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Climate change, human health, and resilience in the Holocene

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Climate change is an indisputable threat to human health, especially for societies already confronted with rising social inequality, political and economic uncertainty, and a cascade of concurrent environmental challenges. Archaeological data about past climate and environment provide an important source of evidence about the potential challenges humans face and the long-term outcomes of alternative short-term adaptive strategies. Evidence from well-dated archaeological human skeletons and mummified remains speaks directly to patterns of human health over time through changing circumstances. Here, we describe variation in human epidemiological patterns in the context of past rapid climate change (RCC) events and other periods of past environmental change. Case studies confirm that human communities responded to environmental changes in diverse ways depending on historical, sociocultural, and biological contingencies. Certain factors, such as social inequality and disproportionate access to resources in large, complex societies may influence the probability of major sociopolitical disruptions and reorganizations—commonly known as "collapse." This survey of Holocene human–environmental relations demonstrates how flexibility, variation, and maintenance of Indigenous knowledge can be mitigating factors in the face of environmental challenges. Although contemporary climate change is more rapid and of greater magnitude than the RCC events and other environmental changes we discuss here, these lessons from the past provide clarity about potential priorities for equitable, sustainable development and the constraints of modernity we must address.

climate adaptation | equitable sustainability | environmental health | IPCC | UN Sustainable Development Goals

The risks of climate change for human societies are complex, with interacting hazards that are compounded and potentially amplified by human responses (1). Anthropogenic global warming is projected to exceed the magnitude and pace of all past rapid climate change (RCC) events (2). The Intergovernmental Panel on Climate Change (IPCC) worst-case scenario projections show the Earth's mean annual surface temperatures potentially increasing in the next century to levels not seen for 55 million years (3). Climate change will impact human societies as part of a suite of concurrent, potentially catastrophic risks including the sixth mass extinction (4), emerging and reemerging infectious disease (5), antibiotic resistance (6), and rising social inequality and polarization (7). How these forces will combine to influence the future of different human communities is difficult to predict but specific targets are identified for research that is relevant to decision-making, mitigation, and adaptation (8). Specifically, the IPCC has argued that planning for a warmer world requires additional research with three major foci, namely climate modeling, understanding societal adaptive capacity, and predicting vulnerabilities (8). It is particularly important to consider human variation across space and time in modeling adaptive capacity and vulnerability to avoid reproducing climate coloniality in designing interventions (9).

Climate change research must operate across the boundaries of disciplinary knowledge to model complex links between ecosystems, social structure, human agency, and the potential for biocultural adaptation in a warming world. Archaeology contributes to the above IPCC research priorities

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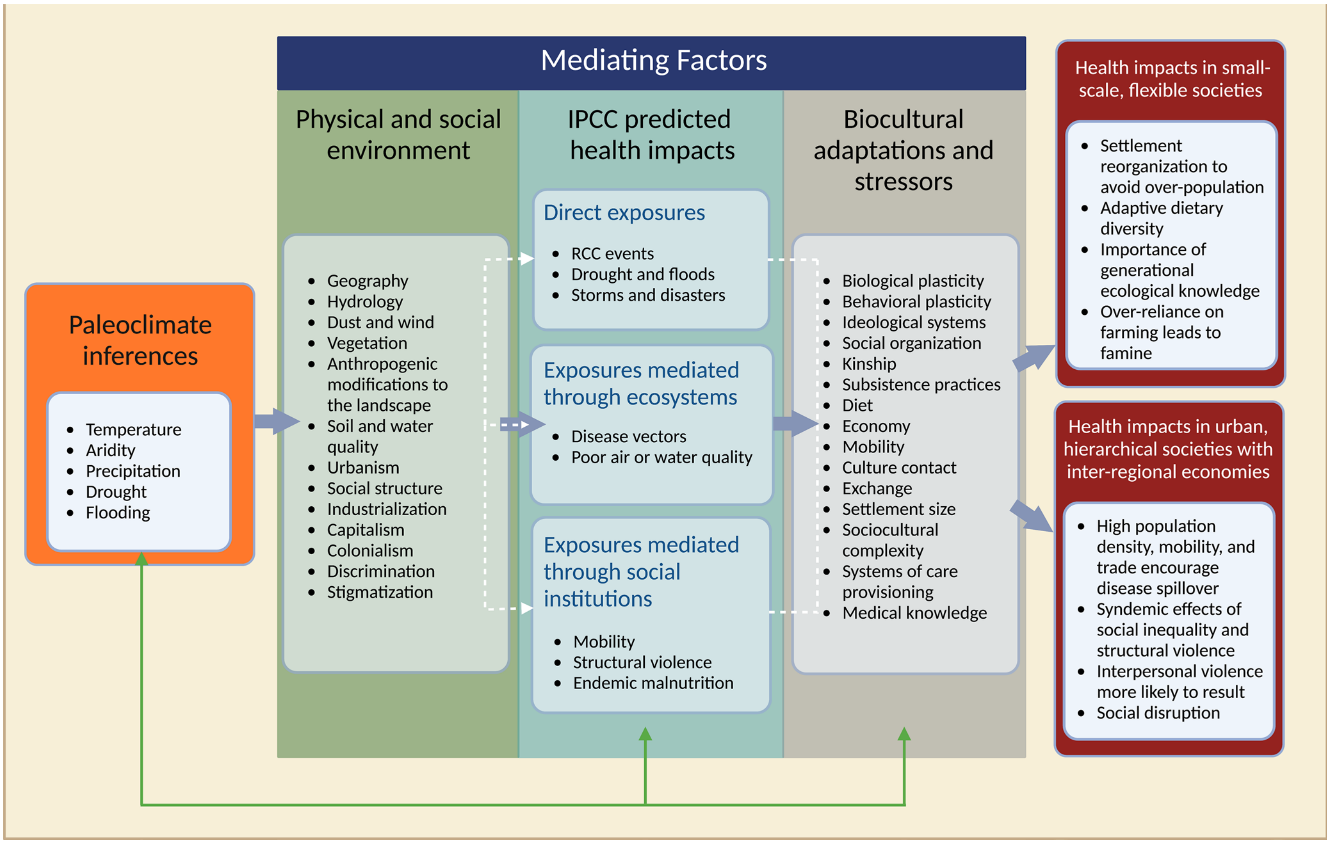

