

Climate challenges, vulnerabilities, and food security

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This paper identifies rare climate challenges in the long-term history of seven areas, three in the subpolar North Atlantic Islands and four in the arid-to-semiarid deserts of the US Southwest. For each case, the vulnerability to food shortage before the climate challenge is quantified based on eight variables encompassing both environmental and social domains. These data are used to evaluate the relationship between the “weight” of vulnerability before a climate challenge and the nature of social change and food security following a challenge. The outcome of this work is directly applicable to debates about disaster management policy.

vulnerability | climate challenge | disaster management | prehistory | history

Managing disasters, especially those that are climate-induced, calls for reducing vulnerabilities as an essential step in reducing impacts (1–8). Exposure to environmental risks is but one component of potential for disasters. Social, political, and economic processes play substantial roles in determining the scale and kind of impacts of hazards (1, 8–12). “Disasters triggered by natural hazards are not solely influenced by the magnitude and frequency of the hazard event (wave height, drought intensity etc.), but are also rather heavily determined by the vulnerability of the affected society and its natural environment” (ref. 1, p. 2). Thus, disaster planning and relief should address vulnerabilities, rather than returning a system to its previous condition following a disaster event (6).

Using archaeologically and historically documented cultural and climate series from the North Atlantic Islands and the US Southwest, we contribute strength to the increasing emphasis on vulnerability reduction in disaster management. We ask whether there are ways to think about climate uncertainties that can help people build resilience to rare, extreme, and potentially devastating climate events. More specifically, we ask whether vulnerability to food shortfall before a climate challenge predicts the scale of impact of that challenge. Our goal is both to assess current understandings of disaster management and to aid in understanding how people can build the capability to increase food security and reduce their vulnerability to climate challenges.

We present analyses of cases from substantially different regions and cultural traditions that show strong relationships between levels of vulnerability to food shortage before rare climate events and the impact of those events. The patterns and details of the different contexts support the view that vulnerability cannot be ignored. These cases offer a long-term view rarely included in studies of disaster management or human and cultural well-being (for exceptions, see refs. 13 and 14). This long time frame allows us to witness changes in the context of vulnerabilities and climate challenges, responding to a call for more attention to “how human security changes through time, and particularly the dynamics

of vulnerability in the context of multiple processes of change” (ref. 10, p. 17).

Approach

In this study, we focus on climate challenges that can impact food security, one of the seven human securities identified by a United Nations Human Development Report (15) (see also ref. 10) and one of the core components of human well-being as identified by the Millennium Ecosystem Assessment Board (16). Food security refers to “physical and economic access to basic food” (ref. 15, p. 27). Integral to our perspective is a multidimensional conceptualization of food security as involving both the availability of food and access to that food (e.g., 17, 18). The capability of people to access food can be limited by structural and social conditions (19, 20), as we identify in this study.

We use the concept of vulnerability to assess resilience of food security to climate challenges. Resilience is the ability of a system to absorb disturbances without losing its identity (21) and its capacity to absorb perturbations or shocks while maintaining essential structures and functions (22, 23). Vulnerability is “the state of susceptibility to harm from exposure to stresses associated

Significance

Climate-induced disasters are impacting human well-being in ever-increasing ways. Disaster research and management recognize and emphasize the need to reduce vulnerabilities, although extant policy is not in line with this realization. This paper assesses the extent to which vulnerability to food shortage, as a result of social, demographic, and resource conditions at times of climatic challenge, correlates with subsequent declines in social and food security. Extreme climate challenges are identified in the prehispanic US Southwest and historic Norse occupations of the North Atlantic Islands. Cases with such different environmental, climatic, demographic, and cultural and social traditions allow us to demonstrate a consistent relationship between vulnerability and consequent social and food security conditions, applicable in multiple contexts.

