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Uncovering the Multibiome Environmental and Earth System Legacies of Past Human Societies

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Abstract

It has been argued that we have now entered the Anthropocene, a proposed epoch in which humans are having a dominant impact on the Earth system. While some geologists have sought to formalize the Anthropocene as beginning in the mid-twentieth century, its social, geophysical, and environmental roots undoubtedly lie deeper in the past. In this review, we highlight the ways in which human activities across the major biomes of our planet significantly altered parts of the Earth system prior to the Industrial Age. We demonstrate ways in which novel, multidisciplinary approaches can provide detailed insights into long-term human–environment–Earth system interactions. We argue that there is clear evidence for lasting Earth system legacies of pre-Industrial human societies and that archaeology, paleoecology, and historical ecology can provide important, practical insights to help navigate current and future relationships with the planet in more equitable and sustainable ways.

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INTRODUCTION

Human societies are having major impacts on the Earth system in the twenty-first century. In their book *The Great Acceleration*, historians McNeill & Engelke (1) note that increases in energy use, global consumption, and human population since World War II have exacerbated environmental changes associated with the Industrial Revolution of the eighteenth and nineteenth centuries. The Great Acceleration concept feeds into a wider, ongoing discourse on the Anthropocene, which emphasizes the fact that human impacts on the environment have extended beyond the local or regional (2). Instead, our species is playing a decisive role in modifying the atmosphere, biosphere, hydrosphere, and geosphere at the planetary scale, with its own portion of the Earth system, the technosphere, now bearing down on the planet (2). Acknowledging this role, and the ongoing high and asymmetrical patterns of global consumption of matter and energy in shaping ecosystems and influencing future climates, the Anthropocene Working Group of the International Commission on Stratigraphy had recommended the formal geological designation of the Anthropocene epoch starting in 1950, thus superseding the Holocene (3). This proposal was recently rejected by the International Commission of Stratigraphy, however, highlighting the difficulty of currently finding an unequivocal onset for this period in a geological sense (4).

Arguably, this rejection emphasizes the importance of studying the changing intensities and types of human–Earth system interactions on different temporal and spatial scales. Indeed, although the Anthropocene is a concept with which the broader scientific community and public are increasingly engaging (5), there remains limited acknowledgement of the ways in which human activities had already interacted with the Earth system prior to the Industrial Age. Academics have devoted significant research efforts to understanding ecosystems undisturbed by modernism, with a conservation focus on the reconstruction, preservation, or maintenance of intact ecosystems in the context of sustainability and biodiversity initiatives (e.g., 6). These approaches, while potentially valuable in their own right, commonly rest on the assumption that pre-Industrial and "traditional" societies have had little to no long-term (here defined as several centuries to millennia) impact. However, it is becoming clearer that pre-Industrial technologies and economic systems of production, distribution, and consumption have left profound legacies in twenty-first-century ecosystems, landscapes, the global technosphere (7)—defined here as the summation of human technology (spanning stone tools, the inception of fire, and the emergence of social media) and innovation and interactions with the environment—and other parts of the Earth system (see also 8).

It is a trope of history that we can only truly understand an era after it has passed. If the world has indeed entered a new, Anthropocene epoch, what Holocene or even Pleistocene processes led us to this point? What were the major human impacts on the Earth system prior to industrialization, and how do they differ in scale and nature across space and time? What are the environmental legacies and path dependencies of these human–Earth system interactions? How are these legacies intentionally or unintentionally maintained or halted by contemporary local and nonlocal communities? Historical ecological approaches that integrate methods and theoretical frameworks from the historical and environmental sciences, as well as Indigenous knowledge, oral traditions, and perspectives from communities of practice, can play a critical role in addressing these questions (e.g., 9–11). An abundance of accessible archaeological and paleoecological data collectively offer insights into variation among past human economies and how they interacted with their environments over the long term in different parts of the world (12). We know that increases in the scale of human collective action long predate the Industrial Age, and we can measure with far greater accuracy—as well as with a greater recognition of uncertainty—the demographic scale of past human societies (e.g., 13). It is easier than ever to investigate long-term relationships between past human behavior, vegetation cover, soil morphology, climate, and plant and animal species over several centuries and millennia (14). These sources of knowledge offer practical insights for twenty-first-century problems (10). However, while there is a growing recognition that we can mobilize the past to help prioritize, plan, and act in the present (e.g., 15), this mobilization remains patchy and underappreciated in the historical and environmental sciences as well as in conservation and natural resource management.

In this review, we highlight the evidence for lasting material legacies of Pleistocene (125,000–11,700 years ago) and pre-Industrial Holocene (11,700 years ago to the start of the Industrial Age) human impacts on aspects of the Earth system across major biomes (**Figure 1**). All too often, Eurocentric biases and environmental determinism have shaped the ways in which the role of human history in different contemporary ecosystems is appreciated. For example, prehistoric and historic impacts on the vegetation and soils of temperate Europe are widely acknowledged (16). By contrast, preservation issues and legacies of assumptions that tropical rainforests were barriers to human settlement (e.g., 17) have meant that the role of past human societies in shaping these habitats remains relatively poorly understood by the public and scholars alike, beyond those directly engaged in data generation, analysis, and knowledge production (18). However, no environment is productive or marginal on its own; rather, it is the relationship between a human economy and an environment that is productive or not (12). What the term productive even means will also vary significantly between cultural contexts. While our review is not exhaustive (for a reading list on the different topics mentioned here see the **Supplemental Material**), we aim to highlight evidence of numerous instances of pre-Industrial human–Earth system interactions in different parts of the planet. The cases we cite may not necessarily be wholly representative of each region and sphere, but they demonstrate the potential for historical ecology research to address human–Earth system interactions in the past, reveal their legacies today, and indicate the breadth of issues examined in current research initiatives. Overall, this review emphasizes the significance of archaeology, environmental history, Indigenous knowledge, and paleoecology for conservation, ecological research, and predictions across the contemporary world.

UNRAVELING PAST HUMAN ECOLOGICAL AND EARTH SYSTEM HERITAGES

The vagaries of preservation and sampling in the archaeological and paleoecological record, as well as the varying availability of historical sources, may make past impacts seem comparatively limited and small scale. Furthermore, very large scale data syntheses are rare, allowing evidence of anthropogenic change to be dismissed as local (20). Compounding these methodological and scalar issues is the common positioning of human activities as constantly in tension with nature (21). This framing relegates the recognition of past human influence on environments to those examples in which observed changes occur in opposition to expected natural trends. In reality, human activity often seeks to complement or exploit natural trends (22). Nevertheless, an increase in multidisciplinary studies has helped unveil facets of human–environment interactions, including those with

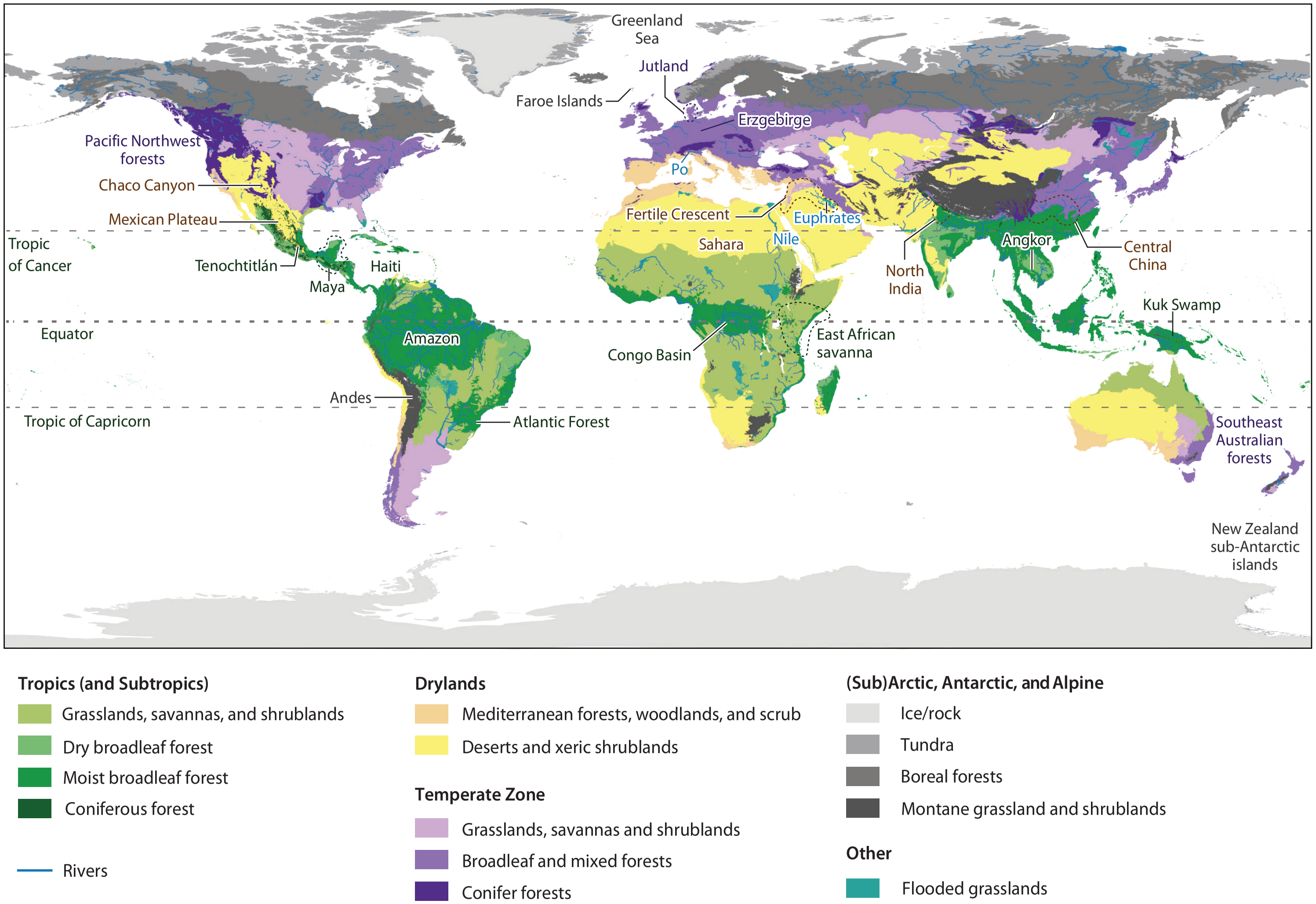


Figure 1

Map showing Earth's main climate zones (tropics, drylands, temperate, and Arctic/sub-Arctic/montane) as well as the main biome divisions within them. Figure based on World Wildlife Fund ecoregion shapefiles (see **https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world**) and Reference 19.

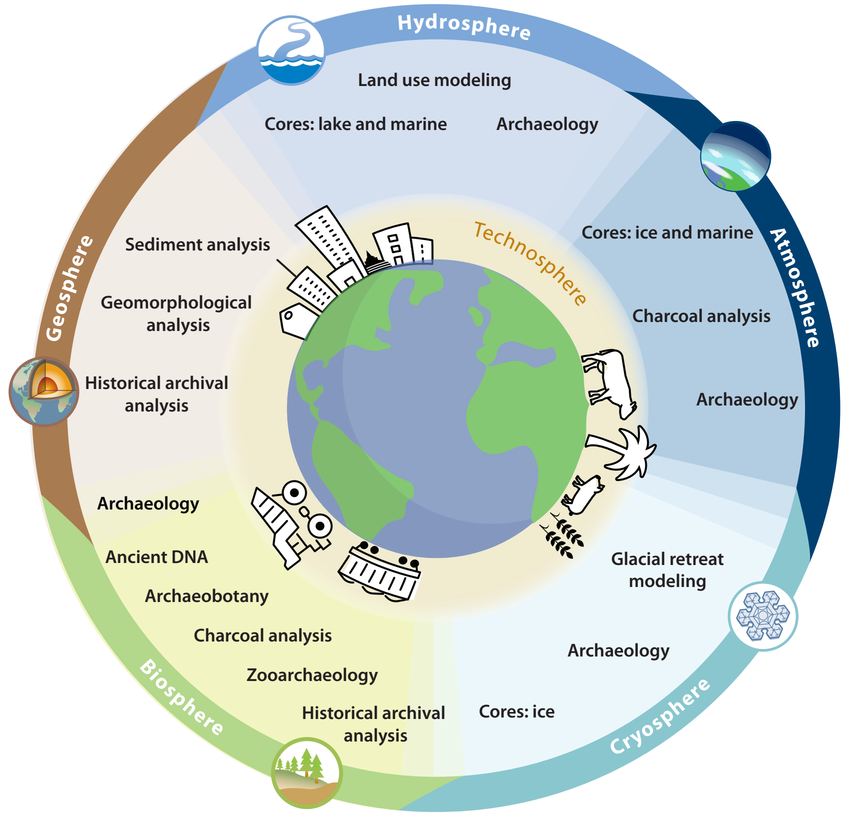


Figure 2

Schematic showing the different archaeological, paleoecological, and historical ecological methods (show in the *middle ring*) available for studying human–technosphere interactions with different parts of the Earth system (*outer ring*).

