ARCHAEOLOGY AND GLOBAL CHANGE:
The Holocene Record

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Abstract Although human-induced changes to the global environment and natural biotic resources, collectively labeled “global change” and the “biodiversity crisis,” have accelerated with industrialization over the past 300 years, such changes have a much longer history. Particularly since the rise of agriculturally based societies and associated population expansion during the early Holocene, humans have had cumulative and often irreversible impacts on natural landscapes and biotic resources worldwide. Archaeologists, often working closely with natural scientists in interdisciplinary projects, have accumulated a large body of empirical evidence documenting such changes as deforestation, spread of savannahs, increased rates of erosion, permanent rearrangements of landscapes for agriculture, resource depression and depletion (and in many cases, extinction) in prehistory. In some areas and time periods, environmental change led to long-term negative consequences for regional human populations, whereas in other cases, changes favored intensification of production and increased population sizes. Drawing upon case studies from North America, Mesoamerica, the Mediterranean, Near East, India, Australia, and the Pacific Islands, the diversity of types of prehistoric human-induced environmental change is assessed, along with the kinds of empirical evidence that support these interpretations. These findings have important implications both for the understanding of long-term human socioeconomic and political changes and for ecologists who need to assess current environmental dynamics in the context of longer-term environmental history.

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INTRODUCTION: ARCHAEOLOGY AND LONG-TERM HUMAN ECODYNAMICS

Over the past 50 years, prehistoric archaeology has developed an increasingly sophisticated and robust approach to investigating interactions between ancient peoples and their environments, accumulating a large and growing database on the cumulative human impacts to the global environment over millennial timescales. Recently, and in consort with colleagues in the natural sciences, archaeologists have become key contributors to the new integrative fields of historical ecology and human ecodynamics. In this review, I canvas the role that archaeology plays in understanding long-term human ecological impacts, drawing upon recent results from a variety of geographic regions. The temporal focus is on the Holocene—the present interglacial, which commenced at the end of the Younger Dryas circa (ca.) 11,000–10,000 years before present (B.P.)—during which time humans extended their geographic reach to the most remote places on Earth, domesticated hundreds of species of plants and animals, developed agriculturally based societies and urbanism, and saw their own numbers increase dramatically. Although the pace of global change unquestionably accelerated with the Industrial Revolution, human impacts to earth’s ecosystems have a much longer history, one whose cumulative effects have been far more pervasive than is often recognized.

Persistence of the Noble Savage Myth

The idea that civilized humanity transforms the earth and its resources through organized activity has deep roots in Western culture, well documented in Hellenistic and Roman literature (1). The poet Lucretius waxed eloquent how “day by day they would constrain the woods more and more to retire up the mountains and to give up the land beneath to tillth, that on hills and plains they might have meadows, pools, streams, crops, and glad vineyards...” (2). Yet when European cultures expanded globally after the late fifteenth century in a burst of “ecological imperialism” (3), observers often failed to see in non-Western peoples a similar relationship of the dominance of culture over nature. Renowned Enlightenment scholars, such as the Count Buffon, judged from the accumulated accounts of exploration that “primitive man in the New World had been unable to play the role of aiding nature and of developing it from its rude state” (1, p. 680). In the same vein, the French philosopher Jean-Jacques Rousseau drew upon accounts of newly
discovered Pacific island cultures to frame his concept of *l’homme naturel*, natural man in a changeless state of harmony with nature (4, 5).

Such late eighteenth century perspectives on the relationships between nonindustrialized peoples and their environments—the myth of the noble savage—have had remarkable persistence and continue, however subtly, to influence modern views. Thus, for example, the anthropologist Krech (6) identifies what he calls “the Ecological Indian,” a view of Native Americans as ultimate conservationists, a potent symbol for Green political movements. Much research in cultural ecology, by the same token, emphasized homeostatic regulation of complex food and energy flows between human populations and their ecosystems, rather than long-term dynamic change. Such views even underlie current land management principles and practices in the United States, with the stated aim of returning ecosystems to their “presettlement equilibrium,” defined as a supposed pre-Columbian baseline (7, p. 162). As Denevan (8) and others have convincingly argued, however, the concept of such a pre-Columbian equilibrium is a continuation of the pristine myth, and in reality the landscape of the Americas in 1492 was one of strongly humanized, densely populated landscapes, the product of millennia of human impacts. Yet, even scholars who are well aware of the long-term impacts of prehistoric peoples on the earth’s ecosystems tend to suggest that global change and the biodiversity crisis are largely phenomena of the past three centuries (9).

### The Rise of Environmental Archaeology

Nearly one-half century ago, the Wenner-Gren Foundation for Anthropological Research organized an international symposium on *Man’s Role in Changing the Face of the Earth* (10), a work which is rightly regarded as a classic in human ecology and environmental history. Although the historians, anthropologists, geographers, and natural scientists who participated in this monumental synthesis greatly assisted in breaking down the myth of natural man, there was notably little contribution from archaeology, which at that time was only just beginning to broaden its research horizons beyond a preoccupation with time-space systematics of ancient cultures (usually referred to as the “culture history” approach) (11). From the late 1940s through the 1960s, prehistoric or anthropological archaeology (in distinction to classical archaeology, which focuses on the Greco-Roman world) rapidly incorporated new perspectives and approaches, often borrowing methods from the natural sciences. The introduction of the “settlement pattern” approach marked a shift away from individual site-centered studies to one that examines entire human settlement systems within the context of their geographic landscapes (11). A number of pioneering projects adopted research agendas in which the central problem was defining the relationships between ancient human populations and their physical and biotic environments. Classic studies of this kind include Clark’s (12) excavations at the Mesolithic site of Star Carr in Yorkshire, the investigation by Braidwood & Howe (13) of animal and plant domestication and early village life in Iraqi Kurdistan, and MacNeish’s (14) multidisciplinary study of the transition from hunting-and-gathering to agricultural subsistence in...
the Tehuacan Valley of Mexico. These and similar studies established the modern approach in prehistoric archaeology in which the analysis of faunal and floral remains was accorded equal attention with human artifacts, thus ushering in the field of “environmental archaeology.”