Fig. 1. Bioarchaeological evidence of IPCC Predicted Health Impacts.

by providing 1) evidence about local and regional paleoclimatic shifts through time and their ecosystem-wide impacts and 2) a deep time perspective on diverse human-environmental interactions and forms of human resilience (10). Unfortunately, anthropological insights are not consistently incorporated into human security literature or policy and planning efforts, which can be based on potentially dangerous misconceptions about human evolution (11). Bioarchaeology provides an evidence-based, scientific rejection of these harmful determinist narratives that climate change inevitably causes environmental migration, violence, or poor health (10) through harmonized long-term observations of human societies for which climate and ecological changes were concurrent with material, ideological, sociocultural, and health-related changes (12).

This perspective piece integrates evidence from published case studies from across the globe to provide insights into human health in past contexts of climate change. The IPCC predicts climate change will affect human health through direct impacts, ecosystem-mediated, and socially mediated impacts. We provide examples where climate change had syndemic effects on human health (13) through these three IPCC-identified pathways (14, 15) (Fig. 1). First, global warming will have direct impacts on human health due to increased average temperature, changing patterns of rainfall, drought, wildfires, and other extreme weather events. Second, health impacts will be heavily mediated through local ecosystems including changing patterns of vector-borne disease, air quality, and water pollution. Third, health impacts will be heavily modulated through social processes and institutions, including migration and population displacement, changes in food production, water management, and potential food shortages. These categories are not mutually exclusive. Rather, each contributes to cascading global health vulnerabilities. The research outlined here confirms that earlier experiences of both resilience and collapse were strongly shaped by contingent historical and sociocultural dynamics, which should be included in current climate mitigation scenarios.

Climate Change Directly Impacts Human Health: Lessons from the 4.2 ka B-P- RCC Event

There were three major prehistoric RCC events that are well documented by paleoclimate proxy data that coincided with abrupt archaeological shifts in Eurasia—the 8.2 ka, 4.2 ka, and the 3.2 ka BP RCC events. These periods of cooling temperature and increasing aridity led to changing patterns of rainfall and drought analogous to conditions we face with global warming today (8, 16–18). We use the 4.2 ka BP RCC event in Asia as an example because it provides an opportunity to address hypotheses about variation in epidemiological patterns in the context of a changing climate for people living in small-scale communities versus newly emerging complex urban societies (19–23). Climate proxy data indicate the 4.2 ka BP event was associated with roughly four centuries of environmental change on a global, regional, and local scale (*SI Appendix*, Table S1), including disruption of the South Asian monsoon system and aeolian dust deposition in Africa and Asia (23). Locally and regionally important environmental changes were coincident with dramatic shifts in archaeological communities across Asia

(*SI Appendix*, Fig. S1); additional detail on archaeological aspects of each of these case studies is provided in the *SI Appendix* (*SI Appendix*, Table S2). The results of research on pathophysiological stress markers, skeletal growth suppression, changing patterns of infectious disease, and violence demonstrate that vulnerability is primarily a social phenomenon. However, the duration of climate change events matters (24) and flexibility in political and socioeconomic structures is the major factor shaping the experience of resilience, suffering, and survival (25, 26).

In the 4.2 ka BP event, complex urban societies across central and South Asia that were built on a foundation of structural inequality were vulnerable to direct, ecosystemic, and socially mediated impacts of climate change (24). For example, the Indus civilization of Pakistan and NW India grew rapidly from 5.3 to 4.2 ka BP in the context of an increasingly arid environment. Economic opportunities provided by an international exchange network may have promoted immigration by farmers and craftspeople to South Asia's first cities (27). Human skeletal evidence demonstrates that urbanism combined with heavy reliance on trade (not climate change *per se*) facilitated the spillover of mycobacterial infections–leprosy, and tuberculosis (28). These diseases thrive globally in the marginalized populations of dense urban communities to this day. After two centuries of increasingly unpredictable monsoon rainfall and shifting regional economic relations, cities in the modern-day states of Pakistan and India were abandoned (29, 30). Indus cities were depopulated in the face of a combination of pressures from climate change, systemic structural inequality, and regional socioeconomic changes. A small remnant population continued to occupy the city of Harappa after this civilization disintegrated. The experience of resilience recorded in the human skeletons buried here included a high frequency of infectious disease, interpersonal violence, and micronutrient deficiencies for infants and children (11). This example demonstrates the value of policies to assist with livelihood transformation in rural areas and to facilitate labor migration in ways that mitigate the risk of overcrowding and disease spillover (31).