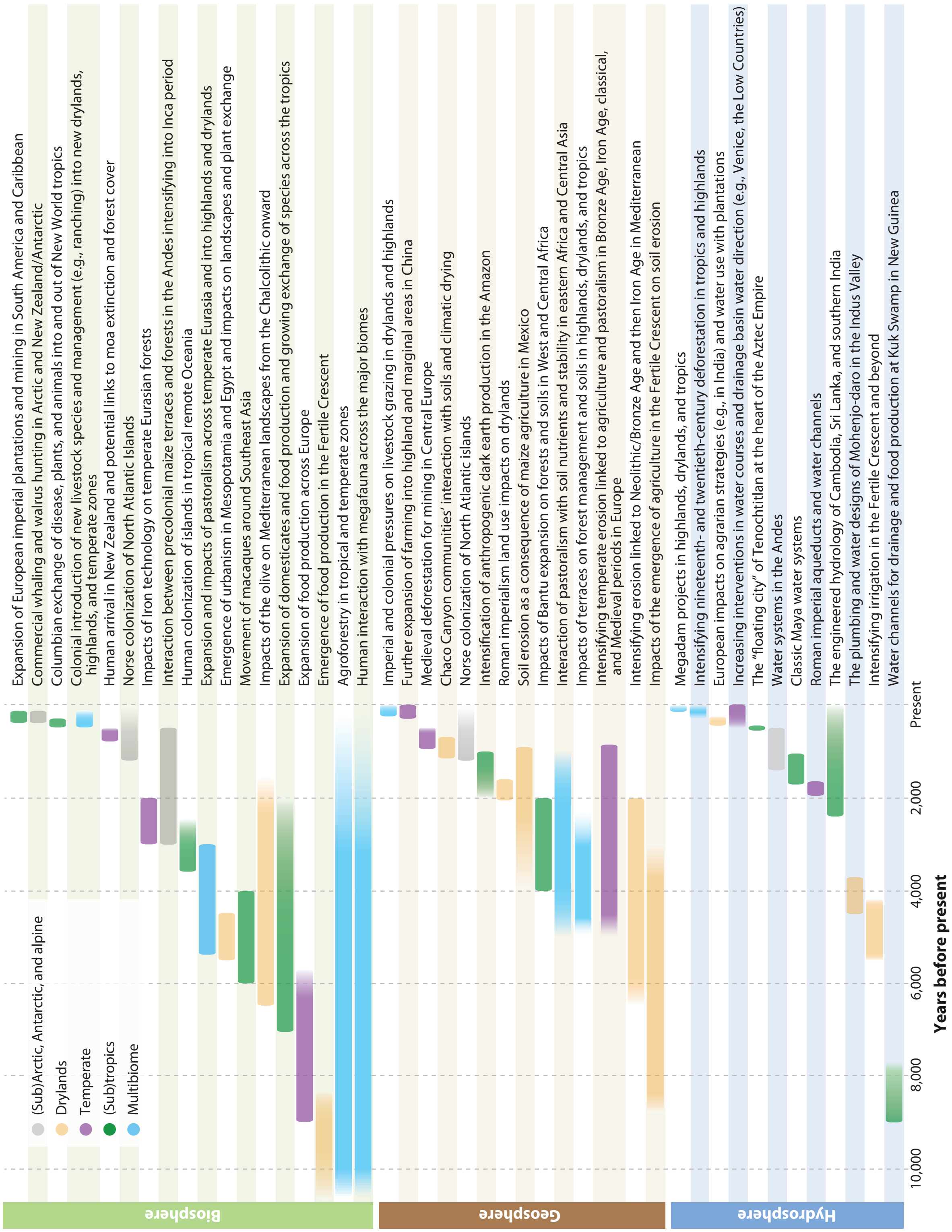
large-scale and long-term consequences for different parts of the Earth system (**Figure 2**). With regard to the biosphere, archaeobotanical and zooarchaeological research can reveal temporal and spatial shifts in biodiversity (23), the introduction of invasive species (24), and fluctuations in vegetation dynamics and boundaries (11) that can be connected to past human activities. Application of isotope analysis, ZooMS (zooarchaeology by mass spectrometry), and ancient DNA analysis to archaeological plant and animal remains has facilitated studies of changing animal migration patterns, niche alterations, variations in nutrient cycles, and soil and plant management (24) and of changes in faunal communities even where remains are poorly preserved (25). Meanwhile, paleoenvironmental archives (e.g., lake sediment layers) can reveal past vegetation structure and composition, approximate the timing and impact of animal and human presence on the landscape, and enable comparisons between local archaeological records and regional changes (26).

Geoarchaeological studies of soils at archaeological sites combined with assessments of paleoenvironmental change are also enabling us to explore past human interactions with the geosphere. For instance, it is possible to gauge how soil erosion, at the level of both local slopes and site catchment, as well as entire drainage basins, might have been linked to changing human land use and settlement dynamics (26–28). In other cases, multielement analysis of soils, alongside more traditional thin-section assessments, is enabling exploration of anthropogenic soil formation (e.g., 29). Moving above the Earth's surface, there is a growing interest in long-term human relationships with fire. Macro- and microcharcoal counting from archaeological and paleoenvironmental sediments, as well as applications of Fourier transform infrared spectroscopy (30), have provided insights into the nature and intensity of past fires and their potential consequences for local and regional carbon cycle dynamics (31). Comparisons of records of fire to changes in vegetation structure assessed through palynology and phytolith analysis of paleoenvironmental sequences have demonstrated the importance of Indigenous fire regimes for biodiversity enrichment, ecosystem resilience, and vegetation structure in places such as Tasmania (32), the Amazon Basin (33), and the Wet Tropics of Australia (34).

There is also a growing recognition that past changes in human land use and land cover influenced precipitation and water dynamics (the hydrosphere) and even the atmosphere (e.g., through carbon emissions) and cryosphere. On regional scales, coarse models of changes in vegetation (e.g., deforestation) can be factored into climate models to study how seasonal and annual precipitation were influenced by human activities (e.g., 35). Meanwhile, pan-regional and global research initiatives, such as LandCover6k, are exploring the degree to which major thresholds in human socioeconomic systems might have led to such dramatic shifts in land cover that emissions may have had globally recognizable effects (20; see also 36, 37). While many of these models have been based on relatively crude calculations of human demography and land use regimes, there are growing efforts to develop detailed insights from historical, archaeological, and paleoecological records to build bottom-up assessments of land use change through time (20). The resulting land use models can then be incorporated into existing land cover–climate/Earth system models to explore the degree to which past human socioeconomic systems had regional or global feedbacks across a variety of different timescales with potential consequences for today.

Archaeology, environmental history, and greater consultation and partnership with local communities who hold local ecological knowledge can also provide insights into the emergence of, and major changes in, the technosphere that underpins anthropogenic impacts on the Earth system (7). Here, for instance, it is possible to study the coevolution of land use practices—including foraging, hunting, extensive and intensive agriculture, and pastoralism—with technologies, forms of settlement (e.g., urbanism), commerce, and political conditions, as well as different aspects of the Earth system. For example, scholars have identified the so-called Early Modern (~1450–1750 CE) emergence of larger states and empires as a major technosphere threshold. At that time, societies developed larger markets with internal specialization and diversification, increased the scale of resource extraction from imperial peripheries for urban and military provisioning, and intensified management of natural resources such as woodlands and forests (38, 39). The rise of merchant empires and overseas colonial imperial expansion enabled, and then accelerated, the global disruption and movement of biota. Colonialism and early capitalism created new frontiers of extraction in the Global South, exporting accelerated anthropogenic pressures to areas beyond primary centers of consumption (38). The commodification of resources at the global scale restructured and reduced the variation of local and regional Indigenous natural resource management practices that had previously had a substantial influence on the Earth's surface (11, 40).

In the remainder of this review, we highlight how novel, multi- and interdisciplinary methodologies are providing evidence for human relationships with different parts of the Earth system in very different biogeographic settings. To ensure comparability between regions, we review human impacts on the biosphere (plant and animal diversity and structure), geosphere (soils), and hydrosphere (water cycle) (**Figure 3**). Focusing on the pre-Industrial period, this review moves through the tropical, dryland, temperate, and Arctic and sub-Arctic zones to emphasize the various ways in which we know past human societies influenced these different habitats (**Figures 1** and **3**). We then provide a broader, global perspective on potential changes to the cryosphere and atmosphere.



(Caption appears on following page)

Figure 3 (*Figure appears on preceding page*)

Timeline of case studies on human impacts in the tropics, drylands, temperate areas, and Arctic/sub-Arctic/montane areas on the biosphere, geosphere, and hydrosphere. The horizontal bar represents the timing of the event and/or its impact through time (shown on the *x*-axis).

We conclude by highlighting how a longer-term view of the world's biomes reveals the impact of European colonial expansion since the fifteenth century and the ongoing legacies associated with imperial and global market expansion. This period in history set the world on accelerated and more homogeneous trajectories and path dependencies that echo through the major juncture of the Industrial Revolution and continue to this day.

THE TROPICS

Biosphere

The tropics contain more than 35% of the Earth's land area and tropical forests are home to over half of the Earth's plant and animal biodiversity, meaning that changes to these ecosystems can have significant knock-on effects for the planet (41). Early possible anthropogenic changes to the tropical biosphere include potential human involvement in the extinction of megafauna, such as gomphotheres (a group related to modern elephants), giant sloths, and glyptodonts (a group of large armadillos) in the Neotropics during the Late Pleistocene (42). The role of humans, whether through direct hunting or indirect environmental impacts, remains disputed. Nevertheless, the demise of these large species and their seed dispersal functions has been associated with changes to local vegetation structure and even to the related carbon cycle (43). Zooarchaeological and archaeobotanical research has also demonstrated the human translocation of animals and plants between different parts of the tropics beginning in the Late Pleistocene and intensifying into the Holocene (e.g., 23). The emergence of food production and the expansion of food production systems in the tropics during the Early to Middle Holocene saw the domestication and promotion of particular tropical plants (e.g., maize, manioc) and animals (e.g., chicken) that are now staples around the world (44).

The Middle to Late Holocene also saw domesticated species spread across the tropics and into the tropics from other climate zones and biomes. The tropical Pacific is a good place for studying this spread given the relatively late arrival of humans in these environments along with the rapid introduction of fire, invasive species such as rats, and domesticated species such as pigs. This colonization process often caused significant deforestation and disturbance of endemic biodiversity (24). However, the impacts were mediated according to island size and aspect, human cultural and economic practices, and dynamic socioeconomic responses; many communities sustainably managed island landscapes for millennia, until the arrival of European colonizers. Similarly, in parts of eastern Africa, the expansion of pastoralism coincided with impacts on biodiversity, such as the Holocene loss of megafauna on Madagascar (45), while, elsewhere in the region, pastoralism has been regarded as supporting biodiversity conservation (46). Many Holocene tropical communities exhibit diverse interactions with different plant and animal species, often transforming the landscape into "managed mosaics" (47) of cultivated crop fields, agroforestry systems with domesticated and nondomesticated tree species, recovering or intact forests, and freshwater ecosystems (48).

The arrival of European colonialism in the tropics provides numerous examples of the ways in which the so-called Columbian Exchange expanded the abrupt movement of species and pathogens along intra- and extratropical gradients and discontinued traditional management practices, resulting in tropical biodiversity and ecosystem reshuffling and new epidemiological landscapes (49). Moreover, new forms of land use, such as cash crop plantations, cattle or sheep ranches, and more intensive mining, led to widespread deforestation and the marginalization of traditional agroforestry and horticultural systems from which many regions (e.g., Haiti and the Brazilian Atlantic Forest) have never recovered (50). The colonial period may also have caused a permanent loss of genetic and crop diversity in other regions such as the Amazon Basin (51). Meanwhile, intensified global circulation of domesticated and invasive plant and animal species, which would further intensify during the Industrial period, reduced the number of endemic plants and diminished biodiversity, legacies that remain in different tropical zones today (52).