The 1971 publication of Karl Butzer’s *Environment and Archaeology: An Ecological Approach to Prehistory* (15) could be said to mark the coming of age of environmental archaeology, and it was followed a decade later by his more theoretically sophisticated programmatic statement, *Archaeology as Human Ecology* (16). The field of environmental archaeology has not only continued to develop and mature over the past three decades (e.g., 17–19) but has spawned the distinct subfields of zooarchaeology, archaeobotany (or paleoethnobotany), and geoarchaeology (e.g., 20–22), each with its own specialty journals. This trend toward subspecialization reflects in part the development and implementation of sophisticated field and laboratory methods, often requiring considerable apprenticeship to master.

The accumulated data and interpretations resulting from several decades of research in environmental archaeology, broadly defined, have led to a vastly enhanced appreciation of the degree to which human populations have modified their environments, beginning in the late Pleistocene and intensifying throughout the Holocene. Several recent syntheses distill this accumulated knowledge concerning the “archaeology of global change” (23–25). These results not only put the final nail into the coffin of the noble savage myth, but they should dispel any lingering notions that truly pristine environments—unmodified by human actions—persisted any place on Earth very long after their occupation by *Homo sapiens*. Moreover, by disrupting and modifying natural processes, and indeed in often reducing or even eliminating (through extinction) the role of formerly dominant species in communities and ecosystems, humans have frequently inserted themselves as keystone species in ecosystem functioning (8).

**Archaeology, Historical Ecology, and Human Ecodynamics**

Despite inevitable specialization, environmental archaeologists of all stripes have increasingly engaged with colleagues in geography, anthropology, environmental history, and ecology in a growing effort to develop an integrative field, variously defined as *historical ecology* or *human ecodynamics* (26, 27). These efforts help to counter the inevitable trend toward subspecialization, for they require interdisciplinary and multidisciplinary approaches. Historical ecology has been defined as “the study of past ecosystems by charting the change in landscapes over time,” with the implicit understanding that the term landscape incorporates “the material manifestation of the relation between humans and the environment” (26, p. 6). Winterhalder (28, p. 40) insists that historical ecology demands “an epistemological commitment to the temporal dimension in ecological analysis,” a recognition that the properties of communities and ecosystems must be sought at least in part in their history. This view is echoed by Barton et al. (29) in their concept of contingent
landscapes, in which “the intertwined social and natural landscapes that are the context of human societies are contingent on socioecological history as well as the physical conditions under which this history took place” (29, p. 285). The practice of historical ecology, to be sure, is not restricted to archaeology, although most recent compilations incorporate a significant archaeological component (30–33).

The approach of human ecodynamics, although intersecting heavily with historical ecology, was explicitly defined from an archaeological perspective by McGlade (27, 34). Human ecodynamics also privileges landscape as a core concept and asserts that there is no environment or ecosystem detached from humans and their behavior; rather there are only socio-natural systems defined as linked socio-historical and natural processes within specific time-space frameworks. The study of human ecodynamics is thus described as being concerned with “the dynamics of human-modified landscapes set within a long-term perspective, and viewed as a nonlinear dynamical system” (27, p. 126). In addition to sharing with historical ecology an emphasis on the contingent long-term histories of landscapes, human ecodynamics incorporates concepts such as hierarchy, resilience, self-organization, and nonlinear causality (35–37). Although drawing heavily on the legacy of a largely qualitative and descriptive environmental archaeology, human ecodynamics thus moves the field toward quantitative approaches and the use of dynamic, nonlinear models.

A point stressed by scholars, espousing either the perspective of historical ecology or of human ecodynamics, is the fundamental necessity of understanding long-term landscape change as the outcome of both natural and social processes. Though constantly shaped and transformed by a variety of natural processes, landscapes are also in real ways socially constructed (38). Thus, Barton et al. (29) advance the term “socioecosystems” for landscapes shaped by dynamically linked human-natural processes. The necessity of incorporating a social as well as natural perspective in human ecodynamics highlights the central role that archaeology often plays in such studies; for the field of archaeology is almost uniquely situated, with what van der Leeuw & Redman (39) have identified as a “strong tradition of multidisciplinarity that combines the social and natural sciences.” Anthropological archaeologists are able to employ a panoply of methods and concepts for identifying and interpreting past social, economic, political, and ideological systems, and at the same time that they have developed—often in concert with colleagues in the natural sciences—the ability to extract increasingly precise data about past human-environment interactions over long timescales (40). Archaeologists, in other words, are well situated to act as interlocutors between the concepts and languages of social and natural science. Moreover, what archaeologists especially bring to the table is a truly long-term view, the temporal scale of the longue durée (41), which offers not only the possibility of understanding the dynamics of socio-natural systems, but the long-term changes in the dynamics themselves, the second order changes not evident in short-term perspective.

