amid these pressures, some societies 'collapsed' by abruptly losing socioeconomic complexity, political coherence and population[14–21].

HCS has revolutionized scholarly understandings of past disasters and provided scenarios that are relevant to the future effects of global warming[22,23]. However, the overwhelming focus in HCS on crisis and collapse misrepresents the character of historical interactions between humanity and climate change[24]. In this equal collaboration between researchers from the four disciplines that are best represented in HCS (archaeology, geography, history and palaeoclimatology), we identify methodological challenges that lead HCS researchers to systematically over-represent disastrous responses to climate change in human history. We then introduce a research framework to address these challenges and allow HCS scholars to more consistently establish convincing causal connections between climatic and human histories.

Using our framework, we introduce case studies that suggest that human responses to climate change were more varied than is implied by the focus on disaster in HCS. These case studies reveal how populations endured and exploited two climatic regimes that have frequently been linked to societal crises: a period of cooling around the sixth century AD (which has recently been labelled the Late Antique Little Ice Age (LALIA)[9]) and the well-established Little Ice Age (LIA), often defined as extending between the thirteenth to nineteenth centuries AD[25]. This preliminary application of our framework suggests five overlapping pathways by which populations developed or demonstrated resilience to climate anomalies.

Methodological challenges in HCS

Although attempts to systematically link climate change to human affairs date back to at least the nineteenth century[24,26–28], HCS has its origins in the discovery by astronomer Andrew Douglass that variations

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in the width of tree rings could serve as a proxy for past weather, and thus permit precisely dated reconstructions of climatic variability[29]. The geographer Ellsworth Huntington combined reconstructions developed by Douglass with the pseudoscience of phrenology and the longstanding assumption that climatic conditions determined human achievement. It was this synthesis that inspired the first detailed accounts of climate-driven crises in the historical record[30–33].

Sensational claims made by the first HCS scholars were tempered by careful historical work in the 1960s and 1970s[34–36], but some of the assumptions and methods that informed Huntington's work continue to influence HCS to this day. Following early twentieth-century anthropological thought, works published by HCS researchers have tended to present past societies as isolated and homogeneous systems with internal characteristics that make each more or less vulnerable to environmental disruption. They have missed the diversity within societies and the connections between societies that gave rise to overlapping local areas of vulnerability and resilience, prosperity and crisis, along schisms shaped by (for example) gender, race or class[37,38]. They have presented societal vulnerability and resilience as straightforward and diametrically opposed concepts, which ignores scholarship that reframes adaptation, transformation and even collapse as ways of accommodating disturbance—and thus expressing resilience[39–44]. HCS works have imagined climate change as a force that causes societies to rise or fall, ignoring scholarship that stresses continuity in periods of demographic, socioeconomic and political transition[45]. They have characterized Indigenous populations or populations of the global south as particularly vulnerable to climate-driven collapse, which misses evidence of flexible responses to environmental change[46].

Similar to that of Huntington, the work of HCS scholars has tended to accept proxy-based climate reconstructions as direct records of past climate rather than estimates based on distinct statistical interpretations of available sources that may differ from each other and have important and substantial uncertainties on spatiotemporal scales that are relevant for historical analysis (Fig. 1). Palaeoclimate estimates of past temperatures and hydroclimates typically capture only a portion of the total climate variability; show seasonal biases or reflect particular monthly responses; and may be influenced by several climate and nonclimatic factors across different frequencies[47–49]. Many sediment records are both time-uncertain and integrate climate over several decades or centuries, which makes it challenging to use them in direct comparisons with historical evidence. Even banded corals, ice core and cave deposits are subject to dating uncertainty[50,51].

The composition of proxy data in climate reconstructions also changes through time: more recent periods (such as the LIA) are covered by abundant networks of tree-ring series, whereas older periods are captured by a sparser mix of disparate palaeoclimate evidence. Some studies in HCS ignore these uncertainties or depend on reconstructions that are either out-of-date, reliant on fragile statistical methods or in disagreement with other equally valid palaeoclimatic evidence[52,53]. Many publications therefore incorrectly identify the cause, magnitude, timing and character of past climate changes. These errors have led some to misidentify causal mechanisms, mischaracterize background factors and misrepresent the distance of causal factors from outcomes[54].

In HCS, few periods have been mischaracterized more than the LIA and the earlier, still-controversial LALIA (Fig. 1). Scholars have assumed that cooling in both periods endured for centuries or that it approached in magnitude the warming that is projected for the twenty-first century AD[55–57]. However, the volcanic, solar and internal forcings that were primarily responsible for the LALIA and LIA rendered the climate of those centuries spatially and temporally heterogeneous, and ensured that—on large scales—cooling never reached even the present-day magnitude of anthropogenic warming[58–64] (Fig. 1). In fact, climate reconstructions now suggest that cooling from the sixth century, associated with the LALIA, affected many areas of the Northern Hemisphere, but in some

