Archaeology, environmental justice, and climate change on islands of the Caribbean and southwestern Indian Ocean

Kristina Douglass[a,b,1] and **Jago Cooper**[c]

Edited by Daniel H. Sandweiss, University of Maine, Orono, ME, and accepted by Editorial Board Member Dolores R. Piperno December 11, 2019 (received for review August 15, 2019)

Climate change impacts island communities all over the world. Sea-level rise, an increase in the frequency and intensity of severe weather events, and changes in distribution and health of marine organisms are among the most significant processes affecting island communities worldwide. On islands of the Caribbean and southwestern Indian Ocean (SWIO), however, today's climate change impacts are magnified by historical environmental injustice and colonial legacies, which have heightened the vulnerability of human and other biotic communities. For some islands, archaeological and paleoecological research offers an important record of precolonial climate change and its interplay with human lives and landscapes. The archaeological record suggests strategies and mechanisms that can inform discussions of resilience in the face of climate change. We detail climate-related challenges facing island Caribbean and SWIO communities using archaeological and paleoecological evidence for past climate change and human response and argue that these cannot be successfully addressed without an understanding of the processes that have, over time, disrupted livelihoods, reshaped land- and seascapes, threatened intergenerational ecological knowledge transfer, and led to increased inequality and climate vulnerability.

archaeology | paleoclimate | islands

Island communities are on the front line of global change. Positioned at the interface of continental geopolitical exchange, islanders have often been the first to experience the rapid socioenvironmental transformations of the planet. This is increasingly apparent when voices such as the Association of Small Island States articulate the existential threats to island communities posed by sea-level rise and extreme weather events (1). Although all island communities in the world face hazards linked to climate change, their vulnerability and exposure to these hazards vary. The Intergovernmental Panel on Climate Change (IPCC) estimates vulnerability and exposure by assessing a community's stress across physical (e.g., floods, drought, erosion/sea level, etc.), biological (e.g., ecosystems, biological productivity, biodiversity, etc.), and human (food production, health, livelihoods, economy, etc.) systems (2). Using this framework to assess vulnerability to climate change, the IPCC has recognized Africa as the world's most vulnerable macroregion. Macroregional syntheses, however, tend to incorporate island groups into analyses of nearby continental landmasses, making it difficult to assess and compare the vulnerability of island regions with one another.

Here, we expand the IPCC's systems-based framework for assessing vulnerability and exposure to climate-driven threats by integrating deeper time perspectives on changing human–environment–climate dynamics. We have selected two island theaters as case studies, the Caribbean and southwestern Indian Ocean (SWIO), each with distinct cultural, historical, and environmental narratives but which are united, being home to some of the world's most vulnerable and exposed island communities and to the majority of the island African diaspora.

Currently, the impacts of climate change are accelerating. Long-term historical models and short-term predictive models show that the Caribbean and SWIO will experience increased intensity of cyclonic activity,

---

[a]Department of Anthropology, The Pennsylvania State University, University Park, PA 16802; [b]Institutes of Energy and the Environment, The Pennsylvania State University, University Park, PA 16802; and [c]Americas Section, Department of Africa, Oceania and the Americas, British Museum, WC1B 3DG London, United Kingdom

Author contributions: K.D. produced the figures and K.D. and J.C. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission. D.H.S. is a guest editor invited by the Editorial Board.

[1]To whom correspondence may be addressed. Email: kdouglass@psu.edu.

relative sea-level rise (RSLR), and unpredictability of precipitation patterns (3, 4). These climate dynamics are closely intertwined with socioecological hazards, including biodiversity loss, pollution, deforestation, coastal erosion and sedimentation, overfishing, and freshwater salinization (5) (Fig. 1 *B–E* and *G–J*). As island communities face these mounting challenges, understanding past human experience of specific climate hazards is important for building more resilient communities, and archaeologists have contributed many insights in this regard (6).

It is not enough, however, to simply look at past human societies for inspiration in developing technological solutions to today's challenges. This has been the focus of many projects to apply past knowledge to present problems with ancient water management systems recreated or resilient indigenous architectural designs rebuilt. We must also recognize more widely the historical disruptions to livelihoods, landscapes, ecologies, and intergenerational knowledge transfer that have made contemporary communities more vulnerable to climate change impacts and less flexible in their response (7).

Here, we trace these disruptions, linked colonial legacies, and persistent inequalities to highlight how they exacerbate climate impacts in the Caribbean and SWIO today. We emphasize that inequality; disenfranchisement from autonomous land, sea, and resource use; and loss of indigenous and local knowledge are social, economic, and political threats that exacerbate climate impacts. These cannot be ignored in favor of efforts to create top-down technological solutions for improved sustainability. Moreover, the predominant top-down model of climate mitigation policy and concurrent losses and devaluing of indigenous and local knowledge severely constrain Caribbean and SWIO communities' ability to innovate sustainable solutions to climate change.

In a landmark special report, the IPCC has recently recognized (8) that indigenous land management plays a vital role in mitigating climate change impacts and protecting biodiversity (9). This paper underscores the critical importance of assessing the physical, biological, social, and historical dimensions of climate vulnerability and prioritizing mitigation planning in close collaboration with local, indigenous, and descendant (LID) communities. Through our case studies, we highlight the global importance of a panoptical understanding of the past and the preservation and revitalization of indigenous and local knowledge for effective and just action to mitigate future impacts of climate change.