Small-scale societies with more malleable political and economic structures demonstrate the variable character of resilience to environmental disruption in the face of RCC (25). The same 4.2 ka BP RCC event was experienced very differently by hunting and gathering communities in Japan, China, and the United Arab Emirates, with fewer signs of poor health in these societies compared to the Indus civilization. In Japan, Jomon cultures are renowned for long-standing economies, which relied heavily on chestnut production in addition to hunting, fishing, and gathering. This semisedentary population thrived for millennia (16500 to 2300 BP) through ecologically transformative events including climatic shifts, volcanic eruptions, and typhoons. The 4.2 ka BP event here had diverse effects but, across Honshu Island, the population size declined and human populations emphasized exchange and solidarity (32). In southwest Japan, skeletal and dental markers of physiological stress are comparable before and after the 4.2 ka BP event (33). Sustainability was derived from a flexible social organization and dietary adaptive diversity (34).

Similarly, the benefits of flexibility in a mixed economic system are seen in the results of research across the 4.2 ka BP event in western China (35). Palaeoclimatological proxy data suggest fluctuating temperatures and changing patterns of precipitation and moisture in the Hexi corridor (36). As the environment became more arid, the people of this region relied more heavily on herding activity over time. In this regard, stable isotope analysis of human skeletons has demonstrated a diverse suite of subsistence activities, including farming, continued without interruption as communities selectively incorporated new plants and animals in their diet in response to changing conditions (37). Human skeletons demonstrate no evidence of somatic growth disruption or pathophysiological changes throughout this period, suggesting that adaptive diversity and intergenerational maintenance of traditional knowledge of local food options successfully buffered this population from nutritional insufficiency (35). This research is a particularly good example of how knowledge about human variation over time contributes key insights into several of the United Nations Sustainable Development Goals (Fig. 2).

The health benefits associated with adaptive diversity and maintaining flexible subsistence practices and lifestyles in the context of a changing environment are also evident among Bronze Age agropastoral communities in southeastern Arabia that experienced the 4.2 ka BP RCC event (38). Biogeochemical evidence from individuals interred at the Shimal necropolis during the Umm an-Nar (2700 to 2000 BCE) and Wadi Suq (2000 to 1600 BCE) periods indicates that these populations did not experience a radical shift in diet despite increasing aridification. Instead, the inhabitants of this region appear to have responded to regional climatic pressures and economic shifts through population dispersal and decentralization into smaller, more stable communities (38). This shift was likely made possible because of a relatively less rigid and hierarchical social structure, unlike that seen in neighboring larger-scale societies such as the Indus Valley. This example shows how the economic diversity of small-scale, community-based efforts in food production is a key factor for building a sustainable future (39).

In the 4.2 ka BP event, it is notable that hierarchical urban societies built on strong interregional economic ties and marked social inequality experienced social disruption, disease spillover, and increased prevalence of interpersonal violence. This was dramatically different from the forms of resilience found in small-scale heterarchical neighboring communities (1, 9). Contemporary heterarchical communities, such as those found in Andean agrarian societies provide an excellent example of how intensive sustainable food production can develop out of Indigenous cosmology and traditional institutions (40). Our conclusion is that Indigenous leadership, traditional knowledge, and Indigenous science may offer sustainable alternatives through holistic land, water, and forest management practices as an antidote to hierarchical and unequal social organization, colonialism, and extractive capitalism (41).

Ecosystem-Mediated Impacts on Human Health: Vector-Borne Diseases in the Past

Sustainable strategies for coping with global warming must also address the growing burden of zoonotic diseases worldwide. Environmental and climate changes are principal