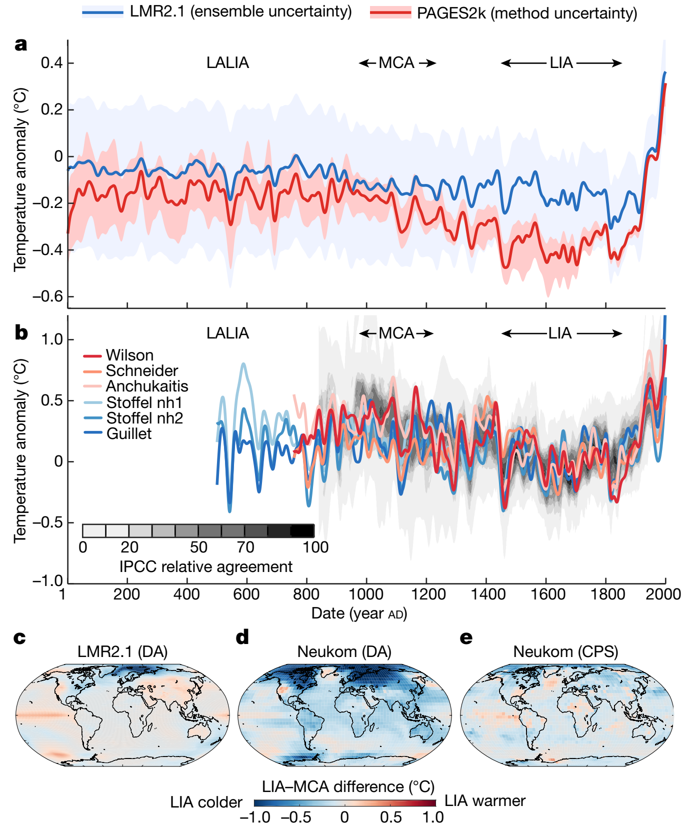

Fig. 1 | Variability and change in palaeoclimate reconstructions. **a**, Reconstructions of global mean annual temperature (anomalies from the mean of AD 1951 to 1980), using large multiproxy databases and a range of statistical methods, suggest coherent multidecadal variability over the past 2,000 years but uncertainty in their magnitude, timing and regional expression[62,63]. The two reconstructions use different approaches for the quantification of uncertainty, indicated by the shaded region around each median value. The last millennium reanalysis incorporates the spread of past temperatures from an ensemble of prior states and predictor series, whereas the uncertainty shown for the PAGES2k product reflects only the difference in methodology. **b**, Northern Hemisphere summer temperature reconstructions (anomalies from the period AD 1500 to 1850 for comparison with the IPCC AR5 agreement range, shown in grey) using more limited sets of temperature-sensitive tree-ring proxies suggest greater variability than global multiproxy reconstructions. The range of agreement in previous Northern Hemisphere temperature reconstructions included in AR4 of the IPCC is shown with grey shading[60]. All reconstructions are smoothed with a 30-year Gaussian filter. In **a**, **b**, differences in the reconstruction can arise from the use of different proxy data; instrumental targets and spatial domains of the reconstruction; assumptions about seasonal sensitivity of proxy data; and statistical techniques. The LALIA, Medieval Climate Anomaly (MCA) and LIA are indicated. **c**–**e**, Spatial field reconstructions of surface temperatures also have differences in both the pattern and magnitude of past epochal changes between warm and cold periods. In **c**, **d**, reconstructions are based on offline data assimilation (DA) statistical approaches and use the PAGES2k multiproxy database[61], but have substantially different patterns and magnitude of temperature change between the MCA and LIA. Using different statistical approaches to interpret a common dataset causes differences between the reconstruction in **d** and that in **e**, which uses a composite plus scale (CPS). LMR2.1 (DA) refers to ref. [62]; Neukom (DA) and (CPS) refer to ref. [63]; the key in **b** refers to ref. [221] (Wilson), ref. [222] (Schneider), ref. [223] (Anchukaitis), ref. [59] (Stoffel NH1 and NH2) and ref. [177] (Guillet).

regions lasted no more than four decades, although high-resolution data remain limited[65]. Indeed, in Europe a shift in seasonality may have characterized the LALIA more than a consistent trend in annual temperature[66–69]. Similarly, although it is possible to approximately define a period of nearly four centuries—from the middle of the fifteenth until the nineteenth century AD—as an epoch of modestly colder hemisphere- or global-scale temperatures[25], the concept of the LIA remains useful only if it incorporates spatial and temporal variability[70].

Challenges in statistical approaches

Although HCS has common challenges, there are two dominant approaches in the field—each of which has distinct problems (Table 1). Studies by geographers, economists and natural scientists often use an exclusively statistical approach by quantifying societal trends in (for example) agricultural production, population, migration, armed conflict, macro-economic output or technological innovation. These works then identify correlations between those trends and climatic time series with a similar temporal resolution[71–74]. Many conclude that statistically significant correlations reveal causal connections between decade- or century-scale periods of cooling or drying and the frequency or magnitude of societal crises[75–82]. Others use statistical methods such as Granger causality tests or wavelet analysis to establish causation[83]. Some introduce models to explain how cooling or drying reduced agricultural production, and thus caused grain shortages, famine, migration, rebellion and mass mortality[84].

Statistical approaches to HCS are influential partly because they appear to permit predictive modelling of the destructive effects of anthropogenic climate change on society[85]. However, many statistical studies either assume that correlation reveals causation or use analytical methods that are poorly suited to establishing causation between climatic causes and delayed or indirect social responses[86]. Studies may not compare climatic and social time series on similar spatial scales or may incorrectly and naively treat all written observations of past weather as equally transparent and reliable[87]. Some studies simplistically assume a linear relationship between the severity of past weather and the recorded magnitude of societal disasters or the number of written sources that describe destructive weather[88].

Econometric studies, in particular, tend not to appreciate that the cultural, economic, social and political pathways by which climate change affected human life evolved over time within the same societies, so that statistically significant correlations between climatic and social trends in one century do not suggest the same causal mechanisms in another[89]. Overall, many statistical approaches to HCS provide examples of the 'McNamara fallacy', in which unquantifiable data are either ignored or arbitrarily quantified to produce superficially impressive but potentially misleading results[90,91]. Many also suffer from the 'streetlight effect' by using accessible but incomplete datasets of social or climatic trends without considering how and why those datasets were created—and how they may be biased[92]. For example, datasets of historical grain prices are widely accessible and frequently correlated to climatic time-series, and some works have even assumed that grain prices so directly responded to weather that they can serve as climate proxies[93]. However, grain price datasets rarely provide comprehensive price data and they do not reveal trends in agricultural yields—let alone weather—but instead market conditions that are only partly influenced by yields[88].

Challenges in qualitative approaches

Approaches to HCS that use qualitative means to establish causation, or which combine those means with statistical methods, can have shortcomings similar to those of many statistical studies (Table 1). Most studies that use these approaches also focus on wars, famines and epidemics, because these disasters affected many people, are well-represented in textual or archaeological evidence and have plausible links to extreme weather[94]. The result is that qualitative scholarship in HCS is also biased towards examples of crisis and collapse[95–97] (Fig. 2).

