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 stressed 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 a 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 of 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; ltvtp.shesc.asu.edu) that conduct field research in the Zuni (41, 42), Salinas (43), Mimbres (44, 45), and Ho-hokam (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 pre-hispanic 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
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 1. Rare climate challenges, vulnerability scores, and total vulnerability load

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

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.

### Table 2. Variables contributing to vulnerability load to food shortage

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

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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
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, Kimver (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 artic and subarctic ecological systems (e.g., the impact of summer temperatures on reducing growing-season length) and


SUPPORTING INFORMATION

FILES 1-3

Climate Challenges, Vulnerabilities, and Food Security

Climate Challenges, Vulnerabilities, and Food Security

Supporting Information #1: Climate Challenges

Scott E. Ingram and Richard Streeter

Supporting information #1 describes the data and methods used to identify climate challenges in the U.S. Southwest and North Atlantic. The focal period in the Southwest is CE 1000 to 1500, 1000 to 1500 in Norse Greenland, and 900-1900 in Iceland. Different data and methods were used to identify the climate challenges in each region due to differences in climate regimes, data availability, and the subsistence strategies of the peoples considered.

Climate challenges, as discussed in the associated paper, are rare climate extremes. Climate extremes are defined as “The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable” (1). In both regions, we identify multi-year climate extremes because single-year events were likely accommodated by existing human adaptive and buffering strategies (2). Multi-year extremes are most likely to influence the productivity of the resources (plant and animal, wild and cultivated) humans rely on, exhaust existing buffering strategies, and prompt larger-scale and more archaeologically detectable behavioral responses.

U.S. Southwest

Paleoclimate Data

Precipitation and streamflow levels substantially influence food production (wild and cultivated) in the arid and semi-arid Southwest. Maize/corn (Zea mays L.) was the primary crop produced during the period of study and climate extremes, especially dry periods (droughts), decrease maize productivity (3-5) and can decrease food security. Cool temperatures that shorten the maize growing season can also decrease maize productivity at higher elevations in the Southwest. We do not consider cool temperature extremes in this study because the proxy data available lack sufficient spatial and temporal resolution. The relationship between the reconstructed temperature variable and maize productivity is also poorly understood.

Identification of climate extremes (dry periods) is accomplished through the analysis of variation in tree-ring widths calibrated with modern, instrumental climate station data. The precipitation and streamflow reconstructions selected were closest to the primary settlement areas of each case. Climate varies substantially across the region (6) so tree-ring stations (sampling areas) closest to settlement areas are often the most representative of past climates in those areas. The Zuni (Cibola) and Salinas (Santa Fe) precipitation reconstructions were developed by Dean and Robinson (7). The Mimbres (Central Rio Grande) precipitation reconstruction was developed by Grissino-Mayer and colleagues (8). The Hohokam streamflow reconstruction (Lower Salt, Tonto, and Verde Rivers) was developed by Graybill (9). For a discussion of the strengths and weaknesses of tree-ring climate reconstructions see Fritts (10) and Dean (11). Methods of tree-ring based precipitation reconstruction are described by Rose and colleagues (12).
Identifying Climate Extremes

We use a two-step method to identify multi-year climate extremes (dry periods).

First, year-to-year variation in each precipitation reconstruction is smoothed with a centered nine-year-interval moving average. Climate in the Southwest, and most arid environments, is highly variable from year-to-year so multi-year periods of unvarying extreme low or high precipitation and streamflow are rare. Smoothing is necessary to identify the extreme periods within this variability. A nine-year interval is used as a compromise between shorter durations, which would not as faithfully represent trends in climate proxy data, and longer durations, which would obscure climate variation that would have been potentially meaningful for human behavior. A nine-year interval duration is supported by studies that have documented persistence (year to year similarity) in climate patterns on decadal scales in both the modern instrumental and proxy records (13-16). Moving averages have been used in a number of tree-ring based paleoclimatic studies to identify multi-year dry and wet periods (17-22). These interval averages accommodate but do not ignore anomalous years within an extreme period that likely do not end the extreme period. For example, a single wet year during a dry period would not end the dry period or necessarily replenish stored food reserves or soil moisture.

Second, a threshold value is used to identify extreme periods within the reconstructions. We define extreme periods as those nine-year intervals in the first quartile (twenty-fifth percentile) of the distribution of interval averages of a precipitation reconstruction. Similar approaches have been used with standard deviation units by Dean (11) and percentile approaches to identify thresholds are currently used by the U.S. Drought Monitor (www.cpc.noaa.gov) and others to track drought severity across the U.S. (23-25). A first quartile threshold is arbitrary but assumed to represent periods with sufficient rarity to have substantially influenced resource productivity or human perceptions of productivity relative to typical conditions. We use the entire duration of the reconstructions (~1,500 years) to calculate the percentiles. The percentile value is assigned to year five of each moving nine-year interval. When four or fewer years of separation exist between the middle years of two identified extreme intervals, the intervals are merged into a single extreme period because the nine-year intervals substantially overlap. We ignore all extreme periods of four or fewer years. Shorter deleterious periods were likely effectively addressed by existing buffering strategies (e.g., storage, diet modification, trade).

Identifying Rare Climate Challenges

Rare climate challenges are identified among the frequently occurring extreme dry periods by calculating the number of years since a dry period of equal or greater duration had occurred. Table S1-1 contains the start and end dates, duration, and rarity of dry periods identified as rare climate challenges. Figure S1-1 identifies these periods in the context of all dry periods during the CE 1000 to 1500 focal period. The dry periods are considered rare because a dry period of equal or greater duration had not been experienced for at least 400 years. Existing human adaptive social and technological strategies for coping with dry period declines in food production would likely have been significantly challenged by these long and rare dry periods.
Table S1-1. Major climate challenges identified in the U.S. Southwest CE 1000 to 1500.