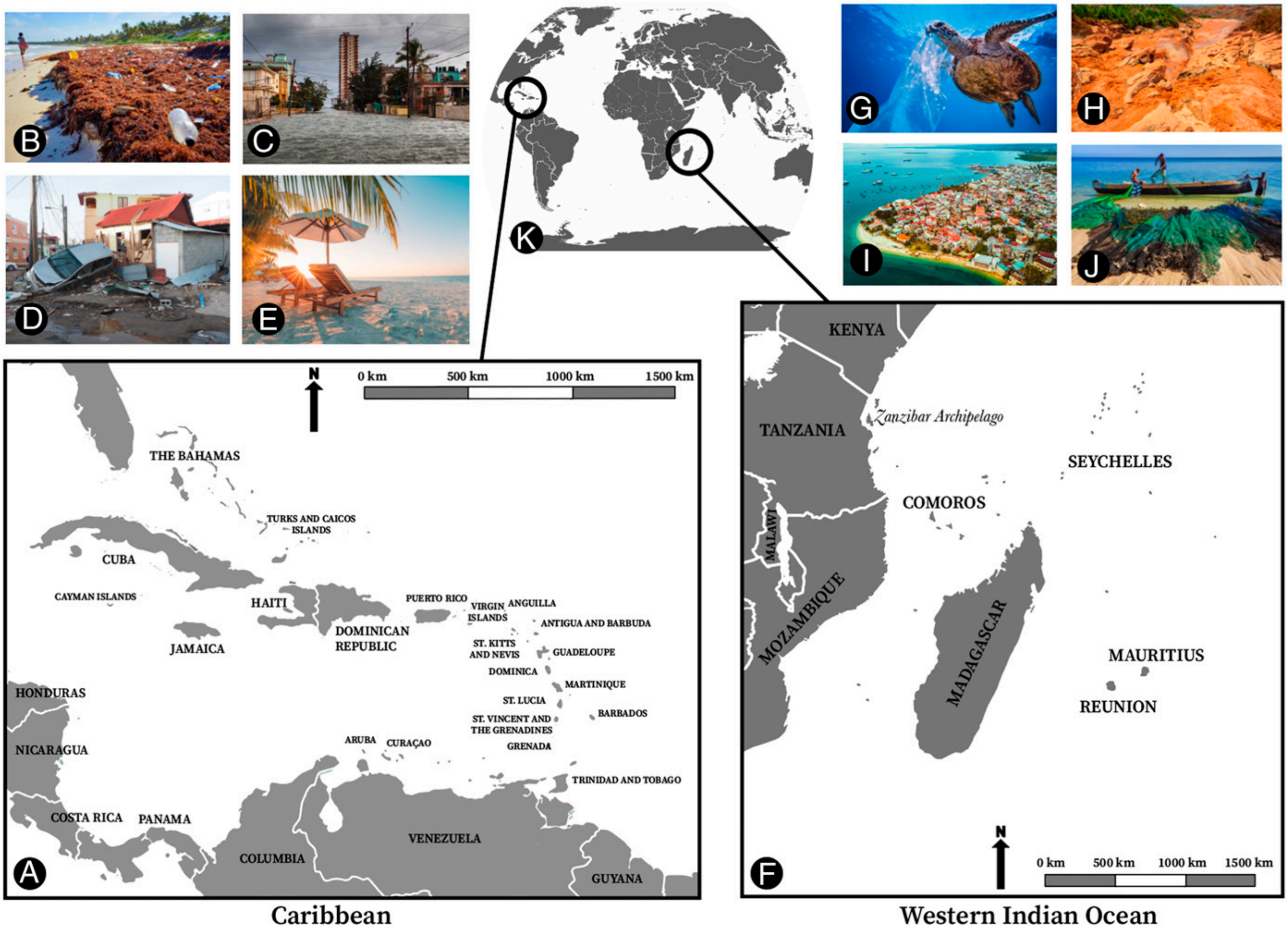

Fig. 1. Maps of the case study areas highlighting some climate-related challenges in these regions: (*A*) map of Caribbean islands; (*B*) sargassum pollution (Caribbean); (*C*) storm surge flooding in Havana, Cuba; (*D*) damage from Hurricane Maria on Dominica; (*E*) sunset at a Caribbean beach resort; (*F*) map of SWIO islands; (*G*) green sea turtle (Chelonia mydas) ingesting plastic waste; (*H*) severe erosion and sedimentation of the Betsiboka River, Madagascar; (*I*) dense urban development on Unguja Island, Zanzibar; (*J*) traditional Vezo fishers preparing nets, southwest Madagascar; and (*K*) global position of each case study region.

Case Study 1—Caribbean Islands

Humans have lived on the islands of the Caribbean since ~6 ka (10) (Fig. 2), providing an opportunity to study the interaction between cultural lifeways and island ecologies contextualized within Holocene climate variability and contemporary Global Change (11). The landscapes and material records of Caribbean islands reveal the 16th century genocide of millions of indigenous peoples with a corresponding loss of thousands of years of traditional ecological knowledge; the 17th and 18th century translocation of European and African lifeways (including plants and animals) transforming island ecologies; and the 19th century industrialization of landscape modification and biodiversity loss before a 20th century revolution in political and economic models for cultural development and sovereign determination (12) (Fig. 2).

The Caribbean Community Climate Change Center (CCCCC) has long identified the greatest hazards of global climate change in the Caribbean as 1) sea-level rise, 2) hurricane events, and 3) precipitation variability (3). Human communities have experienced all of these impacts over time, necessitating a review of divergent human experiences based on the interplay between ways of life, ecological context, and environmental hazard. Archaeological and historical investigations demonstrate how human communities have lived through the impacts of climatic hazards over the past 6 ka.

Sea-Level Rise. The melting of polar ice and related isostatic forcing have driven extensive RSLRs in the Caribbean, which vary based on local geomorphology and tectonics. Some island populations have experienced >6 m of RSLR during the last 6 ka, with one-sixth of Cuba's land area submerged during the human occupation of the island (10). Archaeological and paleoenvironmental case studies suggest that the human experience of RSLR is not in increments of millimeters per year but in sudden events with permanent salt water flooding of low-lying coastal plains associated with cyclonic storm surges (13) (Fig. 1*C*). Past human communities have sometimes abandoned these vulnerable coastal areas before the flooding events. This is because coastal freshwater aquifers in low-lying coastal settlements are often salinized by slowly rising relative sea levels, which force people to abandon the marginal littoral zone years before a hurricane storm surge then permanently floods the area (14). Today, sea level continues to rise and to exert similar pressures on coastal communities. However, instead of seeing salinization of coastal freshwater sources as an early warning of vulnerability that requires settlement relocation, contemporary strategies are focused on geoengineering (15): construction of desalination plants, piped water systems, and flood defense barriers (Fig. 3 *A*–*C*). The scale of past flooding events with up to 8-m storm surges underlines the extreme vulnerability of communities and the unreliability of these short-term engineered solutions, which will fail to cope with the forecasted changes in the lifetime of the current generation (16).

Hurricane Events. Recent hurricanes have consistently destroyed livelihoods, ended major infrastructure investment projects, and crippled island economies (Fig. 1*D*). Paleotempestological records demonstrate that human communities have always lived with the threat of hurricanes in the Caribbean (17). Variability in frequency and intensity is linked to movements of the Intertropical Convergence Zone (ITCZ) and sea surface temperatures (SSTs) in the North Atlantic, but hurricanes have always posed a significant hazard to Caribbean settlements (Fig. 3*D*). Contemporary climate change is increasing the intensity of cyclonic events in the Caribbean (18), and this is of great concern to Caribbean nations. Comparative studies between 5 ka of pre-Columbian household architecture, settlement locations, and food systems and the last 500 y of colonially introduced lifeways highlight distinctly different vulnerabilities and disaster management strategies (14). The adoption of European settlement patterns for new towns in river valleys and estuaries from the 16th century onward as well as European