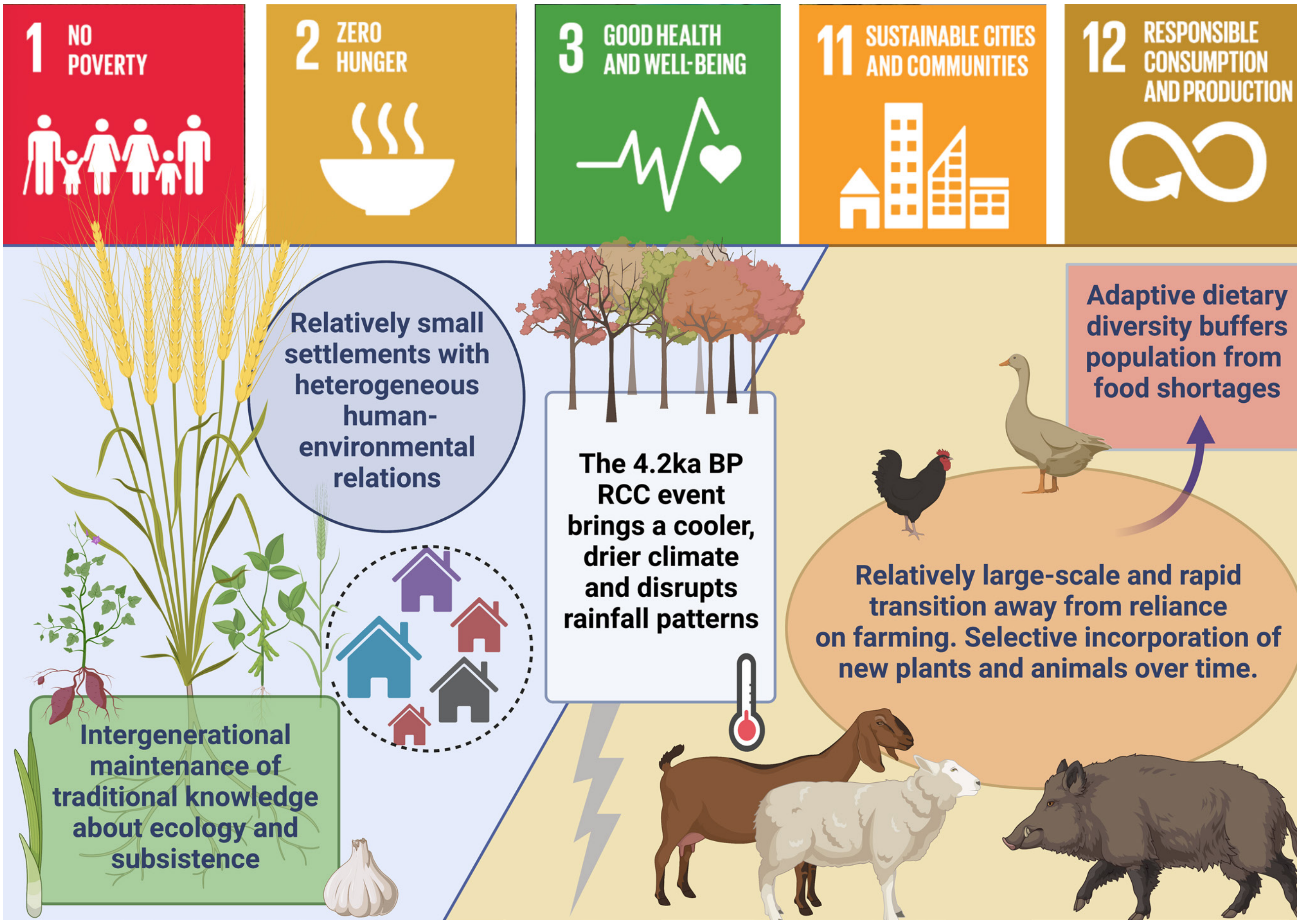

Fig. 2. Diverse pathways to resilience relevant to the UN Sustainable Development Goals.

drivers for the coevolution of humans, animals, and our pathogens. The first epidemiological transition began in the early Holocene, some 7,000 y ago. Agriculture and associated lifestyle changes—settled farming communities, closer contact with other animals, high population density, and less varied diet—created significant challenges for human communities facing rising infection rates and significant opportunities for pathogen evolution (42). Worldwide, human skeletal remains from the first farmers demonstrate evidence of the relationship between anthropogenic ecological changes and changing disease ecology (43), including the emergence, evolution, and global spread of malaria, plague, tuberculosis, leprosy, brucellosis, leishmaniasis, salmonella, smallpox, hepatitis B, treponemal infections, and Chagas' disease among others (44). Urbanism has also contributed to infectious disease ecology for millennia (45). High-density human populations, poor sanitation, and crowded living conditions facilitate the spread of communicable pathogens from person to person, compounding the risk for endemic and epidemic diseases due to contaminated air, water, and soils. Deforestation and increasing contact with other species create additional opportunities for emerging disease spillover and provide new reservoirs for existing diseases.

Bioarcheologists use a suite of theoretical frameworks to understand epidemiological patterns through time (*SI Appendix*, Fig. S2). Communities today face health challenges from the convergence of three historical epidemiological trends: farming, industrialization, and modernity (46). Global warming will increase the risk of infectious disease epidemics among human populations. While this topic has been of concern for some time, recent global pandemics have made a One Health perspective more urgent (47). Zoonotic infections will emerge with increasing frequency as biodiversity loss, habitat destruction, antibiotic resistance, and global warming combine with health challenges from urbanism and social inequality to add complexity and uncertainty to public health planning. Climate change and anthropogenic landscape alteration are longstanding phenomena (48) and the archaeological record demonstrates trophic cascades of changing disease ecology (47). These challenges in the contemporary context are compounded by demographic trends suggesting that, in the future, an even greater percentage of people will live in relatively unsustainable urban environments if local, rural livelihoods are not supported.

Of particular concern are the changing habitats of insect vectors, such as *Anopheles* mosquitoes, the primary carrier of malarial pathogens (*Plasmodium* spp.) (49). Malaria is a leading cause of childhood mortality today; it can lead to delayed skeletal maturation and is associated with osteopenia, neurological sequelae and cognitive impairment, and increased susceptibility to other infections—bacterial (e.g., tuberculosis) and those caused by helminths (50). *P. falciparum* causes more than 240 million episodes of malaria per year (51). This disease is also the single strongest known selective pressure driving an increase in the prevalence of genetic anemias (52).