<table>
<thead>
<tr>
<th>U.S. Southwest Cases</th>
<th>Climate challenges, Years CE</th>
<th>Duration, years</th>
<th>Rarity: Years Since a Dry Period of Equal or Greater Duration(^1)</th>
<th>Start of Precipitation or Streamflow Reconstruction, CE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zuni</td>
<td>1133 - 1154</td>
<td>22</td>
<td>&gt; 697</td>
<td>436</td>
</tr>
<tr>
<td>Salinas</td>
<td>1335 - 1351</td>
<td>17</td>
<td>&gt; 456</td>
<td>879</td>
</tr>
<tr>
<td>Mimbres 1</td>
<td>1127 - 1147</td>
<td>21</td>
<td>&gt; 505</td>
<td>622</td>
</tr>
<tr>
<td>Mimbres 2</td>
<td>1273 - 1295</td>
<td>23</td>
<td>&gt; 651</td>
<td>622</td>
</tr>
<tr>
<td>Hohokam(^2) 1</td>
<td>1338 - 1352</td>
<td>15</td>
<td>580</td>
<td>572</td>
</tr>
<tr>
<td>Hohokam(^2) 2</td>
<td>1436 - 1452</td>
<td>17</td>
<td>678</td>
<td>572</td>
</tr>
</tbody>
</table>

Notes:
\(^1\) Years with the “>” sign indicate that the duration of the dry period exceeds the duration of any previously identified dry period in the tree-ring precipitation reconstruction.

\(^2\) Hohokam farmers relied on irrigation agriculture from a perennial river. A streamflow reconstruction is used to identify dry periods for this case.
Figure S1-1. Extreme Dry Periods in the U.S. Southwest from CE 1000 to 1500.
Notes:
1. Shaded areas show the dry periods and the rare climatic challenges discussed in the associated paper are identified with arrows.
2. The Zuni (Cibola) and Salinas (Santa Fe) precipitation reconstructions were developed by Dean and Robinson (7). The Mimbres (Central Rio Grande) precipitation reconstruction was developed by Grissino-Mayer and colleagues (8). The Hohokam streamflow reconstruction (Lower Salt, Tonto, and Verde Rivers) was developed by Graybill (9). All reconstructions were developed in association with the Laboratory of Tree-ring Research at the University of Arizona. Dry periods (shaded areas) were identified by Ingram using the methods described in this SI.

North Atlantic

The North Atlantic differs from the U.S. Southwest in climatic variability, paleoclimatic proxies, and the challenges faced by the predominantly pastoral farming and hunter gathering societies who lived there. Therefore a different methodology for identifying climate challenges was adopted. Our aim was to identify only the most significant climate challenges, where we could have reasonable certainty that they would have presented difficulties for the societies living there.

Paleoclimate data

The proxy records and reconstructions used are described in Table S1-2. Records were selected on the basis of geographical proximity to settlement areas, duration over the period of interest, and reconstructions which are relevant to the challenges outlined below. The main climatic challenges for societies living in the North Atlantic are 1) cold summer temperatures which severely inhibit fodder production crucial to animal provision (26), 2) increased sea ice occurrence, which decreases temperatures in northern Iceland and 3) increased storminess, which makes sea travel and fishing riskier, and may also decrease fodder production. Relative to the U.S. Southwest records, the North Atlantic climate proxies are of poor spatial and chronological resolution. Although documentary sources are an excellent source of climate information in this region (e.g., 27) we did not include them here as they are incomplete prior to CE 1500 and none exist for Greenland.

Identifying climate challenges in the North Atlantic

We identify climate extremes within the proxy records by selecting significant negative (cold) deviations from long-term means. These may be episodes of extended or exceptional (when considered on a multi-century scale) cold temperatures or increased storminess. We do this by identifying extended (> 3 years) deviations greater than one standard deviation from the mean. These can be considered climatic extremes.

In order to identify climatic challenges within the climate extremes we use additional criteria and sources of climate information. We considered the duration since an event of equal or greater magnitude (Table S1-2). We are most interested in identifying the first experienced occurrence of climatic extremes, as we assume these are most likely to have had the largest impact. Subsequent extremes, unless they involve significantly larger deviations from the new colder or stormier average conditions may have been less stressful, as societies are likely to have possessed enhanced traditional environmental knowledge in response to previous stresses. Given the generally poor spatial and chronological resolution of the records (chronological uncertainty for records was 5-20 years) we decided that climatic extremes must be visible in a minimum of two records to be classified as a climate challenge. This criterion decreases the likelihood of including changes that may have been only local in extent.
In addition to the proxy records identified in Table S1-2, we used information from climate models and additional climate proxies. It is known that not all proxy records (especially tree-ring based reconstructions) are sensitive to large magnitude climatic forcings. The VEI 7 magnitude eruption of Samalas, Indonesia in CE 1257 (28) results in the largest sulfate spike in the ice core record in the past 7000 years (37), but the proxy evidence here shows little cooling at this time (e.g., Figure S1-2 c, d). However, there are methodological reasons for this event to be under represented in tree ring records (32). When this volcanic forcing is incorporated into global circulation models there is a significant 2-3 year cooling in the northern hemisphere (31, 32), and this cooling is recorded in documentary sources in Europe (38). On this basis we include this event in our challenges, despite limited evidence for it in the proxy records shown in Figure S1-2. Secondly, although Figure S1-2 shows some evidence of cooling in the early 1300s, noticeably in the increased incidence of sea ice north of Iceland, there is additional evidence that this time represents the start of a climatic shift in the North Atlantic. In Iceland there are changes in lake sediments (33) and in the Greenland region there is glaciological evidence of readvances starting during this time (35).

Table S1-2 – Major climate challenges identified in the North Atlantic region AD 900-1900.