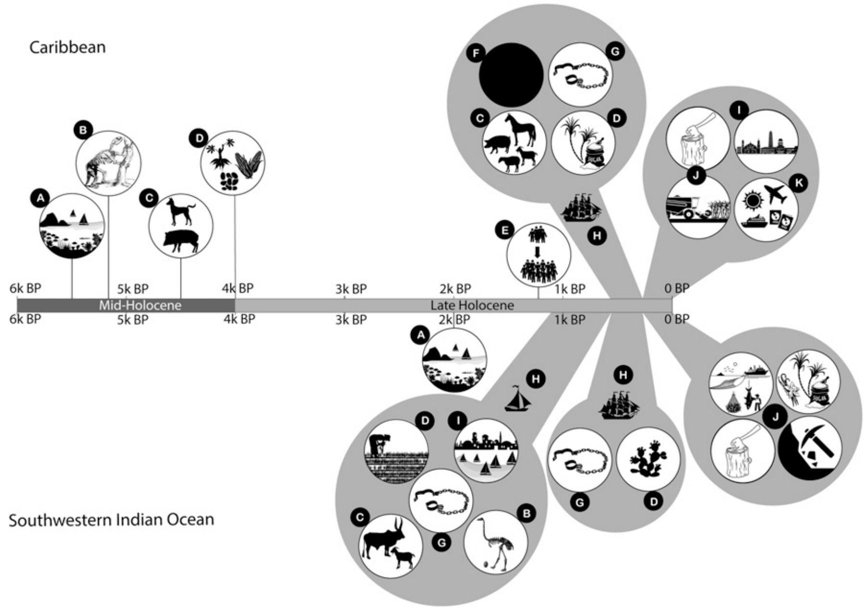

Fig. 2. Timeline of significant periods of change in interlinked human–environment dynamics: (*A*) island colonization, (*B*) megafauna extinction, (*C*) animal translocations, (*D*) plant translocations, (*E*) population numbers in the millions, (*F*) genocide, (*G*) transoceanic slave trade, (*H*) boom in transoceanic trade (Columbian Exchange in the Caribbean and Swahili Trade in the SWIO), (*I*) urbanization, (*J*) industrial-scale resource extraction, and (*K*) international tourism.

Fig. 3. Sea-level rise, hurricane events, and precipitation variability case study illustrations: (*A*) water desalination plant, St. Thomas, US Virgin Islands; (*B*) waves crashing against sea wall, Havana, Cuba; (*C*) vintage postage stamp from the Dutch Antilles featuring a water treatment facility; (*D*) hurricane damage to a concrete house, Baracoa, Cuba; and (*E*) traditional wood house made primarily of locally available materials, Las Terrenas, Samana, Dominican Republic.

household architecture and building materials have increased the relative vulnerability of post-Columbian communities to hurricane-related flooding and wind shear. Current disaster management strategies are predominantly based on robustness and resistance to hurricane wind shear, storm surges, and flooding events. This approach gives primacy to preventing damage through a strong built environment in total contrast with preexisting indigenous frameworks for resilience that focused on speed of recovery. Today, reinforced concrete is normally considered hurricane-resilient architecture in the Caribbean (Fig. 3*D*). A thousand years ago, resilient architecture facilitated swift posthurricane reconstruction using locally available materials, privileging the ability to swiftly rebuild and recover over attempts to be robust and withstand a hurricane's destructive impact (19) (Fig. 3*E*).

Precipitation Variability. Precipitation variation has significant implications for human occupation in the Caribbean, particularly as many communities live with limited freshwater supplies (15). Water is often a key tipping point in forcing island abandonment as archaeological examples demonstrate (20). The Caribbean has seen considerable long-term variation in precipitation rates, which is particularly relevant for islands with small water catchment areas. The 16th century translocation of monoculture agriculture later exacerbated by island-dependent cash crop economies has reduced water retention, increased soil erosion, and exposed people to greater vulnerability to droughts (Fig. 2*D*). At the same time, increasingly urbanized communities with high water consumption have depleted freshwater supplies and require engineered water management systems (Fig. 3*A*). Long-term indigenous strategies for effective water management included rainwater capture, managed exploitation of coastal freshwater aquifers, and use of lower water-dependent food crops.

Environmental vulnerability is also linked to environmental justice for these historically contingent and economically divergent communities. The impacts of climate change exacerbate existing risks, including earthquakes, tsunamis, landslides, and volcanic activity, contextualized within island-specific socio-environmental vulnerabilities (21, 22). The opportunities for post-disaster migration and costly reconstruction vary greatly between the islands of the Caribbean. This is often linked to the history of an island's geopolitical context, ecological vulnerability, and economic capacity to plan for and recover from climate change impacts.

Case Study 2—SWIO Islands

The SWIO includes continental islands off the coast of East Africa, such as the islands of the Zanzibar Archipelago, and oceanic islands, such as Madagascar and the Mascarene islands (Mauritius, Réunion, and Rodrigues) (Fig. 1). The region's oceanic islands formed when Gondwana split apart around 90 Ma ago. The SWIO's continental islands were part of mainland Africa during Pleistocene glacial periods. During interglacials, most recently after the Last Glacial Maximum, warming trends drove RSLR and reshaped the biogeography of the region. With the exception of Madagascar and Zanzibar, which have both yielded limited Early to Mid-Holocene cultural deposits (23, 24), the islands of the SWIO do not have records of human settlement and activity earlier than the Late Holocene (Fig. 2). This short human history is particularly surprising given the region's physical proximity to eastern and southern Africa's paleoanthropological record and recurrent physical connection to the mainland. In the case of some SWIO islands, like Mauritius, the human record is remarkably recent, with initial human settlement ~300 y ago (25). In addition to the surprising timing of SWIO island colonization events, the region experienced migration from around the Indian Ocean rim, including the westernmost expansion of Austronesian speakers (26).

Islands of the SWIO sit at the crossroads of one of the world's most dynamic maritime trading spheres, connecting at various points in time the ports of China and Indonesia to those of East Africa and the Persian Gulf. Long distance Indian Ocean trade networks emerged at least as early as 2 ka (27), but evidence for population growth and the appearance of large villages and towns on SWIO islands seems connected to the emergence of Swahili trade beginning ~1 ka (Fig. 2*H*). The rise of Swahili trade thus marks a turning point in the SWIO human–environment story. Along with urbanism, this trade resulted in the translocation of plants, animals, and people on a scale not yet seen in the region (28, 29). By ~500 y B.P., European disruption of trade along the East African coast and Madagascar marks another turning point, involving forced translocation of people across the Indian and Atlantic Oceans. Subsequent European colonialism and the postcolonial 20th and 21st centuries have seen the advent of massive extractive industries (fisheries, logging, and mining) and efforts to "modernize" indigenous communities, all of which have exacted a heavy toll on local livelihoods and environments (Fig. 2*J*).

