Tropical forests as key sites of the "Anthropocene": Past and present perspectives

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Tropical forests are on the front line of climate change and human sustainability challenges, being key environments in discussions of the "Anthropocene" and some of the most threatened land-based habitats on the face of the Earth. However, while it has been acknowledged that 21st-century anthropogenic alterations to tropical forests have the potential to set off major earth systems feedbacks on regional to global scales, there has been less discussion on how past human activities may have had similar impacts. Indeed, difficult working conditions, poor preservation, and environmental determinism have traditionally led to these habitats being framed as "blanks" on the map of human history. In this Special Feature, we draw on multidisciplinary contributions from archaeology, history, paleoecology, climate science, and Indigenous traditional knowledge to explore our species' interaction with tropical forests across space and through time. The contributions highlight that human societies have not only occupied and utilized these habitats over the long-term, but that they, in many cases, have also actively impacted them. This has often had persistent ramifications for local flora and fauna composition and biology, levels of biodiversity, landscape structure, and regional climate both before and after the industrial era. These deep-time perspectives provide insights for the development of more effective and just management practices in the present and future: ones that take into account the long and shifting cultural histories of these critical environments.

In the last 5 y, tropical forests have experienced wildfires sweeping across the Amazon Basin, Australia, and Southeast Asia (1, 2), outbreaks of Ebola and COVID-19 causing severe global public health challenges (3), and unprecedented loss of habitat through clearance (4). Unsurprisingly, these environments are increasingly seen, in media and academic circles alike, as being at the core of the Anthropocene (5), the epoch during which human activities have come to have an extensive, dominating impact on planetary systems (6). Geological approaches to determining the beginnings of the Anthropocene have typically focused on the search for a "golden spike," often associated with fossil fuel burning during the Industrial Revolution (7) or nuclear fallout (^{14}C and plutonium), increase in atmospheric CO_2 concentration, and plastic manufacture in the 20th century (8). However, there has been increased multidisciplinary interest in highlighting the critical influence of human land-use in the tropics on the operation of earth systems. Systems modelers have now demonstrated, for example, the interconnected chains of impacts that local and regional deforestation in the tropics can have on biodiversity, soils, precipitation, temperature, and the carbon cycle on continental and even planetary scales (9, 10) (Fig. 1*A*). Given that the tropics are today some of the most populated places on Earth (11), are home to staggering cultural diversity [including over three quarters of all languages (12)], and that by 2050 they will host over two-thirds of the world's children (13), the future of our species and these high-value habitats are impossible to disentangle. As a result, tropical forests provide, and will continue to provide, some of the most critical sites for exploring the onset of the Anthropocene and flow-on implications for the future of humanity.

However, as is increasingly recognized across the social and ecological sciences, it is important to look for the deep roots of the Anthropocene in order to best understand its manifestation and progression today (23, 24). This is particularly the case in tropical forests, given their critical position in the functioning of a variety of earth systems (5, 25). Although once seen as pristine "green hells" (26) and barriers to human expansion and agricultural practices, multidisciplinary archaeology has demonstrated that our species rapidly occupied forests in different parts of the tropics following its evolution and dispersal (27). Furthermore,

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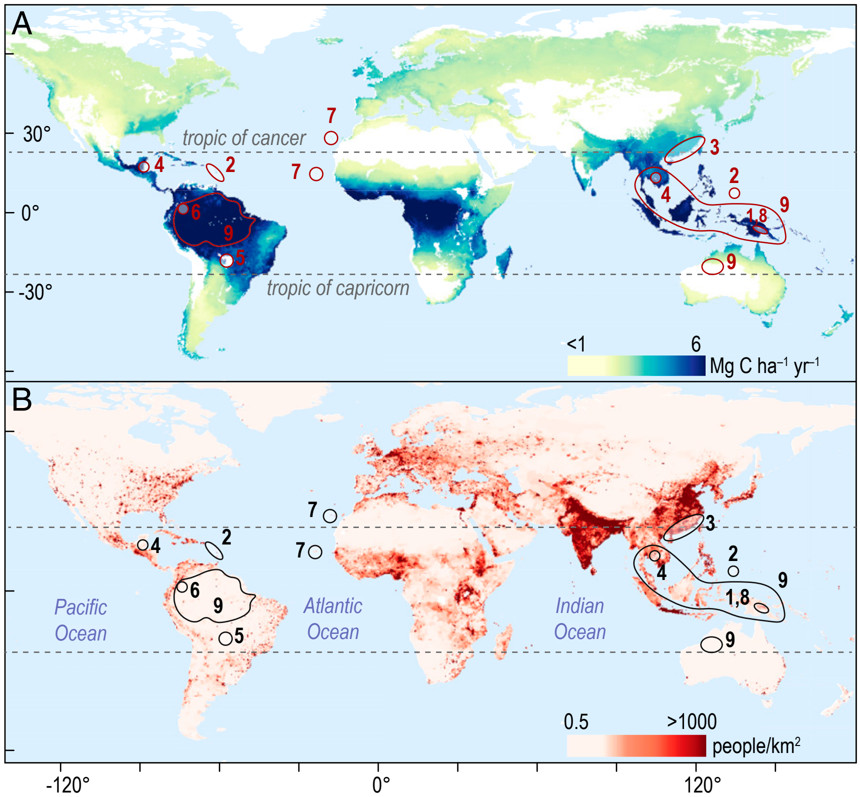