<table>
<thead>
<tr>
<th>North Atlantic Cases</th>
<th>Climate challenges, Year CE</th>
<th>Rarity – Years since an extreme of equal or greater duration</th>
<th>Type of climate challenge</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iceland 1</td>
<td>1257-1260</td>
<td>&gt;338 (29)</td>
<td>Cool temperature extreme</td>
<td>Volcanically forced cooling due to eruption of Samalas, Indonesia in CE 1257 (28). Some indication in proxy records although uncertain due to low-resolution chronology (Figure 2, 29). Modeled scenarios show a large cooling (30, 31), which lasts for 2-3 years.</td>
</tr>
<tr>
<td>Greenland 1</td>
<td>1257-1260</td>
<td>NA</td>
<td>Cool temperature extreme</td>
<td>See above.</td>
</tr>
<tr>
<td>Iceland 2</td>
<td>ca. 1310</td>
<td>90 (29); &gt;589 (32)</td>
<td>Cool temperature extreme and abundant sea ice</td>
<td>Start of change to Little Ice Age conditions and cooler temperatures in temperature reconstructions (29, 32). Shift to mean cooler temperatures recorded from CE 1300 in proxies in Iceland (33). Sea Ice proxies (34) see return of regular drift ice off the north coast of Iceland which had been largely absent for at least 700 years.</td>
</tr>
<tr>
<td>Location</td>
<td>Year</td>
<td>Duration</td>
<td>Cool Temperature Extreme</td>
<td>Cool Temperature Extreme and Sea Ice Extremes</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>----------</td>
<td>---------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Greenland 2</td>
<td>ca. 1310</td>
<td>NA</td>
<td>Cool temperature extreme and abundant sea ice</td>
<td>See above, and (35).</td>
</tr>
<tr>
<td>Greenland 3</td>
<td>1421</td>
<td>NA</td>
<td>Storminess extreme and cool temperature extreme</td>
<td>Indicators of storminess in the North Atlantic show shift to increasing storminess around CE 1420, and a peak from 1451-1480 (Figure 2; 35,36). A large volcanic forcing around CE 1450 (30) suggests a cold period lasting 2-3 years.</td>
</tr>
<tr>
<td>Iceland 3</td>
<td>1640</td>
<td>102 (29), &gt;1200 (34), 22 (32)</td>
<td>Cool temperature extreme and abundant sea ice extreme</td>
<td>Significantly below average temperatures (29, 32) and highest levels of sea ice since start of record (34).</td>
</tr>
</tbody>
</table>

**Notes:**

1. Where challenges have a clearly defined duration this is shown, otherwise just the start date is identified.
2. Where challenges are based upon records which were not statistically tested for extremes such as the model scenarios and changes in lake sediments, NA is shown here.
3. Proxy record from which the rarity of the event is calculated.
Notes:
Shaded areas show identified climatic challenges. (a) An alkenone based sea surface temperature reconstruction from core MD99-2275 taken from off the north coast of Iceland (29). (b) A sea ice reconstruction using the IP25 biomarker from the same core (MD99-2275). (c) A multi-proxy temperature reconstruction for the grid cell occupied by west Iceland, and (d) shows the same reconstruction for the Eastern Settlement in Greenland (32). (e) Na+ anomalies from the GISP ice core, which are here used as a proxy for storminess in the North Atlantic (35). Graphs a–c are relevant for understanding changes in Iceland, and graphs d and e for understanding changes in the Eastern Settlement in Greenland.
References


improved ice core-based index for climate models (vol 113, D2311, 2008). *J Geophys Res Atmos* 117.

Supporting Information #2 includes the archaeological and historical evidence used to support codes assigned to each of the eight variables contributing to vulnerability to food security in each case. A case is delineated by the time frame around a climate challenge (see SI#1) in each of the regions included in this study (Fig. S2-1 and Fig. S2-2). We focus on four regions in the US Southwest and three regions in the North Atlantic. The North Atlantic and US Southwest cases are used because in both macro-regions, teams of researchers have a decade-long history of studying the same kinds of questions about human-environment interaction over long time frames (500 to over 1000 years). These studies provide the basis for the evidence documented in SI#1, SI#3 and below. The collaboration of researchers in both macro-regions provided an opportunity to identify patterns of human-environment-climate interactions that supersede the specifics of cultural tradition and of climate and environmental conditions. Coding was done by all co-authors in face-to-face meetings.

Figure S2-1: Four regions in the US Southwest used for this study: Hohokam, Zuni, Salinas, Mimbres

1 All authors to the article as listed on the cover page of this SI document
Vulnerability can encompass a wide range of factors, but for the purpose of this study we identified eight variables, three population-resource and five social, to quantify the vulnerability of people to food shortage (1). These are variables that we know contribute to food security and that can be observed in the archaeological and historical record. They allow calculation of “vulnerability load,” which can be thought of as the weight of human-created factors in the potential for shortfalls in food.

The codes for vulnerability load are 1 = no contribution to vulnerability, 2 = limited contribution to vulnerability, 3 = more than limited but not substantial, 4 = substantial contribution to vulnerability load. Codes 1 and 4 define the ends of a continuum for the contribution of each variable to vulnerability load. Between these ends, Code 2, “limited contribution to vulnerability,” is recognized by mixed evidence for potential contribution to shortfall that is closer to “no vulnerability” than to substantial vulnerability. Code 3, “more than limited but not substantial,” is recognized by multiple lines of evidence that are closer to substantial contribution than to no contribution. For example, among the population-resource variables, depletion of one minor food resource would be coded as 2, “limited contribution to vulnerability,” while depletion of a key resource would be coded as 3. As a further example, in the social realm, mobility was coded 2 if either inside region movement or mobility to areas outside the region was restricted in any way – by lack of adequate transport, by laws, social norms, or conflict. Mobility would be coded 3 if these conditions limited both inside and outside movement. With strong evidence that people did not move, the variable would be coded 4.
Table S2-1. Codes and supporting archaeological and historical evidence are presented by case. Dates in red are the start dates for the climate challenges; vulnerability loads are calculated for the period immediately before the date in red by adding the eight numbers for each case.