Table 1 | Common methodological problems in HCS

Methodological problem	Statistical	Qualitative
Climate data are inappropriate, used selectively or misinterpreted[a]	X	X
Climate change and climate variability are used interchangeably[a]	X	X
Excessive focus on large spatiotemporal scales[b]	X	X
Historical primary sources are taken at face value[c]	X	
McNamara fallacy (ignoring what cannot be quantified)[c]	X	
Changing climate–society pathways ignored[c]	X	
Selection bias toward crisis and collapse[c]	X	X
Excessive focus on agrarian empires[c]	X	X
Simplistic dichotomy between resilience and vulnerability[c]	X	X
Societies mischaracterized as homogeneous entities[c]	X	X
Correlation equated with or too easily associated with causation	X	X
Insufficient attention to uncertainties		X
Streetlight effect (use of accessible but incomplete datasets)	X	
Relevant disciplines missing or under-represented	X	X

Entries without a footnote represent problems that affect several domains.
[a]Falls under the 'Climate change' domain of Fig. 3.
[b]Falls under the 'Regional environment' domain of Fig. 3.
[c]Falls under the 'Society' domain of Fig. 3.

Many qualitative publications focus on the fate of agrarian empires across large spatiotemporal scales and therefore miss the diversity within and between societies[57,98]. Many also confuse association with causation by ignoring the mechanics by which climatic trends on vast spatiotemporal scales influenced local environments and communities or by simplifying the relationship between local responses and broad historical developments[99–101]. Because works by palaeoclimatologists in particular may accept historical and archaeological sources and interpretations as fact, they are especially likely to draw naive associations between their records and historical events[43]. In general, qualitative scholarship does not always compare social and environmental datasets of comparable quality and resolution, and may therefore simply assume causation between changes that appear coeval[102].

A central challenge for HCS scholars is that approaches to historical causation that can characterize the recorded interactions between individuals or social groups cannot explain relationships between climatic and societal variability. Qualitative scholarship often characterizes climate change as a force that caused social change, but climatic pressures are better understood as narrowing, widening or redistributing the range of possible human action. Simplistic approaches to causation are encouraged by the tendency in HCS scholarship to ignore the uncertainties that are involved in connecting large-scale climatic trends to local weather events—let alone connecting weather events to human responses in the distant past[103].

HCS scholars have attempted to address these challenges in part by distinguishing between more- and less-direct effects of climate change on human history. However, in making and modelling these distinctions, many works by these scholars have assumed that links between climate changes and grain prices were more direct than connections between climate changes and (for example) socioeconomic or

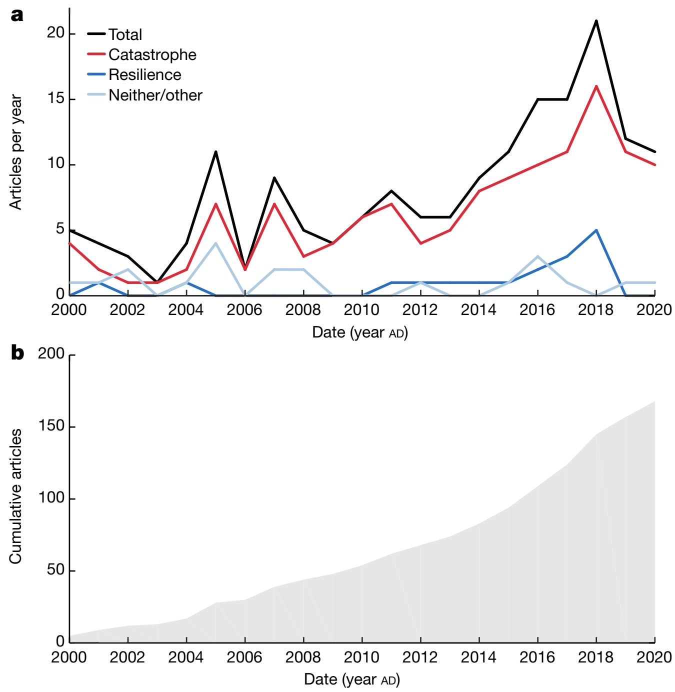

Fig. 2 | Meta-analysis of HCS studies. a, Primary emphasis for qualitative and statistical HCS studies on climate–society interactions within Europe during the LIA, from 2000 to October 2020[24]. Of 168 studies, 77% emphasize 'catastrophe' (a disastrous effect of LIA temperature, precipitation or circulation changes); 10% focus on 'resilience' (continuity and adaptation amid LIA changes); and 13% concentrate on 'neither/other' (either because they equally consider both calamity and resilience, or because they instead investigate—for example—cultural developments or long-term trends in human height and grain yields). All the studies included present original research; no HCS survey texts are included (all such texts emphasize disasters during the LIA). All studies included focus on climate–society interactions rather than mentioning them incidentally; all are limited to the past 2,000 years; and the only global studies included devote considerable attention to Europe (here broadly defined as extending from Iceland to western Russia). Europe has perhaps been the most frequently studied region in HCS[24], but also the least associated with examples of civilizational collapse; the bias towards studies of crisis could therefore be greater for HCS studies that consider other regions. **b**, Cumulative number of publications in HCS studies. This graph reveals the surging pace of publications in the field. All studies in **a**, **b** are derived from the Climate History Network Zotero Bibliographical Project[97].

military activities. This assumption has led to more scrutiny of periods in which high grain prices coincided with cold, wet or dry conditions, and has therefore strengthened the selection bias towards examples of crisis in HCS[94,104].

A research framework for HCS

To help HCS scholars overcome these challenges, we propose a framework for establishing more convincing links between climatic and human histories. To follow the framework, scholars answer a series of binary questions that address four key challenges in HCS: interpreting evidence, bridging dynamics across scales, establishing causal mechanics and estimating uncertainty (Fig. 3). Any negative answer should delay the project until an affirmative answer can be provided. If an affirmative answer is impossible, projects should be revised or abandoned to minimize the risk of problematic results that may mislead future research and public discourse.

Many problems in HCS stem from the challenge of integrating data and knowledge between mutually unfamiliar academic disciplines, with different practices, standards of evidence, inferential frameworks and approaches to uncertainty. Our framework therefore requires researchers either to consult with scholars in scientific, social scientific and humanistic disciplines or—better yet—form 'consilient' teams in which all researchers have an equal role in imagining, designing and undertaking a project[105–107]. There are of course disadvantages to this approach[95]. Inequalities in disciplinary and epistemic power relations, inspired in part by the ascendency of quantification and modelling in scholarly cultures of prediction, can discourage it[108,109]. However, consilient partnerships increase the likelihood that complexities in both natural and social systems are fully accounted for in HCS studies.