Fig. 1. Carbon sequestration and population maps showing the location of the studies included in this special issue in the context of the global tropics. Tropical zones (the region between 23.5°N and 23.5°S) include (*A*) some of the richest systems in terms of carbon accumulation potential, while also (*B*) representing some of the most populated regions on Earth. Carbon sequestration data from Cook-Patton et al. (10) and population data GPW v4 5-km gridded (11) from the Center for International Earth Science Information Network (2018). Maps are overlain with the location of the studies included in this Special Feature: 1) Douglass et al. (14), 2) Fitzpatrick and Giovas (15), 3) Zheng et al. (16), 4) Penny and Beach (17), 5) Duncan et al. (18), 6) Piperno et al. (19), 7) Castilla-Beltrán et al. (20), 8) Long et al. (21), and 9) Fletcher et al. (22).

increasing numbers of archaeobotanical, zooarchaeological, paleoecological, and genetic analyses have demonstrated the diverse economies of a number of farming communities and preindustrial urban complexes that emerged in tropical forests during the Holocene (28–30). This, in turn, had long-term impacts on the composition and structure of ecosystems within and around tropical forests (31–34). Finally, the last 500 y has witnessed a "swift, ongoing, radical reorganization of life on Earth without geological precedent" (35), with the arrival of European colonialism, imperialism, and the associated expansion of capitalist economic systems leading to the transferral of diseases, plants, animals, forms of land-use, and administrative systems to all corners of the tropics (36, 37).

Exploring long records of human presence is crucial for disentangling how different tropical habitats have responded to economic, social, political, and climatic changes over centennial to millennial time-scales (38), as well as the importance of long legacies of Indigenous knowledge and stewardship in shaping and protecting many of these biomes (e.g., ref. 39). This Special Feature uses tropical forests as a lens for exploring the temporal, practical, social, and cultural dimensions of the origins of the Anthropocene as a long-term and varied process. Bringing archaeologists, anthropologists, historians, ecologists, earth scientists, historical geographers, climate scientists, conservationists, and Indigenous voices together, the nine different articles address at least one of three main questions stemming from the above discussion:

1) What are the time-spans over which preindustrial human societies occupied and impacted tropical forests?
2) How can detailed archaeological, historical, paleoecological, and Indigenous traditional knowledge be used to explore shifts in types of preindustrial human land management in different parts of the tropics, and their accompanying ecological and earth systems feedbacks?
3) How does understanding the changing nature and tempo of anthropogenic impacts on tropical forests—from the first arrival of our species in these environments through the arrival of European colonialism and current 21st-century practices—allow us to better plan for the future?

The diverse authors, topics, regions (Fig. 1), and timescales (Fig. 2) covered in this volume are designed not only to address these themes, but also to encourage intersection between them, leading to a vibrant, interdisciplinary, and multivocal product. Given that tropical forests are the most threatened terrestrial settings after the polar ice-caps (41), the integration of multidisciplinary datasets, and the use of the past to contribute to the present and future of the battle for human sustainability, is more pressing than ever.

The Deep-Time Roots of the Tropical Anthropocene

Human ecologists in the 1980s argued that it was impossible for human foragers to live in tropical forests without access to agriculture, with small, fast, difficult-to-catch prey, a lack of reliable carbohydrate resources, diseases, and issues of thermoregulation making these habitats inhospitable to human presence (42, 43). These ideas were taken up in archaeology and allied disciplines, with some prominent scholars arguing tropical forests were marginal

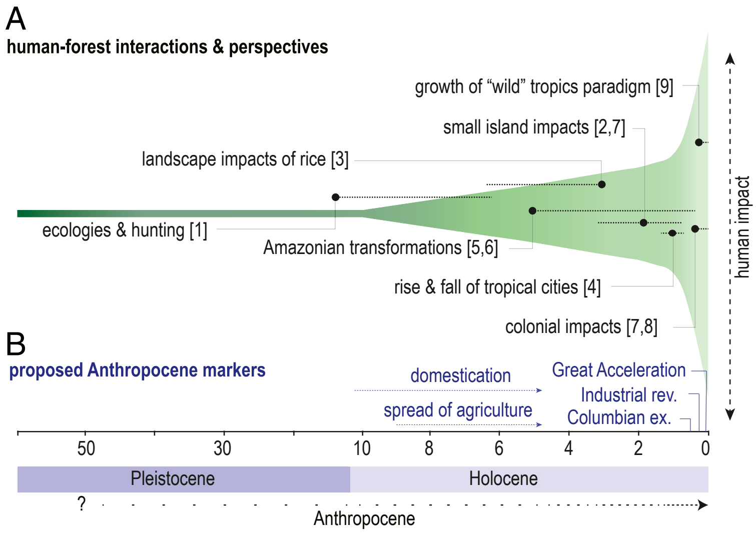

Fig. 2. Schematic showing timeframes and topics covered in the special issue relative to the currently proposed markers of the Anthropocene. (*A*) the topics (annotated) and timeframes (black dots and dashed lines) covered by the articles included in this Special Feature: 1) Douglass et al. (14), 2) Fitzpatrick and Giovas (15), 3) Zheng et al. (16), 4) Penny and Beach (17), 5) Duncan et al. (18), 6) Piperno et al. (19), 7) Castilla-Beltrán et al. (20), 8) Long et al. (21), and 9) Fletcher et al. (22). The study points are underlain with a simplified schematic of the increased influence of humans on the global tropics (green shading) (40). (*B*) The timing of some of the most commonly proposed markers for the onset of the Anthropocene epoch (8, 35) or the process of the Anthropocene (23).