Geosphere

Some of the best-known pre-Industrial human impacts on the geosphere come from the tropics in the form of the Amazonian dark earth soils (known in Brazil as *terra preta do índio*), which have now been found across significant portions of the Amazon Basin. These dark, organic-rich soils have been linked to human burning and concentration of organic waste in settlements since the mid-Holocene, especially during the last 1,000–2,000 years (53, 54). Not only do humans seek to exploit and manufacture these soils for fertilizer solutions in the twenty-first century, but also their location on the landscape continues to shape smallholder settlement patterns and food production across the Amazon Basin (54). Modified soils are characteristic not only of this part of South America, however; numerous other examples, as well as forms of terracing used to slow soil erosion, are documented across the tropics (53).

Multidisciplinary studies of nutrient hot spots in eastern Africa have also documented more indirect actions on the geosphere, demonstrating that pastoral communities have produced pockets of nutrient-rich soils since the mid-Holocene that continue to dictate the location of the best grazing lands and wildlife movements around tropical savanna ecosystems in Kenya and Tanzania (55). Beyond inputs in the geosphere, past farming activities and deforestation have led to soil erosion and landscape morphology change on both local and regional scales (56). Although disputed, it has been argued that deforestation is linked to the expansion of food production and iron technology through Central Africa, resulting in erosion so pronounced it was detectable in the estuary of the Congo River (57) and in lacustrine records (26). As with the biosphere, European colonial land use represented a major rupture in human–soil dynamics in the tropics; the planting of sugarcane across much of the Neotropics is a well-known case of sapping nutrients and wasting soils (58). Similarly, in Kenya, colonial restriction of traditional grazing lands through ranches, wildlife parks, and fencing led to a concentration of pastoral herds, overgrazing, and large-scale soil erosion (59).

Hydrosphere

Tropical environments play a major role in hydrological cycles, with two-thirds of overland evapotranspiration linked to tropical forests (41). This means that vegetation changes in the tropics can have significant feedbacks on rainfall and water distribution. Early interactions with local hydrology are documented from around 9,000 years ago at the site of Kuk Swamp in New Guinea, where populations managing taro, banana, and the early ancestor of sugarcane dug drainage ditches to create more appropriate habitats for these various species (60). Human management of water in the tropics became increasingly intensive through time, however; the Aztec capital of Tenochtitlan is a particularly prominent example of hydrological engineering that shaped the water level and flow of an entire lake basin (61). Meanwhile, among the pre-Columbian Classic Maya, the highly varied hydrology of the region stimulated the emergence of a wide variety of water management techniques in seasonally dry tropical regions (10, 62), and similar concerns are found in the construction of vast reservoirs at the ancient urban centers of Greater Angkor (63), South India, and Sri Lanka (64).

Studies of feedbacks between tropical land use change, deforestation, and precipitation in the past remain limited but may prove informative. For example, Cook et al. (65) modeled generalized land use and land cover estimates associated with Classic Maya food production and urbanism in regional precipitation models, finding that human action may have reduced rainfall by as much as 15% in Central America. Documentation and estimation of this kind of impact become much more frequent for the colonial period in the tropics, as many observers and scientific studies have highlighted the ways in which deforestation linked to the expansion of plantation monoculture and ranching led to the drying of tropical landscapes through feedback mechanisms that continue to pose problems today. Today, current land use trajectories are at risk of pushing the Amazon Basin toward a tipping point, where water cycling and vegetation dynamics may cause the rainforest to transition permanently into a savanna (66).

DRYLANDS

Biosphere

Drylands cover 40% of the Earth's land area and support more than 20% of the world's population (67). Yet, arid and semiarid lands are often stereotyped as more depauperate and risky relative to wetter biomes, making them particularly interesting in discussions of human interactions with the biosphere through time. Late Pleistocene faunal turnover has been considered less extreme in the dry regions of Africa and South Asia (e.g., 68) than in other regions, although the degree to which humans might have influenced significant megafaunal extinctions in Australia remains hotly disputed (69). Arid and semiarid regions have featured prominently in discussions around the impacts of food production on the biosphere, such as in the Fertile Crescent (70). In these contexts, arid regions have been found to have encouraged the concentration of cultivated species planting along river edges and marshes, providing early examples of new human-mediated niches that were to appear and extend across the planet (71).

In the case of the Levant, during the Pre-Pottery Neolithic, approximately 10,000 years ago, agropastoralism likely caused a decrease in overall arboreal taxa and an increase in pastoral-adapted taxa, as evidenced in regional pollen records (72). At the start of the Chalcolithic period, approximately 6,500 years ago, early olive horticulture appeared in the southern Levant at around the same time as a large increase in *Olea europaea* (olive) pollen counts (73), a trend that increased through the Bronze Age and Hellenistic period as olive groves replaced woodlands across Mediterranean landscapes. This pattern is still visible today. Arid and semiarid habitats have also been central to discussions of the emergence of urbanism and its concomitant impacts on landscapes. Mesopotamia (and the Euphrates) and ancient Egypt (and the Nile) provide instances of the ways in which population concentrations and trading hubs near water bodies such as rivers, marshes, and irrigation canals in otherwise dry contexts witnessed both the arrival of new species from often significant distances and species extinctions (74). Indeed, marshlands and constrained ecological diversity have been argued to be especially relevant environmental variables in Mesopotamian urbanism (75).

Dry regions, including Australia, parts of Central America, South America, and southern Africa and Madagascar, saw major biodiversity changes with the arrival of European colonialism, including vegetation changes linked to introduced, large-scale livestock rearing, cash crop agriculture, pest species, overhunting, and the disruption of Indigenous land management strategies (11, 76). These changes have persisted into the twenty-first century.

Geosphere

Limited biological activity, dryness, and hardness can make arid soils prone to dramatic runoff, erosion, salinization, and desertification (77). Research has long emphasized how local political and economic contexts have shaped the timing and intensity of landscape destabilization in the semiarid Mediterranean and Levant. Major soil erosion episodes began to occur in the eastern Mediterranean as a result of deforestation, first attested in Syria for the Pre-Pottery Neolithic, approximately 9,000 years ago (78), only to increase as metallurgical and other pyrotechnic activities demanded increasingly greater amounts of wood fuel in later periods (79; but see, e.g., 80). Major soil erosion episodes also appear to follow 500–1,000 years after the arrival of agriculture in different parts of Greece in the late Neolithic and Early Bronze Age, while the middle of the first millennium BCE witnessed increasing erosion intensity in many areas (81). On the other side of the world, in the semiarid Mexican Highlands, geomorphological studies document severe soil erosion 900 years after the onset of maize cultivation (82). The introduction of livestock grazing in arid areas [which often (e.g., Australia), but not always, occurred with the arrival of European colonialism] (76) almost certainly had a major impact on soil stability and nutrient availability, as observed in modern studies of soil organic carbon values in northern China (83), with carbon flux increasing alongside grazing intensity.

Vulnerability to desertification has led to a number of cases of documented human–soil interactions ending with site abandonment. Well-known examples are the "great house" communities of Chaco Canyon in the southwestern United States that, through increasing woodland tree removal and maize agriculture, appear to have exacerbated soil erosion, lowering landscape resilience in the face of extreme aridity in the very early second millennium CE (84). Nevertheless, dramatically different local outcomes can occur depending on the presence and intensity of extractive economies, local ecological knowledge, and historical contingency. For example, in a comparison of two Roman-period settlements on the desert fringes of Roman Africa and Arabia, Barker (85) highlights the ways in which, in one location, irrigation agriculture and extensive pastoralism remained resilient while, in the other, imperial demands for mining and farming tribute led to dramatic soil erosion and abandonment. Notably, the application of later European colonial and imperial policies, as well as the eventual emergence of global capitalism, drove demands for larger herds and land use strategies unsuited to local ecological conditions (59). Alongside the denial of historic access to rangelands (59), these new ways of viewing and managing land often led to the significant destabilization of soils in dryland regions.

Hydrosphere

The potential for semiarid and arid ecosystems to desertify makes them potentially prone to human-induced feedbacks on the water cycle. At the broadest scale, Earth system modeling supports proposals that humans could have been active agents in the desertification of the Sahara following the African Humid Period (~14,500–5,000 years ago) (86). In particular, Wright (86), reviewing the available archaeological and paleoenvironmental literature, notes that the arrival of pastoralism across the region from 8,000 to 4,000 years ago would have reduced net productivity, led to a dominance of shrubs, and increased dry-adapted vegetation that, alongside climate factors, could have contributed to perhaps one of the most dramatic hydrological and landscape changes witnessed during the Holocene (but see 87). On a more local scale, Henry et al. (88) have argued that population increase, widespread trade, and an expansion of pastoralism (particularly higher stocking rates and a focus on secondary products) during the Chalcolithic (~5000–3500 BCE) and Early Bronze Age (~3500–2000 BCE) of Jordan resulted in desertification.

Past human societies also inserted themselves directly into the hydrosphere. From 6,500 years ago there is evidence for the construction of irrigation canals for agriculture along the Tigris and Euphrates plains in Mesopotamia that slowly raised the water table and initiated soil salinization, causing farmers to switch from wheat to salt-tolerant barley (89). With the emergence of dryland urbanism came the construction of entirely new water networks. In South Asia, the citizens of the Indus Civilization city of Mohenjo-daro cut hundreds of wells into their neighborhoods, channeled wastewater into public drains (90), and constructed the world's first massive public bath (90). In other parts of the Indus Civilization, agropastoral communities established themselves in locations that allowed them to take advantage of a wide range of water resources, from fed watercourses to monsoon rainfall (91). European colonialism and imperialism, followed by increasing global market pressures, saw more intense and global impacts on the hydrosphere in arid-prone environments, with ideals of urban planning, pastoral intensity, and the channeling of water for cash crops having major environmental and economic consequences. In what is now northwest India, British colonial institutions promoted sedentary agriculture, the planting of certain cash crops over traditional mobile pastoralism or mixed food production strategies in a land use change that, alongside major alterations to hydrology, Bhattacharya (92) has described as "the Great Agrarian Conquest."

THE TEMPERATE ZONE

Biosphere

Human impacts on temperate megafauna in the Late Pleistocene have long captured public and academic imaginations. The debate relating to the role of humans in the demise and extinction of megafauna, and the corresponding ecosystem changes that would have occurred with the loss of keystone species, has been particularly intense in North America (93). Moving into the Holocene, the spread of food production strategies to many parts of Europe during the Neolithic from 7,000 to 4,000 BCE, as well as the introduction of secondary products in the Bronze Age (94), established new domesticated plants and animals in temperate landscapes. Since at least the Bronze Age, long-distance trade of plants (such as grains) (95), animals (such as rabbits), and pathogens (such as smallpox) across the temperate zones of Eurasia (96), along with deforestation, transformed this region into a so-called cultural landscape (97). The consequences of the cultivation of indigenous grains, the eventual expansion of maize into temperate North America, and the impacts of pre-Columbian trade networks across the Americas remain relatively underexplored in this regard. However, recent historical ecology research in the temperate rainforests of the Pacific Northwest, comparing botanical diversity in former forest garden ecosystems with that of surrounding conifer forest, highlights a lasting legacy of past Indigenous management on contemporary forest health and resilience (98).

The appearance of iron technology increased human impacts on forest structure and species distributions in temperate Europe from the first millennium BCE onward (97), while the staged retreat of heavily wooded areas and large mammals over the past 3,000 years, including elephants and tigers, in the face of expanding populations and agriculture has been documented in China (99). The relatively late arrival of humans in the temperate portions of the Southern Hemisphere, notably New Zealand, has provided a particularly prominent case study of human impacts on the biosphere, with evidence for forest burning and the demise of large flightless birds (100). European colonization of the Americas, Oceania, and Asia undoubtedly intensified such impacts through global exchange of diseases, weeds, pests, and crops [the Columbian Exchange (49)]. Crops moving out of the equatorial regions (e.g., potato, maize), in turn, had impacts on temperate food systems, agricultural organization, and demography in Europe, as demonstrated by, for example, the rapid adoption of potato agriculture across northwestern Europe. These impacts had drastic consequences, especially when combined with colonial political neglect, on local environments and food supplies, such as in nineteenth-century Ireland (44).