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with environmental and social change and from the absence of capacity to adapt” (ref. 24, p. 268). Turner and colleagues (9) identify exposure, sensitivity, and resilience as key components of vulnerability. Our study focuses specifically on Turner et al.’s dimension of sensitivity. We examine conditions that impact the capability of people to maintain food security, including both availability and access. Vulnerability to climate challenges is mediated by institutional structures (23) (see also refs. 11 and 25) that are constantly changing and impacting people’s capabilities to avoid declines in food security.

Disaster managers are especially concerned with vulnerabilities, the preconditions that lead climate challenges such as droughts, floods, and extreme cold conditions to become disasters, recognizing that it is at the interface of environmental and social conditions that disasters occur (9, 12, 13, 26). Our research builds on arguments that resilience to the impacts of climate (and other) challenges can be built by reducing vulnerabilities (2–6, 9, 12). However, people “tend to push the risk spectrum toward catastrophic events occurring with increasing probability” (ref. 14, p. 8).

To explore the relationship between vulnerability, food security, and the impacts of climate challenges, we quantify social and climate conditions in seven centuries-long sequences. First, we identify 13 points in our climate sequences that are rare and extreme. We then quantify the extent of vulnerability to food shortfall for the period immediately preceding each climate event. Finally, we identify the conditions following each climate event in terms of major social changes and declines in food security, specifically food shortage. We compare these conditions with the vulnerability before each climate challenge to consider the role of vulnerabilities in the impact of climate challenges.

The Cases

Archaeological and historical cases are used to examine the role of vulnerability in climate impacts. Two features of the cases are particularly important. First, each is a long record of coupled social and environmental change, with data on demography, social institutions and traditions, food economies, political relations, and climate conditions. This long-term record documents the contexts and impacts of climate challenges. Building robustness to climate challenges is a daunting task complicated by limitations of current and recent experience on scenarios of possible challenges and solutions (14, 27). Long historical sequences provide series of known changes in human–landscape–climate interactions that represent a set of completed experiments in human ecodynamics (12, 28–31). We use these sequences to identify when rare climate events occurred, what the vulnerability load was before each event, and the scale and type of changes following each climate challenge. This requires a window in time much longer than is usually available from contemporary experiences (see also refs. 14 and 27), although local and traditional knowledge offers some perspective on vulnerability to long-term or rare processes (32).

Second, the cases are from very different regions of the world—the arid, warm deserts of the US Southwest and the subarctic region of the North Atlantic Islands. Patterns in one region or impacts of one type of climate challenge may be informative only for that region. The cases we compare are from different climate regimes, physiographic regions, cultural traditions, and historical contexts. Patterns evident in this diverse database indicate relationships between vulnerability and the impacts of extreme climate events that have import for resilience planning and disaster management generally.

North Atlantic. The North Atlantic cases include Norse occupations in Iceland (33, 34), Greenland (35), and the Faroe Islands (36) beginning in the late 9th to late 10th centuries and extending into the 18th century, except in Greenland, depopulated by the

Norse in the 15th century. Data derive from decades of climate, historical, and archaeological research by the North Atlantic Biocultural Organisation (NABO; www.nabohome.org) (*SI Appendix, section 2*), which promotes international and interdisciplinary research collaboration. Recurring research themes have been colonization and interactions of human–environmental impact, climate change, and early globalization that have produced remarkably different outcomes on the millennial scale (e.g., 34, 37–40).

US Southwest. The cases from the US Southwest are all indigenous occupations of what is now Arizona and New Mexico during the 10th to 16th centuries. Data derive from research teams within the Long-Term Vulnerability and Transformation Project (LTVTP; lvtvp.shesc.asu.edu) that conduct field research in the Zuni (41, 42), Salinas (43), Mimbres (44, 45), and Hohokam (46, 47) archaeological regions. LTVTP researchers examine the relationships between vulnerabilities in the social and ecological realms and the magnitude and scale of social–ecological transformations (48), comparing long sequences of change and stability. These sequences illustrate the extent to which short-term strategies create vulnerabilities that play out over time.