Research suggests that past anthropogenic landscape alterations brought malaria to regions where it is not currently endemic (53, 54). Over time, evolutionary consequences of endemic malaria are seen in the high prevalence of thalassemia in southern Europe, where deforestation and the occupation of marshy environments by marginalized social classes were exacerbated by the widespread adoption of agriculture. While farming was likely a significant precursor for malaria in the Mediterranean, agriculture does not always precede malarial environments. For example, malaria was already a significant health problem for inhabitants of tropical habitats in northern Vietnam by 7,000 y BP (49). The risk of malaria later increased further with population growth, reduced residential mobility—the frequency people move residences—and the growing practice of agriculture, irrigation, and land clearance (52).

A major contemporary concern is how climate and environmental change will impact zoonotic epidemic diseases. Evidence from Medieval epidemics provides fertile ground for testing epidemiological hypotheses. For example, *Yersinia pestis* has been infecting human populations in Eurasia for at least 5,000 y and has caused pandemics since at least the sixth century CE (55). Perhaps the best-known historical pandemic, commonly referred to as the Black Death (1346 to 1353 CE), caused by *Yersinia pestis,* affected populations spanning Afro-Eurasia, ultimately killing up to 50% of affected human populations in the largest pandemic in human history (56). Arguably, the emergence and effects of this zoonotic disease were facilitated and exacerbated by climate changes (the end of the Medieval Climate Anomaly and the transition to the Little Ice Age) and preexisting socioeconomic conditions (57).

Studies of skeletal remains dating to the period before and during the Black Death in England (c. 1348 to 1350 CE) demonstrate that the disease struck populations that were already dealing with extreme structural socioeconomic inequality, overpopulation, and several consecutive famines at the end of the Medieval Climate Anomaly. As a result, the general population suffered from physiological stressors prior to the pathogen's arrival (58). This research indicates the pandemic was not an indiscriminate killer. Rather, evidence from the skeletal remains of people buried in mass graves in London suggests that chronic disturbances to homeostasis experienced prior to infection contributed to increases in morbidity and mortality (59). The Black Death had far-reaching intergenerational impacts on population structure and political, economic, religious, and sociocultural configurations.

Pandemics also have evolutionary impacts on human populations. Importantly, evidence is emerging that the Black Death acted as a selective force that shaped genetic diversity around some human immune loci; these alleles may have provided some protection from the pandemic but they are currently associated with autoimmune disorders (60). Pandemic diseases cause demographic changes that can persist for centuries and, while evolutionary impacts of past pandemics have yet to be fully elucidated (58), social determinants of health likely shaped variation in the risks of exposure, illness severity, and probability of death (61). We know this to have been true in modern pandemics such as influenza, polio, and COVID-19 (61). Bioarchaeological research suggests that present and future pandemic diseases in human societies will have evolutionary impacts conditioned by structural inequality (61).

Impacts Modulated through Social Institutions: Migration, Interpersonal Violence, and Famine

Migration is a central attribute of our species, and it shapes the genetic and population structure of human communities past, present, and future. The scale of human migrations today is different than in the past, given our current unprecedented access to rapid transportation and communication technology that contribute to global migrant flows. In addition, modern nation-states with monetary economies can constrain mobility for different groups in ways that are recent in human history (62). Nonetheless, there are shared characteristics across time and space including the basic reasons for seasonal, temporary, or permanent resettlement (62). Notably, climate and environmental change combined with poor socioeconomic and political conditions have been an impetus for human movement (26, 63) and large-scale migrations over the past 12,000 y (62).

For example, migration offered a successful strategy for dwindling local resources in the middle Holocene of Sub-Saharan Africa. In the period known as the Climatic Optimum (10 to 5 ka B.P.), hundreds of human burials were placed within dunes surrounding a series of lakes in central Niger, in what is now the Sahara (64). The Gobero site complex includes burials from two different periods—the first dating from 9.7 to 8.3 ka and the second dating from 7.2 to 4.9 ka. These burial events occurred during relatively humid phases that bracket a RCC event known as the 8.2 ka BP arid event (which lasted from 8.3 to 7.5 ka at Gobero) (65). The earlier burials at Gobero derive from a hunting–fishing–foraging community that was linked to other small-scale mobile fisher–forager communities across a large area (64).

Radiogenic strontium isotope values in human teeth and bones are used to trace migration in archaeological populations. The Early Holocene community buried at Gobero was relatively less mobile than expected for hunting and foraging groups (64). In fact, there is little evidence of residential mobility except for adult immigration potentially related to marriage. An assessment of the Middle Holocene burials demonstrated this later human population ranged more widely to meet their subsistence needs (66). These skeletons showed fewer signs of childhood growth disruption, indicating that expanding their foraging and hunting territory in the later period allowed for successful adaptation to increasing aridity. The flexibility of this small-scale society enabled them to persist and thrive in a context of environmental change.