environments for human settlement or, where small communities existed, for food production, dense populations, and urbanism (44–47). Alongside perceived issues of organic preservation (e.g., ref. 48), tropical forests were thus largely seen as unproductive settings for archaeological investigation, especially when compared to their savanna or coastal counterparts (e.g., refs. 47 and 49). However, the last three decades have seen a dramatic increase in archaeological evidence for the early occupation of tropical forest environments by our species in South and Southeast Asia (~45,000 y ago) (50, 51), Oceania (~45,000 y ago) (52), Central and South America (by ~16,000 to 13,000 y ago) (53, 54), and potentially as far back as 200,000 to 100,000 y ago in Africa (e.g., ref. 55).

Perhaps most significantly for us here, however, is the fact that humans have now been found to not only be present in tropical forests over deep time, but also were, in some cases, modifying them (see refs. 34, 56, and 57). In the context of the Late Pleistocene, hunter-gatherers may have played a role in the extinction of many genera and species of "megafauna" during the Late Pleistocene–Holocene, resulting in a cascading loss of biodiversity, which phenotypic analyses suggest represented 2 billion years worth of evolution (58). Not only that, but as megafauna are often major seed dispersers and disturbance agents in tropical forests, any human role in their demise could be considered an early example of our species' influence on tropical nutrient cycling (59). In island ecosystems, the loss of large birds, such as the moa of Aotearoa (New Zealand) and the elephant birds of Madagascar, have been iconic examples of potential human impacts on megafaunal populations. In this issue, Douglass et al. (14) present a novel methodology for looking at human–megafaunal interactions for another large insular bird: the cassowary. By examining the microstructure of cassowary egg shell, they show a potential human focus on egg exploitation rather than the hunting of adults, providing unique detail into the types of ecological pressures placed on these populations by people. Not only that, but they postulate that their data may indicate human hatching and rearing of cassowary chicks as early as the Late Pleistocene, providing a new perspective on the breadth and intensity of possible early human interactions with tropical megafauna.

Beyond potential impacts on megafaunal populations, it has also been suggested that Pleistocene human foragers may have burned landscapes to maintain productive mosaics (60) and even actively transported plant and animals as resources (61). Human modification of landscapes became more intensive in the Holocene as food production emerged across the tropics. Combined botanical, archaeological, and genetic evidence has identified tropical forests as the natural habitats of the wild progenitors of major seed and root crops and indicated that in some regions their domestication occurred as early as in other major independent "agricultural" centers around the world (e.g., refs. 30 and 62). Ample evidence has now emerged for varied systems of cultivation (30, 63, 64), animal domestication (65), and the emergence of urbanism (29, 66) in many different parts of the tropics.

Each of these developments had its own potential ramifications for earth systems and a deep-time view of the Anthropocene (67). Local domestication of plants and animals was often applied within mixed agroforestry systems and the ongoing exploitation of wild aquatic and terrestrial resources (e.g., 31 and 68). However, the movement of food production economies into tropical forests from outside, particularly in the case of more isolated island ecosystems, could have major repercussions for biodiversity, soils, and even climate. To date, much work on human manipulation of remote island ecosystems has focused on the modification and cultivation of terrestrial environments. In this volume, Fitzpatrick and Giovas (15) deploy a holistic "ridge-to-reef" model within island systems in the Pacific and the Caribbean to explore how humans may have progressively modulated and adapted to intertangled terrestrial and marine ecosystems. The authors highlight the critical role of both land- and sea-based food and resource procurement for long-term human survival. In doing so, they highlight the crucial value of behavioral adaptations to—and effective management of—habitat-specific environmental change for

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the establishment of sustainable livelihoods within supposedly sensitive and resource-limited settings.

From "Wilderness" to Managed Landscapes

It is now clear that there is a long span of human presence within, and manipulation of, tropical forests. Given the known potential ramifications of local and regional impacts on tropical landscapes for earth systems (5, 25), it is increasingly recognized that paleoecological, archaeological, and historical data of human activities in tropical forests should be factored into modern conservation and ecological considerations of these landscapes. For example, in this Special Feature, Zheng et al. (16) assess the broad-scale ecological implications of rice agriculture intensification in southern China and southeast Asia in the Late Holocene. Moving away from a focus on simply assessing the degree of "deforestation," they also undertake analysis of the composition and diversity of pollen records from across the region to look at how agriculture may have impacted tropical forest tree species diversity. Their results demonstrate that the landscape implications of the intensification of wetland rice production from 3,000 to 2,000 y ago in the region was so large that it not only led to clearance of forest across a variety of interior settings, but also that it had lasting impacts on forest biodiversity. In particular, they highlight how appreciating these past human influences are key for understanding the conservation plight of the conifer (*Glyptostrobus pensilis*) that was previously present in the region for millions of years, but now exists only in a few localized patches.