According to our framework, HCS scholars may initiate or interrogate research projects by considering how climates, local environments or societies changed. Our approach requires careful investigation of climate reconstructions, because uncertainties in these reconstructions—or disagreements between equally valid estimates of past climate—may alter the inferred relationship between environment and society (Fig. 1). We recommend that HCS scholars identify interactions between environments and populations on small scales before considering connections between broad features of the climatic and human records[95,105,110]. All projects should also recognize the statistical consequences of comparing smoothed, low-resolution or time-uncertain data series, and particularly the effects on correlation coefficients and their apparent significance.

Our framework requires that HCS scholars carefully consider how both palaeoenvironmental and historical evidence was created and interpreted to develop datasets. Researchers should highlight shortcomings in evidence, and especially areas of disagreement between different evidence for climate variability and change (Supplementary Information). They must remember that absence of evidence for climatic effects on society could be understood as evidence of societal resilience in the face of climate change[53,94,111].

HCS scholars using statistical methods should use analytical tools suited not only to establishing correlation or simple causation, but also to identifying complex and potentially nonlinear links between climatic and social change. They must consider the magnitude of the relationship between climatic and socioeconomic variables, because a relatively weak relationship with little explanatory power may be trivially statistically significant if estimated for large-enough datasets.

All HCS scholars should emphasize uncertainties in the causal connections that they identify between human and climatic histories. They should pursue multicausal explanations of societal change, in which climatic pressures interact with cultural, socioeconomic and political influences on past societies[112,113]. They should characterize their findings as provisional, and subject to change with the publication of new reconstructions of regional climates or local environments[114,115].

Case studies of resilience

Our framework will also aid HCS scholars in uncovering local, subtle or unexpected responses to climate change that encompass more than societal crisis and collapse. Using the methods of archaeology, history, geography and palaeoclimatology, we introduce qualitative case studies that suggest five pathways by which societies or communities were resilient to climate anomalies during the LALIA and LIA (Fig. 1).

HCS scholars have increasingly explored the resilience of populations to climate change[8,103,116–120]. However, resilience is a contested concept with distinct meanings in different disciplines. Approaches by many archaeologists once defined resilience as a function of the connectedness and potential of social ecological systems, a property that systems gain and then lose as they pass through stages in an adaptive cycle model[121,122]. But archaeologists have differed over whether and how to operationalize this model, and some have argued that it simplistically implies automatic, large-scale social responses to environmental stress[123]. Many archaeologists and historians now favour

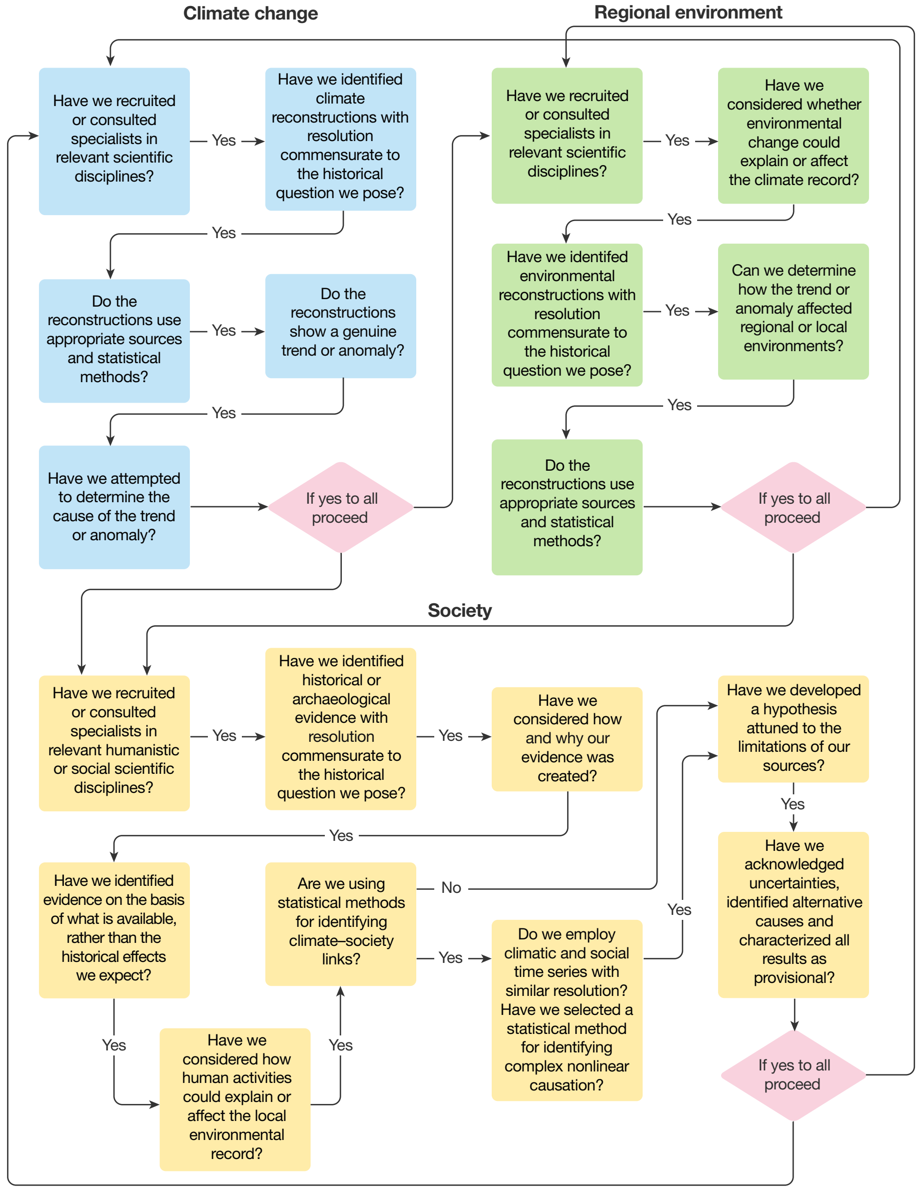

Fig. 3 | A process for undertaking research into past climate–society dynamics. HCS scholars can start in any domain: climate, local environment or society. They should then work through each question until they have answered all questions in every domain. This process should ideally be followed at the beginning of research projects, but it can also be used to strengthen projects already underway or to revise completed projects. Answering 'no' to any of the questions in our steps should prompt researchers to return to previous steps, revise the project or abandon the project altogether, because a convincing link between past climatic and social changes cannot be established.

broad and informal definitions of resilience that are useful for analysing responses to environmental disruption across a wide range of complex societies[124]. However, these definitions can be contradictory or encompass social changes of such magnitude that the term 'resilience' loses interpretive power[125].