The introduction of European cattle also had a strong impact on the temperate areas of the Americas, which were ideal for cattle reproduction and played a crucial role in the incorporation of these regions into colonial and, later, capitalist markets. The effect of this introduction was enhanced by the fact that, in many parts of the temperate Americas, European cattle had no competitors and could expand rapidly over Indigenous landscapes, generating long-lasting ecological and social impacts (101). Similar transformations occurred in temperate southeast Australia, where colonial invasion and introduction of hoofed animals transformed soft wetlands and woodlands into compacted, polluted swamp forest (102). Meanwhile, the removal of Indigenous care and management of their lands in southeast Australia following colonial invasion led to an increase in woody fuel accumulation. This shift resulted in the onset of catastrophic wildfire in these flammable landscapes that is contributing to current biodiversity crises in the region (103).

Geosphere

The abovementioned historical processes are intimately connected with changes in the geosphere in the form of impacts on temperate soil erosion and fertility. The role of Neolithic food production and Bronze Age agropastoralism in stimulating soil erosion in various parts of temperate Europe tends to be considered fairly minimal (104), though the interaction of pastoralism with soil systems in Central Asia may represent an early case of eco-engineering (105). Researchers have also suggested that the construction of Bronze Age barrows on Jutland may have influenced the distribution of topsoil by removal (106). In Central Europe, a comprehensive study (107) of ancient soils and hillslope erosion, land use, and climate change highlights that sediment mobility in small catchments was very sensitive to local land use and that basin-wide changes were related to regional trends. Progressively intensive erosion was witnessed during the Iron Age and the Roman and Medieval periods, leaving hillslopes vulnerable to subsequent extreme precipitation events. Two particularly severe occurrences in the early fourteenth and mid-eighteenth centuries CE resulted in intensive runoff on agricultural slopes that formed gully systems characteristic of European landscapes to this day (107).

Such erosion could be particularly extreme when associated with extraction of minerals from the land. For example, in a study of the Erzgebirge (Ore Mountains) along the German/Czech border, Kaiser et al. (108) combined pedology, archaeology, paleobotany, and geochronology to highlight a decline in mountain forests in the late twelfth to fifteenth centuries CE that resulted in soil erosion and colluvial deposition. While anthropogenic initiation of colluviation in the region extends back to the Bronze Age and Iron Age, the mining of ore in the Medieval and post-Medieval periods is associated with the most intense erosion (108). Paleoenvironmental and archival data demonstrate that entire landscapes became bereft of trees, with significant effects on local economies, soil nutrients, and resilience to external factors (108). So dramatic were these changes that they have been argued to represent the greatest landscape change of the Central European Uplands in the Late Holocene, and they have been the subject of significant reforestation initiatives since the eighteenth century (108). Although other temperate zones have been less well studied in this regard, extensive erosion following large farming population movements in China over the past 300 years has also been documented (109).

Hydrosphere

Human modifications to temperate landscapes have also taken the form of the deliberate redirection of water. It is clear that the Late Holocene witnessed significant human intervention in the hydrosphere. The extensive aqueducts and water infrastructure of the Roman Empire extended into temperate France and Germany, for example. The coasts of Europe have produced particularly prominent case studies of water management that are still referenced in engineering discussions today. Medieval migrants to the alluvial region of the present-day Netherlands, for example, built embankments, dikes, dams, sluices, and canals to protect sinking agricultural land from the encroachment of the sea and to channel water around the landscape (110). These efforts led to a massive reclamation of land from the sea that continued through the twentieth century CE. In sixteenth-century CE Venice, engineers diverted the entire course of the Po River, changing its deltaic organization permanently and destabilizing one of Italy's largest wetlands (111). Meanwhile, temperate China saw major hydraulic interventions, including dams, levees, and canals, to control water during the early imperial period (112).

Intentional human interventions in temperate river basins have increased over the last half-millennium, and water flow across many agricultural and urban landscapes in temperate Europe and North America, as well as parts of Asia, has been shaped by historical trajectories. Arguably, pervasive changes to the hydrosphere may also have occurred as a result of past changes in land use. Several observational and model simulation studies have explored the impacts of contemporary agricultural land use and deforestation on climate in temperate North America (113) and China (114). For Europe, modeling studies show that proposed reforestation of rain-fed agricultural land could trigger significant increases in precipitation (115), with the opposite occurring in the face of clearance. So far, few direct paleoenvironmental and modeling studies of past land use and its impacts on precipitation have been performed. However, given that major thresholds in deforestation have been proposed for temperate regions, it is reasonable to assume that the expansion of food production and agropastoralism, the introduction of iron technology, and changing socioeconomic use of forests may have had the potential to influence local and regional precipitation in temperate Europe, Asia, and North America.

ARCTIC, SUB-ARCTIC, AND HIGH-ALTITUDE ENVIRONMENTS

Biosphere

Arctic, sub-Arctic, and high-altitude environments have often been characterized as having patchy, dispersed resources and as being sensitive to climatic fluctuations. Nevertheless, they host a variety of endemic and introduced fauna that play a series of important ecosystem functions while providing food sources for human populations (116). Human interactions with mammoth communities provide one of the earliest potential instances of anthropogenic influence on sub-Arctic fauna communities, especially given the evidence of close cultural connections between human societies and mammoths (e.g., mammoth bone dwellings/structures) (117). A later but particularly evocative case study of past human impacts on sub-Arctic biospheres is that of the Norse colonization of the Faroe Islands (early ninth century CE), Iceland (late ninth century CE), and Greenland (tenth century CE). The Norse introduced domestic animals (e.g., sheep, goats, cattle, horses, and pigs) and husbandry practices that altered local vegetation communities (118), creating a mosaic of effects that caused endemic species decline as well as biodiversity promotion (e.g., creation of Faroese home fields) (119).

In Arctic, sub-Arctic, and montane settings, growing global market pressures for mining, cash crops, and food sources over the past 500 years, as well as the hunting of large game and introduction of pest species, saw more sustained and sweeping biodiversity impacts occur in many highland regions. Beginning in the seventeenth century, commercialized whaling and walrus hunting polluted coastal environments and fundamentally altered marine ecosystems (120). In the Greenland Sea, for example, the extirpation of bowhead whales likely permitted the rapid growth of cod and capelin populations, which in turn fed growing numbers of fish-eating birds, seals, and minke whales (15). Because alternating periods of warming and cooling changed how and where whalers could pursue whales in ways that ultimately benefited the whaling industry, the history of the Greenland Sea provides a particularly clear example of the role of modest pre-Industrial climate change in channeling human impacts on premodern environments (15, 121). A similar extractive approach to whales was also witnessed in the sub-Antarctic islands of New Zealand in the nineteenth century (122).

In montane settings, plant communities have been particularly vulnerable to the introduction of animal grazing. For example, on the Qinghai–Tibetan Plateau, Huang et al. (123) document the presence of *Stellera* pollen, an indicator of grazing-induced grassland degradation, by 4,700 years cal. BP following the expansion of agropastoral groups ~5,000 years ago, with an intensification by 1,600 years ago, from the Tang dynasty onward. The construction of agricultural terraces could lead to significant deforestation and biodiversity loss, as it did with the spread of *Zea mays* in some parts of the Peruvian Andes during the Late Holocene, especially with the expansion of imperial Inka land use and tribute demands in different regions (124). Nevertheless, there is evidence that multiple highland groups promoted biodiversity of both domesticated and wild species in their terraces, and the Inka also promoted locally contingent food production strategies (125). Larger impacts on highland biodiversity occurred during the European colonial period with the introduction and expansion of sheep and goats in many regions and the deliberate hunting or replacement of native species, such as vicuñas in the Andes (126).

Geosphere

Sub-Arctic and montane settings pose a series of geomorphic and pedological challenges for human societies. In a sub-Arctic context, the abovementioned Norse colonization of Iceland represents a particularly well studied instance of widespread human impacts on soils. The andosols of Iceland are highly vulnerable to erosion if exposed (127); habitats familiar to Norse farmers, such as heath and upland grasslands, are particularly sensitive to disturbance (e.g., 27). Woodland clearance for the grazing of livestock resulted in enhanced soil erosion, compounding the effects of volcanic eruptions and extreme weather. The cumulative degradation of grazed landscapes, through the interplay of social and ecological factors over the past millennium, has enhanced desert areas that now cover 35,000–45,000 km^2 (or 35–45%) of the island (128). Before tenth-century CE settlement, many of these current desert areas were vegetated and covered with fertile andosols (127). Nevertheless, the Norse subsistence system, based on utilizing resources from domesticated and wild species in terrestrial and marine ecosystems, has also proven to be remarkably resilient (129), even increasing biodiversity in some places and maintaining highly productive areas for fodder production until today (130).

In high-altitude areas, shallow rooting, slope instability, rocky escarpments, and exposure to harsh weather can all increase the propensity for soil erosion and natural hazards such as mudslides (131). In the Andes, the impacts of more than 82,000 hectares of terraces and raised fields on soil stability have long been discussed and characterize the appearance of vast portions of this mountain chain today (132). Nevertheless, evidence for agroforestry along these managed field systems, as well as reforestation efforts following observations of regional erosion, by Inka societies in the early second millennium CE (133) highlight the ways in which local knowledge of terrain was implemented. Many high-altitude areas have suffered significantly from European colonial policies, including the introduction of sheep and goats, monoculture terracing, deforestation, and mining (134), which have left lasting sustainability issues and landscape legacies for twenty-first-century communities.

Hydrosphere

Sub-Arctic and high-altitude settings are closely tied to the hydrosphere, in terms of both the presence of significant ice and glacier formations (including sea ice), respectively, and the role of these environments in climate system dynamics on regional and global scales (66). Potential human impacts on the hydrosphere, notably in high-altitude areas, include reshaping of drainage basins through terraces and water channels. In the Andes, 1,400-year-old pre-Inka water diversion systems may have permanently enhanced the yield and resilience of natural springs, particularly in the dry season (135). Anthropogenic intervention in high-altitude water systems may have very different consequences, however. For example, in a review of nineteenth- and twentieth-century historical processes in mountain areas in the Swedish Arctic, Swiss Alps, Colorado Front Range, and Papua New Guinea, Wohl (136) highlights the ways in which dams, diversion, and land use have had major impacts on stream persistence, stability, and connectivity.

Finally, contemporary observations show that the removal of trees and organic-rich humus and soil from highland areas can lead to both local and regional drying and reductions in rainfall as a result of loss of evapotranspiration, something that has been suggested for both the Himalayas and Andes in recent history (137). Reinhardt-Imjela et al. (138), focusing on the Ore Mountains of southeastern Germany in the twentieth century, have also highlighted how deforestation can significantly worsen the magnitude of flood events in montane environments. These feedbacks require further multidisciplinary examination in different pre-Industrial high-altitude contexts to determine the degrees to which past land use has shaped the resilience and dynamics of water discharge systems and local climate in these regions today.

ATMOSPHERE AND CRYOSPHERE

We have separated past human impacts on the atmosphere and cryosphere from the more specific biome and climate zone studies because suggested human influence on these portions of the Earth system tends to be a product of summed local and regional impacts. For example, Ruddiman (36) proposed in 2003 that, by 5,000 years ago, the expansion of food production, especially crop agriculture and domesticated ruminant animals, had resulted in such significant land use changes that CO_2 and methane emissions in the atmosphere became detectable. However, the magnitude of this contribution is uncertain and has also been attributed, at least in part, to natural emissions (139). Regardless of their exact contribution, early land use emissions likely began a trend in atmospheric change that, following well-documented Industrial fossil fuel burning and under moderate twenty-first-century emissions scenarios, is expected to delay our planet's movement into a new glacial state by at least 100,000 years (140). While there are different regional cases—for example, water buffalo and rice have been considered major contributors to emissions in the tropics, where Earth system feedbacks may have been particularly powerful (141)—it is the summed impact on the atmosphere that has been regarded as important.

Similarly, the arrival of Europeans in the Neotropics in 1492 brought diseases to which local Indigenous populations had limited previous exposure. The resulting mortality from these diseases, as well as the colonial massacres, dispossession, enslavement, and concentration of Indigenous populations in confined areas (142), has been estimated to have been as high as 90% in parts of the Americas after two to three generations (37, 142). This demographic collapse has been argued to have resulted in a dramatic reduction of Indigenous land use and regrowth of forest that was significant enough to have been the cause of the so-called Orbis spike in atmospheric CO_2 decline, which may—alongside volcanic eruptions—have contributed to cooling during a particularly cold stretch of the Little Ice Age (37), though this hypothesis remains very hotly debated (143, 144). Although the nature of environmental change, and the relevance of this process on a global scale (e.g., in colonial Southeast Asia and the Pacific), remains to be further explored (144, 145), it represents another potential example of pre-Industrial human impact on the atmosphere and, ultimately, the cryosphere.