<table>
<thead>
<tr>
<th>Iceland 1 1257</th>
<th>Code</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pop/ Resource Domain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Plenty of food</td>
<td>1</td>
<td>Zooarchaeological data indicate adequate food supply (2). Limited erosion and environmental degradation in North Iceland, some similar patterns in south Iceland but also evidence of stable or declining levels of erosion (3-8). Barley production on-going (9).</td>
</tr>
<tr>
<td>2. Diversity of Available Food</td>
<td>1</td>
<td>Zooarchaeological data indicate wide range of animals, marine resources (2). Full range of domestic animals and farming practices recognizable (2).</td>
</tr>
<tr>
<td>3. Resource Depression</td>
<td>2</td>
<td>Geomorphic evidence of ongoing erosion in lowland areas in south Iceland that limit people’s options (3, 6, 8, 10). People could not gain any more resource productivity from manuring; no extra manuring was required for existing level of productivity (11). Woodland clearing had progressed across landscape (12). Grassland ecosystems slowly replacing woodland (13, 14).</td>
</tr>
</tbody>
</table>

Social Domain

<table>
<thead>
<tr>
<th>Iceland 2 1310</th>
<th>Code</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pop/ Resource Domain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Diversity of Available Food</td>
<td>1</td>
<td>Zooarchaeological data indicate wide range of animals, marine resources (2). Full range of domestic animals and farming practices recognizable (2). Shift away from cows and goats and declines in barley local production but barley was being imported (18).</td>
</tr>
<tr>
<td>3. Resource Depression</td>
<td>2</td>
<td>Geomorphic evidence of ongoing erosion in lowland areas in south Iceland that limited people’s options (3, 6, 8, 10). People could not gain any more resource productivity from manuring; no extra manuring was required for existing level of productivity (11). Woodland clearing had progressed across landscape (12). Grassland ecosystems slowly replacing woodland (13, 14).</td>
</tr>
</tbody>
</table>

Social Domain
<table>
<thead>
<tr>
<th>Domain</th>
<th>Code</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Outside area network</td>
<td>1</td>
<td>Historical records document connections between communities and direct communication with Scandinavia, British Isles, and Greenland. The Norwegian kings tied together Scandinavia, the North Atlantic and the British Isles (15). Material evidence for interactions among communities within Iceland in different resource zones (16).</td>
</tr>
<tr>
<td>5. Storage</td>
<td>1</td>
<td>Evidence of hay storage - excavated houses with large hay barrels (17). Evidence for dried fish (18, 19). Some resources could be stored for several years (19).</td>
</tr>
<tr>
<td>6. Mobility</td>
<td>2</td>
<td>Internal mobility was possible and Iceland is big enough to have diverse options; but leaving island would have been challenging; movement more constrained by social structure (textual evidence – 16).</td>
</tr>
<tr>
<td>7. Equal access to food</td>
<td>2</td>
<td>Presence as hreppur - way to mediate food stress by creating obligations between classes; rules/laws determine order of access, which creates vulnerabilities for under class (27). Zooarchaeological data for unequal access to food (21).</td>
</tr>
<tr>
<td>8. Barriers to access</td>
<td>2</td>
<td>Conflict of the previous century was over (16) but sea ice had developed in summer, which limited access to many marine resources (28-30).</td>
</tr>
<tr>
<td>Iceland 3 1608</td>
<td>Code</td>
<td>Evidence</td>
</tr>
<tr>
<td>Pop/ Resource Domain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Plenty of food</td>
<td>2</td>
<td>Increasing levels of soil erosion (8, 10, 31). Historic records document people complaining about hunger, food system not breaking down, but some stress (23).</td>
</tr>
<tr>
<td>2. Diversity of Available Food</td>
<td>1</td>
<td>Increased sea ice (30, 32, 33); high levels of sea ice off North Coast (34). Some resources not available, but other new resources available – increased food imports offset cessation of cereal cultivation (16).</td>
</tr>
<tr>
<td>3. Resource Depression</td>
<td>3</td>
<td>Soil erosion high but not at highest level recorded (8, 35), which limited people’s options. Fodder and pasture productivity maintained but could not be increased by manuring (11). River sedimentation caused loss of access to certain fish (13, 36). Some glacial buildup started that reached maximum in late 17th century or early 18th century (37-39); farms threatened by encroaching ice (40, 41). Zooarchaeological data indicate decline in proportion of all domestic stock in relation to fish, so less meat and dairy in diet (42).</td>
</tr>
<tr>
<td>Social Domain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Outside area network</td>
<td>2</td>
<td>Historic documents for erosion of capacity for storage based on increasing numbers of low status people, who moved often; with tenants moving often, infrastructure for storage was not a priority for them. Wealth was a major conditioner of ability and interest in storing (16). Home fields still productive (46) but hay not storable in field anymore (20).</td>
</tr>
<tr>
<td>5. Storage</td>
<td>2</td>
<td>Evidence for commitment to specific place and residential stability by only small group of elites; tenants were forced to be mobile (47); lots of abandoned farms. Difficulty of leaving island because of limited access to boats (16).</td>
</tr>
<tr>
<td>6. Mobility</td>
<td>2</td>
<td>The same condition of social inequality as earlier, but under conditions of less available food suggests worse conditions for some. In the cannons, some people were referred to as the expendables; their access to food was limited by their class (43).</td>
</tr>
<tr>
<td>7. Equal access to food</td>
<td>2</td>
<td>Increased erosion and growth in ice limited transportation routes (23, 29). Glacial expansion caused lakes to be dammed and caused flooding in a few places (48).</td>
</tr>
<tr>
<td>Greenland 1 1257</td>
<td>Code</td>
<td>Evidence</td>
</tr>
<tr>
<td>Pop/ Resource Domain</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Plenty of food</td>
<td>1</td>
<td>Paleoenvironmental, zooarchaeological, and bio-physical assessments indicate an adequate resource base (49-53).</td>
</tr>
</tbody>
</table>
### 2. Diversity of Available Food