We adhere to the broad and transdisciplinary definition of resilience presented by the Intergovernmental Panel on Climate Change (IPCC): the ability for coupled human and natural systems 'to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure'[126]. For us, resilience includes both 'the capacity of a given system to absorb energy and to redirect or to convert it, without losing the fundamental features and shape of the system as a whole'[127], and adaptation, a concept which the IPCC defines as the 'process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities'[126]. We use these definitions because they are broad enough to encourage cooperation between disciplines, but narrow enough to identify easily in time and space.

The case studies in this Review challenge the simplistic dichotomy between crisis and continuity that is often made in HCS. They suggest adaptive responses and sources of resilience in populations and institutions that were also stressed by climate anomalies, and suggest that resilience for some social groups could exacerbate or exploit vulnerability among others[128] (Supplementary Information). They also reveal how crises encouraged adaptations that contributed to the long-term resilience, and therefore continuity, of some social groups and structures[129].

In crafting and revising our case studies, we consulted our research framework and found that nearly every case study initially included at least one of the problems with HCS scholarship that we critique in this Review (Supplementary Information). Some depended on outdated or unacceptably low-resolution climate reconstructions. Others could not easily accommodate inferences from discrepant reconstructions compiled using different data or methods. Several confounded century-scale climatic trends with decade-scale climatic variability, and therefore misidentified a cause for social change. Others assumed that climatic trends provoked historical events that—when scrutinized against the palaeoclimatic record—really occurred in weather made less likely by those trends. Some made indefensibly broad or certain claims or assumed that climate change caused social trends that had more likely, social causes. By following our framework, we were able to correct these errors by consulting new evidence or by modifying our conclusions (Supplementary Information).

Exploiting new opportunities

Climatic trends helped to make some regional environments easier to exploit for economic or military ends, especially in societies and communities that were most sensitive to climatic trends other than those in temperature[130]. For example, reconstructions compiled using lake sediments, speleothems and other proxy sources provide evidence for a multidecadal trend towards greater winter precipitation in the eastern Mediterranean that began in the fifth century AD and continued through the LALIA period. Winter is the wet season in this region, during which soil moisture and water resources recharge after the dry summer[69]. Palynological evidence and surface surveys reveal that regional cereal cultivation, arboriculture and pastoral activities thrived as winter precipitation increased, and that many settlements increased in density and spatial extent[131–134]. Communities could exploit precipitation trends because the taxation system of the eastern Roman empire allowed goods to easily circulate between communities, and thus brought the fruits of higher agricultural production to consumers. Elites invested resources into market-oriented agriculture and financed the construction of dams, channels, pools and other infrastructure that allowed farmers in the most arid areas (such as the Negev) to manage water more effectively. Although land-owning elites and peasants had the most to gain from increased moisture, the benefits were widespread because they reinforced the economic expansion and state consolidation that was already underway in the eastern Mediterranean[45,135,136].

Similar socioeconomic and environmental relationships prevailed during the sixteenth and seventeenth centuries AD in the commercial cities that would eventually unite to form the Dutch Republic (the precursor state to the present-day Netherlands). Annual-resolution tree rings and contemporary accounts of flooding suggest that regional precipitation was generally higher in the sixteenth century than it had been in the fifteenth century (Fig. 4a). Greater moisture helped Dutch rebels break away from the Spanish empire by making it harder for besieging armies to surround cities with makeshift fortifications, and by enhancing the deadliness of deliberate defensive inundations[103,137]. Logbooks written aboard ships suggest that changes in atmospheric circulation later benefitted the inhabitants of the wealthy cities of the republic by shortening journeys in the lucrative 'rich trades' with Asian ports, and increasing the likelihood that Dutch fleets would gain the tactical advantage of the 'weather gage' in naval wars that preserved Dutch primacy in European trade[138]. Meanwhile, off the northern archipelago of Svalbard, bowhead whales responded to cooling sea surface temperatures by departing the coast and congregating along the edge of the expanding pack ice. Dutch whalers benefitted relative to their English rivals when they learned to pursue the whales in the open ocean[139,140].

Resilient energy systems

Societies could also prosper amid climatic cooling if they used sources of energy for subsistence or industry that were resilient to climatic variability[141]. Societies that did not depend on temperature-sensitive grains could be especially resilient to cooling. For example, populations

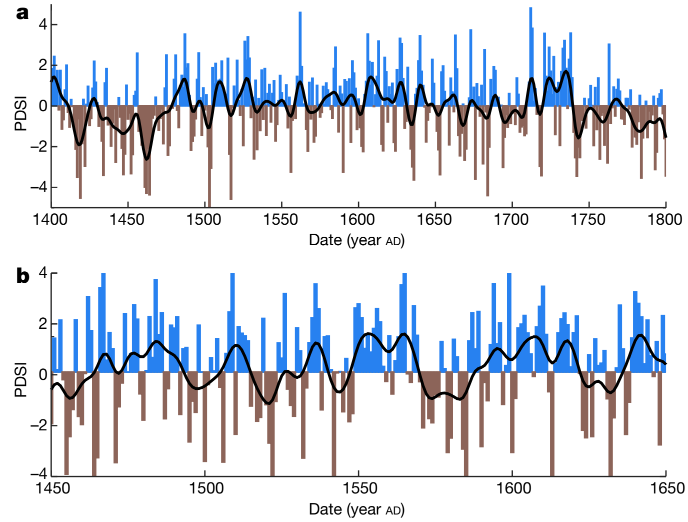

Fig. 4 | Palmer drought severity indices for the Low Countries and southeastern California. **a**, Summer Palmer drought severity indices (PDSI) for the Low Countries (49–51° N, 2–7° E) between the fifteenth and nineteenth centuries AD[137]. **b**, Tree-ring-reconstructed summer PDSI from the North American Drought Atlas[169,170] for the approximate region of the Mojave ancestral lands in southeastern California (33–36° N, 113–116° W), from AD 1450 to 1650. PDSI is an integrative estimate of soil moisture that reflects accumulated precipitation and the effect of temperature on evapotranspiration of the preceding and current seasons.