The human harnessing and application of fire to multiple landscapes, from the tropics to temperate grasslands, represent another instance where human behavior interacted with the air. Clear evidence of the deliberate use of fire by our species has been argued to date back to 80,000 years ago in Malawi, where burning seems to have altered the environments surrounding a river system (146). Further examples of human use of fire to maintain vegetation structure and pathways of movement, promote new growth and movement of animals, and shape fire resilience are documented in various environments, from California and the eastern United States (147) to Australia (148). It may have even had strong combined consequences. For example, Kaplan et al. (149) proposed that the scale of forest burning in Europe during the Last Glacial Maximum, the last major, maximum extent of global ice sheets, was enough to have led to emissions that buffered the worst effects of cooling during this period and to have resulted in further land cover change than would have otherwise been expected.

While these cases of fire are registered primarily in the form of vegetation change, it is clear that the growing frequency and scale of wildfires today, in some cases an intensification that can be linked to colonial era policy and land use disruption (103), can be major causes of pollution and the transport of charcoal and ash over vast distances (150). The deposition of macrocharcoal (>125 μm) in lake basins and other sequences highlights the ways in which human fire use interacted with the air, albeit perhaps without significant Earth system consequences beyond the biosphere until industrialization. Other examples of early atmospheric impact appear in the form of the introduction of pollutants into the air by past societies. For example, lead produced from mining in Europe is documented in NGICP (North Greenland Ice Core Project) ice cores, where variations in emissions are synchronous with historical events. In particular, high emissions are often observable during periods of economic prosperity, such as the height of the Roman Empire (151). Similarly, lead by-products linked to Indigenous Inka mining in South America are also detectable on a regional basis in Andean glaciers, with significant increases then documented with the Spanish takeover of these mines and their addition of mercury to mining technology (152).

The most dramatic human impacts on the atmosphere begin with the Industrial Revolution. Related emissions have played a major role in the warming of the planet to 1.2°C (so far) compared with late-nineteenth-century, pre-Industrial levels (153). In turn, this warming has altered the cryosphere substantially. The polar ice caps have increasingly been shrinking as concentrations of greenhouse emissions in the atmosphere have increased, approaching a tipping point in their stability and the role they play in the Earth system (66). Although our review is limited to the pre-Industrial era, understanding historical records of the burning of fossil fuels and their role in global warming reveals how much of the contributing emissions came from the Global North up until the last 20 years (when China and, more recently, India began to contribute significantly), highlighting the imbalance within the Anthropocene and the political difficulties in attempting to phase out fossil fuel burning without some form of compensatory mechanism for other nations. Evidence of pre-Industrial and Industrial pollutants in the atmosphere also provides an important baseline for understanding the degree to which the changes observed in the so-called Great Acceleration (e.g., microplastics, fertilizers) represent a logarithmic departure from previous human impacts on the atmosphere.

DISCUSSION AND CONCLUSIONS

This review has highlighted the diverse and growing evidence for pre-Industrial human impacts on the Earth system in all of the major climate zones and biomes mentioned above (**Figure 3**).

Pleistocene hunter-gatherers influenced biodiversity through hunting and fire management, influences that may have extended even to the carbon cycle (43). The emergence and expansion of food production brought new human-mediated ecosystems; the expansion of domesticated and invasive species; soil changes; and growing impacts on land use, land cover, and associated emissions (36). Since 5,500 years ago, the appearance of urban centers and regional networks in different parts of the globe has expanded biodiversity exchange across continents, creating new cultural niches with mixed wild and domesticated plant and animal species. These networks also stimulated the expansion of different technologies and economic systems that placed new demands on environments (7), resulting in the more rapid spread of disease between regions and pressures of expanding populations on regional hinterlands and landscapes. These "thresholds" (for discussion in the tropics, see 141) saw the expanding footprint of human societies on the Earth system that left tangible impacts across a variety of different environments by the Late Holocene. However, the emergence and development of pre-Industrial human impacts on the Earth system should not be considered a unidirectional process but rather a set of varied interactions, molded by diverse geographic, economic, demographic, social, and cultural contexts, that profoundly shaped global human history. This interaction began with local human niche constructions, affecting both environments and societies, and eventually took on a global dimension through the creation of ever more densely connected networks among these local and regional human niches. In the course of this history, the comprehensive impact of humans on the Earth system and the underlying political and economic transformations contributed to shifts in the dynamics of an additional Earth sphere, the technosphere, embedded within the wider Earth system (7).

As has been documented in all of the biomes mentioned above, human impacts on the environment clearly accelerated from the late fifteenth century onward. In part, this acceleration reflects regional recoveries in population following plague pandemics of the mid-fourteenth to mid-fifteenth centuries and the demographic impacts of the first introductions of Old World pathogens to the Americas in the sixteenth and seventeenth centuries (142). Yet it was primarily rising market economies, increasingly powerful states, and global trade that encouraged the extraction of distant commodities for a growing population of consumers in Europe (154). As a result, some forms of modification of the environment were replaced by others, including unsustainable and eventually maladapted practices concerned primarily with the centralization of wealth and the growth of asymmetrical consumption. States and empires increased the scale of resource extraction in their core territories for urban and military provisioning, such as timber for navies (155). In their peripheries—including arid, tropical, Arctic, and marine regions—they typically permitted or encouraged activities such as fur trapping, whaling, forest clearance, and cash crop production, which had significant and enduring effects on the biosphere, geosphere, and possibly atmosphere and cryosphere (15). Colonization also involved both deliberate and accidental exchange of plants, animals, and microbes. Although this review has focused on European colonization, which certainly played the dominant role in the emergence of contemporary global sustainability challenges and economic and social inequalities, we should not overlook the impacts of some of the other empires in the seventeenth and eighteenth centuries, including the Mughal Empire expansion into South Asia, Ming and Qing dynasty expansions across China and Central Asia, and Tokugawa expansion into Hokkaido (e.g., 156).

The resulting global interactions and formalization of certain attitudes to landscapes had reverberations that extended into the nineteenth and twentieth centuries. In both plantation and settler colonies, empires and their agents deliberately replaced existing populations and land use with enslaved or waged workers while also introducing new crops and livestock (157). In Brazil, Cuba, and the US South, plantation dynamics and large-scale deforestation continued during the nineteenth century in a period of "second slavery" that supported industrial production in Europe

(158). In settler colonies such as Australia, in the nineteenth century, many Indigenous communities were forced away from Country that they had long managed, cultivated, and occupied (11). British settler colonial structures have had an ongoing impact in both Australia and Canada, where colonizers removed First Nations children from their families under the guise of child protection and educational schemes in the twentieth century, while land rights struggles have continued into the twenty-first century (159). Meanwhile, conservation initiatives to maintain "natural" park areas have sometimes reinforced the confiscation of Indigenous land, obstructing practices such as burning, seed planting, and animal management that have shaped ecosystems over millennia (11, 160). This model of "fortress conservation" has also had massive human rights implications in Africa and Asia (161). The magnitude of these environmental changes during the Early Modern period has raised significant questions about contemporary baselines for environmental preservation and restoration, as well as the modern conception of wilderness enshrined in, for example, the US Wilderness Act of 1964 and the Land Conservation Act of 1970 (Victoria) in parts of Australia (160).

On a broader theoretical level, numerous historians and sociologists have argued that European colonialism and imperialism played a key role in the emergence of capitalism and the commodification of subjugated peoples, their labor, their land, and the ecosystems within which they lived. Certainly, other imperial forces in Central and South America and Asia, which encountered European colonizers, had significant environmental impacts too. In many cases, European empires fed into the existing extractive infrastructures of the regions that they conquered (38, 39). Nevertheless, the mobilization of resources from colonies to serve imperial ambition and elite wealth accumulation took on a new, global intensity with the European establishment of colonies on different continents. The sixteenth, seventeenth, and eighteenth centuries saw various European empires compete in an increased focus on landscape conversion, the growth of cash crops, and the emergence of the Atlantic slave trade, with the associated capital accumulation helping to launch the Industrial Revolution (162). The subsequent expansion of fossil fuel burning drove technological change, along with the development of new transport networks and capitalist enterprises. The benefits of this economic transformation were long concentrated within the hands of a few wealthy nation-states in the Global North, with these countries contributing the largest cumulative share of greenhouse gas emissions from fossil fuel sources to date (163). These processes also saw the emergence of new frontiers of extraction, the application of racist ideologies to landscape management and economic activities, and a further reification of the unequal relationship between countries in the North Atlantic and their colonies (164). Such trends continued into the twentieth century and the Great Acceleration. Even after the wave of decolonization following World War II, the ongoing economic dominance of the United States, along with the rise of China and the continuation of extractivist policies by both these global powers, has shaped the socioenvironmental and economic landscape of the twenty-first century (165, 166).

Studying past human impacts on the Earth system in a way that is relevant to contemporary societies demands new methodologies and new levels of disciplinary integration and collaboration. At the local level, we have seen how multidisciplinary approaches can provide new, high-resolution insights into how particular ecosystems, soil structure and stability, and water management have changed over time in a given area, as well as the degree to which historical activities have influenced contemporary dynamics. At the broadest level, there is a growing interest in exploring patterns, trends, ruptures, and tipping points in the technosphere and its coevolution with the rest of the Earth system (167). The recognition that pre-Industrial human socioeconomic systems have influenced different parts of the Earth system has led to collaborative modeling of past land use and land cover change so that they can be factored into models of soil erosion, precipitation, carbon cycling, and biodiversity change (20). Meanwhile, applying theory from biological systems improves our understanding of how certain socioeconomic system dynamics might lead to regenerative or deleterious human interactions with the environment and portions of the Earth system. While archaeology has often been resistant to such models of social change and human–environment interactions, acknowledging this dynamic coevolution and the potential existence of certain trends, limits, or vulnerabilities can be critical for determining the degree to which interplays between external conditions (e.g., climate change) and internal dynamics (e.g., social structures) shaped the adaptability and sustainability of different societies in the past. Archaeology also enables investigation of the deep-time aspect of the technosphere, and how changes in flows of information, energy, labor, and resources have shaped human lives around the planet up to the present day (7). The scale of expansion and extraction within the technosphere from the fifteenth century onward requires greater attention, as sources of resistance and pathways of divergence may guide future efforts to bend these dynamics toward more sustainable lifeways. Here, research into Indigenous resistance and governance, local politics, and geography is critical (11, 168).

To address the scale of human influence on different parts of the Earth system and their legacy effects over time, research communities must assess and apply insights from the past to future predictions of our relationship with the planet. While such work promises to identify connections between the past and present more clearly than ever before, we argue that our current state of knowledge is already providing important contributions to twenty-first-century ecosystem services maintenance, conservation, and policymaking in a series of different ways. For example, studies combining ethnography, archaeology, paleoecology, and ecological modeling document how intensive wood and fire use by Native American Pueblo ancestors influenced fire size, fire–climate relationships, and fire intensity (169). These long-term perspectives offer an alternative model for fire management within the modern wildland–urban interface in the western United States, where local management of woody fuels through use (domestic wood collecting) coupled with small prescribed fires enhance communities' self-reliance and increase resilience to wildfire hazards. Areas of dryland Australia to which Indigenous management has returned following removal and dispossession have shown a remarkable return of biodiversity and a reduction in the severity and incidence of wildfires that have affected these regions (170). Meanwhile, local park reserves in the United Kingdom have consulted paleoecologists to understand the presence or absence of historical human impacts when managing forest composition and dynamics today (171). Such engagement, as well as exploration of the historical trajectories of human–environment–Earth system interactions discussed here, offers the opportunity to explore the degree to which certain policies, land management strategies, and cultural actions can have predictable, or unintended, impacts on environmental and Earth system change. This is a critical question as we seek to navigate the Anthropocene, but little archaeological and historical research has focused on this question until now.

Within the context of the Holocene, the last 500 years of colonial and imperial expansion have heavily shaped humans' current relationship with the Earth system, which has left a mark on socioeconomic and political relationships between the Global North and Global South. Recognition of this fact encourages further emphasis on reparation programs, global support for communities living on the front line of climate change, and the mobilization and vocalization of local stakeholders in expressing the urgency and human costs of climate change and exploitative economic practices that continue to damage environments and local livelihoods. Historical perspectives can help us understand the origins of the current climate crisis. In so doing, they can also help us explore the ways out of it, highlighting the urgency arising from recent human impacts, repairing the disconnect between local land use and global economic demands, and acknowledging the need for just political, economic, and environmental policy.