These archaeological and historical sequences are not sources of “lessons” as much as they are sources of information on how decisions and actions created vulnerabilities and how these vulnerabilities played out over time under different challenges [see also Turner and Sabloff (13) for the Classic Maya; Tainter (27) for problem solving and collapse in the Roman Empire; and Butzer (26) for a collection of historical studies]. This research posits that existing vulnerabilities to food shortages can be triggered by rare climate challenges, for which planning and anticipation are difficult. Planning that includes a focus on keeping vulnerabilities low can contribute to resilience to unanticipated (or unpredictable) climate challenges (9).

Results and Discussion

Rare Climate Challenges. Across seven regions, four in the prehispanic US Southwest and three that are Norse occupations of the North Atlantic Islands, various kinds of climatic records are used to identify rare climate challenges with considerable potential to result in “disaster.” For the US Southwest, we identified dry periods (droughts) in annual tree-ring proxy records of precipitation and streamflow (*SI Appendix, section 1*). Dry periods decreased the productivity of the resources people relied on for food. Climate conditions associated with each case are represented by separate climate reconstructions that begin between 436 and 879 C.E. The rare climate challenges identified in Table 1 (fourth column) are the longest (15–23 y in duration) and rarest (they had not occurred for at least 456 y) dry periods of the 10th through 16th centuries, and most are the longest in each reconstruction. Although dry periods were common in the region, the challenges to the food security of farmers were likely unprecedented during these long and rare dry periods. For the North Atlantic, challenges are rare extremes or regime changes for climate systems that involve cold temperatures, sea ice, and/or storminess (Table 1, fourth column). Proxy records of temperature, sea ice, and storminess are used to identify climate challenges during the period 900–1900 C.E. (*SI Appendix, section 1*). These proxy records have strong spatial coverage but relatively poor chronological resolution relative to the US Southwest. Extreme events were identified by both large (at least one sigma) deviation from the previously experienced long-term mean and uniqueness—the event was not experienced in the previous 200 y. Climate regime change (e.g., the onset of the so-called Little Ice Age) events were prioritized if they were the first experienced deviation from the previous normal, even if subsequent larger deviations occurred. Events had to be recognized in two proxy

Table 1. Rare climate challenges, vulnerability scores, and total vulnerability load

Region	Case	Initiation date, C.E.	Kind of challenge	Vulnerability scores for each variable									
				V1	V2	V3	V4	V5	V6	V7	V8	T	
US SW	Z	1133	Extreme dry	1	2	2	2	2	1	1	1	1	12
	S	1335	Extreme dry	1	2	1	3	2	4	1	3	1	17
	M 1	1127	Extreme dry	2	2	3	4	2	2	2	1	1	18
	M 2	1273	Extreme dry	1	2	1	1	2	1	1	1	1	10
	H 1	1338	Extreme dry	2	2	2	4	2	4	4	3	2	23
	H 2	1436	Extreme dry	3	2	3	4	2	4	4	3	2	25
NA	G 1	1257	Extreme cold	1	2	2	2	1	3	3	2	2	16
	G 2	ca. 1310	RC: colder system, increasing sea ice	1	3	2	3	1	4	3	2	1	19
	G 3	ca. 1421	RC: stormier, extreme cold	1	4	3	4	2	4	1	3	2	22
	I 1	1257	Extreme cold	1	1	2	1	1	2	2	2	2	12
	I 2	ca. 1310	RC: colder system with sea ice	2	1	2	1	1	2	2	2	2	13
	I 3	1640	Extreme cold, sea ice greatest extent	2	1	3	2	2	2	2	2	2	16
	F	1257	Extreme cold	2	1	2	2	2	3	2	2	2	16
Mean vulnerability score for each variable				1.5	1.9	2.2	2.5	1.7	2.8	2.2	2.1		

F, Faroes; G, Greenland; H, Hohokam; I, Iceland; M, Mimbres; NA, North Atlantic; RC, climate regime change; S, Salinas; T, total vulnerability load; US SW, US Southwest; V1, available food; V2, resource diversity; V3, resource depression; V4, connection; V5, storage; V6, mobility; V7, equal access; V8, barriers; Z, Zuni.

records to confirm a climate challenge. Some events were unprecedented in Norse experience on the North Atlantic Islands.