in low-lying coastal Frisia (comprising parts of the present-day Netherlands and northern Germany) expanded during the LALIA by pursuing an animal-centred subsistence strategy: dairy and meat from domesticates, supplemented by fish, shellfish, waterfowl, barley and oats[142–148]. During cold summers in the LALIA, Frisians avoided the harvest failures and famines that repeatedly affected Francia, Frisia's neighbour to the south[145].

Similarly, although archaeological and palynological evidence reveal settlement desertion and reforestation among Swedish and Baltic populations during the LALIA, there is no evidence for crisis in western Finland. Whereas the livelihoods of most Swedish and Baltic populations relied on temperature-sensitive cultivation, communities in coastal Finland instead used food resources from marine, freshwater and terrestrial ecosystems that all responded differently to temperature trends[149–151]. Diets were equally diverse in the coastal cities of the seventeenth-century Dutch Republic, which largely avoided food shortages[152]. The thriving economy of the coastal republic also depended on plentiful access to low-cost energy sources, including wind to power merchant ships and windmills, and peat for local industry. The climatic anomalies of the LIA did not diminish these sources of energy[103,153,154].

In Finland, tree-ring density series suggest that decade-scale summer cooling during the LIA coincided with reductions in grain yields that provoked socioeconomic hardship for peasants, particularly those without hereditary and usufruct rights[155]. However, palynological and archaeological evidence indicate that these reductions encouraged innovations that ultimately reduced the sensitivity of agriculture to climate change[156]. For example, after the onset of an especially cold phase of the LIA in the fifteenth century AD, Finnish farmers introduced a rye variety that was suitable for slash-and-burn agriculture, which produced higher yields than earlier methods[157–159]. During the next regionally cold phase of the LIA in the late seventeenth and early eighteenth centuries AD, farmers adapted by identifying slash-and-burn cultivation across eastern Finland. Farmers changed the main cultivated crop in Finland from barley to rye, partly because the earlier-ripening autumn-sown rye provided steadier yields than the spring-sown barley in cold temperatures[156].

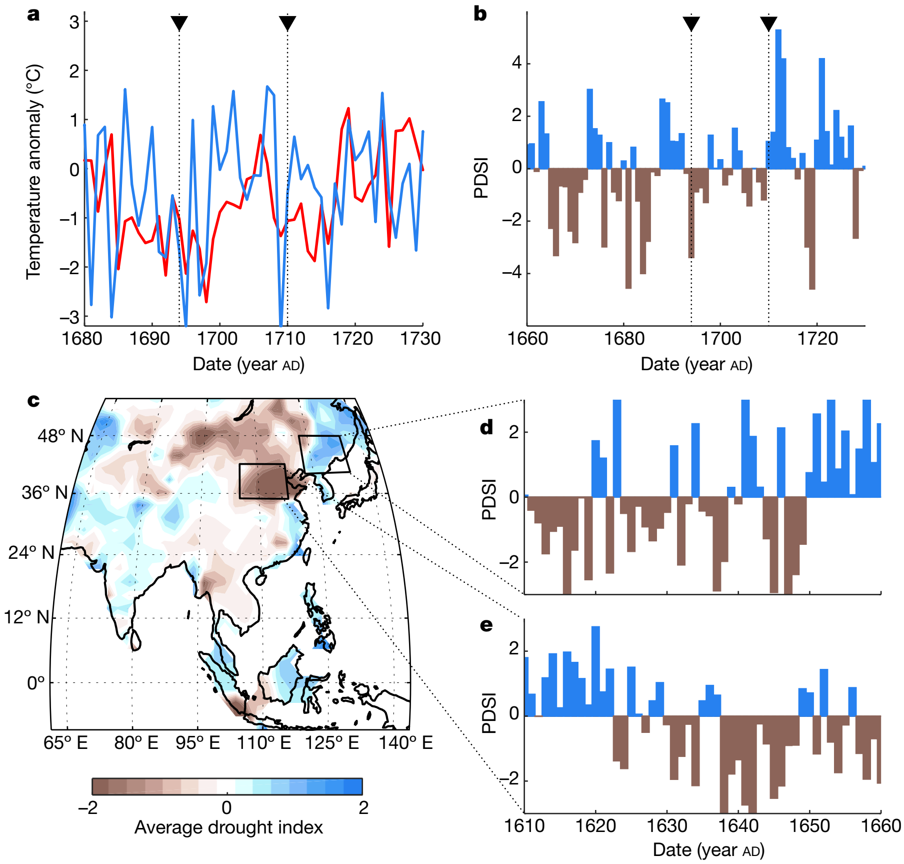

Fig. 5 | Tree ring reconstructions of temperature in France, and moisture in both France and China. a, **b**, Reconstructed summer[186] (red line) and winter[192] (blue line) temperature anomalies (calculated relative to the length of the full length of the respective records) (**a**) and PDSI for late seventeenth and early eighteenth-century France (43–51° N, 2° W–7° E)[137] (**b**). The AD 1693 and 1710 harvest failures and grain shortages in France are indicated with triangles and dashed lines. **c**, The mean tree-ring reconstructed PDSI from the Monsoon Asia Drought Atlas for AD 1638 to 1643[201]. **d**, **e**, Multiyear monsoon failures in China in the seventeenth century contributed to drought in the Jurchen polity (shown in **d**), which was not as severe as it was in Ming China (**e**).