SUMMARY POINTS

1. Formal geological designation of the Anthropocene epoch starting in 1950 was recommended by the Anthropocene Working Group of the International Commission on Stratigraphy.
2. The recent rejection of this designation by the International Commission on Stratigraphy highlights the need to explore human–Earth system dynamics across a variety of spatial and temporal scales.
3. Indeed, it is clear that the social and environmental roots of the Anthropocene lie deeper in the past.
4. We review the ways in which archaeology, historical ecology, and paleoecology, alongside Indigenous knowledge, document the ways in which human societies influenced the Earth system prior to the Industrial Age and left legacies for the twenty-first century.
5. While not exhaustive, the examples provided cover all of the major climate zones and biomes of the planet, highlighting the diverse and growing evidence for pre-Industrial human impacts on environments, as well as their Earth system feedbacks.
6. It is clear that European colonialism resulted in some of the more visible consequences for human societies, in particular economic and social inequalities along with dramatic landscape and environmental transformation, shaping the manifestation of the Anthropocene and its challenges.
7. We argue that understanding long-term relationships between humans and the Earth system will be essential to develop more equitable and sustainable relationships with the planet in the present and future.

FUTURE ISSUES

1. The emerging body of research reviewed here highlights the practical ways in which the past can help us to envisage alternative futures in the Anthropocene present.
2. Multidisciplinary research at local scales should focus on characterizing and quantifying how soil structures, distribution, and content; ecosystem diversity and dynamics; and water management have changed in a given area through time, as well as the ways in which historical processes influence contemporary contexts.
3. Meanwhile, regional and even global documentation of land use and land cover change can be factored into Earth system models to explore how human actions have influenced soil erosion, precipitation, carbon cycling, and biodiversity, along with the use of quantitative data sets to inform modeled scenarios of the present as well as future predictions.
4. There is also a need to explore trajectories, ruptures, and tipping points in the history of the technosphere and its coevolutionary interactions with the other parts of the Earth system.

5. More study is required to determine the degree to which European colonialism in different parts of the world, as well as other imperial formations, initiated novel human–environment–Earth system interactions that continued with the expansion of global market economics.
6. Additionally, examining historical evidence of resistance to, and divergence from, these dominant structures can help steer future efforts toward more sustainable alternatives.
7. There is also a pressing need to communicate findings from archaeology, environmental history, historical ecology, and paleoecology to policymakers responsible for conservation, cultural access to land use, and climate change management.
8. In this way, we can perhaps repair the disconnect between local land use and global economic demands and acknowledge the need for just political, economic, and environmental policy.

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The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

P.R., V.L.S., K.D.M., S.W., D.D., A.S.G., and C.I. conceived of the article idea and wrote the original draft. P.R., R.H., R.R., F.S., and M.F. conceived of and worked on drafts of the figures. All authors contributed to writing and revising the article.

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LITERATURE CITED

1. McNeill JR, Engelke P. 2016. *The Great Acceleration: An Environmental History of the Anthropocene Since 1945*. Cambridge, MA: Harvard Univ. Press
2. Zalasiewicz J, Waters CN, Williams M, Barnosky AD, Cearreta A, et al. 2015. When did the Anthropocene begin? A mid-twentieth century boundary level is stratigraphically optimal. *Quat. Int.* 383:196–203
3. Head MJ, Zalasiewicz JA, Waters CN, Turner SD, Williams M, et al. 2022. The proposed Anthropocene Epoch/Series is underpinned by an extensive array of mid-20th century stratigraphic event signals. *J. Quat. Sci.* 37(7):1181–87
4. Witze A. 2024. It's final: The Anthropocene is not an epoch, despite protest over vote. *Nature News*, March 20
5. Malhi Y. 2017. The concept of the Anthropocene. *Annu. Rev. Environ. Resour.* 42:77–104
6. Watson JEM, Evans T, Venter O, Williams B, Tulloch A, et al. 2018. The exceptional value of intact forest ecosystems. *Nat. Ecol. Evol.* 2(4):599–610
7. Renn J. 2020. *The Evolution of Knowledge: Rethinking Science for the Anthropocene*. Princeton, NJ: Princeton Univ. Press
8. Ellis EC, Gauthier N, Klein Goldewijk K, Bliege Bird R, Boivin N, et al. 2021. People have shaped most of terrestrial nature for at least 12,000 years. *PNAS* 118(17):e2023483118

9. Balée W. 2013. *Cultural Forests of the Amazon: A Historical Ecology of People and Their Landscapes*. Tuscaloosa: Univ. Ala. Press
10. Isendahl C, Stump D. 2019. *The Oxford Handbook of Historical Ecology and Applied Archaeology*. Oxford, UK: Oxford Univ. Press
11. Fletcher M-S, Hamilton R, Dressler W, Palmer L. 2021. Indigenous knowledge and the shackles of wilderness. *PNAS* 118(40):e2022218118
12. Green AS, Wilkinson D, Wilkinson TC, Highcock N, Leppard T. 2024. *Cities and Citadels: An Archaeology of Inequality and Economic Growth*. London: Routledge
13. Bevan A, Colledge S, Fuller D, Fyfe R, Shennan S, Stevens C. 2018. Holocene fluctuations in human population demonstrate repeated links to food production and climate. *PNAS* 114(49):E10524–31
14. Boivin NL, Zeder MA, Fuller DQ, Crowther A, Larson G, et al. 2016. Ecological consequences of human niche construction: examining long-term anthropogenic shaping of global species distributions. *PNAS* 113(23):6388–96
15. Degroot D, Anchukaitis KJ, Tierney JE, Riede F, Manica A, et al. 2022. The history of climate and society: a review of the influence of climate change on the human past. *Environ. Res. Lett.* 17:103001
16. Allen RC. 1992. *Enclosure and the Yeoman: The Agricultural Development of the South Midlands, 1450–1850*. Oxford, UK: Oxford Univ. Press
17. Meggers BJ. 1979. Climatic oscillation as a factor in the prehistory of Amazonia. *Am. Antiq.* 44(2):244–56
18. Scarborough VL, Isendahl C. 2020. Distributed urban network systems in the tropical archaeological record: toward a model for urban sustainability in the era of climate change. *Anthr. Rev.* 7(3):208–30
19. Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, et al. 2001. Terrestrial ecoregions of the world: a new map of life on Earth. *Bioscience* 51(11):933–38
20. Morrison KD, Hammer E, Boles O, Madella M, Whitehouse N, et al. 2021. Mapping past human land use using archaeological data: a new classification for global land use synthesis and data harmonization. *PLOS ONE* 16(4):e0246662
21. Roos CI, Zedeño MN, Hollenback KL, Erlick MMH. 2018. Indigenous impacts on North American Great Plains fire regimes of the past millennium. *PNAS* 115(32):8143–48
22. Romano A, Fletcher M-S. 2018. Evidence for reduced environmental variability in response to increasing human population growth during the Late Holocene in northwest Tasmania, Australia. *Quat. Sci. Rev.* 197:193–208
23. Amano N, Bankoff G, Findley DM. 2021. Archaeological and historical insights into the ecological impacts of pre-colonial and colonial introductions into the Philippine Archipelago. *Holocene* 31(2):313–30
24. Swift JA, Roberts P, Boivin N, Kirch PV. 2018. Restructuring of nutrient flows in island ecosystems following human colonization evidenced by isotopic analysis of commensal rats. *PNAS* 115(25):6392–97
25. Janzen A, Balasse M, Ambrose SH. 2020. Early pastoral mobility and seasonality in Kenya assessed through stable isotope analysis. *J. Archaeol. Sci.* 117:105099
26. Garcin Y, Schildgen TF, Torres Acosta V, Melnick D, Guillemoteau J, et al. 2017. Short-lived increase in erosion during the African Humid Period: evidence from the northern Kenya Rift. *Earth Planet. Sci. Lett.* 459:58–69
27. Streeter R, Dugmore A. 2014. Late-Holocene land surface change in a coupled social-ecological system, southern Iceland: a cross-scale tephrochronology approach. *Quat. Sci. Rev.* 86:99–114
28. Kiage LM, Liu K-B. 2006. Late Quaternary paleoenvironmental changes in East Africa: a review of multiproxy evidence from palynology, lake sediments, and associated records. *Prog. Phys. Geogr. Earth Environ.* 30(5):633–58
29. Junqueira AB, Shepard GH, Clement CR. 2010. Secondary forests on anthropogenic soils in Brazilian Amazonia conserve agrobiodiversity. *Biodivers. Conserv.* 19:1933–61
30. Maezumi SY, Gosling WD, Kirschner J, Chevalier M, Cornelissen HL, et al. 2021. A modern analogue matching approach to characterize fire temperatures and plant species from charcoal. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 578:110580
31. Sippel S, Reichstein M, Ma X, Mahecha MD, Lange H, et al. 2018. Drought, heat, and the carbon cycle: a review. *Curr. Clim. Change Rep.* 4(3):266–86

32. Fletcher M-S, Hall T, Alexandra AN. 2021. The loss of an indigenous constructed landscape following British invasion of Australia: an insight into the deep human imprint on the Australian landscape. *Ambio* 50(1):138–49
33. Maezumi SY, Alves D, Robinson M, de Souza JG, Levis C, et al. 2018. The legacy of 4,500 years of polyculture agroforestry in the eastern Amazon. *Nat. Plants* 4:540–47
34. Roberts P, Buhrich A, Caetano-Andrade V, Cosgrove R, Fairbairn A, et al. 2021. Reimagining the relationship between Gondwanan forests and Aboriginal land management in Australia's "Wet Tropics." *iScience* 24(3):102190
35. Cook B, Zeng N, Yoon J-H. 2012. Will Amazonia dry out? Magnitude and causes of change from IPCC climate model projections. *Earth Interact*. 16(3):1–27
36. Ruddiman WF. 2003. The Anthropogenic Era began thousands of years ago. *Clim. Change* 61:261–93
37. Koch A, Brierley C, Maslin MM, Lewis SL. 2019. Earth system impacts of the European arrival and Great Dying in the Americas after 1492. *Quat. Sci. Rev.* 207:13–36
38. Richards JF. 2003. *The Unending Frontier: An Environmental History of the Early Modern World*. Berkeley: Univ. Calif. Press
39. White S. 2011. *The Climate of Rebellion in the Early Modern Ottoman Empire*. Cambridge, UK: Cambridge Univ. Press
40. Cronon W. 1996. The trouble with wilderness: or, getting back to the wrong nature. *Environ. Hist.* 1(1):7–28
41. Malhi Y, Gardner TA, Goldsmith GR, Silman MR, Zelazowski P. 2014. Tropical forests in the Anthropocene. *Annu. Rev. Environ. Resour.* 39:125–59
42. Bush MB, Rozas-Davila A, Raczka M, Nascimento M, Valencia B, et al. 2022. A palaeoecological perspective on the transformation of the tropical Andes by early human activity. *Philos. Trans. R. Soc. B* 377(1849):20200497
43. Doughty CE, Wolf A, Morueta-Holme N, Jørgensen PM, Sandel B, et al. 2016. Megafauna extinction, tree species range reduction, and carbon storage in Amazonian forests. *Ecography* 39(2):194–203
44. Nunn N, Qian N. 2010. The Columbian Exchange: a history of disease, food, and ideas. *J. Econ. Perspect.* 24(2):163–88
45. Godfrey LR, Scroxton N, Crowley BE, Burns SJ, Sutherland MR, et al. 2019. A new interpretation of Madagascar's megafaunal decline: the "Subsistence Shift Hypothesis." *J. Hum. Evol.* 130:126–40
46. Little PD. 1996. Pastoralism, biodiversity, and the shaping of savanna landscapes in East Africa. *Africa* 66(1):37–51
47. Fedick SL, ed. 1996. *The Managed Mosaic: Ancient Maya Agriculture and Resource Use*. Salt Lake City: Univ. Utah Press
48. Sugiyama N, Martínez-Polanco MF, France CAM, Cooke RG. 2020. Domesticated landscapes of the neotropics: osotope signatures of human-animal relationships in pre-Columbian Panama. *J. Anthropol. Archaeol.* 59:101195
49. Crosby AW. 1972. *The Columbian Exchange*. Westport, CO: Greenwood
50. Dean W. 1997. *With Broadax and Firebrand: The Destruction of the Brazilian Atlantic Forest*. Berkeley: Univ. Calif. Press
51. Clement CR. 1999. 1492 and the loss of Amazonian crop genetic resources. II. Crop biogeography at contact. *Econ. Bot.* 53(2):203–16
52. Liu D, Semenchuk P, Essl F, Lenzner B, Moser D, et al. 2023. The impact of land use on non-native species incidence and number in local assemblages worldwide. *Nat. Commun.* 14:2090
53. Arroyo-Kalin M. 2014. Amazonian dark earths: geoarchaeology. In *Encyclopedia of Global Archaeology*, ed. C Smith, pp. 168–78. New York: Springer
54. Schmidt MJ, Goldberg SL, Heckenberger M, Fausto C, Franchetto B, et al. 2023. Intentional creation of carbon-rich dark earth soils in the Amazon. *Sci Adv*. 9(38):eadh8499
55. Marshall F, Reid REB, Goldstein S, Storozum M, Wreschnig A, et al. 2018. Ancient herders enriched and restructured African grasslands. *Nature* 561(7723):387–90
56. Heckmann M, Muiruri V, Boom A, Marchant R. 2014. Human-environment interactions in an agricultural landscape: a 1400-yr sediment and pollen record from North Pare, NE Tanzania. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 406:49–61