Although sometimes uniformly associated with collapse (69), remote sensing, archaeological survey, and historical work are now demonstrating the vast preindustrial urban landscapes that existed in tropical forests, sometimes lasting over significant periods of time (40, 70). Here, Penny and Beach (17) compare and contrast social, political, and economic processes impacting Maya urbanism in Central America during the eighth to 11th centuries CE, with those of the Khmer in southeast Asia during the 14th and 15th centuries CE. Despite major cultural differences, the Maya and Khmer shared a number of similarities, including in their water-management systems and major transformations of landscapes. Penny and Beach argue that past human responses to environmental stresses were heterogeneous across time and space in each region, reflecting how the urban elite and surrounding, dispersed agricultural settlements had different levels of vulnerability to climatic variability. This is attributed to the creation of landesque capital outside of the urban centers that made these areas more resilient to climate change. Indeed, there has been growing recognition that away from the political elites, local food producers continued to occupy many of these supposedly "deserted" landscapes, with some even remaining there to this day (31, 70). Penny and Beach's paper (17) carries lessons for today and the future with regards to the sustainable navigation of environmental stressors.

Fifty years ago, prominent scholars argued that, due to severe environmental constraints (e.g., poor natural resources), prehistoric cultures in the Amazon Basin were mainly small and mobile with little cultural complexity, and exerted low environmental impacts (44). Work carried out over the past few decades, however, has made it clear that some areas of the Basin saw large, permanent settlements that exerted profound, regional-scale environmental impacts still visible today. They included mound settlements, earthworks, roads, canals, fish weirs, and the presence of highly modified anthropic soils, called *terra pretas* or "Amazonian Dark Earths" (e.g., refs. 71–74). In this Special Feature, in one of those areas of regional impacts, the Llanos de Mojos of southwest Amazonia, Duncan et al. (18) examine how varying, climate-controlled hydrological conditions were mediated in different ways by humans to maximize aquatic and terrestrial resources. Their pollen, phytolith, diatom, and charcoal analyses of 7,500- and 5,100-y-old sediment cores indicate that between at least 3,500 and 2,000 y ago people used hydraulic engineering and fire in transforming the region to its current savanna/forest/wetland mosaic. Integrated landscape management began at least 3,500 y earlier than reported in previous paleoecological interpretations. Their work highlights the active roles prehistoric communities played in mitigating otherwise negative effects of climate change, in this case rainfall, by interacting with tropical forest environments.

Against the backdrop of growing efforts to build continental, and even global, schemes of land-use, expanding regional paleoecological studies are demonstrating the importance of reconstructing histories of human land usage in all the major ecological zones to arrive at adequate understandings of prehistoric influences (38, 75). Continental-sized landscapes such as Amazonia, for example, have dramatically varied ecosystems, such as savannas and forests, with different rainfall regimes, species compositions, and soil qualities potentially influencing human exploitation strategies. Through phytolith and charcoal analyses of terrestrial soils, Piperno et al. (19) in this Special Feature carry out a vegetational and fire history of a wet, nonriverine forest in a remote, previously unstudied area of Peru. Modern tree censuses provide an important interpretive framework for the paleoecological analyses. The results indicate that over the last 5,000 y, including the period after European contact, the forests were not periodically cleared for agriculture or otherwise significantly modified by Indigenous populations. Forest diversity and structure appeared stable over this time period, demonstrating how Indigenous societies were, and still are, positive forces on their ecosystem's integrity and biodiversity and how Indigenous knowledge must be used in conservation and sustainability efforts. The research bears importantly on current questions concerning the scale and intensity of human modification of Amazonian forests in prehistory (e.g., refs. 33 and 76), with implications also for modern ecological dynamics and climate change.

From the Past to the Future: Whose Anthropocene Is It, Anyway?

The arrival of Europeans in different parts of the tropics has been argued to have represented a step-change in human impacts on tropical forests and their associated earth systems in the form of the transfer of diseases, new domesticated plants and animals, hitchhiking pests, new political structures, and different ways of viewing land and its productive potential (77–79). For example, recent work has highlighted how the diseases brought by Europeans to the Neotropics led to the deaths of as many as an estimated 90% of the Indigenous populations in the Neotropics within 150 y of colonial arrival, with subsequent changes to land-use and forest cover argued to have potentially influenced the global carbon cycle (37). While the precipitous decline in Indigenous populations is now unquestioned, growing regional paleoecological studies have demonstrated that, in some parts of the Neotropics, significant reforestation was already occurring prior to European arrival (75). Meanwhile, in other areas, the decline of Indigenous populations witnessed deforestation, rather than reforestation, as plantation systems and industrial use of tropical landscapes expanded (38).

Overall, it is clear that, as with the prehistoric examples mentioned above, local, detailed, biome-specific studies are essential to unravel the impacts European colonialism had on tropical forests and a variety of earth systems. In this volume, Castilla-Beltrán et al. (20) analyze paleoecological archives in the subtropical and tropical forest landscapes of the Canary Islands and Cabo Verde, which were first colonized by humans ∼2,000 and ∼500 y ago, respectively. They discuss the varied impacts of precolonial human populations in these different island ecosystems, and their interaction with regional climate change. Significantly, Castilla-Beltrán et al. note how European colonialism resulted in large increases in anthropogenic pressure on these island forests, particularly in the form of the conversion of woodland to agricultural landscapes. Nevertheless, some patches of distinctive subtropical laurel forest persisted in parts of the Canary Islands, with limited incursion of invasive species. Overall, the authors show how paleoecological data provide an important reference for current and future forest restoration and conservation policies in different parts of these islands.