Several recent or current projects in various parts of the world exemplify the approach of human ecodynamics with archaeology as a core integrating discipline.
The Archaeomedes Project, funded by the European Commission’s program on environment and climate, with subprojects in the Argolid of Greece and southern Rhône Valley of France, has explored the natural and anthropogenic causes of land degradation and desertification in the Mediterranean Basin over millennial timescales (42). Three recent and continuing projects, all funded in part by the U.S. National Science Foundation’s Biocomplexity in the Environment Program (43), focus on dynamically coupled human-natural interactions, again integrating several disciplinary approaches around an archaeological core. These projects range in the scale of socioeconomic systems investigated from the tribal level Puebloan societies of Mesa Verde (44), to the emergent archaic states of late prehistoric Hawai’i (45, 46), to the city-states of third-millennium B.C. Mesopotamia (47). These and similar projects demonstrate the increasingly central role that archaeology plays in revealing the deep-time history of human-induced global change.

ARCHAEOLOGY AND THE RECORD OF ENVIRONMENTAL CHANGE

As with any paleoecological study, archaeologists do not study directly past socio-natural systems or landscapes; rather, they depend upon a whole range of proxy data to represent those former systems and landscapes. Typically, such proxy data consist of the culturally modified artifacts, along with the *ecofacts* or detritus of everyday life (such things as plant remains of all kinds, animal bones and shells, as well as inanimate objects including soil and sediments) that humans accumulated and discarded, often at surprisingly high rates. From an empirical perspective, the archaeological record (48) consists of those discards that have survived subsequent diagenetic transformations and that typically occur in nonrandom, concentrated, patterned depositional contexts. The nature of these contexts varies greatly with place and time period, and they range from open-air camps, rockshelters, single house sites to villages (of varied architectural forms and materials), towns, and ultimately cities. Because the patterned activities and short-term events of daily life that created the archaeological record are rarely discernable within such depositional contexts, this record is often likened metaphorically to a palimpsest. The analogy is only partly valid, however, for most archaeological contexts—far from being homogenized—exhibit stratigraphy, which allows for the delineation of temporal structure within the larger deposit. With the increasingly wide array of radiometric and other dating techniques now available to archaeologists and with the development of fine-grained stratigraphic excavation methods (49), this temporal structure can often be finely resolved.

Archaeological sites, in short, are among other things temporally structured repositories or accumulations of a range of proxy indicators of past environmental conditions and processes. The middens, trash pits, living floors, burials, and other contexts that make up archaeological sites contain a record, often spanning a considerable time period, of repeated human actions within a past landscape
that enveloped the site or sites. Wild plants and animals gathered or hunted from a “catchment” territory surrounding the site, crops harvested from fields, wood obtained for fuel or construction, and stone or other resources mined or quarried for craft production all end up—usually after considerable modification through butchering, cooking, burning, eating, working, and so on—in the artificial concentrations of debris we call sites. The size of such catchments also varies enormously, from the relatively small radius exploited by occupants of a rockshelter or single household dwelling to the extensive territories drawn upon by ancient cities such as Teotihuacán, Mexico, or Harappa, Pakistan.

A critical difference between these archaeological proxies and the kinds of materials more familiar to paleoecologists (pollen grains in lake sediments, for example) is that the former have been collected and transported by humans, used or manipulated in various ways, to end up discarded as artificial and dense accumulations at loci of human habitation or other activity. The archaeological record therefore reflects not only initial cultural selection or bias in which parts of the landscape were being utilized or in which certain resources were exploited, but also a chain of subsequent cultural and natural transforms that act upon these materials. For the study of human ecodynamics, this presents both advantages and disadvantages, and a prodigious literature within archaeology addresses these transform issues (50, 51). Studies of human ecodynamics in particular regions often strive to balance this cultural bias influencing the archaeological record of environmental change by incorporating paleoecological data sets from nonarchaeological contexts within the same catchment. For example, a sequence of human exploitation of plant and animals resources by the occupants of the Tangatatau Rockshelter on Mangaia Island (resulting, over several centuries, in severe resource depression and avifaunal extinction) was derived from analysis of the accumulated floral and faunal remains within the stratified floor of the rockshelter (52, 53). At the same time, larger-scale changes in the site’s landscape catchment were revealed through a parallel program of coring of nearby lake sediments and studying these through geochemical and palynological techniques (54, 55), showing severe deforestation, erosion, and valley infilling. A similar example is provided by the Belo-sur-mer site on Madagascar (56), where archaeological, paleontological, and palynological data could all be brought to bear using an “integrated site” concept to examine the processes of vertebrate extinction. These examples, as with other projects mentioned above (42–47), exemplify the power of combining archaeological and paleoecological methods within an integrated multidisciplinary approach, a model that has now been widely adopted.

Although we are accustomed to thinking about the archaeological record in terms of the concentrated debris accumulations known as sites, the physical remains of past human activity frequently also extend over entire landscapes. This is especially the case with agrarian landscapes, where former episodes of cultivation have left a permanent record of agronomic modifications, ranging from simple soil modifications to abandoned canals, field systems, terrace complexes, or entire irrigation networks. These kinds of spatially extensive sites have characteristics quite
different from stratified habitation deposits, but they are also amenable to dating and chronological control. In recent decades, the archaeological study of ancient agrarian landscapes has advanced tremendously (57–60), so that for many parts of the world it is now possible to piece together long-term sequences of development, expansion, intensification, and sometimes, collapse of agricultural systems. Since much of humanity’s imprint upon the Earth derives from agricultural activity, investigating this aspect of the archaeological record of environmental change has proved essential.