57. Bayon G, Dennielou B, Etoubleau J, Ponzevera E, Toucanne S, Bermell S. 2012. Intensifying weathering and land use in Iron Age Central Africa. *Science* 335(6073):1219–22
58. Moore JW. 2010. Madeira, sugar, and the conquest of nature in the "first" sixteenth century. Part II: From regional crisis to commodity frontier, 1506–1530. *Rev. Fed. Am. Health Syst.* 33(1):1–24
59. Boles OJC, Shoemaker A, Courtney Mustaphi CJ, Petek N, Ekblom A, Lane PJ. 2019. Historical ecologies of pastoralist overgrazing in Kenya: long-term perspectives on cause and effect. *Hum. Ecol.* 47(3):419–34
60. Golson J, Denham T, Hughes P, Swadling P, Muke J. 2017. *Ten Thousand Years of Cultivation at Kuk Swamp in the Highlands of Papua New Guinea*. Canberra: Aust. Natl. Univ. Press
61. Armillas P. 1971. Gardens on swamps. *Science* 174(4010):653–61
62. Lucero LJ. 2023. Ancient Maya reservoirs, constructed wetlands, and future water needs. *PNAS* 120(42):e2306870120
63. Evans D, Pottier C, Fletcher R, Hensley S, Tapley I, et al. 2007. A comprehensive archaeological map of the world's largest preindustrial settlement complex at Angkor, Cambodia. *PNAS* 104(36):14277–82
64. Bebermeier W, Abeywardana N, Susarina M, Schütt B. 2023. Domestication of water: management of water resources in the dry zone of Sri Lanka as living cultural heritage. *Wiley Interdiscip. Rev. Water* 10(4):e1642
65. Cook BI, Anchukaitis KJ, Kaplan JO, Puma MJ, Kelley M, Gueyffier D. 2012. Pre-Columbian deforestation as an amplifier of drought in Mesoamerica. *Geophys. Res. Lett.* 39:L16706
66. Wunderling N, Donges JF, Kurths J, Winkelmann R. 2021. Interacting tipping elements increase risk of climate domino effects under global warming. *Earth Syst. Dyn.* 12(2):601–19
67. Barker G, Gilbertson D. 2003. *The Archaeology of Drylands: Living at the Margin*. London: Routledge
68. Roberts P, Delson E, Miracle P, Ditchfield P, Roberts RG, et al. 2014. Continuity of mammalian fauna over the last 200,000 y in the Indian subcontinent. *PNAS* 111(16):5848–53
69. Louys J, Braje TJ, Chang C-H, Cosgrove R, Fitzpatrick SM, et al. 2021. No evidence for widespread island extinctions after Pleistocene hominin arrival. *PNAS* 118(20):e2023005118
70. Zeder MA. 2011. The origins of agriculture in the Near East. *Curr. Anthropol.* 52(Suppl. 4):S221–35
71. Hritz C, Pournelle JR. 2016. Feeding history: deltaic resilience, inherited practice, and millennial-scale sustainability in an urbanized landscape. In *Viewing the Future in the Past: Historical Ecology Applications to Environmental Issues*, ed. HT Foster, LM Paciulli, DJ Goldstein, pp. 59–85. Columbia: Univ. S. C. Press
72. Arranz-Otaegui A, López-Sáez JA, Araus JL, Portillo M, Balbo A, et al. 2017. Landscape transformations at the dawn of agriculture in southern Syria (10.7–9.9 ka cal. BP): plant-specific responses to the impact of human activities and climate change. *Quat. Sci. Rev.* 158:145–63
73. Langgut D, Cheddadi R, Carrión JS, Cavanagh M, Colombaroli D, et al. 2019. The origin and spread of olive cultivation in the Mediterranean Basin: the fossil pollen evidence. *Holocene* 29(5):902–22
74. Weissbrod L, Malkinson D, Cucchi T, Gadot Y, Finkelstein I, Bar-Oz G. 2014. Ancient urban ecology reconstructed from archaeozoological remains of small mammals in the Near East. *PLOS ONE* 9(3):e91795
75. Pournelle JR. 2003. *Marshland of cities: deltaic landscapes and the evolution of early Mesopotamian civilization*. PhD Thesis, Univ. S. C., Columbia
76. Connor SE, Schneider L, Trezise J, Rule S, Barrett RL, et al. 2018. Forgotten impacts of European land-use on riparian and savanna vegetation in northwest Australia. *J. Veg. Sci.* 29(3):427–37
77. Kar A, Moharana PC, Raina P, Kumar M, Soni ML, et al. 2009. Desertification and its control measures. In *Trends in Arid Zone Research in India*, ed. A Kar, BK Garg, MP Singh, S Kathju, pp. 1–47. Jodhpur, India: Cent. Arid Zone Res. Inst.
78. Yasuda Y, Kitagawa H, Nakagawa T. 2000. The earliest record of major anthropogenic deforestation in the Ghab Valley, northwest Syria: a palynological study. *Quat. Int.* 73/74:127–36
79. Wertime TA. 1983. The furnace versus the goat: the pyrotechnologic industries and Mediterranean deforestation in antiquity. *J. Field Archaeol.* 10(4):445–52
80. Proctor L, Smith A, Stein GJ. 2022. Archaeobotanical and dung spherulite evidence for Ubaid and Late Chalcolithic fuel, farming, and feasting at Surezha, Iraqi Kurdistan. *J. Archaeol. Sci. Rep.* 43:103449
81. van Andel TH, Zangger E, Demitrack A. 1990. Land use and soil erosion in prehistoric and historical Greece. *J. Field Archaeol.* 17(4):379–96

82. McAuliffe JR, Sundt PC, Valiente-Banuet A, Casas A, Luis Viveros J. 2001. Pre-columbian soil erosion, persistent ecological changes, and collapse of a subsistence agricultural economy in the semi-arid Tehuacán Valley, Mexico's "Cradle of Maize." *J. Arid Environ.* 47(1):47–75
83. Fan L, Liang Y, Li X, Mao J, Wang G, et al. 2023. Grazing decreases soil aggregation and has different effects on soil organic carbon storage across different grassland types in northern Xinjiang, China. *Land* 12(8):1575
84. Lentz DL, Slotten V, Dunning NP, Jones JG, Scarborough VL, et al. 2021. Ecosystem impacts by the Ancestral Puebloans of Chaco Canyon, New Mexico, USA. *PLOS ONE* 16(10):e0258369
85. Barker G. 2002. A tale of two deserts: contrasting desertification histories on Rome's desert frontiers. *World Archaeol*. 33(3):488–507
86. Wright DK. 2017. Humans as agents in the termination of the African Humid Period. *Front. Earth Sci.* 5:4
87. Brierley C, Manning K, Maslin M. 2018. Pastoralism may have delayed the end of the green Sahara. *Nat. Commun.* 9:4018
88. Henry DO, Cordova CE, Portillo M, Albert R-M, DeWitt R, Emery-Barbier A. 2017. Blame it on the goats? Desertification in the Near East during the Holocene. *Holocene* 27(5):625–37
89. Viollet P-L. 2017. *Water Engineering in Ancient Civilizations: 5,000 Years of History*. Boca Raton, FL: CRC
90. Wright RP, Garrett Z. 2018. Engineering feats and consequences: workers in the night and the Indus civilization. In *Archaeology of the Night: Life After Dark in the Ancient World*, ed. N Gonlin, pp. 287–306. Boulder: Univ. Press Colo.
91. Petrie CA, Singh RN, Bates J, Dixit Y, French CAI, et al. 2017. Adaptation to variable environments, resilience to climate change: investigating land, water and settlement in Indus Northwest India. *Curr. Anthropol.* 58(1):1–30
92. Bhattacharya N. 2019. *The Great Agrarian Conquest: The Colonial Reshaping of a Rural World*. Albany: SUNY Press
93. O'Keefe FR, Dunn RE, Weitzel EM, Waters MR, Martinez LN, et al. 2023. Pre–Younger Dryas megafaunal extirpation at Rancho La Brea linked to fire-driven state shift. *Science* 381(6659):eabo3594
94. Sherratt AG. 1986. Two new finds of wooden wheels from later Neolithic and early Bronze Age Europe. *Oxf. J. Archaeol.* 5(2):243–48
95. Jones M, Hunt H, Lightfoot E, Lister D, Liu X, Motuzaite-Matuzeviciute G. 2011. Food globalization in prehistory. *World Archaeol*. 43(4):665–75
96. Habicht ME, Pate FD, Varotto E, Galassi FM. 2020. Epidemics and pandemics in the history of humankind and how governments dealt with them: a review from the Bronze Age to the Early Modern Age. *Riv. Trimest. Sci. Ammin. Studi Teor. Ric. Soc.* 2020(2). **https://doi.org/10.32049/RTSA.2020.2.03**
97. Roberts N, Fyfe RM, Woodbridge J, Gaillard MJ, Davis BAS, et al. 2018. Europe's lost forests: a pollen-based synthesis for the last 11,000 years. *Sci. Rep.* 8:716
98. Armstrong CG, Miller JED, McAlvay AC, Ritchie PM, Lepofsky D. 2021. Historical Indigenous land-use explains plant functional trait diversity. *Ecol. Soc.* 26(2):6
99. Elvin M. 2004. *The Retreat of the Elephants: An Environmental History of China*. New Haven, CT: Yale Univ. Press
100. Holdaway RN, Allentoft ME, Jacomb C, Oskam CL, Beavan NR, Bunce M. 2014. An extremely low-density human population exterminated New Zealand moa. *Nat. Commun.* 5:5436
101. Ficek RE. 2019. Cattle, capital, colonization: tracking creatures of the Anthropocene in and out of human projects. *Curr. Anthropol.* 60(Suppl. 20):S260–71
102. Hamilton R, Gillespie J, Penny D, Ingrey S, Mooney S. 2023. Re-imagining Sydney's freshwater wetlands through historical ecology. *Landsc. Res.* 49(2):268–86
103. Fletcher M-S, Romano A, Connor S, Mariani M, Maezumi SY. 2021. Catastrophic bushfires, Indigenous fire knowledge and reframing science in southeast Australia. *Fire* 4(3):61
104. Ballasus H, Schneider B, von Suchodoletz H, Miera J, Werban U, et al. 2022. Overbank silt-clay deposition and intensive Neolithic land use in a Central European catchment—coupled or decoupled? *Sci. Total Environ.* 806(4):150858