Vulnerability Loads. How vulnerable were people to shortfall in food supply, given the configuration of social and environmental conditions, before each identified climate challenge?

We quantify the “load” of vulnerability to food shortage before these climate challenges using eight variables grouped into two domains: (i) population–resource, which has to do primarily with the overall availability of food relative to population size; and (ii) social institutions and practices, which have more to do with access to food including through social and economic structures (Table 2). With this characterization, we identify the kinds of conditions contributing to vulnerability and the overall load of vulnerability for each case. By load, we mean the extent to which each variable contributed to the likelihood that people might experience impacts from climate challenges (for a related

approach, see ref. 50). We used a qualitative ranking of the state of each variable to quantify its contribution to the vulnerability load (Table 1, *Right*). The rankings ranged from no contribution (1) to substantial contribution (4) to vulnerability. Codes of 2 and 3 capture conditions that were minor (2) to more substantial (3) but not as strong as the ends of the continuum. Coding was based on expert knowledge of case leaders using evidence from archaeological and historical records (*SI Appendix, section 2*). The vulnerability load for a case is represented by the “total” of these scores (Table 1, *Far Right*); a score of 8 indicates no vulnerability presented by any of the variables, whereas a score of 32 indicates strong contributions from all variables to the total vulnerability load.

Differences in the mean contribution of the variables to the vulnerability load illustrate the importance of social institutions and issues of access to food in managing vulnerability (Table 1, *Bottom*).

Table 2. Variables contributing to vulnerability load to food shortage

Vulnerability variables	Evidence for vulnerability	Value of variable for resilient food system
Population–resource conditions		
Availability of food	Insufficient calories or nutrients	Balance of available resources and population size reduces risk of shortfall
Diversity of available, accessible food	Inadequate range of resources responsive to varied conditions	Diverse portfolio reduces risk, increases options (9)
Health of food resources	Depleted or degraded resources, habitats	Healthy habitats contribute to managing risk and change (26, 49)
Social conditions		
Connections	Limited connections with others experiencing different conditions	Social networks expand access to food and land (26) and are sources for risk pooling (49)
Storage	Insufficient, inaccessible storage	Stored foods reduce risk in times of shortage
Mobility	Inability to move away from challenging food conditions	Movement to alternative places, landscapes, and social groups offers potential for addressing resource shortfall through access to food/land (49)
Equal access	Unequal control and distribution of land, water, and food resources	Equal access avoids challenges to coping and adaptive capacity in disaster risk management
Barriers to resource areas	Physical barriers limiting access to key resource areas	Lack of barriers enhances capability of people to provision themselves with food

For the full set of 13 cases, two social domain variables—connections and mobility—contribute more to the vulnerability load than do any other variables, as indicated in the mean scores shown across the bottom of the table. In contrast, lack of an adequate food supply (V1) rarely contributed much to vulnerability.

This pattern is consistent with issues identified by disaster managers, who emphasize that social factors and insufficiencies in aid-related resources limit their abilities to reduce vulnerabilities before extreme climate events (3, 6). Governments and nongovernmental organizations (NGOs) are often loath to allocate or raise funds to change conditions when the general population is not actually experiencing food shortfalls. As a result, disaster management is often oriented toward recovery and response to crises that may have been avoided or reduced had prior vulnerabilities been addressed.

Social Change Following Extreme Climate Challenges. Were climate challenges followed by major social change? Fig. 1 (*Left*) shows the relationship between vulnerability load before a climate event and the extent of social change following that event. The distribution of vulnerability loads for the cases is plotted in ascending order, with colors indicating whether social changes followed the shock. “Transformation” (red) refers to circumstances of both considerable population decline and disappearance of key social institutions and structures (51). “Substantial change” (orange) indicates changes in social institutions and structures without demographic decline. These rankings are based on evidence of change in household and village form and count, change in community structures, and historical records describing the scale and magnitude of change (*SI Appendix, section 3*).