<table>
<thead>
<tr>
<th>Source Domain</th>
<th>Population/Resource Domain</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Plenty of food</td>
<td>1. Paleoenvironmental, zooarchaeological, and bio-physical assessments indicate adequate resource base (49-53).</td>
<td></td>
</tr>
<tr>
<td>2. Diversity of Available Food</td>
<td>Further increases in emphasis on seal hunting extended the pattern of decreased farming. Increased seal hunting based on bioarchaeological isotope data (54) and zooarchaeological data showing increase in seal bones (49, 53).</td>
<td></td>
</tr>
<tr>
<td>3. Resource Depression</td>
<td>Increases in agro-pastoral activities over time contributed to accelerated soil erosion (55). Although soil-erosion indicators decreased after 1230, erosion remained at a high level (55). Creation of hay fields may have caused problems in terms of nutrients available in soils (when compared to landnam); additional effort in soil managements may have been at limits of investments based on paleoenvironmental data (56).</td>
<td></td>
</tr>
</tbody>
</table>

### Social Domain

<table>
<thead>
<tr>
<th>Outside area network</th>
<th>Not much movement of people and no food resources available from outside, although Greenlanders maintained contact with Iceland and Norway (57).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>Architectural indications (elevated stone built storehouses, large wooden barrels in storerooms) of adequate storage capability (58, 59).</td>
</tr>
<tr>
<td>Mobility</td>
<td>Not much movement of people, although isotope data show some movement between Greenland settlements (57) and some to Norway. Historical evidence of Greenlanders present in Bergen (GHM III) and archaeological evidence of contact – imports from Norway.</td>
</tr>
<tr>
<td>Equal access to food</td>
<td>Isotopic data show differentiation in access to food by wealth/class (54). Architectural evidence (sizes of barns, byres, etc.) indicates different capacity to acquire food (58, 59).</td>
</tr>
<tr>
<td>Barriers to access</td>
<td>Long, dangerous sails from mid- and inner fjord settlement to seal hunting grounds on the outer coast based on archaeological and zooarchaeological data (4).</td>
</tr>
</tbody>
</table>

### Greenland 1310

<table>
<thead>
<tr>
<th>Pop/Resource Domain</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plenty of food</td>
<td>Paleoenvironmental, zooarchaeological, and bio-physical assessments indicate adequate resource base (49-53).</td>
</tr>
<tr>
<td>Diversity of Available Food</td>
<td>Further increases in emphasis on seal hunting extended the pattern of decreased farming. Increased seal hunting based on bioarchaeological isotope data (54) and zooarchaeological data showing increase in seal bones (49, 53).</td>
</tr>
<tr>
<td>Resource Depression</td>
<td>Increases in agro-pastoral activities over time contributed to accelerated soil erosion (55). Although soil-erosion indicators decreased after 1230, erosion remained at a high level (55). The creation of hay fields may have been causing problems in terms of nutrients available in soils (when compared to landnam); additional effort in soil management may have been at limits of investments based on paleoenvironmental data (56).</td>
</tr>
</tbody>
</table>

### Greenland 1421, 1450

<table>
<thead>
<tr>
<th>Population/Resource Domain</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plenty of food</td>
<td>Even though high dependence on seals, there was enough for the people who were there. No skeletal evidence of hunger (52).</td>
</tr>
<tr>
<td>Diversity of Available Food</td>
<td>Diversity of food resources decreasing – many more seals – much less animal husbandry based on isotope data (54) and zooarchaeology (49, 53). Substantial decline of agro-pastoral activities (50, 51, 55).</td>
</tr>
</tbody>
</table>
**3. Resource Depression**

- Harbor seal completely gone. Lots of soil had been degraded (55). Irrigation systems and shieling intensification as an effort to continue hay production which was declining in the period 1260 – 1350 (51, 61). Increase in summer sea ice contributed to reduced pasture productivity.

**Social Domain**

- **4. Outside area network**
  - Last known royal-controlled navigation between Norway and Greenland terminated around 1420 but some Icelanders in Greenland around 1400 (via Norway) (62). Last bishop residing in Greenland died in 1378; lack of replacement indicates decline in contact with Norway (60).

- **5. Storage**
  - Architectural indications (elevated stone built store houses, large wooden barrels in storerooms) of storage (58, 59) though fewer kinds of resources to store.

- **6. Mobility**
  - Less internal and external movement -- Western Settlement depopulated before 1400 (57), hunting trips to the North may have ended due to less sale of Arctic commodities in N Europe and the ending of navigation between Greenland and Norway (57).

- **7. Equal access to food**
  - Elite farms still have cattle in their byres -- smaller farmers dependent on the marine resources (seal) -- still fewer differences in diet than in earlier period -- everyone depended on seal (54, 58).

- **8. Barriers to access**
  - Long, dangerous sails from mid- and inner fjord settlement to seal hunting grounds on the outer coast based on archaeological and zooarchaeological data (4) and settlement pattern data (58). As seal had become so essential, this barrier was greater than previously.

---

**Faroes 1257**

<table>
<thead>
<tr>
<th>Code</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Pop/Resource Domain**

- **1. Plenty of food**
  - Though actual evidence is limited, there should have been enough food, given the (probably) low population level (63). However, because of the socio-economic changes occurring prior to the shock (64, 65), there might have been significantly increased pressures on the terrestrial resources.

- **2. Diversity of Available Food**
  - Includes domestic livestock, marine and terrestrial wild resources, and at least some barley production (13, 14, 66-68).

- **3. Resource Depression**
  - Evidence is limited, but there is no indication of significant resource depression at this point (68, 69), though there was pressure on terrestrial resources.

**Social Domain**

- **4. Outside area network**
  - Some trade and other connections to the outside world (NE Europe) (70, 71). There was certainly contact and exchange between communities, though no substantial differences in resources or environmental conditions between island communities in the Faroes.

- **5. Storage**
  - Some storage in the form of grain (barley), livestock, and preserved foodstuffs (eggs, air-dried fish & meat). Evidence for preservation comes mostly from ethnographic record from later centuries (e.g. 72, 73) and known practices elsewhere in the Norse regions.

- **6. Mobility**
  - Investment in place; severe restrictions on relocation of settlements because of the mountainous topography (63). Heavy reliance on boats for transportation and movement between islands and abroad.

- **7. Equal access to food**
  - As in other Norse societies (74), access was limited by social class. Mahler argued that access to resources was tied to land ownership in particular (64).