ARCHAEOLOGICAL EVIDENCE OF HUMAN IMPACT ON ANCIENT ENVIRONMENTS

Archaeologists often make a fundamental distinction between two sorts of materials that make up the archaeological record: between nonportable, or fixed structures and features, and portable artifacts and objects of all kinds. The former include residential, ceremonial, or other kinds of architecture, as well as the more landscape extensive constructions and soil modifications associated with agriculture, or with other kinds of craft and industrial activities. The latter range from potsherds and worked stone (lithics) to animal bones and plant remains, all typically associated with particular nonportable contexts; indeed, it is the critical associations between objects and contexts that allow archaeologists to construct a detailed spatiotemporal record. Here I canvas the main categories of materials that archaeologists use to infer human impacts on environments and the kinds of impacts these reveal, drawing upon specific examples from various regions of the world.

Fauna: Domestication, Translocation, Resource Depression, Extinction

Faunal remains certainly constitute one of the most important classes of archaeological materials for understanding the record of human impact on local and regional environments and biotic resources, and an entire subfield of zooarchaeology has developed around their identification, analysis, and interpretation (e.g., 20, 61–63). Included are the skeletal or other hard parts of both domesticated and wild vertebrates, as well as invertebrate remains of all kinds (ranging from edible mollusks and crustaceans to the shells of terrestrial snails). Zooarchaeological evidence has been fundamental both to our expanding knowledge of the processes and timing of animal domestication in both the Old and the New Worlds and to the cumulative effects of hunting, gathering, and fishing on natural animal populations in terrestrial, coastal, and marine environments (64, 65). Because of the varied cultural and natural transforms that determine which faunal remains are actually preserved in any particular archaeological record (see above), the interpretation of a faunal assemblage can be complex. Issues of taphonomy (weathering, transport, differential preservation), cultural bias in use and discard, and sampling at several
scales are all matters that have received extensive attention from zooarchaeologists (16, 20). Analyses of faunal assemblages likewise range from simple taxonomic identification to metric studies of size or growth rates, aging, sexing of animal populations (often to infer human control and intervention in breeding), and determinations of seasonality of hunting or gathering; stable isotope ratios are used to shed light on dietary shifts.

Massive extinctions of megafauna commenced in the late Pleistocene across parts of the Old World, expanding into Australia and New Guinea ca. 40,000–30,000 years B.P., and into the Americas around the time of the Younger Dryas (66, 67). These late Pleistocene extinctions are beyond the scope of this review except to note that a debate has been waged between scholars over the causes of these dramatic extinction events, with strongly opposed camps stressing the role of climate change on the one hand and human exploitation on the other (68). It is, however, difficult to dismiss out of hand Martin & Steadman’s (69) argument that the timing of these extinctions displays remarkable coincidence with the global course of *Homo sapiens’* dispersal. Moreover, the delay of major extinctions in Madagascar, New Zealand, and the islands of Polynesia (52, 56, 70, 71) until human arrivals in the late Holocene adds weight to the argument that such events are to a large extent driven by human actions, whether through direct hunting or indirect modification of habitats and ecosystem functioning; this is not to say that dramatic climate change at the Pleistocene/Holocene boundary did not also play a role.

During the Holocene, human impacts on animal populations (both terrestrial and marine) have included (a) the domestication of various formerly wild species, resulting in genomic-level modifications with corresponding phenotypic and behavioral changes in the affected species, and in frequently dramatic expansions in the population sizes and geographic ranges of these domesticates; (b) the translocation of nondomesticated animals through purposeful human introduction to novel landscapes; (c) frequently severe impacts on the populations of wild mammals, birds, fishes, mollusks, and other resources, resulting from continued predation pressure, referred to as resource depression or depletion; and (d) when pressure has been sustained, and/or when affected animal populations are vulnerable, local extirpation or global extinction of species (72).

The dog was probably brought under domestication before the end of the Pleistocene, but a number of extremely significant domestications occurred in the Near East in the early Holocene, with the archaeological evidence consisting of faunal assemblages exhibiting phenotypic changes, such as progressive body size reduction. Caprids (sheep and goats) were domesticated by about 7000 B.C. based on evidence from sites such as Ganj Dareh in western Iran, and cattle no later than about 6000 B.C. (73–75). There is some evidence that pigs may have been domesticated, or at least brought under some form of human control, even earlier than sheep and goats. In any event, the significance of these animal domestications cannot be underestimated, for they not only resulted in major changes to human economies and social systems, but the advent of pastoralism and the progressive
expansion of ungulate populations over time had dramatic consequences for Near Eastern and Levantine landscapes, and later for landscapes throughout the Mediterranean Basin. In the New World, the domestication of animals such as the llama and alpaca did not occur until much later (ca. 3000–2000 B.C.) and had much less impact than the Old World ungulates.

The transfer of domesticated animals beyond the geographic ranges occupied by their wild ancestors is a fairly obvious result of human actions, but the translocation of species by humans extends well beyond domesticates and is by no means confined even to vertebrates. Indeed, in reviewing the evidence for animal translocation in prehistory, Grayson (72, p. 17) observes that the variety of animals moved by human colonists is “astonishing,” including for example lice, beetles, fleas, mites, land snails, geckos, rats, mice, birds, deer, fox, and wolf. Although some translocations were purposeful, many others appear to have been inadvertent, a consequence of what Crosby (3) felicitously labeled the “portmanteau biota” that humans carry with them in their movements. For islands, the impact of translocations was often severe and irreversible. A striking case of this is the introduction of the Pacific rat (*Rattus exulans*) to virtually every Oceanic island by prehistoric Austronesian voyagers (76). As a recent analysis of the consequences of rat introduction to the Hawaiian Islands suggests (77), rapid collapse of leeward dryland forests even in advance of the direct effects of human land clearance for agriculture were probably due to exponential increases in the *R. exulans* population and its predation on seeds, seedlings, and other vulnerable vegetation.