Little change occurred only at low levels of vulnerability load; transformation occurred where vulnerability loads were quite high. Substantial change occurred across the spectrum of vulnerability loads.

The end of the Norse occupation in Greenland (Greenland 3), the population decline and end of a cultural tradition in Mimbres

(Mimbres 1), and the depopulation and institutional collapse in the Hohokam area of central Arizona (Hohokam 2) exemplify transformation. In Greenland, the eastern settlement was abandoned by the Norse around 1450 (35). The challenges to people in Greenland were many, including radical decreases in food security and isolation from their original northern European homeland. Norse settlement of Greenland ended shortly after the shock we list as Greenland 3, either because the last settlers died or people found their way off the island at that time (52).

In the Mimbres case, nearly everyone left their village settlements during a severe and long drought event that began in 1127. People had depleted riverine habitats in some parts of the region (53), decreased the abundance of artiodactyls (54, 55), and damaged some upland soils through farming (56). In addition, external relations with other Southwestern groups appear to have been severely limited (57). Nelson and colleagues (30) have estimated that roughly three-quarters of the population (ref. 30, figure 4) migrated away, and Mimbres traditions evident in many material domains ceased.

The Hohokam canal irrigation systems in central Arizona were the largest in pre-Columbian North America. By the mid-1400s, thousands of people had emigrated from these systems and large associated settlement clusters, leaving little visible archaeological trace of villages or settlements (51). Some may have died from malnutrition at some villages (46, 58) but most moved away, leaving an all but unpopulated center that once had supported many thousands.

Food Shortage Following Extreme Climate Challenges. Was each climate event followed by food shortage? Fig. 1 (*Right*) shows the relationship between vulnerability to food shortage before an event and the experience of food shortage following each event. Coding of the experience of food shortage was based on evidence from skeletal analysis of humans and animals, paleoethnobotanical analysis, and historical documents (*SI Appendix, section 3*). “None” (green) indicates no evidence of shortage; “some” (orange) indicates some food shortage for all people or substantial shortage for