Resources of trade and empire

Well before the LIA, the gradual integration of regional, and then global, grain markets buffered grain prices in many localities from trends and anomalies in temperature and precipitation[160]. Integration was spatially heterogeneous and rarely followed a linear trajectory[161–164], but over time trade enhanced the resilience of networked populations—especially in the centres of large territorial or commercial empires. Because these empires encompassed diverse environments and peoples, and because the signature of the LALIA and LIA was spatially heterogeneous, weather that hampered the regional production of resources did not necessarily reduce the supply of resources available to imperial centres. Agents of empires could exploit or compensate for commodity shortfalls in one region by drawing on windfalls in another—sometimes at the expense of populations on imperial peripheries[103,165].

For example, merchants in the Dutch commercial empire of the seventeenth-century AD acquired grains in diverse ports across the Baltic Sea, each of which typically endured distinct weather patterns. They then either imported grains to their republic or sold them across Europe, occasionally for lucrative profits in areas that were affected by weather-related grain shortages. Meanwhile, ice cores, marine sediment cores and surviving documents indicate that climatic cooling interrupted growing seasons to varying degrees across Iceland. However, archaeological assemblages from Skálholt, the cathedral–farm of the Lutheran Bishop of Southern Iceland, reveal that some Icelandic communities continued to enjoy substantial wealth and diverse, nutrient-rich diets. Elites in Skálholt owned properties across Iceland that each controlled different resources, and farmers within them owed rents, tithes and specific obligations to those elites. Because the elites of Skálholt controlled a disproportionate amount of the resources of Iceland and held a privileged position within the Danish empire, they enjoyed enduring access to international trade networks—and resilience to climatic extremes[166,167].

Some populations adapted to climatic variability or change by developing new networks of commodity circulation. Tree ring records and oral histories indicate that, from AD 1450 to 1500, the climate of southeastern California oscillated between cycles of severe droughts and pluvials[168–170] (Fig. 4b). Although Mojave settlements must have weathered similar periods of unpredictable fluctuations in precipitation patterns, they now adopted gathering and trading strategies that used new ceramic technologies and basket-making techniques. These strategies encouraged commodity chains centred on maize, beans and squash produced by Kwatsáan communities to the south[171,172]. By the end of the sixteenth century, mobile, seasonally oriented and interregional economies had spread across the Mojave Desert[39,173–176].

Political and institutional adaptations

Trade was only one among many tools that authorities used to avoid or recover from climate-related disasters during the LIA. Administrative and narrative accounts suggest that, after the eruption of the Samalas volcano in AD 1257 cooled temperatures across the Italian peninsula and contributed to famines that brought starvation to rural communities, the governments of Bologna and Siena avoided famine within their walls by securing new food imports, limiting grain prices, subsidizing grain or bread and banning grain exports[177–179]. They forced the wealthy

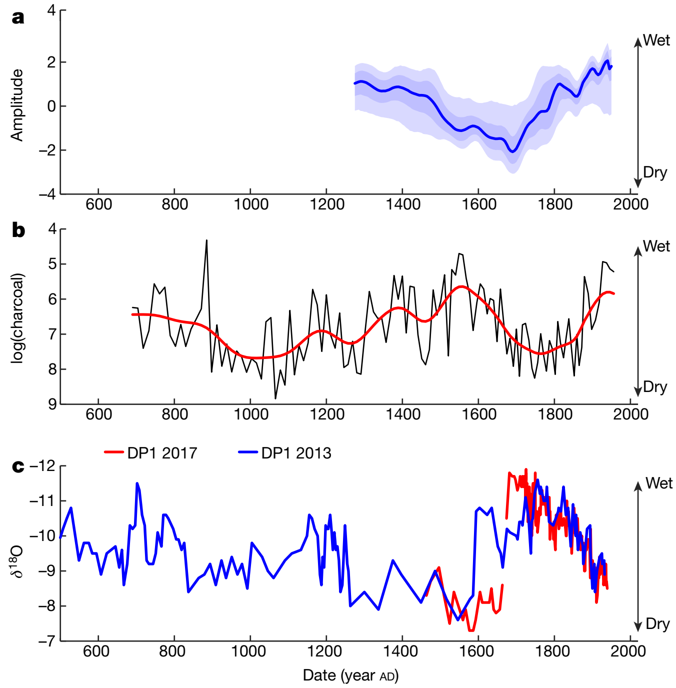

Fig. 6 | Palaeoclimate moisture proxies for Iron Age southern Africa. a, Leading pattern of moisture variability associated with interior eastern Africa lake sediment proxies from Lake Masoko (Tanzania), Lake Malawi (Malawi, Mozambique and Tanzania) and Lake Edward (Democratic Republic of Congo and Uganda)[207–209]. Shaded uncertainties are the 1σ (light blue) and 2σ (darker blue) range from 10,000-member ensemble resampling the individual lake record age models. **b**, Charcoal record from Lake Tanganyika[208]. **c**, Dante Cave (Namibia) speleothem oxygen isotope ratios from ref. [210] (DP1 2013) and ref. [211] (DP1 2017). All records are oriented so that wetter conditions are up and drier conditions are down.

to provide loans to cover grain subsidies, but also banned foreigners, criminals and prostitutes from accessing communal grain reserves. When grain prices nevertheless increased across Italy, city authorities responded by constructing granaries or signing exclusive grain trade arrangements[180].

Even when authorities failed to initially address disruptions influenced by extreme weather, they often learned valuable lessons. Written accounts of rainfall indicate that in Andalusia precipitation probably grew more variable during a cooling trend from the middle of the seventeenth century through to the early eighteenth century AD[181,182]. Precipitation extremes can reduce wheat yields, and tithe records suggest that wheat harvests in Andalusia were poor during the 1640s and 1650s[183]. Local authorities banned exports, impounded one another's wheat shipments and aggressively competed over tax exemptions on cereal imports. Bread prices soared between AD 1647 and 1652, and food shortages catalysed revolts against the Spanish monarchy. In response, officials abandoned an inflationary monetary revaluation, homogenized regional import taxes on grains and lifted international trade embargoes. These measures enhanced the resilience of local institutions and ensured that a poor harvest in AD 1653 did not lead to higher wheat prices or political unrest[184].