- **8. Barriers to access**
  - Some slight differences in resource availability depending on settlement location, but these were generally dealt with through exchange. Boats were a requirement for accessing deep-sea fish (75). There were physical hazards associated with fowling (73).

---

**Mimbres 1 1127**

<table>
<thead>
<tr>
<th>Code</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Pop/Resource Domain**

- **1. Plenty of food**
  - Largest population (76-79). Riparian depletion in Mimbres Valley but not in eastern Mimbres (78, 80).

- **2. Diversity of Available Food**
  - Large game limited -- Artiodactyl depletion well before this time (80). Some riparian depletion (78).
### Mimbres 2 1273

<table>
<thead>
<tr>
<th>Pop/ Resource Domain</th>
<th>Code</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Plenty of food</strong></td>
<td>1</td>
<td>Population low relative to available resources and earlier periods (77-79).</td>
</tr>
<tr>
<td><strong>2. Diversity of Available Food</strong></td>
<td>2</td>
<td>Large game limited -- Artiodactyl depletion well before this time (80). Riparian recovery (78).</td>
</tr>
<tr>
<td><strong>3. Resource Depression</strong></td>
<td>1</td>
<td>Artiodactyl populations may have rebounded somewhat (96-97).</td>
</tr>
<tr>
<td><strong>4. Outside area network</strong></td>
<td>1</td>
<td>Variety of non-local ceramics and architecture (98, 99).</td>
</tr>
<tr>
<td><strong>5. Storage</strong></td>
<td>2</td>
<td>Ethnographic research on Puebloan agriculture records that people tried to keep 2-3 years of stored maize, the primary stored food resource. (86-88). Formal storage areas are rare (98).</td>
</tr>
<tr>
<td><strong>6. Mobility</strong></td>
<td>2</td>
<td>Residential mobility relatively high as evident in house architecture (98, 100). Many pan-regional connections evident in ceramic diversity (98, 99).</td>
</tr>
<tr>
<td><strong>7. Equal access to food</strong></td>
<td>1</td>
<td>All house units similar in size and composition of household features (98).</td>
</tr>
<tr>
<td><strong>8. Barriers to access</strong></td>
<td>1</td>
<td>No physical barriers evident.</td>
</tr>
</tbody>
</table>

### Zuni 1133

<table>
<thead>
<tr>
<th>Pop/ Resource Domain</th>
<th>Code</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. Plenty of food</strong></td>
<td>1</td>
<td>No evidence that people faced food shortages in the region and population estimates (101, 102) for well-documented areas suggest that population levels likely would have been sustained easily, given the distribution of agricultural land.</td>
</tr>
<tr>
<td><strong>2. Diversity of Available Food</strong></td>
<td>2</td>
<td>In general, evidence from excavated sites suggests that people used a diversity of agricultural foods, wild plants, and animals, though the availability of large animals was somewhat reduced by this period (103, 104).</td>
</tr>
<tr>
<td><strong>3. Resource Depression</strong></td>
<td>2</td>
<td>Little zooarchaeological or paleoethnobotanical evidence of resource depression in the region at this time, though ratios of artiodactyls to other animals in excavated assemblages suggest that they were somewhat reduced from earlier periods (103, 104).</td>
</tr>
<tr>
<td><strong>4. Outside area network</strong></td>
<td>2</td>
<td>Ceramic evidence suggests that connections to areas outside of the broader Zuni/Cibola region were limited (numbers of non-local sherd are miniscule) but there is some ceramic (103) and obsidian (105) evidence of connections that span the Colorado Plateau south to the Mogollon Highlands, an area marked by different environmental conditions.</td>
</tr>
</tbody>
</table>
| **5. Storage** | 2    | Extensive evidence of storage in the form of dedicated rooms, pits in habitation rooms, and jars with seeds and other contents suggesting that people in the area were regularly able to store food (103, 104). Ethnographic research on Puebloan agriculture records that people tried to
6. Mobility | 1 | The Zuni region was marked by short-lived sites and a high degree of residential mobility as suggested by settlement data, the frequencies of dated ceramic types, and tree ring dates from several regions (101, 102, 106).

7. Equal access to food | 1 | No evidence that any segment of society controlled access to food resources in the study area, in particular due to the high frequency of mobility (101, 102).

8. Barriers to access | 1 | No evidence that substantial barriers to access to food resources existed. Settlement was extensive during this period (101, 102) and people residing across the region used a common suite of resources.

Salinas 1335 | Code | Evidence
Pop/ Resource Domain
1. Plenty of food | 1 | No evidence for imbalance.

2. Diversity of Available Food | 2 | In general, paleoethnobotanical and zooarchaeological evidence from excavated sites suggests that people used a diversity of agricultural foods, wild plants, and animals, though the availability of large animals was somewhat reduced by this period (107). Pinyon was an important complement to agricultural and hunted foods (108).


Social Domain
4. Outside area network | 3 | Little evidence for outside area connections, with only a small amount Rio Grande glaze wares (109-111).

5. Storage | 2 | Ethnographic research on Puebloan agriculture records that people tried to keep 2-3 years of stored maize, the primary stored food resource (86-88).

6. Mobility | 4 | As agriculturalists people were tethered to the water table and did not move away from it (79).

7. Equal access to food | 1 | No evidence for differential distribution or access to resources.

8. Barriers to access | 3 | Localized areas of high water table limited where people could acquire and grow key resources (79).

Hohokam 1 1338 | Code | Evidence
Pop/ Resource Domain
1. Plenty of food | 2 | Population was large as documented with settlement data (112).

2. Diversity of Available Food | 2 | Zooarchaeological data show decline in terrestrial game, which led to increased dependence on riparian resources (James 2003). Artiodactyls limited (113).

3. Resource Depression | 2 | Zooarchaeological data indicate impact on game resources (114-116).

Social Domain
4. Outside area network | 4 | Balkanized system – widespread ballcourt system that had supported market exchange over large region was gone (117). Population was concentrated in river valleys (112, 117).

5. Storage | 2 | Ethnographic research on Puebloan agriculture records that people tried to keep 2-3 years of stored maize, the primary stored food resource (86-88).