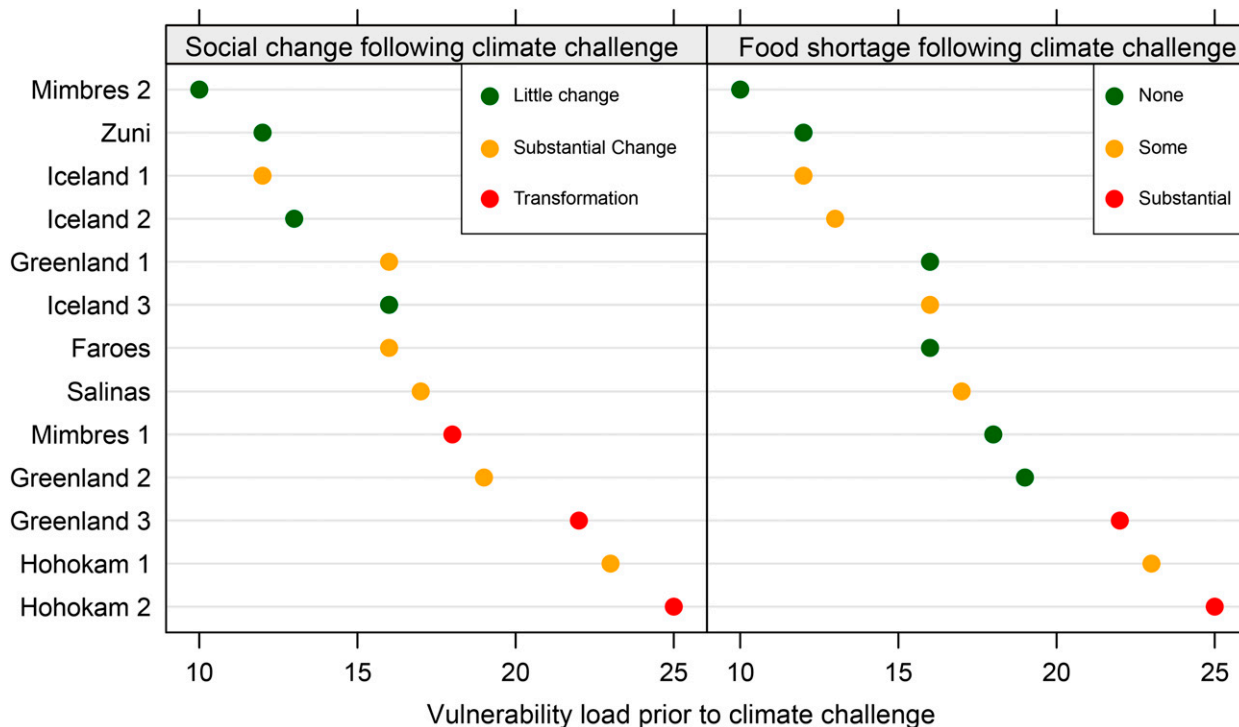


Fig. 1. Social changes and food conditions following climate challenges.

some people; and “substantial” (red) marks those cases with substantial shortage for all.

No shortage (green) following climate events is evident in six cases. Among those cases, Mimbres 1 and Greenland 2 offer perspectives on disaster management. In the Mimbres 1 case, most of the regional population emigrated, which reduced the local population to a level that avoided food provisioning issues but which had dramatic impacts socially—the transformative change noted above. In the Greenland case, people shifted toward substantial reliance on marine mammals (59–61), narrowing their diet by focusing on a resource that was abundant at that time. However, this narrowing of diet increased vulnerability to shortfall, which was realized just over a century later when the Norse occupation of Greenland ended just after the climate challenge we label as Greenland 3 (35, 62). In both cases, food shortage was avoided but at a high cost.

In 7 of the 13 cases, food shortage is evident at some level (yellow or red). The three Iceland cases at the lower end of the vulnerability load spectrum were contexts of persistent hunger. Climate challenges increased the extent of hunger but never to extreme levels for the whole population. Vulnerability to food shortfall remained low throughout, perhaps because people were aware and responsive to the reality that hunger was a constant challenge. These low vulnerability loads may have played a role in preventing extreme shortages following climate challenges. Streeter and colleagues (63) have noted that Icelandic society was consistently resilient to an array of challenges, bouncing back from plagues, conflicts, and difficult climate conditions.

The three cases with the highest vulnerability loads (Fig. 1, *Lower Right*) all have evidence of food shortage. Hohokam 1 is a period, beginning in 1338, when there is some evidence of food shortage for one segment of the population in central Arizona (46). By the second dry period, Hohokam 2, beginning in 1436, nearly everyone had left the massive irrigation systems. We interpret this as evidence of substantial food shortage, because it resulted in the disuse of a massive irrigation system and large amounts of previously cultivated land. The Greenland shock that began in 1421 coincides with the end of the Norse occupation in Greenland, which has been attributed to a variety of challenging conditions of which access to the key food resource—off-shore seals—is but one (62).

Summary and Recommendations

This analysis of historically and archaeologically documented cases from substantially different regions and cultural traditions shows a consistent relationship between the load of vulnerability to food shortage before a challenging climate event and the scale of impact following that challenge. Major social changes and food shortfall followed climate challenges in the cases with the highest existing vulnerability loads. Social change and food shortage were less often experienced and were never extreme in the cases with lowest vulnerability. The pattern is consistent across different regions of the world experiencing substantially different climate conditions—the role of vulnerability cannot be ignored.

Our stated goal was to assess current understandings of disaster management and to aid in understanding how people can build capability to increase food security and reduce their vulnerability to climate challenges. Our analysis suggests several points in this regard that are well-understood in the risk management community even though changes to vulnerability remain elusive and disasters grow more common (2, 3, 5).

i) Strategies for coping with climate challenges should include focus on the reduction of vulnerabilities, which disaster managers and others identify as an essential step in reducing impacts (1–8). The climate events we document were truly unanticipated, yet in those cases with low vulnerability loads we find little or no evidence for major impacts. What are often

called “natural disasters” were avoided by maintaining conditions, especially social conditions, that kept vulnerability low (9).