Tree ring and documentary evidence suggest that, across France, a cooling trend in the final decades of the seventeenth century disrupted growing seasons and thus reduced grain yields and tax revenue, just as the Nine Years' War increased demand for military provisions—and government credit[185,186]. When cold and exceptionally dry conditions contributed to widespread harvest failures in AD 1693 and 1694, government finances were already strained and granaries had been emptied across France (Fig. 5a, b). Correspondence between French administrators reveals that the state partnered with merchants to distribute grain to areas of high demand, but local resistance to grain allocations, inadequate government credit and low overall grain supplies hampered these efforts[187]. By the severe winter of AD 1694–1695, average national grain sale prices reached triple their previous value and food shortages contributed to widespread mortality[188–190].

Snowfall measurements suggest that precipitation fell primarily in the growing season across France in the seventeenth and eighteenth centuries AD, and tree ring reconstructions indicate that growing season precipitation was lower than average in the first decade of the eighteenth century[191] (Fig. 5b). After years of poor harvests and warfare, sustained and severe cold starting in the winter of AD 1709 ruined winter grains planted in autumn, and again contributed to steep increases in grain prices[192]. Many granaries were empty, but this time French administrators loosened trade regulations and negotiated emergency grain imports from Algeria. The French state had adapted: mortality among peasants did not approach the levels it had reached in AD 1693–1694[193].

Near the end of the LIA, the eruption of the Laki Fissure in 1783 cooled European winter temperatures. Across central Europe, snow and ice accumulated steadily until, in February 1784, a compound event unfolded in which sudden thawing coincided with heavy rain. Meteorological and hydrological measurements confirm that catastrophic flooding followed along the rivers Rhine, Neckar, Moselle, Main and Elbe[194–198]. Eye-witness reports reveal that, although warning systems such as church bells and cannons alerted merchants and peasants along the Rhine to the imminent threat of floodwaters, thousands lost their lives or livelihoods. Monasteries and wealthy inhabitants of cities such as Cologne donated supplies to surrounding communities. Authorities responded quickly to the destruction. Quartering orders compelled citizens to take in those who had lost their homes, and bakers were ordered to use municipal or state reserves of flour to bake bread that was distributed free of charge. Affected citizens were exempted from taxation. Governments recommended precautionary hygienic measures, such as washing the walls of flooded buildings, and directed the demolition, repair or rebuilding of structures in devastated districts. Resilient institutions compensated for the vulnerability of citizens in flood-prone regions[199].

Migration and transformation

Mobility often fostered resilience to climate change, whether it involved the circulation of commodities or the mass movement of people. Transformative adaptations that culminated in migration could be particularly effective when they exploited the failure of authorities to respond to climate change[200]. For example, tree ring and documentary evidence indicates that in the early seventeenth century AD, cooling—and droughts provoked by a weakened east Asian monsoon—repeatedly ruined harvests across Ming China and the neighbouring Jurchen polity[201,202]. The latter polity was at first worst-affected by drought (Fig. 5c–e), and the recently united Jurchen chieftains adapted by plundering grain and other supplies from regions along the Chinese and Korean borders. Meanwhile, droughts grew more severe in China, where food scarcity contributed to famine, starvation and banditry that the Ming dynasty—weakened by corruption, political infighting and years of military neglect—could not control[203–205]. Between AD 1638 and 1643, the Jurchen polity (by then known as the Manchu) intensified its raids as drought worsened in China but gave way to a pluvial across Manchuria (Fig. 5D). Eventually, Jurchen armies exploited civil strife in China by migrating south, overthrowing the Ming state and declaring a new Qing dynasty. Millions died in the dynastic transition, but, for Jurchen military leaders, climate variability had provided lucrative opportunities—at the cost of migrating and adopting new modes of life[206].

In south-central Africa, the palaeoclimate record is sparse, requiring cautious inference from uncertain datasets beyond the immediate region (Fig. 6). Lake and speleothem records probably integrate moisture conditions across years to decades, and inferred anomalies are not well-fixed in time[207–211]. But linguistic history, a source that is only rarely considered in HCS scholarship, suggests that Botatwe languages (a sub-branch of the Bantu language family) diverged into new languages during hydroclimatic anomalies. Wetter conditions reflected in most data for southern Africa (peaking between AD 800 to 1000 in some records) appear to have prevailed during the period of greatest linguistic change in the Botatwe group. From approximately AD 750 to 1450, a succession of divergences in both main branches (east and west) unfolded as speakers of protolanguages spread from the Kafue floodplain and other wetlands of central Zambia into what were probably no longer drier lands to the west and south. Speakers innovated vocabulary for new fishing technologies and large-scale hunting techniques for waterbuck, which represent strategies that are also reflected in the archaeological record. Farmers grafted these strategies onto enduring farming economies between AD 750 and 1250 in the eastern region, opening up new and gendered opportunities for political and economic influence within agrarian societies[212–214].

Some proxy-based climate reconstructions suggest that the second half of the seventeenth century AD involved a change towards drier conditions in south-central Africa, although the pattern of these anomalies was probably complex in space and time[209,215]. Linguistic history reflects divergence at this time for the protolanguage (Falls) spoken in the driest, southerly region, which indicates that household mobility was a key strategy of resilience during periods of both rainfall decline and increase[213,216]. Language divergences and lexical data therefore suggest resilient responses to climate change in south-central Africa, in the absence of the usual archives of history.

Better histories for better futures

Model simulations provide consistent forecasts of the future temperatures of the Earth under different emissions scenarios; however, predictions of the societal consequences of future warming are less certain[217,218]. Many researchers pursue HCS partly to gain insight into these consequences. Studies in HCS unearth 'fatal synergies' between cooling or drying, harvest failures, food shortages, epidemic outbreaks and violence within or between polities that were vulnerable to disruption[8]. Statistical studies, in particular, now inform many of the most-concerning and influential forecasts of the future effects of global warming on civilization[219,220].

However, the past does not reveal that societies and communities inevitably succumbed when confronted with climate change and variability. Our case studies suggest that a combination of continuity and flexibility characterized many—perhaps most—social responses to shifting climatic conditions. Previously overlooked examples of resilience may aid present-day efforts at adaptation in the face of unprecedented warming, and may provide nuance to popular accounts of the future that draw uncritically from historical examples of crisis and collapse. A new wave of research, deploying the framework we have outlined in this Review, is needed to clarify the lessons from history for the coming century.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-021-03190-2.

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