One of the most pervasive kinds of human impact on animal populations is that of resource depression as a result of increasing or sustained predation pressure by humans, which can be recognized in the archaeological record by several indicators (72). Among these are declines over time in the relative abundance of “high-return” prey, usually larger species (often high on the trophic ladder), increases in lower-return, smaller taxa, and an expansion of diet breadth (the number of species exploited) to compensate for the loss of high-return taxa. Resource depression is also often accompanied by measurable decreases in body size. Broughton’s analyses of resource depression in the San Francisco Bay and the Sacramento Valley of California (78–80) have become classic studies, but the phenomenon has been recognized in many parts of the world, from continents to islands, and among both vertebrates and invertebrates (e.g., 53, 81). Figure 1, taken from Broughton’s work with bones of sturgeon fish (*Acipencer* sp.) from the Holocene deposits of the great Emeryville Shellmound site on the shores of San Francisco Bay, illustrates the progressive course of resource depression as measured both by the decline in the “sturgeon index” (relative abundance of sturgeon) and in the systematic decrease in the mean length of sturgeon dentaries. As Broughton argues, these tightly correlated indices can only have resulted from sustained human predation pressure.

On continents, major extinction episodes had already occurred by the onset of the Holocene, but on islands of all sizes (in the Mediterranean, Caribbean, Indian Ocean, and Pacific) the arrival of humans characteristically brought new
waves of extinction (30, 52–56, 66, 67, 69–72, 76). Nowhere is the ability of newly arriving human populations to decimate a naïve and vulnerable fauna more evident than in New Zealand, an ancient remnant of Gondwanaland—continental in its geological underpinnings and biota, if not in its size—that did not see human footprints until around A.D. 1200 (82–84). In this truly pristine land prior to human colonization, there had evolved the *moa*, 11 or possibly more species of large wingless birds in two families (Dinornithidae and Emeidae). The largest of the dinornithids stood up to 2 m high and weighed 200 kg; even smaller moa were 0.7–1 m high and weighed between 25 and 100 kg. They appear to have

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**Figure 1** Resource depression in the exploitation of sturgeon fish in San Francisco Bay. Archaeological strata are depicted along the x-axis, with the oldest stratum being 11. Note that both the sturgeon index and the mean dentary width of sturgeon decrease over time. [Graphs redrawn from Broughton (80).]
been completely exterminated from both South and North Islands within 200–400 years after the arrival of Polynesians, as a consequence of direct predation and of massive habitat destruction and alteration (the latter to a large degree owing to human-ignited fires).

The smaller islands of tropical and subtropical Polynesia have revealed multiple histories of avifaunal extirpation and extinction, again correlating with the arrival of humans (52, 53, 70, 71, 77). On some of these islands—Easter Island and Mangareva being cases in point—the removal of large populations of nesting seabirds had far-reaching consequences for their island ecosystems because these birds were probably responsible for major inputs of phosphorus, nitrogen, and other nutrients (through deposition of guano) essential to the maintenance of forest cover. Easter and Mangareva are among the most severely degraded islands identified in a recent study by Rolett & Diamond (85), and on both of these islands, we now have evidence of formerly extensive and diverse populations of seabirds that were eliminated owing to human predation pressure, probably within a few decades to centuries after the Polynesian arrivals (86).

Plants and Vegetation: Exploitation, Domestication, Agriculture, Deforestation

In parallel with faunal materials, floral (or paleobotanical) remains constitute a second major category of archaeological evidence, exhibiting many of the same kinds of issues and complexities and engendering an entire subfield of archaeobotany (21, 87–89). Here a distinction is often made between macrobotanical materials (seeds, nuts, wood, charcoal) and microbotanical remains (pollen, phytoliths, starch grains), the former typically recovered through screening and/or flotation methods, the latter requiring more elaborate extraction techniques and the use of high-resolution microscopy for identification and analysis. Early work in archaeobotany tended to emphasize the remains of cultivated plants such as carbonized cereal grains from arid zone sites in the Near East (e.g., H. Helbaeck, in 13) or early maize cobs in Mexico (e.g., 14), thus providing critical evidence for early cereal domestication and the spread of farming systems. The extension of archaeobotanical research into tropical regions dominated by tuber, root, or tree crops has proved more challenging, requiring the development of new methods and greater emphasis on microbotanical remains (21). Archaeobotanical materials are by no means restricted to the remains of cultigens, however, and such materials as charcoal, derived from burning fuel in hearths and ovens, or the remains of wild plants gathered for a diversity of purposes are often abundant in archaeological contexts, providing a wealth of data on human exploitation of vegetal resources (90). As in zooarchaeology, much work has centered around complex issues of identification, differential preservation, and sampling bias, all essential for adequate interpretation of archaeobotanical assemblages (89).

Human impacts to plants and vegetation communities certainly began well into the Pleistocene, both as a consequence of plant gathering for food and materials

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and, more importantly, of the control and application of fire for a variety of purposes. Just when *Homo sapiens* first acquired the skills to ignite fires is a matter of some debate among paleoanthropologists and archaeologists (91), but it was not later than 100,000 years ago, and possibly considerably earlier. Well before the domestication of plants and onset of widespread agricultural burning in the early Holocene, fires purposefully set or that escaped intended control often had dramatic consequences for landscapes, especially in arid zones more susceptible to ignition (92). Nowhere is this more evident than in Australia, where the arrival of humans at about 40,000 years B.P. coincides with orders-of-magnitude increases in microscopic charcoal particles in sedimentary basins and lakes and with dramatic reductions in conifers and other rainforest taxa relative to sclerophyllous taxa (93). A half century ago, the great geographer Carl Sauer (94) proposed that the savanna lands of tropical America and the Caribbean Islands were largely the result of (or at least greatly expanded by) repeated burning by indigenous peoples in pre-Columbian times, a hypothesis that was largely rejected at the time but increasingly appears to be correct (95).