105. Ventresca Miller AR, Wilkin S, Hendy J, Turbat T, Batsukh D, et al. 2022. The spread of herds and horses into the Altai: how livestock and dairying drove social complexity in Mongolia. *PLOS ONE* 17(5):e0265775
106. Holst MK, Rasmussen M, Kristiansen K, Bech J-H. 2013. Bronze Age "herostrats": ritual, political, and domestic economies in Early Bronze Age Denmark. *Proc. Prehist. Soc.* 79:265–96
107. Dotterweich M. 2008. The history of soil erosion and fluvial deposits in small catchments of central Europe: deciphering the long-term interaction between humans and the environment—a review. *Geomorphology* 101(1/2):192–208
108. Kaiser K, Tolksdorf JF, de Boer AM, Herbig C, Hieke F, et al. 2021. Colluvial sediments originating from past land-use activities in the Erzgebirge Mountains, Central Europe: occurrence, properties, and historic environmental implications. *Archaeol. Anthropol. Sci.* 13(12):220
109. Ye Y, Fang X, Ren Y, Zhang X, Chen L. 2009. Cropland cover change in Northeast China during the past 300 years. *Sci. China D* 52(8):1172–82
110. TeBrake WH. 2002. Taming the waterwolf: hydraulic engineering and water management in the Netherlands during the Middle Ages. *Technol. Cult.* 43(3):475–99
111. Simeoni U, Corbau C. 2009. A review of the Delta Po evolution (Italy) related to climatic changes and human impacts. *Geomorphology* 107(1):64–71
112. Lander B. 2022. Small scale water control works in Early Imperial China. *Water Hist.* 14(2):233–46
113. Cooley HS, Riley WJ, Torn MS, He Y. 2005. Impact of agricultural practice on regional climate in a coupled land surface mesoscale model. *J. Geophys. Res.* 110:D03113
114. Fu C. 2003. Potential impacts of human-induced land cover change on East Asia monsoon. *Glob. Planet. Change* 37(3):219–29
115. Meier R, Schwaab J, Seneviratne SI, Sprenger M, Lewis E, Davin EL. 2021. Empirical estimate of forestation-induced precipitation changes in Europe. *Nat. Geosci.* 14(7):473–78
116. Olofsson J, Hulme PE, Oksanen L, Suominen O. 2004. Importance of large and small mammalian herbivores for the plant community structure in the forest tundra ecotone. *Oikos* 106(2):324–34
117. Pryor AJE, Beresford-Jones DG, Dudin AE, Ikonnikova EM, Hoffecker JF, Gamble C. 2020. The chronology and function of a new circular mammoth-bone structure at Kostenki 11. *Antiquity* 94(374):323–41
118. Streeter R, Dugmore AJ, Lawson IT, Erlendsson E, Edwards KJ. 2015. The onset of the Palaeoanthropocene in Iceland: changes in complex natural systems. *Holocene* 25(10):1662–75
119. Brewington S, Hicks M, Edwald Á, Einarsson Á, Anamthawat-Jónsson K, et al. 2015. Islands of change versus islands of disaster: managing pigs and birds in the Anthropocene of the North Atlantic. *Holocene* 25(10):1676–84
120. Avango D, Hacquebord L, Wråkberg U. 2014. Industrial extraction of Arctic natural resources since the sixteenth century: technoscience and geo-economics in the history of northern whaling and mining. *J. Hist. Geogr.* 44:15–30
121. Degroot D. 2022. Blood and bone, tears and oil: climate change, whaling, and conflict in the seventeenth-century Arctic. *Am. Hist. Rev.* 127(1):62–99
122. Jackson JA, Carroll EL, Smith TD, Zerbini AN, Patenaude NJ, Baker CS. 2016. An integrated approach to historical population assessment of the great whales: case of the New Zealand southern right whale. *R. Soc. Open Sci.* 3(3):150669
123. Huang X-Z, Liu S-S, Dong G-H, Qiang M-R, Bai Z-J, et al. 2017. Early human impacts on vegetation on the northeastern Qinghai-Tibetan Plateau during the middle to late Holocene. *Progr. Phys. Geogr. Earth Environ.* 41(3):286–301
124. Branch NP, Kemp RA, Silva B, Meddens FM, Williams A, et al. 2007. Testing the sustainability and sensitivity to climatic change of terrace agricultural systems in the Peruvian Andes: a pilot study. *J. Archaeol. Sci.* 34(1):1–9
125. Denevan WM. 2003. The native population of Amazonia in 1492 reconsidered. *Rev. Indias* 63(227):175–88
126. Yacobaccio H. 2009. The historical relationship between people and the vicuña. In *The Vicuña: The Theory and Practice of Community Based Wildlife Management*, ed. IJ Gordon, pp. 7–20. Boston: Springer

127. Arnalds O. 2015. *The Soils of Iceland*. Dordrecht, Neth.: Springer
128. Arnalds O, Kimble J. 2001. Andisols of deserts in Iceland. *Soil Sci. Soc. Am. J.* 65(6):1778–86
129. Dugmore A, Jackson R, Cooper D, Newton A, Júlísson ÁD, et al. 2020. *Going Forward by Looking Back: Archaeological Perspectives on Socio-Ecological Crisis, Response, and Collapse*. Oxford, UK: Berghahn
130. Sigurðardóttir R, Newton AJ, Hicks MT, Dugmore AJ, Hreinsson V, et al. 2019. Trolls, water, time, and community: resource management in the Mývatn District of northeast Iceland. In *Global Perspectives on Long Term Community Resource Management*, ed. LR Lozny, TH McGovern, pp. 77–101. Cham, Switz.: Springer Int.
131. Nott J. 2006. *Extreme Events: A Physical Reconstruction and Risk Assessment*. Cambridge, UK: Cambridge Univ. Press
132. Erickson CL. 1992. Prehistoric landscape management in the Andean highlands: raised field agriculture and its environmental impact. *Popul. Environ.* 13(4):285–300
133. Chepstow-Lusty A, Jonsson P. 2000. Inca agroforestry: lessons from the past. *Ambio* 29(6):322–28
134. Harvey WJ, Nogué S, Stansell N, Adolf C, Long PR, Willis K. 2021. A palynological perspective on the impacts of European contact: historic deforestation, ranching and agriculture surrounding the Cuchumatanes Highlands, Guatemala. *Veg. Hist. Archaeobot.* 30(3):395–408
135. Ochoa-Tocachi BF, Bardales JD, Antiporta J. 2019. Potential contributions of pre-Inca infiltration infrastructure to Andean water security. *Nat. Sustain.* 2:584–93
136. Wohl E. 2006. Human impacts to mountain streams. *Geomorphology* 79(3):217–48
137. Basistha A, Arya DS, Goel NK. 2008. Spatial distribution of rainfall in Indian Himalayas—a case study of Uttarakhand Region. *Water Resour. Manag.* 22(10):1325–46
138. Reinhardt-Imjela C, Imjela R, Bölscher J, Schulte A. 2018. The impact of late medieval deforestation and 20th century forest decline on extreme flood magnitudes in the Ore Mountains (southeastern Germany). *Quat. Int.* 475:42–53
139. Canadell JG., Monteiro PMS, Costa MH, Cotrim da Cunha L, Cox PM, et al. 2021. Global carbon and other biogeochemical cycles and feedbacks. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the 6th Assessment Report of the Intergovernmental Panel on Climate Change*, ed. V Masson-Delmotte, P Zhai, A Pirani, SL Connors, C Péan, et al., pp. 673–816. Cambridge, UK/New York: Cambridge Univ. Press
140. Ganopolski A, Winkelmann R, Schellnhuber HJ. 2016. Critical insolation–CO_2 relation for diagnosing past and future glacial inception. *Nature* 529(7585):200–3
141. Roberts P, Kaplan JO, Findley DM, Hamilton R, Caetano-Andrade VL, et al. 2023. Mapping our reliance on the tropics can reveal the roots of the Anthropocene. *Nat. Ecol. Evol.* 7(5):632–36
142. McNeill JR, ed. 2022. *Environmental History in the Pacific World*. London: Routledge
143. Degroot D. 2018. Climate change and society in the 15th to 18th centuries. *Wiley Interdiscip. Rev. Clim. Change* 9(3):e518
144. Hamilton R, Wolfhagen J, Amano N, Boivin N, Findley DM, et al. 2021. Non-uniform tropical forest responses to the "Columbian Exchange" in the Neotropics and Asia-Pacific. *Nat. Ecol. Evol.* 5(8):1174–84
145. Bush MB, Conrad S, Restrepo A, Thompson DM, Lofverstrom M, Conroy JL. 2022. Human-induced ecological cascades: extinction, restoration, and rewilding in the Galápagos highlands. *PNAS* 119(24):e2203752119
146. Thompson JC, Wright DK, Ivory SJ, Choi J-H, Nightingale S, et al. 2021. Early human impacts and ecosystem reorganization in southern-central Africa. *Sci Adv*. 7(19):eabf9776
147. Long JW, Lake FK, Goode RW. 2021. The importance of Indigenous cultural burning in forested regions of the Pacific West, USA. *For. Ecol. Manag.* 500:119597
148. Mariani M, Connor SE, Theuerkauf M, Herbert A, Kuneš P, et al. 2022. Disruption of cultural burning promotes shrub encroachment and unprecedented wildfires. *Front. Ecol. Environ.* 20(5):292–300
149. Kaplan JO, Krumhardt KM, Ellis EC, Ruddiman WF, Lemmen C, Goldewijk KK. 2011. Holocene carbon emissions as a result of anthropogenic land cover change. *Holocene* 21(5):775–91
150. Pyne SJ. 2001. Perils of prescribed fire: a reconsideration. *Nat. Resour. J.* 41(1):1–8
151. McConnell JR, Wilson AI, Stohl A, Arienzo MM, Chellman NJ, et al. 2018. Lead pollution recorded in Greenland ice indicates European emissions tracked plagues, wars, and imperial expansion during antiquity. *PNAS* 115(22):5726–31

152. Uglietti C, Gabrielli P, Cooke CA, Thompson LG. 2015. Widespread pollution of the South American atmosphere predates the industrial revolution by 240 y. *PNAS* 112(8):2349–54
153. Lee H, Calvin K, Dasgupta D, Krinner G, Mukherji A, et al., eds. 2023. *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the 6th Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge Univ. Press
154. Davis GA, Tilton JE. 2005. The resource curse. *Nat. Resour. Forum* 29(3):233–42
155. Lange M, Mahoney J, vom Hau M. 2006. Colonialism and development: a comparative analysis of Spanish and British colonies. *Am. J. Sociol.* 111(5):1412–62
156. Bourgeon G, Nair KM, Ramesh BR, Seen DL. 2012. Consequences of underestimating ancient deforestation in South India for global assessments of climatic change. *Curr. Sci.* 102(12):1699–703
157. Tomich D. 2003. The wealth of empire: Francisco Arango y Parreño, political economy, and the second slavery in Cuba. *Comp. Stud. Soc. Hist.* 45(1):4–28
158. Marquese R, Parron T, Berbel M. 2016. *Slavery and Politics: Brazil and Cuba, 1790–1850*. Albuquerque: Univ. N. M. Press
159. Wolfe P. 2016. *Traces of History: Elementary Structures of Race*. London: Verso
160. Laming A, Fletcher M-S, Romano A, Mullett R, Connor S, et al. 2022. The curse of conservation: empirical evidence demonstrating that changes in land-use legislation drove catastrophic bushfires in Southeast Australia. *Fire* 5(6):175
161. Duffy R. 2014. Waging a war to save biodiversity: the rise of militarized conservation. *Int. Aff.* 90(4):819–34
162. Marques L, Marquese RB. 2020. Ouro, café e escravos: o Brasil e "a assim chamada acumulação primitiva." In *Os tempos plurais da escravidão no Brasil: ensaios de história e historiografia*, ed. RB Marquese, pp. 105–32. Santos, Braz.: Intermeios (in Portuguese)
163. Jones MW, Peters GP, Gasser T, Andrew RM, Schwingshackl C, et al. 2023. National contributions to climate change due to historical emissions of carbon dioxide, methane, and nitrous oxide since 1850. *Sci. Data* 10(1):155
164. Gonzalez CG. 2023. Racial capitalism and the ecological crises of the Anthropocene. *Perspect. Glob. Dev. Technol.* 21(5/6):323–37
165. Arrighi G. 1994. *The Long Twentieth Century: Money, Power, and the Origins of Our Times*. London: Verso
166. Alonso-Fernández P, Regueiro-Ferreira RM. 2022. Extractivism, ecologically unequal exchange and environmental impact in South America: a study using material flow analysis (1990–2017). *Ecol. Econ.* 194:107351
167. Laubichler MD, Renn J. 2015. Extended evolution: a conceptual framework for integrating regulatory networks and niche construction. *J. Exp. Zool. B* 324(7):565–77
168. Taddei R. 2022. Kopenawa and the environmental sciences in the Amazon. In *Philosophy on Fieldwork: Case Studies in Anthropological Analysis*, ed. N Bubandt, TS Wentzer, pp. 352–72. London: Routledge
169. Roos CI, Swetnam TW, Ferguson TJ, Liebmann MJ, Loehman RA, et al. 2021. Native American fire management at an ancient wildland–urban interface in the Southwest United States. *PNAS* 118(4):e2018733118
170. Bird RB, Bird DW, Codding BF, Parker CH, Jones JH. 2008. The "fire stick farming" hypothesis: Australian Aboriginal foraging strategies, biodiversity, and anthropogenic fire mosaics. *PNAS* 105(39):14796–801
171. McCarroll J, Chambers FM, Webb JC, Thom T. 2017. Application of palaeoecology for peatland conservation at Mossdale Moor, UK. *Quat. Int.* 432:39–47