Today, the island communities of the SWIO are experiencing significant and interlinked threats to environments and livelihoods. According to the Indian Ocean Observing System (IndOOS), key threats across the region are 1) food insecurity due to degradation of coastal and marine environments and declining agricultural productivity, 2) water scarcity due to freshwater salinization and pollution, and 3) rising energy demands due to population growth and urbanization (5). Increasingly rapid climate change exacerbates all of these threats. The Indian Ocean is warming more rapidly than any other ocean in the world, with significant consequences for regional and global climate regimes, ecosystems, and people (4). Observations from the SWIO indicate a century-long SST warming trend that is poised to alter biological productivity dramatically in the region (30). Although there is growing evidence of significant climate change in the region, two overarching issues constrain our ability to mitigate the impacts of change. First, despite recent efforts to improve Indian Ocean observation systems (e.g., IndOOS), a lack of basin-wide observational data limits our ability to assess current climate variability and predict future change across this ocean (4). Second, although SWIO island communities have experienced, influenced, and responded to many extreme shifts in climate and environment over the course of the Holocene, current economic inequality and political marginalization, often rooted in the region's relatively recent colonial history, compound the impacts of climate change. In this context, archaeological and historical insights into past lived experiences in the region can inform current climate and environmental policy debates.

Food Insecurity. With the exception of the southern tip of Madagascar, the islands of the SWIO fall within the tropics, and several important forcing mechanisms shape today's SWIO climate. The Southwest Indian Ocean Monsoon system brings heavy rains from December to March, with lighter rainfall from October to December (31). Influenced by the north–south shifting of the ITCZ, rainfall patterns are highly variable (32). The SWIO is particularly susceptible to variability in SSTs, which also influence regional rainfall (33–37). SSTs, in turn, are sensitive to and influence the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (38). The ENSO's influence likely extends to the frequency and intensity of extreme weather events, such as cyclones, in the region (37, 39).

As the Indian Ocean continues to warm, variability in precipitation is expected to increase, suggesting that severe droughts and floods may become more frequent (40). This poses a great threat to food security as the majority of SWIO communities are reliant on rain-fed agriculture and pastoralism (41). The interlinked threats of precipitation variability, colonial legacies, and food insecurity are clear in the case of southern Madagascar, where successive years of crop failures due to insufficient rainfall precipitated a catastrophic famine in 2016 that directly affected nearly half a million people (42). Although periodic famine is an accepted risk in the lives of southern Malagasy communities, centuries of coevolution with the landscapes of the south have led to important agropastoral adaptations that mitigate disastrous incidences of climate-driven famine. The cultivation and widespread dispersal of *raketa*, the nonnative prickly pear cactus (*Opuntia* spp.), as fodder for cattle; as a source of water for cattle, people, and other plants; and as a defensive barrier against intruders, were two of the most important adaptations of southern Malagasy pastoralists to climate stochasticity, turning the dry south into a subterranean anthropogenic wetland (43) prior to prickly pear eradication (see below).

Since the prickly pear's introduction to Madagascar from the Americas by French colonialists in 1769, southern "cactus" pastoralists have tightly integrated it into their ecology (44) (Fig. 4*A*). In the 1930s, however, the French colonial administration waged biological warfare on southern Malagasy by dispersing parasitic cochineal larvae (*Dactylopius tomentosus*) to eradicate the prickly pear (45). This attack was framed by the French as a measure to civilize the south, disrupt a way of life deemed unproductive and prone to failure, and force southerners to adopt "modern" agropastoral practices through the cultivation of cash crops, irrigation, and improvement of grasslands (46, 47). As a result of the eradication of *raketa gasy* (*Opuntia monocantha*), the preferred prickly pear, imminent drought was followed by widespread famine, decimation of cattle herds, and the economic crippling of southern communities, the effects of which continue today to make southern communities less resilient to drought.

Fig. 4. Food insecurity, water scarcity, and rising energy demands case study illustrations: (*A*) a southern Malagasy herder provisions his cattle with prickly pear (*Opuntia* spp.) fodder; (*B*) southwest Madagascar's Vezo seminomadic fishers sail traditional laka (outrigger canoes) at dusk; (*C*) freshwater infinity pool at a luxury tourist resort on the Zanzibar Archipelago; (*D*) vintage postage stamp from Réunion featuring a plantation worker harvesting sugar cane; and (*E*) an aerial view of sugar cane plantations on Mauritius (*Saccharum officinarum*).

Water Scarcity. Linked to the threat of food insecurity is water scarcity, a challenge that SWIO communities have faced for millennia. The SWIO Holocene paleoclimate record has been reconstructed from cave stalagmites, lake sediment and coral cores, and archaeological evidence (48). These records show that the Pleistocene–Holocene transition was characterized by significant hydrological shifts toward more mesic conditions throughout the SWIO. Wetter conditions during the Early Holocene likely drove social and ecological changes in the broader Indian Ocean region (49, 50). Despite an overall shift toward wetter conditions, successive dry and wet phases characterize the SWIO Holocene record (51–55).

At the time of the major 4-ka desiccation event, only Madagascar and the continental islands of East Africa were inhabited by small-scale foraging and fishing communities. Archaeological evidence from coastal southwest Madagascar spanning the last 2 ka suggests that early communities were highly mobile, leaving relatively ephemeral traces of their presence at individual sites (56). Likewise, oral histories of the southwest indicate that the *razana* (ancestors) responded to the adaptive challenge of limited freshwater through a high degree of settlement mobility. Today, the combined effect of multiple factors exacerbates the climate-driven threat of SWIO water scarcity. Postcolonial resource management approaches, an emphasis on international tourism for economic development, and the vulnerability of many islands' shallow freshwater aquifers pose an underappreciated threat to indigenous livelihoods. This is particularly problematic in the dry coastal zones of southwest Madagascar and on the SWIO's smaller islands. In coastal southwest Madagascar today, settlement mobility is constrained by conservation and development initiatives that seek to regulate resource use within recently established zones managed by spatially fixed associations of local communities (57). Although positive outcomes have emerged from these efforts, such as increased catch of commercially valuable taxa (58), tensions have also arisen as zone-based management approaches conflict with established migratory practices (59) (Fig. 4*B*). The social and ecological consequences of rapid sedentarization of long nomadic or seminomadic communities have not been evaluated carefully.

As conservationists in the SWIO emphasize the need to shift communities toward alternative livelihoods less reliant on mobility and the use of wild aquatic and terrestrial resources, SWIO governments and development agencies have looked to international tourism as a sustainable, alternative source of income. On Zanzibar, however, tourism has brought with it unsustainable use of the archipelago's thin lenses of freshwater as a growing number of foreign travelers consume water with little awareness or concern for its scarcity or the extreme vulnerability of the water table to rainfall variability (60) (Fig. 4*C*). Similar pressure from international tourism is likely impacting other SWIO island communities. On Zanzibar, the shallow nature of freshwater aquifers is compounding the ecological and public health hazards of human waste and garbage, which are mounting as the tourism industry expands and disproportionately impact impoverished communities (5).