In some cases, where paleoecological records are of a high enough resolution, it is possible to semiquantitatively or quantitatively determine how human interactions with tropical forests have varied from prehistory, through the arrival of colonialism and the expansion of industrialized societies, to the present day. In the context of tropical Papua New Guinea, one of the most culturally and biologically diverse places on earth, Long et al. (21) explore the recent historical ecological impacts of mining, population growth, and deforestation on a globally significant, Ramsar-listed wetland. Using a range of geochemical and biological indicators, the authors reveal the large and difficult-to-reverse impacts of 20th century land-use change on the contemporary ecological health of the site. In doing so, they not only demonstrate the persistent impact of people in the region, but, importantly, highlight the value of a multiproxy, deep-time approach for reconstructing otherwise unclear ecological baselines in the Anthropocene and the degree to which current land-use may be departing from generations of more sustainable human interactions with tropical forest environments.

What clearly emerges from all of the examples of prehistoric land management and historical change, is the important role that Indigenous populations have played in the management of tropical forest structure, species, biodiversity, and linked earth systems over the course of millennia. Subsequent formulation of tropical forests as "wildernesses" have often hindered the ability of these same communities to practice traditional land management, to the great detriment of their well being, and that of the tropical forest ecosystems themselves. Concluding this volume, Fletcher et al. (22) review more than 50 case studies from tropical ecosystems in southeast Asia and the Pacific, South America, and Australia to showcase how high-value, diverse landscapes have long been shaped and valued by Indigenous people. However, despite this evidence, many conservation policies continue to deny Indigenous people access to such places under the guise of wilderness protection. This mode of management has, in several cases, demonstrably degraded ecological conditions and hastened the demise of several important landscapes, highlighting the important need for Indigenous-led management of tropical ecosystems. The importance of growing support for Rainforest Aboriginal ranger groups and traditional burning applications has also recently been documented in tropical habitats in Australia (80, 81).

Pasts, Presents, Futures

Tropical forests are becoming increasingly important environments for exploring the long-term adaptations of our species and its interaction with earth systems (5, 56). The papers in this Special Feature show the ways in which archaeology, paleoecology, history, climate science, and Indigenous knowledge can be brought together to provide new, detailed insights into how past human societies have utilized and promoted different tropical resources; how land cover, species distributions, and local climates have changed in response to human activities; and how the past has a major relevance for thinking about the management and conservation of these important habitats in the 21st century. By tracking long-term trajectories of human impacts on tropical environments and their relationship to earth systems feedbacks on different scales (82), we gain the ability to better examine the thresholds of anthropogenic influences on our planet (34). It is now clear that hunting and gathering, food producing, and urban communities in the past could, and did, have major impacts on tropical forest cover, biodiversity, and their relationship with precipitation, temperature, soil stability, and the carbon cycle (83). However, while this could lead to challenges, close knowledge of tropical ecosystem dynamics, and the flexibility to move, change settlement patterns, or adopt new subsistence strategies, enabled the establishment of resilient settlements within these key environments. With potential roots in the colonial period, global 21st-century pressures on tropical forests are now breaching thresholds of coexistence with tropical forests, leading to dire consequences for these habitats and their associated earth systems functions. Indeed, recent discussions of the Amazon Basin becoming a carbon source rather than a carbon sink (84) highlight the pressing nature of understanding our current tropical Anthropocene.

Given the evidence for past human interaction and coexistence with tropical forests, it is clear that the enormous challenges facing tropical forests are not only threatening the immense natural heritage of these environments, but also millennia of cultural heritage locked up within their realms (85). Whether this is in the form of undiscovered archaeological sites, or in the living vegetation that still displays legacies of how humans managed these tropical landscapes in the past, the increasing loss of tropical forests is also erasing one of the most important sources of knowledge as to how humans can adapt to live with them in ways that may actually increase their resilience to major existential issues such as climate change (86). A positive step forward in this regard is UNESCO's desire to list more joint natural and cultural heritage sites (87). Meanwhile governments and policy makers are increasingly recognizing the practical use of deep-time data in their planning for tropical futures, ecosystem management, and the sustainability of humans as a species moving forward (see also refs. 88 and 89). We hope that the papers highlighted in this Special Feature will encourage further engagement of policy makers and ecologists with scholars from the paleosciences and social sciences, and a recognition of the long-term significance of Indigenous traditional management practices in many parts of the tropics (22). In this way, we have the best chance of developing more fair, sustainable, and resilient futures for human–environment interactions with habitat types that have stood on this planet for over 300 million y but are increasingly disappearing from view. We hope that this volume provides a framework for further open, cross-disciplinary discussions as to how the past can be used to directly inform our present and future with habitats that are going to be evermore essential for navigating the whole of humanity's relationship with planetary biodiversity, the Earth's carbon cycle, and continental climate circulation systems.