Human manipulation of and impact on plants entered into a whole new dimension with the initial experiments toward plant domestication and cultivation, beginning at the Pleistocene/Holocene boundary and continuing thereafter (the latest developments in genetic engineering of crops are simply a continuation of this long process). Cereal crops including tetraploid emmer and diploid einkorn wheat, together with barley and rye, begin to appear in prepottery settlements in the Fertile Crescent of southwestern Asia as early as 8500 B.C. and are shortly thereafter joined by legumes including pea, lentil, and chickpea (91, 96, 97). Between 6500 and 4000 B.C., the farming systems developed in this core region had spread—in part through a process of human population expansion and demic diffusion fueled by the productivity of agriculture itself—throughout the Mediterranean and Europe as far as Britain, to Egypt and North Africa, and as far east as Pakistan. In northern China, millet and rice were domesticated between 7000–6000 B.C., underwriting a parallel expansion of agricultural economies in East Asia. In the New World, a completely independent trajectory of plant domestication begins with squash as early as 8000 B.C.; maize was added about 4500 B.C., and the common bean by 500 B.C. (98). In addition to these so-called centers of domestication of cereals and legume crops, human populations dispersed over extensive noncenters of the tropical Old and New Worlds brought a truly amazing range of root, tuber, and seed crops under human control.

The plant geneticist Harlan (99) lists more than 450 species of cultivated plants in a “short list” that is by no means exhaustive. To varying degrees, the genomes of all of these taxa were altered by human manipulation and selection, but the impacts of this collective domestication process go far beyond the genomic level. In developing the basis for plant cultivation and agrarian systems, humans also unleashed their own reproductive potential, for agricultural economies permitted an unprecedented demographic expansion (96). Whereas population densities of hunting-foraging populations in the Pleistocene are estimated at between
0.1–0.4 persons per square kilometer (pp/km²; 100), preindustrial agrarian populations frequently achieved densities of 50–150 pp/km², and in zones with highly intensive cropping involving irrigation or terracing, up to 250 pp/km². Moreover, the development of agriculture laid the basis for sedentism and village life, economic systems based on control of surplus (hence the emergence of durable inequality), and finally, urbanism.

The environmental impacts of increasingly large, and frequently dense, populations as agrarian systems expanded during the Holocene to replace hunting-foraging economies throughout most of the Old and New Worlds were orders of magnitude greater than those caused by the smaller-scale populations of the Pleistocene. Forest clearance for fields, agricultural burning, erosion and/or soil nutrient depletion due to overly intensive cultivation, and secondary impacts of dense village or urban populations (exploitation of wood resources for fuel and construction; hunting and fishing to feed larger populations) resulted in cumulative and irreversible modifications of landscapes over increasingly large regions of the tropical, subtropical, and temperate world. For North America, Delcourt & Delcourt (7, Figure 3.4) argue that as indigenous populations expanded from the late Pleistocene into mid-Holocene, and as their economies were transformed from strictly hunting-foraging to mixed, and finally in many regions to fully agrarian systems based heavily on maize, their activities correspondingly expanded from having mostly population (resource depression) or community-level (successional) impacts to landscape-level (forest fragmentation, resource depletion) and truly regional effects with reorganization of entire ecosystems.

In many areas, the cumulative impacts of agricultural (and pastoral) economies led to what can only be described as degradation of landscapes, sometimes requiring major reorganization of economic, social, and political systems in response. This would appear to have been the case in parts of the third millennium B.C. Near East, for example, where the cumulative effects of 4000–6000 years of farming and herding, when combined with minor fluctuations in climate, precipitated social collapse over much of southwestern Asia (101–103). Archaeobotanical remains from a diversity of sites in Mesopotamia and elsewhere in the Near East (104, 105) have demonstrated major forest declines in the third millennium. Miller (105, p. 206) argues that whereas climate had been the “primary determinant of vegetation in the Near East until the Bronze Age,” by 3000–2000 B.C. the cumulative impacts of “cultivation, herding, pyrotechnology and associated higher population densities” began to have an influence that was, at least in certain areas, greater than climate. It has similarly been argued that agriculture-related deforestation and erosion are correlated with the demise of the Classic Maya civilization (106–109) and with later collapse of agricultural systems in the Tehuacan Valley of Mexico ca. 900 B.P. (110).

Archaeobotanical and related archaeological evidence for human impacts to vegetation communities is not restricted to agriculture. Early Holocene settlements in the Levant systematically deforested the landscapes around their villages in a continual quest for fuel to produce lime plaster. At the site of ‘Ain Ghazal,
a “devegetated area with a radius of 3.0 km or more” from the settlement was created in the seventh to early sixth millennium B.C. (111, Rollefson in 103). Wertime (112) has estimated that slag deposits from smelting copper, lead, silver, iron, and other ores around the Mediterranean littoral in antiquity probably amount to between 70 million and 90 million tons, “representing the divestiture of at least 50–70 million acres of trees.” Although regrowth obviously occurred, the long-term impacts on landscapes cannot be discounted. The Romans increasingly turned to “the forested flanks of Europe for its metals and glass,” and indeed measurable trace-element increases in lead in Swedish lake sediments have been linked to preindustrial airborne pollution derived from Greek and Roman smelting (113). On a smaller scale, but no less severe in its impact, the Anasazi who inhabited Chaco Canyon between A.D. 720 and 1490 seriously depleted the pinyon-juniper woodlands that had been persistent for at least 5000 years prior to Anasazi occupation (114, 115).