- ii*) Supporting the work of many others (1, 8–12), our analysis demonstrates that social factors are substantial contributors to vulnerability. Although researchers and managers recognize the role of social conditions, management of food security may address simply the availability of food resulting from population–resource balance. We can err in our management of food security by assuming that in contexts of adequate food availability there is no vulnerability to food shortage. Attention to social conditions that create vulnerabilities to food shortage is essential in resilience to climate challenges.
- iii*) As many have noted (e.g., 8, 9, 11–14), disasters are not inevitable; they are the result, in large part, of human-made conditions. The concept of natural disaster is unfortunate because it removes focus from the social conditions that set the stage for disasters to be triggered by various challenges. Our diverse cases suggest that human-created vulnerability can influence the outcome of climate challenges in many environmental, cultural, and historical contexts.
- iv*) Disaster relief should include addressing vulnerabilities, rather than returning systems to previous conditions (6). We recognize that change from untenable conditions is difficult (64). However, Kinver (3), reporting on responses to famine, notes consistent evidence that early action is cheaper.

Debates about disaster management, responses to climate shocks, attainment of human securities, and resilience to uncertainty rarely benefit from long time spans over which to evaluate claims. Our analyses offer a long-term view that allows assessment of full cycles of coupled social–ecological systems. Our work demonstrates that at the lowest and highest levels of vulnerability load, impacts are felt from climate challenges in different climate and social contexts. The pattern of outcomes from this cross-case study of different cultures, traditions, times, and environments underscores the critical need for reducing vulnerabilities to food shortfall to avoid the actual experience of shortage and painful social changes. And this, we hope, can help move discussions and actions forward.

Materials and Methods

Climate reconstructions and identification of climate challenges used an array of data sources and techniques (*SI Appendix, section 1*). The climate challenges identified in the US Southwest are the longest and rarest dry periods during the focal period. To represent climatic conditions for each case, we selected annually resolved tree-ring precipitation and streamflow reconstructions closest to the primary settlement areas of each case. Each reconstruction was smoothed with a centered 9-y-interval moving average to identify trends in the data obscured by year-to-year variation inherent in most arid regions. Years in the first quartile of the distribution of interval averages of each reconstruction were classified as dry periods. For each identified dry period, we calculated the number of years since a dry period of equal or greater duration had occurred. The dry periods classified as rare climate challenges had not been experienced by people or the arid environment they relied on for at least 456 y.

The climate challenges identified in the North Atlantic include cold summer temperatures, increased sea ice occurrence, and increased storminess. These were identified from ice cores, marine cores, lake sediments, and glaciological records. Extremes are identified as extended (>3-y) deviations greater than 1 SD from the mean from ice core and multiproxy climate reconstructions. Climate reconstructions from global circulation models were used to identify additional large-magnitude cooling events due to volcanic forcing. Due to the relatively poor chronological and spatial resolution of these datasets, we only considered a climate event significant if it was observed in more than one record. Although the chronology is not as precise as we would like for the regime shift scenarios, change would have been rapid in both human and environmental terms. The multiyear climate extremes identified in both regions decreased the productivity of resources people relied on and increased the risk of food shortages. We can infer from our current knowledge of arctic and subarctic ecological systems (e.g., the impact of summer temperatures on reducing growing-season length) and

documentary records [e.g., high rates of livestock mortality on Inuit farms associated with cold weather (65)] that these climate events would have had significant consequences and could be considered “shocks.”

Calculation of vulnerability load used historical, archaeological, and paleoethnobotanical data (SI Appendix, section 2). We used a qualitative ranking of the state of each variable to quantify the contribution of each to the “vulnerability load.” These rankings represent expert knowledge based on empirical evidence for each case (SI Appendix, section 2). Experts were assembled and participated together in coding.

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- Conditions following challenges were coded from empirical historical and archaeological data for social change and change in access to food (SI Appendix, section 3).

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