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1 S. E. Page, A. Hooijer, In the line of fire: The peatlands of Southeast Asia. *Phil. Trans. Roy. Soc. B-Series* **371**, 1–9 (2016).
2 J. Barlow, E. Berenguer, R. Carmenta, F. França, Clarifying Amazonia's burning crisis. *Glob. Change Biol.* **26**, 319–321 (2020).
3 A. P. Dobson *et al.*, Ecology and economics for pandemic prevention. *Science* **369**, 379–381 (2020).
4 E. T. A. Mitchard, The tropical forest carbon cycle and climate change. *Nature* **559**, 527–534 (2018).
5 Y. Malhi, T. A. Gardner, G. R. Goldsmith, M. R. Silman, P. Zelazowski, Tropical forests in the Anthropocene. *Annu. Rev. Environ. Resour.* **39**, 125–159 (2014).
6 Y. Malhi, The concept of the Anthropocene. *Annu. Rev. Environ. Resour.* **2017**, 42 (2017).
7 W. Steffen, J. Grinevald, P. Crutzen, J. McNeill, The Anthropocene: Conceptual and historical perspectives. *Philos. Trans.- Royal Soc., Math. Phys. Eng. Sci.* **369**, 842–867 (2011).
8 J. Zalasiewicz *et al.*, The Working Group on the Anthropocene: Summary of evidence and interim recommendations. *Anthropocene* **19**, 55–60 (2017).
9 D. Lawrence, K. Vandecar, Effects of tropical deforestation on climate and agriculture. *Nat. Clim. Chang.* **5**, 27–36 (2015).
10 S. C. Cook-Patton *et al.*, Mapping carbon accumulation potential from global natural forest regrowth. *Nature* **585**, 545–550 (2020).
11 Center for International Earth Science Information Network, *C.C.U., Gridded Population of the World, Version 4 (GPWv4): Population Density Adjusted to Match 2015 Revision UN WPP Country Totals, Revision 11. NASA Socioeconomic Data and Applications Center* (SEDAC, Palisades, NY, 2018).
12 D. M. Eberhard, G. F. Simons, C. D. Fenning, Eds., *Ethnologue: Languages of the World* (SIL International, Dallas, Texas, 2020), ed. 23.
13 State of the Tropics, *A State of the Tropics Report 2021* (James Cook University, Cairns, 2021).
14 K. Douglass *et al.*, Late Pleistocene/Early Holocene sites in the montane forests of New Guinea yield early record of cassowary hunting and egg harvesting. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2100117118 (2021).
15 S. M. Fitzpatrick, C. M. Giovas, Tropical islands of the Anthropocene: Deep histories of anthropogenic terrestrial–marine entanglement in the Pacific and Caribbean. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2022209118 (2021).
16 Z. Zheng *et al.*, Anthropogenic impacts on Late Holocene land-cover change and floristic biodiversity loss in tropical southeastern Asia. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2022210118 (2021).
17 D. Penny, T. P. Beach, Historical socioecological transformations in the global tropics as an Anthropocene analogue. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2022211118 (2021).
18 N. A. Duncan, N. J. D. Loughlin, J. H. Walker, E. P. Hocking, B. S. Whitney, Pre-Columbian fire management and control of climate-driven floodwaters over 3,500 years in southwestern Amazonia. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2022206118 (2021).
19 D. R. Piperno *et al.*, A 5,000-year vegetation and fire history for *tierra firme* forests in the Medio Putumayo-Algodón watersheds, northeastern Peru. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2022213118 (2021).
20 A. Castilla-Beltrán *et al.*, Anthropogenic transitions from forested to human-dominated landscapes in southern Macaronesia. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2022215118 (2021).
21 K. E. Long *et al.*, Human impacts and Anthropocene environmental change at Lake Kutubu, a Ramsar wetland in Papua New Guinea. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2022216118 (2021).
22 M.-S. Fletcher, R. Hamilton, W. Dressler, L. Palmer, Indigenous knowledge and the shackles of wilderness. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2022218118 (2021).
23 W. F. Ruddiman, E. C. Ellis, J. O. Kaplan, D. Q. Fuller, Geology. Defining the epoch we live in. *Science* **348**, 38–39 (2015).
24 L. Stephens *et al.*, Archaeological assessment reveals Earth's early transformation through land use. *Science* **365**, 897–902 (2019).
25 P. Roberts, N. Boivin, J. O. Kaplan, Finding the Anthropocene in tropical forests. *Anthropocene* **23**, 5–16 (2018).