Investigating population mobility in the past can address questions about the link between environmental migration, social disruption, and its contribution to interpersonal violence (62, 63). Currently, governments and other planning bodies worldwide rely on the Human Security field to understand the potential consequences of mobility resulting from global warming. This literature often misuses human evolution in ways that dangerously assume that humans facing climate change always migrate, that this migration inevitably results in competition for resources, and that it promotes violence and leads to civilizational collapse (11). Importantly, cross-cultural findings over time evidence much more variability (26, 62). Evidence from human skeletons demonstrates that both migration and intergroup conflict have indeed occurred in association with past climate change, but there are also many cases where this does not occur in a predictable fashion. Throughout most of human prehistory, conflicts seem to have been resolved without escalating to violence (67).

Migration and cultural contact often led to relationships and support between groups that mitigated levels of violence in the past. For example, the frequency of violent injury was relatively low in the Middle Horizon (600 to 1100 CE) and Late Horizon (1400 to 1532 CE) when the Wari and Inka empires flourished. They established geographically broader interregional exchange networks that fostered contact and collaboration between diverse cultures (68), though there were some situations of increased violence during points in the imperial expansionist eras. Notably, those Andean imperial eras were characterized by climatic amelioration with rainfall sufficient for agriculture. In contrast, in some parts of the Andes, insularity and a reduction in intergroup contact were associated with increases in physical violence and, during the Late Intermediate Period (LIP, 1100 to 1400 CE) in particular, a severe drought was coterminous with this tumultuous time. Many Andean LIP societies became less mobile, as indicated by strontium isotope analysis of human skeletons from across the region (69).

Another lesson from bioarchaeology is that small differences in regional geography and local sociopolitical circumstances affect subsistence and the risk of interpersonal violence. In the Atacama Desert of Chile during the LIP, communities that were once tied to the Tiwanaku interregional exchange network became more insular relative to the Middle Horizon, with a marked decline in outside contact and exchange (70, 71). This pattern of increased violence in the LIP is repeated in other areas, such as the central Andean highlands and mid-valleys of southern Peru (68, 72, 73). Notably, the significant uptick in violence in some Andean LIP communities was associated with drought that affected agricultural production and grazing lands for camelid pastoralism (71). In contrast, violent injuries did not increase in the LIP in other regions, including north highland Peru, some south highland regions, north coast Peru, northern Chile, and northwest Argentina (68). As we have already seen above, this research affirms the notion that supporting local livelihoods and rural food production will be a key strategy for coping with contemporary climate changes.

Food insecurity has syndemic effects including increasing the risk of violence. Large-scale social reorganization occurred in the LIP, with the decline of both the Wari Empire in the central Peruvian Andes and the Tiwanaku State in highland Bolivia and southern Peru. As severe drought made farming difficult and state influence waned, the Wari capital was abandoned. Stable isotope analysis of carbon and nitrogen reveals that women had less access to maize, a socially and politically valuable food in post-Wari times (73), suggesting differential access to food contributed to social changes and exacerbated the spread of tuberculosis in Terminal Wari and post-Wari populations (74). In the former Tiwanaku zones, violent injury due to warfare, raiding, corporal punishment, ritual sacrifice, and manipulation of bodies after death then became more frequent (75). These factors combined to limit available responses to climate change. These data reveal the complex interactions between climate change, political collapse, violence, food insecurity, and infectious disease.

Interpersonal violence in the context of climate change. Violence was not a consistent response to environmental and social change in the past (66, 76). It is also important to note that violence itself is not a uniform concept. The meaning of violence and violent acts is historically and culturally contingent (66). It includes a variety of behaviors—ritual and institutionalized violence, homicide and suicide, warfare, massacres, raiding, torture, and genocide to name a few—that are enacted by individuals and groups, legally and illegally, for many different reasons and on a variety of scales (66). In cases where climate and environmental change contributed to social upheaval or increased prevalence of violent trauma in the past, cultural influences were more strongly at play. In addition, a nuanced view of violence includes in this category trauma-related injuries and the syndemic effects of poverty, malnutrition, racism, and other forms of structural inequality. Because violence is not a preordained response to environmental change, policymakers and planning bodies must be aware of the historical and anthropological context of different societies to understand the likelihood and the meaning of violent outcomes.

The North American Southwest (Four Corners region) offers an excellent opportunity to examine the variation in human responses to environmental change and in the meaning of violence in different communities occupying the same region (66). The Black Mesa region of northern Arizona is a desert ecozone considered relatively marginal for human settlement and farming because of its unpredictable rainfall, periodic and sustained droughts, and difficult conditions for successful agriculture. Challenges for settlement in this area include the high-altitude ecosystem with infrequent water sources, relatively few wild edible plant species, and limited large mammals for hunting. However, this region has been occupied by diverse Puebloan groups for more than a millennium, all of whom practiced maize agriculture for over 500 y and who still live and farm in their ancestral homelands today. Archaeology provides clues as to how they accomplished this, and the human skeletal record provides evidence as to the experience of resilience for the Ancestral Pueblo people.

At Black Mesa (800 to 1350 CE), despite extreme temperature variation and regular periods of increased aridity, drought, flooding, crop failures, and food shortages, human populations grew slowly and steadily (66). Archaeological research demonstrates highly successful cultural and technological advances that reflect concrete and specific adaptations to the challenges of being a desert farmer in extreme climatic conditions. Some of these adaptations include heterarchical social structures, centrally placed ceremonial centers that encouraged interconnectedness and flows of information and resources, community movement according to changing water sources, and econiches created to attract rabbits and other small mammals that supplemented their diet (66).