The islands of Remote Oceania, which were not settled by humans until the expansion of seafaring Austronesian-speaking peoples between 3200 and 800 years B.P. (116), have provided a series of case studies demonstrating just how rapidly preindustrial societies can effect massive deforestation through a combination of agricultural and other kinds of burning (30, 76, 85). Mangaia in the southern Cook Islands had its interior volcanic hills stripped of forest soon after Polynesian arrival (53–55). Over the course of no more than 600–700 years, Easter Island lost a forest cover formerly dominated by a large, now extinct Jubea palm, a process of anthropogenic deforestation independently confirmed by palynology (117, 118) and by the analysis of thousands of charcoal fragments from archaeological contexts (119). In the much larger Hawaiian archipelago, the native vegetation of the lowland zones below about 1000 m elevation was extensively altered by Polynesians through agricultural clearing, burning, and the depredations of introduced rats (30, 76, 77). As on Easter Island, the progressive modification of the Hawaiian lowland forests can be tracked by several independent lines of evidence, including changes in pollen frequencies in sediment catchments, charcoal sequences from archaeological contexts, and changing assemblages of endemic land snails. Figure 2 shows a stratigraphic sequence of charcoal frequencies from a rockshelter site on the Kalaupapa Peninsula, Moloka’i Island, illustrating the conversion of a native dryland forest to a landscape dominated by herbs and shrubs (120). The most dramatic case, however, is surely New Zealand, where Polynesians did not arrive until around A.D. 1000–1200, yet managed to deforest vast tracts of both the North and South Islands (83).

Geoarchaeology: Erosion, Sedimentation, Nutrient Loss, Salinization

A third major category of evidence for human-induced environmental change is the purview of geoarchaeology, a subfield of archaeology that intersects with and derives much of its methodology from geology, geomorphology, and pedology, and
Figure 2 Progression of anthropogenic change in the vegetation of the Kalaulapa Peninsula, Moloka’i Island, as indicated by charcoal assemblages from the Kalaulapa Rockshelter site. Analytical zone 3, the oldest, is dominated by native trees. Analytical zones 1 and 2 are increasingly dominated by shrubs, with declining taxonomic diversity. Diagram by J. Coil, adapted with modifications from (120).
it is concerned with the sedimentary and depositional contexts of archaeological sites as well as anthropogenic landscapes at large (15, 16, 22, 121). Geoarchaeologists work at spatial scales ranging from the microscopic (the micromorphological structure of soils or sediments), to mesoscale (formation processes and stratification within archaeological sites), to macroscale (sedimentary regimes at a landscape level). In any particular project, work at all three scales may be required for an adequate understanding of how human actions and socioeconomic systems have interacted with natural processes to shape landscapes. Pioneering work in geoarchaeology tended to emphasize methods derived from sedimentology and geomorphology (15, 16), although more recent work has expanded to incorporate soil micromorphology and geochemical analysis of soil properties (22).

Whereas archaeobotany chronicles the history of human plant use, expansion of agrarian systems, and deforestation through the record of microscopic and macroscopic plant remains, geoarchaeology traces anthropogenic landscape effects by examining the physical evidence for erosion and sedimentation. A classic example of such geoarchaeological work comes from the southern Argolid of Greece, where extensive studies by Wagstaff, Van Andel and others (122–124) have demonstrated that intermittent pulses of erosion and sediment deposition are tightly correlated with phases of human settlement and land use. This is especially noteworthy because earlier geological study (125) had interpreted a widespread sequence of valley infills in the Mediterranean region as having been controlled by climatic events. Finer-grained geoarchaeological research in the Argolid revealed a far more complicated series of cut-and-fill deposits within the Holocene (encompassed too grossly within Vita-Finzi’s “Younger Fill”), which—rather than correlating to climate change—are tightly linked with episodes of farming, grazing, and human settlement. As Van Andel and others interpret the evidence, a major phase of erosion and alluviation commenced about 4500 years B.P., roughly one millennium after the introduction of agriculture, and “as the result of gradual shortening of long fallow produced by increasing settlement density or of rapid clearing of steep, marginal soils” (123, p. 125). Later in the Argolid sequence, the development of terraces and check dams helped to reduce but did not wholly eliminate such anthropogenic erosion. Subsequent work in the Argive Plain and Thessaly, Greece, has revealed similar sequences, again pointing to the dominant role of human activity (124). Moreover, the picture emerging from geoarchaeological studies in Greece is by no means unique; Goldberg & Bar-Yosef (126) summarize geoarchaeological evidence from the Levant and adjacent areas suggesting that during the last five millennia, “human interference with the environment” has supplanted climatic fluctuations as the “decisive factor” in shaping Levantine landscapes.