26 A. Curry, 'Green hell' has long been home for humans. *Science* **354**, 268–269 (2016).
27 P. Roberts, M. D. Petraglia, Pleistocene rainforests: Barriers or attractive environments for early human foragers? *World Archaeol.* **47**, 718–739 . (2015).
28 R. A. E. Coningham *et al.*, The state of theocracy: Defining an early medieval hinterland in Sri Lanka. *Antiquity* **81**, 699–719 (2007).
29 D. Evans *et al.*, A comprehensive archaeological map of the world's largest preindustrial settlement complex at Angkor, Cambodia. *Proc. Natl. Acad. Sci. U.S.A.* **104**, 14277–14282 (2007).
30 D. R. Piperno, The origins of plant cultivation and domestication in the New World tropics: Patterns, process, and new developments *Curr. Anthropol* **52**, 453–470 (2011).
31 A. Ford, R. Nigh, *The Maya Forest Garden: Eight Millennia of Sustainable Cultivation of the Tropical Woodlands* (Routledge, London, 2015).
32 S. Y. Maezumi *et al.*, The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon. *Nat. Plants* **4**, 540–547 (2018).
33 C. Levis *et al.*, Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. *Science* **355**, 925–931 (2017).
34 E. C. Ellis *et al.*, People have shaped most of terrestrial nature for at least 12,000 years. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2023483118 (2021).
35 S. L. Lewis, M. A. Maslin, Defining the anthropocene. *Nature* **519**, 171–180 (2015).
36 J. W. Moore, Madeira, sugar, and the conquest of nature in the "first" sixteenth century. Part I: From "Island of timber" to sugar revolution, 1420-1506. *Rev. Fernand Braudel Cent.* **32**, 345–390 (2009).
37 A. Koch, C. Brierley, M. M. Maslin, S. L. Lewis, Earth system impacts of the European arrival and Great Dying in the Americas after 1492. *Quat. Sci. Rev.* **207**, 13–36 (2019).
38 R. Hamilton *et al.*, Non-uniform tropical forest responses to the 'Columbian Exchange' in the Neotropics and Asia-Pacific. *Nat. Ecol. Evol.* **5**, 1174–1184 (2021).
39 N. C. González, M. Kröger, The potential of Amazon indigenous agroforestry practices and ontologies for rethinking global forest governance. *For. Policy Econ.* **118**, 102257 (2020).
40 D. M. Olson *et al.*, Terrestrial ecoregions of the world: A new map of life on Earth. *Bioscience* **51**, 933–938 (2001).
41 P. Roberts, *Tropical Forests in Prehistory, History, and Modernity* (Oxford University Press, Oxford, 2019).
42 T. B. Hart, J. A. Hart, The ecological basis of hunter-gatherer subsistence in African rain forests. *Hum. Ecol.* **14**, 29–55 (1986).
43 R. Bailey *et al.*, Hunting and gathering in tropical rain forest; Is it possible? *Am. Anthropol.* **91**, 59–82 (1989).
44 B. J. Meggers, *Amazonia: Man and Culture in a Counterfeit Paradise* (Harlan Davidson, Illinois, 1971).
45 P. C. Mangelsdorf, Review of agricultural origins and dispersals. *Am. Antiq.* **19**, 87–90 (1953).
46 C. Gamble, *Timewalkers: The Prehistory of Global Colonization* (Alan Sutton, Stroud, 1993).
47 M. Bird, D. Taylor, C. Hunt, Palaeoenvironments of insular Southeast Asia during the last glacial period: A savanna corridor in Sundaland? *Quat. Sci. Rev.* **24**, 2228–2242 (2005).
48 M. Tappen, Bone weathering in the tropical rain forest. *J. Archaeol. Sci.* **21**, 667–673 (1994).
49 N. Boivin, D. Q. Fuller, R. Dennell, R. Allaby, M. D. Petraglia, Human dispersal across diverse environments of Asia during the Upper Pleistocene. *Quat. Int.* **300**, 32–47 (2013).
50 K. E. Westaway *et al.*, An early modern human presence in Sumatra 73,000-63,000 years ago. *Nature* **548**, 322–325 (2017).
51 O. Wedage *et al.*, Specialized rainforest hunting by Homo sapiens ~45,000 years ago. *Nat. Commun.* **10**, 739 (2019).
52 G. R. Summerhayes *et al.*, Human adaptation and plant use in highland New Guinea 49,000 to 44,000 years ago. *Science* **330**, 78–81 (2010).
53 G. Morcote-Ríos *et al.*, Colonisaton and early peopling of the Colombian Amazon during the Late Pleistocene and the Early Holocene: New evidence from La Serranía La Lindosa. *Quat. Int.* **578**, 5–19 (2021).
54 A. J. Ranere, R. G. Cooke, Late glacial and Early Holocene migrations, and Middle Holocene settlement on the lower isthmian land-bridge. *Quat. Int.* **578**, 20–34 (2021).