After 1050 CE, a prolonged and severe drought persisted for generations. Black Mesa communities were buffered from marginal environmental conditions by deep knowledge of their crops, local ecological circumstances, and widespread cooperative networks that provided the ability to trade and redistribute resources across a large area. These populations appear quite healthy based on their skeletal remains, with little evidence of growth disruption, interpersonal violence, or disease (66). The resilience and success of Ancestral Pueblo people are reflected in their specific adaptive responses and the fact that Hopi and Zuni Pueblo communities still practice many of these strategies today, allowing them to maintain life in this region for centuries despite additional challenges of settler colonialism and genocide.

Nearby, during the late Pueblo I and early Pueblo II (850 to 1150 CE) periods at Chaco Canyon in New Mexico, a complex society developed a sophisticated system of water management that sustained agricultural productivity despite the naturally arid environment. These communities relied heavily on imported maize, and the subsistence system was frequently overwhelmed by severe drought conditions. The most severe drought came after 1100 CE and was associated with the abandonment of Great Houses in the Canyon (in 1090 CE) and the depopulation of the Four Corners region (1125 to 1150 CE).

The prevalence of nonlethal violent injuries increased in the human remains from Chaco Canyon after that time, perhaps due to ideological shifts that developed to maintain social control (66). These communities were more stratified and hierarchical than those at Black Mesa, and their villages were less flexible in their ability to respond to ecological challenges. Facing similar challenges to those of Black Mesa but with a much-reduced capacity to respond, Ancestral Pueblo people in the Chaco area may have turned to violence against religious practitioners that they believed were causing the world to be out of balance, leading to declining food production (76). In the case of Chaco and the Ancestral Pueblo settlements in the Four Corners region, drought brought on by climate change and associated ideological shifts, may eventually have contributed to the eventual abandonment of these settlements.

Violence is neither an inevitable outcome of climate change nor is it the most likely outcome. However, there was a strong upsurge in violence accompanying socioeconomic and political upheavals in the Medieval Warm Period (900 to 1300 CE) and the subsequent Little Ice Age (1300 to 1850 CE) in Europe (77). This time period saw food insecurity, famine, starvation anthropophagy, and other forms of violence accompanied by epidemic diseases, including the Black Death, leprosy, tuberculosis, syphilis, smallpox, and cholera, among others. The uptick in violence in Medieval Europe reflects another example of how specific historical and sociocultural contexts—endemic warfare, emergent capitalism, deep socioeconomic inequality, and religious fundamentalism, alongside climate and environmental changes—create an atmosphere conducive to violence as a response to stress.

In sum, migration and violence have both been associated with periods of climatic and environmental change in the past, but there are few direct links between these two phenomena. When Global North scholars assume an association between climate change and violence, it is perhaps because of a bias toward using European history as the reference point. Knowledge of Indigenous philosophy, science, and history challenges these assumptions about human nature. Climate change is only one of the factors influencing human behavior; most bioarchaeological research demonstrates that economic inequality, political instability, and hierarchical, inflexible social processes that create basic resource insecurity are more likely to result in violence than the simple act of migration or the effects of climate change alone.

Endemic malnutrition in the context of past environmental change. Like most of the health impacts of climate change, hunger and food insecurity in the past resulted from a combination of sociocultural and environmental forces (78, 79). Particularly for complex societies built on structural inequality, famine and skeletal emaciation resulted from a lack of access to food, not from a lack of food (80). However, there are also risks of endemic malnutrition resulting from environmental degradation in small-scale societies without the hierarchical social organization of structural inequality. This section provides such an example and demonstrates how famine is syndemic; susceptibility to starvation is a risk for rural populations living in impoverished conditions where sociosanitation challenges and comorbidities also increase susceptibility to communicable diseases (15).

Throughout these case studies, we have seen the advantage of flexibility for relatively small populations facing climate and environmental change. However, when small-scale communities rely heavily on monocropping for agricultural production to feed a growing population, their small size can make them vulnerable to demographic collapse. This vulnerability is especially significant for groups who are already deeply exploiting local subsistence resources in semiarid and marginal ecosystems. For example, environmental degradation associated with unsustainable farming practices and soil salinization contributed to a significantly deleterious health experience for small agrarian communities along the river valleys of west-central India, including a site called Inamgaon. Archaeological research demonstrates that the people of Inamgaon maintained a mixed economic system based on farming, stock raising, hunting, fishing, and foraging. Unlike the human communities of the Hexi Corridor, they began to rely heavily on agriculture to feed a growing population after 3.4 ka BP (81). By 3.1 ka BP, this region was largely depopulated (82).

In the small handful of villages that persisted past that point, the population increasingly relied on herding animals and wild foods, including aquatic resources. Regional food resources were already heavily exploited to feed a growing population and could not compensate for the loss of agricultural production. Analysis of human remains from Inamgaon demonstrates that the transition away from agriculture had significant health consequences, especially for infants. Although a few villages persisted after the large-scale abandonment of much of this region, people stayed at the cost of high infant mortality, stunting, and bone wasting among infants and children (81, 83). In this example, small environmental shifts in a semiarid ecosystem resulted in famine due to lack of food, rather than lack of access to food. After 200 y of struggling to cope with salinization and other consequences of overfarming, these villages were eventually abandoned.