Rising Energy Demands. Biological productivity in the SWIO is shaped on land by the availability of rainfall and in the ocean by SSTs that influence the degree of upwelling of cool, nutrient-dense waters. Recent observations suggest that rapid warming of the SWIO will have negative impacts on biological productivity (4). As population growth and globalization cause energy demands to rise, pressure on resources such as fuel will intensify.

Meeting rising energy demands in the context of climate-driven decreases in biological productivity is a multifaceted challenge. Wood charcoal, for example, remains an essential fuel for cooking in the SWIO, with Kenya, Tanzania, and Madagascar ranking among the heaviest users of charcoal in the world (61). Efforts to transition communities in the region to stoves powered by cleaner and more sustainable sources are motivated by concerns about the negative health consequences of cooking with charcoal, especially indoors; extensive deforestation; and carbon dioxide emissions. Energy policies aimed at encouraging the use of more sustainable fuel sources in the SWIO, however, have often been implemented abruptly without considering legacies of colonial era land grabs and resource disenfranchisement (5) and the cultural importance of timber products as sources of fuel. As a result, rigid policies banning or restricting the use of charcoal have often resulted in increased deforestation by driving up fuel prices (61).

Past expansion of transoceanic trade and colonial era land policies similarly drove deforestation, exacerbating the energy crisis today. SWIO islands were sparsely populated by forager–fisher communities until a boom in trade ∼1 ka sparked rapid urbanization and population growth along the Swahili corridor (62) (Fig. 2*H*). The emergence of Swahili port cities like Mahilaka (63) coincided with indications of deforestation (64), suggesting that urban expansion required substantial timber for fuel and construction. A spike in deforestation is next seen beginning in the 17th century, when European powers sought to maximize the profitability of SWIO colonies by extracting resources and farming cash crops on an industrial scale (65, 66). Colonial administrations dispossessed indigenous communities of the most productive land and supplanted indigenous management with cash cropping and commercial logging (65, 67) (Fig. 4 *D* and *E*). Indigenous farmers and herders were pushed onto marginal lands where soils were quickly depleted, a process that led to increasing economic inequality; energy insecurity; and more rapid deforestation, erosion, and sedimentation of waterways and fragile coastal habitats (5, 68).

Discussion

The archaeological and paleoclimatic records of the Caribbean and SWIO offer glimpses of past human responses to climatic and environmental change and the human actions that continue to interact with climate and environment today. Looking at the past highlights how periods of rapid environmental change were often precipitated by social, political, and economic transformations, such as the emergence of transoceanic trading networks, the translocation of nonnative plants and animals, and urbanization. Our two case studies also reveal commonalities in how patterns of cultural and ecological transformation are entangled with issues of environmental justice that create contingent vulnerabilities to climate change impacts today. Even simple ambitions to create goals for sustainability require an appreciation of the great transformations that all of the islands discussed above have experienced over time. Our case studies underscore 1) the variety of different environmental baselines that could be used to chart ecological restoration and sustainable development targets; 2) the dialectical relationship between local and global desires and socioecological entanglements; 3) the irreversible thresholds that many island ecologies have already undergone; and 4) the value and vulnerability of intergenerational ecological knowledge transfer.

Baselines and Restoration. The introduction of cattle to Madagascar and the subsequent threats to pastoral livelihoods described above provide an important example of the challenge of identifying baselines for ecological restoration and future sustainability planning in the face of climate change. Zebu cattle (*Bos indicus*) were introduced to the island ∼1 ka (69) and likely contributed to declines in endemic megafauna populations through ecological competition. Despite these consequences, the archaeological and historical records suggest that ancient Malagasy communities maintained large herds of zebu that may have buffered against crop failure, drought, and political instability (70). Colonial efforts to disrupt pastoral lifeways were accompanied by the introduction of cash crops, like corn (*Zea mays*), that have high water requirements and are maladapted to local climate (66). Despite these coercive measures and the violent illicit trade in zebu today, cattle remain a central pillar of southern Malagasy cultures (71).

Local vs. Global Practices. As transoceanic trade networks connected the islands of the Caribbean and SWIO to broader regions, nonlocal technologies, practices, and aesthetics were imposed on indigenous communities. The same dialectic between local and global exists today. For example, archaeological evidence of a pre-Columbian mode of domestic architecture across the Caribbean island region suggests that semipermanent houses were well adapted to climate hazards (72). The labor-intensive components of houses were designed to withstand hurricane winds and other hazards, while other components were easy to rebuild. This approach to domestic architecture contrasts with modern houses, which are built from rigid materials, are more dangerous during natural disasters, and are costlier to rebuild. Perceptions of modernity and the simultaneous devaluing of indigenous forms and practices are trends throughout the Caribbean and SWIO as well other island communities around the world. The Caribbean and SWIO, however, have been less well represented in historical ecological studies than other island groups (5, 73, 74) and require further research on the adaptive role of indigenous forms and practices alongside efforts to disseminate research findings to a broad audience, including policy makers. When indigenous forms and practices are celebrated in these regions today, it is typically in a fetichized context of ecotourism, where foreign visitors are offered opportunities to experience "traditional" lifeways, rather than in a context of developing and revitalizing successful solutions to climate hazards (72).

Tipping Points. The human colonization of islands of the Caribbean and SWIO significantly impacted endemic island fauna and flora. Subsequent human activity and the translocation of people, animals, and plants throughout these regions precipitated further irreversible ecological shifts, such as extinction. Several faunal and floral extinction events are documented in both regions at different times. The Mid-Holocene extinction of megafauna on Caribbean islands (75) and Late Holocene animal and plant extinctions in the Caribbean and SWIO have irrevocably changed local ecologies (76–79). Despite ongoing debate as to the precise cause and timing of extinction on some islands (24), in cases like Mauritius, direct anthropogenic pressures led to swift population crashes of plant and animal taxa such that the contemporary and ancient landscapes bear little resemblance to one another (80–82).

Intergenerational LID Knowledge. Loss of LID knowledge correlates closely with ecological change (83). The histories of human–environment dynamics in the Caribbean and SWIO are punctuated by periods of significant ecological change that also resulted in loss of LID ecological knowledge. The most extreme case of knowledge and culture loss in these regions was caused by the genocide of indigenous Caribbean peoples by European colonists beginning in AD 1492 (Fig. 2*F*). Although the consequences of this genocide extend far beyond knowledge loss, knowledge accumulated and transmitted over millennia by communities that had long coevolutionary relationships with island environments was destroyed, severely constraining communities' capacity to draw on generations of past experience to innovate future adaptive strategies. The revitalization and preservation of indigenous languages, knowledge, and oral histories represent a critical dimension of planning for a just and sustainable future.