6. Mobility | 4 | Canal infrastructure tied people to canals, restricting mobility (118) relative to other regions of the Southwest (106).

7. Equal access to food | 4 | Control of irrigation system by some; platform mounds for ceremony and possibly elite residence were at headgates to canals controlling water and land (119-121).

8. Barriers to access | 3 | Canals delimited primary agricultural areas (122-124).

Hohokam 2 1436 | Code | Evidence
Pop/ Resource Domain
Domain

1. Plenty of food 3 Population was large as document with settlement data (112). In addition, the primary source of food, the fields fed by the canal system, were decreasing in extent (123, 124).

2. Diversity of Available Food 2 Zooarchaeological data show decline in terrestrial game, which led to increased dependence on riparian resources (115). Artiodactyls limited (113).

3. Resource Depression 3 Zooarchaeological data indicate impact on game resources (114-116). In addition, soil degradation has been documented along the Salt River (125).

Social Domain

4. Outside area network 4 Balkanized system – widespread ballcourt system that supported market exchange over large region was gone (117) and population was concentrated in river valleys (112, 117).

5. Storage 2 Ethnographic research on Puebloan agriculture records that people tried to keep 2-3 years of stored maize, the primary stored food resource (86-88).

6. Mobility 4 Canal infrastructure tied people to canals, restricting mobility (118) relative to other regions of the Southwest (106).

7. Equal access to food 4 Control of irrigation system by some; platform mounds for ceremony and possibly elite residence were at headgates to canals controlling water and land (119-121).

8. Barriers to access 3 Canals delimited primary agricultural areas (122-124).

References


9. Trigg H, Bolender D, Johnson K, Patalano M, Steinberg J (2009) Note on barley found in dung in the lowest levels of the Farm Mound Midden at Reynistaður, Skagafjörður Iceland. Archaeologia Islandica 7:64-72


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Supporting Information #3 includes the archaeological and historical evidence used to support codes describing the nature of change following each of the thirteen climate challenges in the seven regions in this study. Climate challenges are defined and described further in SI#1; regions are delineated and illustrated in SI#2. The codes below are based on change occurring during and immediately after the period marked as a climate challenge. Coding was done by all co-authors in face-to-face discussion.

Social/demographic changes are coded with supporting evidence in Table S3-1. The codes for the nature of social changes associated with climate challenges are 1 = little change, 2 = substantial change, and 3 = transformative change.

1 - Challenges/cases coded as 1 represent contexts where there were no major changes in population levels and no loss of institutions, but may include cases marked by minor changes in the organization of population or economic practices. Cases coded 1 are characterized by substantial continuity.

2 - Challenges/cases coded as 2 represent cases where there were major changes in the organization or distribution of populations or major changes in institutional reach or function, but also substantial evidence for continuity.

3 - Challenges/cases coded as 3 represent major instances of change marked by major population loss (depopulations), dramatic changes in social organization, and the loss of institutions or infrastructure. Many cases marked 3 represent the terminal phases of occupation of regions by a given social group or most of that social group.

Codes and supporting archaeological and historical evidence are presented by the climate challenges identified within each case. Each code characterizes changes immediately following the date of the initiation of the climate challenge.

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2 All authors to the article as listed on the cover page of this SI document.
Table S3-1. Social/demographic changes following the climate challenge.

<table>
<thead>
<tr>
<th>CASE</th>
<th>CLIMATE CHALLENGE START</th>
<th>CODE</th>
<th>EVIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iceland 1</td>
<td>1257</td>
<td>2</td>
<td>End of commonwealth; dramatic social changes in laws and independence; previous legal and social relations abolished (1). Legal structure remains same and civil war continues (1).</td>
</tr>
<tr>
<td>Iceland 2</td>
<td>1310</td>
<td>1</td>
<td>Continuation of the new royal administration (1).</td>
</tr>
<tr>
<td>Iceland 3</td>
<td>1608</td>
<td>1</td>
<td>Many changes in administration and global relations; integrated into Danish state (1) but locally similar to previous centuries.</td>
</tr>
<tr>
<td>Greenland 1</td>
<td>1257</td>
<td>2</td>
<td>Depopulation of the marginal regions and decline in agro-pastoralism. Livestock numbers were reduced and flocks of sheep and goats increased to the exclusion of cattle (2-5). Dependence on outer fjord marine resources (migrating seals) increased. Settlement contracted to the inner and mid fjord regions and the authority and central functions of society including economic power was gathered on fewer hands, witnessed by closed down churches and the building of fewer larger and more monumental structures (2). Norse Greenlanders were now under Norwegian authority, which may have impacted the local authority. The influence of the Norwegian bishops is uncertain (6).</td>
</tr>
<tr>
<td>Greenland 2</td>
<td>1310</td>
<td>2</td>
<td>Change in food mix that had impact on the food base and on organization of food getting that ultimately affected the outcome of Norse occupation (2, 5).</td>
</tr>
<tr>
<td>Greenland 3</td>
<td>1421</td>
<td>3</td>
<td>Abandonment of the Norse settlement was definitive around 1450. The northern Western settlement was abandoned a few generations before the southern Eastern Settlement (7, 8).</td>
</tr>
<tr>
<td>Faroes</td>
<td>1257</td>
<td>2</td>
<td>There may have been a further restriction of access to resources for the poor (as exemplified by the Sheep Letter of 1298); this was part of a long period of social change (much of which was driven by Norwegian forces (9, 10).</td>
</tr>
<tr>
<td>Mimbres 1</td>
<td>1127</td>
<td>3</td>
<td>Major population decline and social reorganization evident in settlement organization and domestic architecture (11, 12).</td>
</tr>
<tr>
<td>Mimbres 2</td>
<td>1273</td>
<td>1</td>
<td>No evidence of regional changes in settlement organization or social relations. From 1150 on, the region was sparsely populated with considerable diversity in pottery, architectural, and other material forms and styles (11, 13).</td>
</tr>
<tr>
<td>Zuni</td>
<td>1133</td>
<td>1</td>
<td>Region-wide change with limited local impact. This period saw the end of the Chaco phenomenon, which was a major force in the earlier century. In some communities in the Zuni area, things kept going right on as they had previously including the continued occupation of great house/great kiva communities. In a few other places, people began to build post-Chacoan architectural complexes with a decidedly more local flavor but there was apparently a lot of continuity in community organization (14).</td>
</tr>
</tbody>
</table>
End of settlement reorganization from jacals to masonry pueblos. Documented burning is interpreted as evidence for conflict in the mid 1300s that immediately followed the “reorganization” transformation (15).