One conclusion that emerges from these findings is that for communities occupying areas already marginal for survival, the experience of resilience in the face of climate change is often one of endemic malnutrition. The risk of mortality and morbidity is typically greatest for infants, children, and those adults who survived prior developmental stress and growth disruption (84). Protein-energy malnutrition and micronutrient deficiencies are found among neonates and infants during famines as mothers are unable to meet the basic nutritional requirements of gestation (85). The impacts of gestational and early-life adversity are long-lasting across the lifespan and intergenerationally (86). The consequences of low lean body mass, short adult stature, and dietary restriction include, for example, epidemiological shifts toward a greater risk of metabolic conditions, infectious diseases, and other health problems later in life (87).

Anthropological research also demonstrates that global food insecurity will be mediated through biocultural factors: consumption patterns, population size and density, local and regional structures of power, corruption, global trade policy, access to energy and its cost, and other political, financial, and economic variables (88). Coping strategies for dealing with food insecurity in the short term are context specific. Households and groups respond to food insecurity through complex negotiations to garner support and access to resources that can include a wide range of specific behaviors based on historical, social, and cultural circumstances. For communities occupying areas already marginal for survival, the experience of resilience in the face of climate change can be endemic malnutrition, and this will be particularly true in the contemporary context with added structural barriers to accessing food.

Challenges and Opportunities for Applying Bioarchaeological Insights into Climate Predictions and Planning

Research over the past 50 y has documented substantial variability in Earth's climate and rapid climatic shifts that have occurred over the course of human evolution. This perspective has demonstrated some of the ways climate has contributed to changing epidemiological profiles in past populations and how sociocultural factors deeply affected health and disease. The Holocene history of humankind reveals the health impacts concomitant with an increasing reliance on agriculture and the resulting loss of adaptive diversity versus the relative resilience of communities relying on mixed economies, pastoralism, hunting, fishing, and gathering. Bioarchaeology reinforces a transdisciplinary understanding of the promises and problems of urbanism and the consequences of structural inequality, vulnerability, marginalization, and exploitation. It confirms a strong association between climatic conditions, human biocultural environments, and the biological and sociocultural risk factors that promote endemic and new infectious diseases. The results of this research suggest that migration is not an imperative outcome of climate change; rather, they demonstrate some of the parameters that limited or promoted migration as a strategy for coping with environmental change. The analysis of human skeletal remains provides direct evidence about the likelihood of violence based on ideological, historical, and sociocultural factors.

There are limitations to bioarchaeological research that should be considered. For example, this work requires high-resolution regional and local paleoclimate data, a good site chronology, and appropriately preserved human remains. There are regions of the world with an extremely well-researched, geographically diverse, and temporally deep archaeological record where the climate data are not high enough in resolution, or where multiple spatial and temporal scales are regularly combined in an unsystematic way, and the invocation of climate change is undertaken uncritically. There are also gaps in knowledge in some areas that are not so intensively studied by bioarchaeologists or where remains do not preserve well. Further research in these regions will be required to support the invocation of climate as an explanatory model for human adaptation, health, and resilience. Despite these limitations, bioarchaeology adds a critically important deep-time evolutionary perspective to inform us about the impact of global warming on human health in the current millennium. By combining evolutionary theory with insights from the social sciences, our research demonstrates how socioculturally influenced environments are both major contributors and the biggest barriers to good health even in the face of RCC events and other significant environmental challenges. Social forms that promote institutionalized inequality alongside the indisputable consequences of colonialism, chattel slavery, racism, economic inequality, structural violence, and all types of discrimination have been key determinants of health over human history (89, 90).

We argue that knowledge of this type of evidence is valuable to governments, policymakers, and the general public as we devise and implement strategies for equitable sustainable development in the face of climate change. Knowledge of human variation through time is critical to creating evidence-based equitable sustainability. Bioarchaeology also provides a critical foundation for combating misconceptions about human evolution and human nature. For example, there is a perception that humans inevitably respond to crises through migration and, ultimately, violence (11). These oversimplifications of complex issues, if integrated into narratives that shape planning and policy decisions for the future, will lead to policies with serious, deleterious consequences for human security. Early anthropological narratives also suffered from a unicausal view of the climate-culture nexus and proposed static, deterministic links between humans and our environments. Although anthropologists have moved on substantially from those narratives, these views predominate in some scholarship and in the popular literature on climate change and subsequent predictions of sociocultural and technological change and collapse (11).

It is therefore imperative that anthropologists, especially bioarchaeologists, contribute to discourses about climate change, emphasizing contextualized perspectives on violence and its syndemic association with social inequality and illuminating the complexities of resilience and collapse in different sociocultural circumstances. We must not underappreciate the complexity of humankind's history and the lessons learned from past encounters with climate change and other crises. Mounting an effective, sustainable, and equitable solution to global warming, such as is suggested by the United Nations Sustainable Development Goals 2030, requires historical data to ensure the longevity of human habitation on Earth.

Data, Materials, and Software Availability. All study data are included in the article and/or *SI Appendix*.

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