Conclusion

We have highlighted how the integration of historical, archaeological, paleoenvironmental, and paleoclimatic research adds a critical missing dimension to the current IPCC framework for assessing communities' vulnerability to climate impacts. Put simply, past environmental injustices have created underlying vulnerabilities to present and future climate change. These must be concretely identified and integrated into assessments of climate vulnerability alongside the physical, biological, and human systems stresses currently outlined by the IPCC framework. Integrating deeper time data on human–environment–climate dynamics and past injustices and disruptions into climate vulnerability assessments will more accurately reveal regions with the greatest vulnerability. Meanwhile the revitalization and preservation of intergenerational LID knowledge and practices can highlight potential ways to build resilience. The Caribbean and SWIO are well placed to demonstrate the role of the past in creating effective plans for cultural adaptation to the impacts of climate change as well as revealing a global context of environmental injustice for those who bear the greatest burden of global change (84, 85).

The impacts of climate change in the Caribbean and SWIO are profound, tangible, and intensifying. The human experience of more extreme climate events combined with the increased vulnerability of communities is the source of great public concern. In recent years, entire islands in the Caribbean have been depopulated (86), many people have died, and island economies have been devastated (87). In the SWIO, communities face a future of more frequent droughts, declines in biological productivity, and growing economic inequality (4). These threats are rooted in complex, oftentimes long-term human–environment interactions that must be carefully parsed if we are to develop effective solutions for sustainable, just, and resilient futures.

Methods

We aim to demonstrate the importance of deeper time perspectives in assessing vulnerability and innovating just and effective solutions for mitigating the impacts of climate change. Using the United Nations Development Program's Human Development Index (HDI) and Multidimensional Poverty Index (MPI) as proxies for climate vulnerability across physical, biological, and human systems (88), we selected the Caribbean and SWIO island groups as our case studies (Fig. 1) as these regions are home to several island nations with the lowest HDI scores and highest MPI scores. Moreover, our work enhances recent studies of long-term human–environmental interactions in other groups, including the Pacific (77, 78).

In each case study, we focus on three climate-driven threats identified by the CCCCC and the IndOOS, the leading climate observation and action organizations in each region. Each case study describes diachronic human–environment interactions in the region and historical and archaeological evidence of past and present human responses to the three highlighted climate-driven threats. This approach emphasizes the historical contingency of today's most urgent climate-driven threats and the role of environmental injustice in influencing island communities' vulnerability and resilience to climate change.

Data Availability. All data synthesized in this paper are published and accessible through consultation of cited works.

Acknowledgments

We thank Drs. Daniel H. Sandweiss and Torben Rick for the invitation to contribute a paper to the Special Feature on Archaeology, Climate, and Global Change and for their constructive comments on the manuscript.

---

1 AOSIS, *Rising Tides, Rising Capacity: Supporting a Sustainable Future for Small Island Developing States* (Association of Small Island States, United Nations Development Programme, New York, NY, 2017).

2 IPCC, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, R. K. Pachauri, L. Meyer, Eds. (Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2014), p. 151.

3 Caribbean Community Climate Change Centre, *Climate Change and the Caribbean: A Regional Framework for Achieving Development Resilient to Climate Change (2009-2015)* (Caribbean Community Climate Change Centre, Belmopan, Belize, 2009).

4 J. C. Hermes *et al.*, A sustained ocean observing system in the Indian Ocean for climate related scientific knowledge and societal needs. *Front. Mar. Sci.* **6**, 1–21 (2019).

5 K. Douglass *et al.*, Historical perspectives on contemporary human-environment dynamics in southeast Africa. *Conserv. Biol.* **33**, 260–274 (2019).

6 J. H. Altschul *et al.*, Opinion: Fostering synthesis in archaeology to advance science and benefit society. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 10999–11002 (2017).

7 P. Nunn, R. Kumar, Understanding climate-human interactions in Small Island Developing States (SIDS). *Int. J. Clim. Chang. Strateg. Manag.* **10**, 245–271 (2018).

8 IPCC, Climate change and land: An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. https://www.ipcc.ch/srccl/. Accessed 23 September 2019.

9 R. Schuster, R. R. Germain, J. R. Bennett, N. J. Reo, P. Arcese, Vertebrate biodiversity on indigenous-managed lands in Australia, Brazil, and Canada equals that in protected areas. *Environ. Sci. Policy* **101**, 1–6 (2019).

10 R. Valcárcel Rojas, J. Ulloa Hung, O. Feria Garcia, "Levisa 1. Studying the earliest indigenous peoples of Cuba in multicomponent archaeological sites" in *Insular Caribbean: Dearchaising the Archaic*, C. L. Hofman, A. T. Antczak, Eds. (Sidestone Press, Leiden, the Netherlands, 2019), pp. 177–190.

11 J. Cooper, M. C. Peros, The archaeology of climate change in the caribbean. *J. Archaeol. Sci.* **37**, 1226–1232 (2010).

12 B. W. Higman, *A Concise History of the Caribbean* (Cambridge University Press, Cambridge, UK, 2011).

13 G. A. Milne, M. C. Peros, Data-model comparison of Holocene sea-level change in the circum-Caribbean region. *Global Planet. Change* **107**, 119–131 (2013).

14 J. Cooper, "Fail to prepare then prepare to fail: Re-thinking threat, vulnerability and mitigation in the pre-Columbian Caribbean" in *Surviving Sudden Environmental Change: Answers from Archaeology*, J. Cooper, P. Sheets, Eds. (University Press of Colorado, Boulder, CO, 2012), pp. 91–114.

15 A. C. Cashman, Water policy development and governance in the Caribbean: An overview of regional progress. *Water Policy* **14**, 14–30 (2011).

16 M. A. Mycoo, Beyond 1.5 °C: Vulnerabilities and adaptation strategies for Caribbean Small Island Developing States. *Reg. Environ. Change* **18**, 2341–2353 (2018).

17 B. Malaize *et al.*, Hurricanes and climate in the caribbean during the past 3700 years BP. *Holocene* **21**, 911–924 (2011).

18 K. T. Bhatia *et al.*, Recent increases in tropical cyclone intensification rates. *Nat. Commun.* **10**, 635 (2019).

19 J. Cooper, "Building resilience in Island communities: A paleotempestological perspective" in AGU Chapman Conference on Climates, Past Landscapes, and Civilizations, L. Giosan, P. Clift, D. Fuller, R. Flad, S. VanLaningham, J. Aimers, Eds. (Geophysical Monograph Series, Geopress, Washington, DC, 2012), vol. 198, pp. 43–49.

20 H. Dawson, *Mediterranean Voyages. The Archaeology of Island Colonisation and Abandonment* (Left Coast Press Inc., Walnut Creek, CA, 2014).

21 S. Fitzpatrick, On the shoals of giants: Natural catastrophes and the overall destruction of the Caribbean's archaeological record. *J. Coast. Conserv.* **16**, 173–186 (2012).

22 S. R. Scheffers, J. Haviser, T. Browne, A. Scheffers, Tsunamis, hurricanes, the demise of coral reefs and shifts in prehistoric human populations in the Caribbean. *Quat. Int.* **194**, 69–87 (2009).