Beginning of substantial depopulation of the Phoenix Basin. The abandonment of the Phoenix Basin (see below) was preceded by a slow demographic decline in the late Classic Period from the AD 1300s until abandonment of the region in the mid AD 1400s (16, 17).

End of the Classic Period, which saw the depopulation of the entire Phoenix Basin and the abandonment of the massive irrigation canal system (16, 18).

<table>
<thead>
<tr>
<th>CASE</th>
<th>CLIMATE CHALLENGE START</th>
<th>CODE</th>
<th>EVIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinas</td>
<td>1335</td>
<td>2</td>
<td>End of settlement reorganization from jacals to masonry pueblos.</td>
</tr>
<tr>
<td>Hohokam 1</td>
<td>1338</td>
<td>2</td>
<td>Beginning of substantial depopulation of the Phoenix Basin.</td>
</tr>
<tr>
<td>Hohokam 2</td>
<td>1436</td>
<td>3</td>
<td>End of the Classic Period, which saw the depopulation of the Phoenix Basin and the abandonment of the massive irrigation canal system (16, 18).</td>
</tr>
</tbody>
</table>

In addition to social/demographic change, changes in food conditions following the climate challenge were identified. Food conditions include actual suffering of hunger but may also include difficulty getting to food resources (as in Greenland). Changes in food shortage were coded from 1 to 3. 1 = little change, 2 = more shortage for some or a small decline for all, and 3 = substantial decline for all.

Table S3.2. Declines in food shortage following climate challenges

<table>
<thead>
<tr>
<th>CASE</th>
<th>CLIMATE CHALLENGE START</th>
<th>CODE</th>
<th>EVIDENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iceland 1</td>
<td>1257</td>
<td>2</td>
<td>Starvation increased as a result of poor weather (19). As noted by Ogilvie (20) the Icelandic Annals for 1287 state that: “At this time, many severe winters came at once, and following them, people died of hunger.” Extreme bone processing of harp seals suggests nutritional stress (follow Outram's study standards [21]) from the ca. 1250-1300 deposit at Hofstadir (22).</td>
</tr>
<tr>
<td>Iceland 2</td>
<td>1310</td>
<td>2</td>
<td>Increasing use of seals and marine fish at inland settlements suggests use of secondary resources (22). Continued references to famine and shortages but evidence of substantial population up to impact of Black Death in early 15th c. (23).</td>
</tr>
<tr>
<td>Iceland 3</td>
<td>1608</td>
<td>2</td>
<td>Recurring famines as always, but increasingly bad for lower class (1).</td>
</tr>
<tr>
<td>Greenland 1</td>
<td>1257</td>
<td>1</td>
<td>No evidence for shortage.</td>
</tr>
<tr>
<td>Greenland 2</td>
<td>1310</td>
<td>1</td>
<td>No evidence for shortage.</td>
</tr>
<tr>
<td>Greenland 3</td>
<td>1421</td>
<td>3</td>
<td>Seals had kept people alive, and as long as the landowners controlled the seal hunt the seals also kept the social system alive, at least on the face of it. The seals also masked serious structural problems, which perhaps are expressed in the social equalization of diet. Not even the elite farms were profitable anymore. This climate challenge made sealing difficult contributing, among many factors, to the end of Norse settlement. (8).</td>
</tr>
<tr>
<td>Faroes</td>
<td>1257</td>
<td>1</td>
<td>Evidence is extremely limited, but there is no evidence of food access (23).</td>
</tr>
<tr>
<td>Site</td>
<td>Year</td>
<td>Evidence</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td>Mimbres 1</td>
<td>1127</td>
<td>No skeletal evidence of food shortage (24); no substantial changes in diet across this century (11, 25).</td>
<td></td>
</tr>
<tr>
<td>Mimbres 2</td>
<td>1273</td>
<td>No evidence of reduction in available food.</td>
<td></td>
</tr>
<tr>
<td>Zuni</td>
<td>1133</td>
<td>No evidence for a change in food availability across the transition considered here; similar frequencies and diversities of foods have been noted at sites occupied before and after the transition (e.g., 26-28).</td>
<td></td>
</tr>
<tr>
<td>Salinas</td>
<td>1335</td>
<td>The hostile landscape and burning of stored food, including corn (28), would have created some food shortfall or certainly a food challenge.</td>
<td></td>
</tr>
<tr>
<td>Hohokam 1</td>
<td>1338</td>
<td>Canal system declining in extent (30, 31), and streamflow was variable (32). Archaeological research has shown that health was declining at some places during the Classic Period (33), although McClelland and Lincoln-Babb, in a conference presentation, claim that poor health was not widespread and originally may have been overstated. Nevertheless some poor nutrition is evident (16).</td>
<td></td>
</tr>
<tr>
<td>Hohokam 2</td>
<td>1436</td>
<td>Abandonment of the canal massive canal system at this time (16, 18) would have prompted considerable food shortage locally.</td>
<td></td>
</tr>
</tbody>
</table>

References

15. Rautman AE (2013) Final report on the excavation of LA-9032, Frank’s Pueblo, Socorro County, New Mexico (State of New Mexico Department of Cultural Affairs, Historic Preservation Division, Santa Fe, NM).
27. Varien MD (1990) Excavations at three prehistoric sites along Pia Mesa Road, Zuni Indian Reservation, McKinley County, New Mexico. *Zuni Archaeology Program Report No. 233* (Zuni Archaeology Program, Pueblo of Zuni, NM).