55 N. Taylor, "Across rainforests and woodlands: A systematic reappraisal of the Lupemban Middle Stone Age in Central Africa" in *Africa from MIS 6-2: Population Dynamics and Paleoenvironments*, S. C. Jones, B. A. Stewart, Eds. (Springer, Dordrecht, 2016), pp. 273–299.
56 P. Roberts, C. Hunt, M. Arroyo-Kalin, D. Evans, N. Boivin, The deep human prehistory of global tropical forests and its relevance for modern conservation. *Nat. Plants* **3**, 17093 (2017).
57 D. R. Piperno, "Prehistoric human occupation and impacts on tropical forest landscapes during the Late Pleistocene and Early/Middle Holocene" in *Tropical Rainforest Responses to Climate and Human Influences*, M. B. Bush, J. Flenley, W. D. Gosling, Eds. (Springer, Chichester, UK), ed. 2, 2011, pp. 185–212.
58 M. Davis, S. Faurby, J.-C. Svenning, Mammal diversity will take millions of years to recover from the current biodiversity crisis. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 11262–11267 (2018).
59 C. E. Doughty *et al*., Megafauna extinction, tree species range reduction, and carbon storage in Amazonian forests. *Ecography* **39**, 194–203 (2015).
60 C. O. Hunt, D. D. Gilbertson, G. Rushworth, A 50,000-year record of late Pleistocene tropical vegetation and human impact in lowland Borneo. *Quat. Sci. Rev.* **37**, 61–80 (2012).
61 C. Gosden, N. Robertson, "Models for Matenkupkum: Interpreting a late Pleistocene site from Southern New Ireland, Papua New Guinea" in *Report of the Lapita Homeland Project*. Occasional Papers in Prehistory 20. J. Allen, C. Gosden, Eds. (Department of Prehistory. Research School of Pacific Studies, The Australian National University, Canberra, 1991), pp. 20–91.
62 T. Denham, Early agriculture and plant domestication in new Guinea and Island Southeast Asia. *Curr. Anthropol.* **52**, S379–S395 (2011).
63 J. Golson, T. Denham, P. Hughes, P. Swadling, J. Muke, *Ten Thousand Years of Cultivation at Kuk Swamp in the Highlands of Papua New Guinea* (Terra Australis 46, Australian National University Press, Canberra, 2017).
64 E. G. Neves, M. J. Heckenberger, The call of the wild: Rethinking food production in ancient Amazonia. *Annu. Rev. Anthropol.* **48**, 371–388 (2019).
65 M.-S. Wang *et al*., 863 genomes reveal the origin and domestication of chicken. *Cell Res.* **30**, 693–701 (2020).
66 A. F. Chase *et al*., Airborne LiDAR, archaeology, and the ancient Maya landscape at Caracol, Belize. *J. Archaeol. Sci.* **38**, 387–398 (2011).
67 K. J. Willis, L. Gillson, T. M. Brncic, Ecology. How 'virgin' is virgin rainforest? *Science* **304**, 402–403 (2004).
68 M. Bleasdale *et al*., Isotopic and microbotanical insights into Iron Age agricultural reliance in the Central African rainforest. *Commun. Biol.* **3**, 619 (2020).
69 J. Diamond, *Collapse: How Societies Choose to Fail or Survive* (Penguin Books, London, 2005).
70 L. J. Lucero, R. Fletcher, R. Coningham, From 'collapse' to urban diaspora: The transformation of low-density, dispersed agrarian urbanism. *Antiquity* **89**, 1139–1154 (2015).
71 C. L. Erickson, An artificial landscape-scale fishery in the Bolivian Amazon. *Nature* **408**, 190–193 (2000).
72 E. G. Neves, J. B. Petersen, R. N. Bartone, M. J. Heckenberger, "The timing of terra preta formation in the central Amazon: Archaeological data from three sites" in*Amazonian Dark Earths: Explorations in Space and Time*, B. Glaser, W. I. Woods, Eds. (Springer, Berlin, 2004), pp. 125–133.
73 W. Woods *et al*., Eds., *Amazonian Dark Earths: Wim Sombroek's vision* (Springer, Berlin, 2012).
74 B. S. Whitney, R. Dickau, F. E. J. Mayle, J. D. Soto, J. Iriarte, Pre-Columbian landscape impact and agriculture in the Monumental Mound region of the Llanos de Moxos, lowland Bolivia. *Quat. Res.* **80**, 207–217 (2013).
75 M. B. Bush *et al*., Widespread reforestation before European influence on Amazonia. *Science* **372**, 484–487 (2021).
76 C. N. H. McMichael, M. B. Bush, Spatiotemporal patterns of pre-Columbian people in Amazonia. *Quat. Res.* **92**, 53–69 (2019).
77 J. W. Moore, Sugar and the expansion of the early modern world-economy: Commodity frontiers, ecological transformation, and industrialization. *Rev. Fernand Braudel Cent.* **23**, 409–433 (2000).
78 J. T. Wing, *Roots of Empire: Forests and State Power in Early Modern Spain, c 1500–1750* (Brill's Series in the History of the Environment, Volume 4, Brill, Leiden, 2015).
79 A. Polónia, J. M. Pacheco, "Environmental impacts of colonial dynamics 1400-1800: The first global age and the Anthropocene" in *Economic Development and Environmental History in the Anthropocene: Perspectives on Asia and Africa*, G. Austin, Ed. (Bloomsbury, London, 2017), pp. 23–49.
80 P. Roberts *et al*., Primordial Gondwanaland or human forests? Reimagining the Australian 'Wet Tropics' and their conservation. *iScience* **24**, 102190 (2021).
81 R. B. Bird, N. Taylor, B. F. Codding, D. W. Bird, Niche construction and dreaming logic: Aboriginal patch mosaic burning and varanid lizards (*Varanus gouldii*) in Australia. *Proc Biol Sci* **280**, 20132297 (2013).
82 F. Taubert *et al*., Global patterns of tropical forest fragmentation. *Nature* **554**, 519–522 (2018).
83 P. Roberts, *Jungle: How Tropical Forests Shaped the World and Us* (Viking/Penguin Random House, London, 2021).
84 L. V. Gatti *et al*., Amazonia as a carbon source linked to deforestation and climate change. *Nature* **595**, 388–393 (2021).
85 V. L. Caetano-Andrade *et al*., Tropical trees as time capsules of anthropogenic activity. *Trends Plant Sci.* **25**, 369–380 (2020).
86 R. Hamilton, D. Penny, T. L. Hall, Forest, fire & monsoon: Investigating the long-term threshold dynamics of south-east Asia's seasonally dry tropical forests. *Quat. Sci. Rev.* **238**, 106334 (2020).
87 N. Sanz, "The way forward for more sustainable natural and cultural diversity all over the world" in *Exploring Frameworks for Tropical Forest Conservation: Managing Production and Consumption for Sustainability*, N. Sanz, Ed. (UNESCO, Mexico City, 2017), pp. 336–351.
88 K. Morrison, Routes to relevance in archaeology. *Antiquity* **95**, 1070–1072 (2021).
89 N. Boivin, A. Crowther, Mobilizing the past to shape a better Anthropocene. *Nat. Ecol. Evol.* **5**, 273–284 (2021).