23 M. E. Prendergast *et al.*, Continental island formation and the archaeology of defaunation on zanzibar, Eastern Africa. *PLoS One* **11**, e0149565 (2016).

24 K. Douglass *et al.*, A critical review of radiocarbon dates clarifies the human settlement of Madagascar. *Quat. Sci. Rev.* **221**, 1–11 (2019).

25 K. Seetah, The archaeology of Mauritius. *Antiquity* **89**, 922–939 (2015).

26 A. Crowther *et al.*, Ancient crops provide first archaeological signature of the westward Austronesian expansion. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 6635–6640 (2016).

27 L. Casson, *The Periplus Maris Erythraei: Text with Introduction, Translation, and Commentary* (Princeton University Press, Princeton, NJ, 1989).

28 D. Q. Fuller, N. Boivin, T. Hoogervorst, R. Allaby, Across the Indian ocean: The prehistoric movement of plants and animals. *Antiquity* **85**, 544–558 (2011).

29 P. Beaujard, *Histoire et Voyages des Plantes Cultivées à Madagascar* (Karthala, Paris, France, 2017).

30 M. K. Roxy, K. Ritika, P. Terray, S. Masson, The curious case of Indian ocean warming. *J. Clim.* **27**, 8501–8509 (2014).

31 M. R. Jury, *The Climate of Madagascar*, S. M. Goodman, J. P. Benstead, Eds. (The University of Chicago Press, Chicago, IL, 2003), pp. 75–88.

32 R. E. Dewar, A. F. Richard, Evolution in the hypervariable environment of Madagascar. *Proc. Natl. Acad. Sci. U.S.A.* **104**, 13723–13727 (2007).

33 C. A. Grove *et al.*, Madagascar corals reveal pacific multidecadal modulation of rainfall since 1708. *Clim. Past* **9**, 641–656 (2013).

34 C. A. Grove *et al.*, Confounding effects of coral growth and high SST variability on skeletal Sr/Ca: Implications for coral paleothermometry. *Geochem. Geophys. Geosyst.* **14**, 1277–1293 (2013).

35 J. E. Tierney *et al.*, Northern hemisphere controls on tropical southeast African climate during the past 60,000 years. *Science* **322**, 252–255 (2008).

36 J. E. Tierney, S. C. Lewis, B. I. Cook, A. N. LeGrande, G. A. Schmidt, Model, proxy and isotopic perspectives on the East African humid period. *Earth Planet. Sci. Lett.* **307**, 103–112 (2011).

37 J. Zinke, M. Pfeiffer, O. Timm, W. C. Dullo, G. J. A. Brummer, Western Indian ocean marine and terrestrial records of climate variability: A review and new concepts on land–ocean interactions since AD 1660. *Int. J. Earth Sci.* **98**, 115–133 (2009).

38 T. Crueger, J. Zinke, M. Pfeiffer, Patterns of Pacific decadal variability recorded by Indian Ocean corals. *Int. J. Earth Sci.* **98**, 41–52 (2008).

39 A. F. Mavume, L. Rydberg, M. Rouault, J. R. E. Lutjeharms, Climatology and landfall of tropical cyclones in the South-West Indian Ocean. *Western Indian Ocean J. Marine Sci.* **8**, 15–35 (2010).

40 R. d'Arrigo, R. Wilson, El Niño and Indian Ocean influences on Indonesian drought: 1342 implications for forecasting rainfall and crop productivity. *Int. J. Climatol.* **28**, 611–618 (2008).

41 C. Funk *et al.*, Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. *Proc. Natl. Acad. Sci. U.S.A.* **105**, 11081–11086 (2008).

42 T. Healy, *The Deep South: Constraints and Opportunities for the Population of Southern Madagascar towards a Sustainable Policy of Effective Responses to Recurring Droughts/Emergencies*, C. Gevers, M. Lundell, D. Ringold, Eds. (The World Bank, Washington, DC, 2017).

43 J. C. Kaufmann, Prickly pear cactus and pastoralism in Southwest Madagascar. *Ethnology* **43**, 345–361 (2004).

44 J. C. Kaufmann, The non-modern constitution of famines in Madagascar's spiny forests: "Water-food" plants, cattle and Mahafale landscape praxis. *Environ. Sci.* **5**, 73–89 (2008).

45 P. Binggeli, "Cactaceae, *Opuntia* spp., prickly pear, raiketa, rakaita, raketa" in *The Natural History of Madagascar*, S. M. Goodman, J. P. Benstead, Eds. (University of Chicago Press, Chicago, IL, 2003), pp. 335–339.

46 H. P. de la Bâthie, Les pestes végétales à Madagascar. *Rev. Bot. Appl. Agric. Colon.***8**, 36–43 (1928).

47 H. P. de la Bâthie, Les famines du sud-ouest de Madagascar: Causes et remèdes. *Rev. Bot. Appl. Agric. Trop.* **14**, 173–186 (1934).

48 K. Douglass, J. Zinke, Forging ahead by land and by sea: Archaeology and paleoclimate reconstruction in Madagascar. *Afr. Archaeol. Rev.* **32**, 267–299 (2015).

49 V. Prasad *et al.*, Mid–late Holocene monsoonal variations from mainland Gujarat, India: A multi-proxy study for evaluating climate culture relationship. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **397**, 38–51 (2014).

50 G. W. Preston, A. G. Parker, Understanding the evolution of the Holocene pluvial phase and its impact on neolithic populations in South-East Arabia. *Arab. Archaeol. Epigr.* **24**, 87–94 (2013).

51 B. E. Crowley, K. E. Samonds, Stable carbon isotope values confirm a recent increase in grasslands in Northwestern Madagascar. *Holocene* **23**, 1066–1073 (2013).

52 E. J. de Boer *et al.*, Climate variability in the SW Indian Ocean from an 8000-yr long multi-proxy record in the Mauritian lowlands shows a middle to late Holocene shift from negative IOD-state to ENSO-state. *Quat. Sci. Rev.* **86**, 175–189 (2014).

53 D. Fleitmann *et al.*, Holocene ITCZ and Indian Monsoon dynamics recorded in stalagmites from Oman and Yemen (Socotra). *Quat. Sci. Rev.* **26**, 170–188 (2007).

54 F. Gasse, E. Van Campo, A 40,000-yr pollen and diatom record from lake tritrivakely, Madagascar, in the Southern Tropics. *Quat. Res.* **49**, 299–311 (1998).

55 L. Wang *et al.*, The African Humid Period, rapid climate change events, the timing of human colonization, and megafaunal extinctions in Madagascar during the Holocene: Evidence from a 2m Anjohibe Cave stalagmite. *Quat. Sci. Rev.* **210**, 136–153 (2019).

56 K. Douglass, "An archaeological investigation of settlement and resource exploitation patterns in the velondriake marine protected area, Southwest Madagascar, ca. 900 BC to AD 1900," PhD dissertation, Yale University, New Haven, CT (2016).

57 A. Harris, "To live with the sea" development of the velondriake community-managed protected area network, Southwest Madagascar. *Madag. Conserv. Dev.* **2**, 43–49 (2007).

58 S. Benbow *et al.*, Lessons learnt from experimental temporary octopus fishing closures in southwest Madagascar: Benefits of concurrent closures. *Afr. J. Mar. Sci.* **36**, 31–37 (2014).

59 G. Cripps, C. J. Gardner, Human migration and marine protected areas: Insights from Vezo fishers in Madagascar. *Geoforum* **74**, 49–62 (2016).

60 S. Gössling, The consequences of tourism for sustainable water use on a tropical island: Zanzibar, Tanzania. *J. Environ. Manage.* **61**, 179–191 (2001).

61 S. Batchelor *et al.*, Solar electric cooking in Africa: Where will the transition happen first? *Energy Res. Soc. Sci.* **40**, 257–272 (2018).

62 C. M. Radimilahy, Z. Crossland, Situating Madagascar: Indian ocean dynamics and archaeological histories. *Azania* **50**, 495–518 (2015).

63 C. Radimilahy, "Mahilaka: An archaeological investigation of an early town in Northwestern Madagascar," PhD thesis, University of Uppsala, Uppsala, Sweden (1998).

64 S. J. Burns *et al.*, Rapid human-induced landscape transformation in Madagascar at the end of the first millennium of the Common Era. *Quat. Sci. Rev.* **134**, 92–99 (2016).

65 L. Jarosz, Defining and explaining tropical deforestation: Shifting cultivation and population growth in colonial Madagascar (1896-1940). *Econ. Geogr.* **69**, 366–379 (1993).

66 I. R. Scales, Farming at the forest frontier: Land use and landscape change in Western Madagascar, 1896-2005. *Environ. Hist.* **17**, 499–524 (2011).

67 G. Sodikoff, *Forest and Labor in Madagascar: From Colonial Concession to Global Biosphere* (Indiana University Press, Bloomington, IN, 2012).

68 J. Maina *et al.*, Linking coral river runoff proxies with climate variability, hydrology and land-use in Madagascar catchments. *Mar. Pollut. Bull.* **64**, 2047–2059 (2012).

69 K. Douglass *et al.*, Multi-analytical approach to zooarchaeological assemblages elucidates Late Holocene coastal lifeways in southwest Madagascar. *Quat. Int.* **471**, 111–131 (2018).

70 M. Parker Pearson, *Pastoralists, Warriors and Colonists: The Archaeology of Southern Madagascar* (British Archaeological Reports, Oxford, UK, 2010).

71 G. Heurtebize, Les anciennes cultures de l'Androy central. *Taloha* **10**, 171–182 (1986).

72 A. V. Samson, C. A. Crawford, M. L. Hoogland, C. L. Hofman, Resilience in pre-columbian caribbean house-building: Dialogue between archaeology and humanitarian shelter. *Hum. Ecol. Interdiscip. J.* **43**, 323–337 (2015).

73 S. F. Fitzpatrick, W. F. Keegan, Human impacts and adaptations in the Caribbean islands: An historical ecology approach. *Trans. R. Soc. Edinb.* **98**, 29–45 (2007).

74 P. E. Siegel, Ed., *Island Historical Ecology: Socionatural Landscapes of the Eastern and Southern Caribbean* (Berghahn Books, New York, NY, 2018).

75 S. B. Cooke, L. M. Dávalos, A. M. Mychajliw, S. T. Turvey, N. S. Upham, Anthropogenic extinction dominates Holocene declines of West Indian mammals. *Annu. Rev. Ecol. Evol. Syst.* **48**, 301–327 (2017).

76 S. Federman *et al.*, Implications of lemuriform extinctions for the Malagasy flora. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 5041–5046 (2016).

77 T. Braje, T. P. Leppard, S. M. Fitzpatrick, J. M. Erlandson, Archaeology, historical ecology and anthropogenic island ecosystems. *Environ. Conserv.* **44**, 286–297 (2017).

78 T. Rick, P. V. Kirch, J. M. Erlandson, S. M. Fitzpatrick, Archeology, deep history, and the human transformation of island ecosystems. *Anthropocene* **4**, 33–45 (2013).

79 L. A. Newsom, E. S. Wing, *On Land and Sea: Native American Uses of Biological Resources in the West Indies* (The University of Alabama Press, Tuscaloosa, AL, 2004).

80 D. Angst, A. Chinsamy, L. Steel, J. P. Hume, Bone histology sheds new light on the ecology of the dodo (*Raphus cucullatus*, Aves, Columbiformes). *Sci. Rep.* **7**, 7993 (2017).

81 K. F. Rijsdijk *et al.*, Mid-Holocene (4200 kyr BP) mass mortalities in Mauritius (Mascarenes): Insular vertebrates resilient to climatic extremes but vulnerable to human impact. *Holocene* **21**, 1179–1194 (2011).

82 V. F. B. Florens, "Conservation" in *Mauritius and Rodrigues: Challenges and Achievements from Two Ecologically Devastated Oceanic Islands. Conservation Biology: Lessons from the Tropics*, P. H. Raven, N. S. Sodhi, L. Gibson, Eds. (John Wiley & Sons, Ltd, Oxford, UK, 2013), pp. 40–50.

83 L. Maffi, "On the interdependence of biological and cultural diversity" in *On Biocultural Diversity: Linking Language, Knowledge, and the Environment*, L. Maffi, Ed. (Smithsonian Institution Press, Washington, DC, 2001), pp. 1–50.

84 A. M. Bauer, E. C. Ellis, The anthropocene divide: Obscuring understanding of social-environmental change. *Curr. Anthropol.* **59**, 209–227 (2018).

85 E. Ronneberg, "Small islands and the big issue: Climate change and the role of the alliance of small Island States" in *The Oxford Handbook of International Climate Change Law*, K. R. Gray, R. Tarasofsky, C. Carlarne, Eds. (Oxford University Press, Oxford, UK, 2016), pp. 761–778.

86 A. K. Baptiste, H. Devonish, The manifestation of climate injustices: The post-Hurricane Irma conflicts surrounding Barbuda's communal land tenure. *J. Extr. Even.* **06**, 1940002 (2019).

87 C. E. Willison, P. M. Singer, M. S. Creary, S. L. Greer, Quantifying inequities in US federal response to hurricane disaster in Texas and Florida compared with Puerto Rico. *BMJ Glob. Health* **4**, e001191 (2019).

88 UNDP, Human development indices and indicators: 2018 statistical update. http://hdr.undp.org/sites/default/files/2018_human_development_statistical_update.pdf. Accessed 2 October 2019.