Other examples can be cited from the Oceanic tropics. Aneityum Island in southern Vanuatu was first colonized around 2900 years B.P. by Austronesian peoples of the Lapita culture, who introduced an agrarian economy based heavily on root crop production using shifting cultivation (127). Microscopic charcoal
particles in Anauwau Swamp mark the immediate onset of burning (associated with shifting cultivation), and pollen frequencies show precipitous declines in tree and shrub taxa relative to increases in grasses and ferns. After about one millennium of human occupation and gardening on the island, major episodes of valley infilling commenced with sediment derived from the steep volcanic hillslopes. These sediments also extended out onto former reef flats, creating coastal plains, which then became settings for intensive agricultural practices including irrigation. The Aneityum story is repeated over much of the southwestern and central Pacific. For the large island of New Caledonia, Sand (128) reports massive sediment accumulations (in some cases burying earlier occupation deposits under 6 m of alluvium) in the island’s valleys by around 2000 B.P., about one millennium after initial human colonization. In the Koné region of New Caledonia, sediment deposition onto coral reefs and sandy bays transformed these into mud flats, in the process completely transforming the spectrum of mollusks available for human consumption (129). Similarly, on the large island of Viti Levu in the Fiji archipelago, significantly increased sediment loads deriving from anthropogenic alteration of the landscape in the drainage basin of the Sigatoka River (probably primarily as a result of shifting cultivation) began around 1500 B.P. resulting in the accumulation of a massive parabolic dune field at the valley mouth, burying late Lapita period occupations (130). And, on the island of Mo’orea in the Society Islands, Lepofsky et al. (131) examined sedimentary deposits containing macroscopic charcoal and dated a rapid sequence of erosion and alluviation in the ‘Opunohu Valley that again correlates to human colonization and the establishment of cultivation systems on the interior valley slopes.

Geoarchaeology also contributes to our understanding of the impact of cultivation systems on soils and their ability to sustain productive agriculture over long time spans. Sandor (132, 133) contrasts two cases, from New Mexico and Peru, in which prehistoric farming practices had very different outcomes for the properties of the respective agricultural soils. In New Mexico, soils cultivated prehistorically by the Mimbres people remain partly degraded nearly 900 years after agriculture ceased, indicated by significant losses of organic matter, nitrogen, and phosphorus. In contrast, soils in agricultural terraces in the Colca Valley of Peru display elevated fertility status, even after 1500 years of cultivation, a consequence of a “carefully constructed agricultural system well-adapted to its mountainous environment” (133, p. 241). Recent and ongoing geoarchaeological research on prehistoric dryland cultivation systems in the Hawaiian Islands (46, 134) has quantified nutrient loss due to intensive farming of sweet potato and taro root crops. In these systems, elemental soil nutrients in cultivated soils show losses of up to 50% when compared to uncultivated soils in the same areas, after about four centuries of intensive farming practices.

Soils have also been adversely affected by ancient cultivation regimes through extensive irrigation resulting in salinity damage. The classic case is southern Mesopotamia (135, 136) where irrigation elevates the shallow water table, and capillary action brings mineral salts to the surface. Major salinization occurred in
southern Mesopotamia from about 2400 to 1700 B.C., requiring a shift from wheat to more salt-tolerant barley. Even barley yields declined progressively, however, as indicated by temple records showing a drop from an average of 29 bushels per acre around 2400 B.C. to as low as 10 bushels per acre by 1700 B.C. The great urban centers of southern Mesopotamia were not able to be sustained under these declining agricultural regimes, and the long-term legacy is “a saline plain that requires expensive salinity control methods for intensive agricultural production” (136, p. 330).

Settlement Patterns, Agrarian Landscapes, and the Built Environment

In canvassing the diversity of evidence acquired by archaeologists relating to how humans have shaped the global environment, I have thus far stressed faunal and floral remains and geoarchaeological data. But one cannot neglect the vast category of archaeological remains referred to as nonportable artifacts: structures, settlements, permanent agrarian landscapes, and the built environment generally. The “settlement pattern” approach in archaeology was formally introduced by Gordon Willey (137) in his study of the Virú Valley, Peru, and defined broadly by him as “the way in which man disposed himself over the landscape on which he lived.” In the five decades since this pioneering study, settlement archaeology and its offspring (spatial archaeology, landscape archaeology) have advanced in theoretical perspectives and methodological rigor as well as in geographic diversity of landscapes that have been intensively studied (e.g., 138–141). Geographic information systems (GIS) are playing an increasing role in archaeology, especially in the integration of multidisciplinary data sets obtained at a range of spatial scales (142), from site excavation to regional survey and to remote sensing. GIS databases are increasingly linked to agent-based models and computer simulations in order to test hypotheses of human-environment interactions over time in specific landscapes (143).

As human societies increased in size and scale throughout the course of the Holocene (see below), from simple village communities to urban centers and eventually empires linked by roads and transportation networks spanning vast regions (144), the surface area of the Earth modified by human constructions increased geometrically. The archaeological literature on settlement landscapes is too extensive to review here, but a few examples may demonstrate the importance of this category of evidence. The Archaeomedes Project (42, 145) has examined a sequence of human occupation and use of the Rhône Valley, France, from early Holocene times through the Roman and Medieval periods. Their study demonstrates particularly well how modern landscapes have been shaped by long-term processes of human settlement, sometimes through multiple cycles of settlement expansion, agrarian system transformation, crisis, and reorganization. In the Rhône Valley, the urban component of the present-day spatial system and the road system derive from the Roman period, whereas the village structure is essentially Medieval. “The overall
spatial configuration and the main anchor points are spatially stable. Neither colonization, wars, political disasters nor epidemics have fundamentally changed the spatial organization of the area, because they operate on different spatio-temporal scales” (145, p. 345). Here truly, is an example of Braudel’s *longue durée* (41), human-natural systems that endure over thousands of years even as shorter-term political structures wax and wane.

Extensive reshaping of landscapes in both the Old and New Worlds was frequently linked to trajectories of agricultural intensification. As noted earlier, archaeobotanical evidence for deforestation resulting from both cultivation and pastoralism is abundant for many regions. The intensification of agriculture, however, also frequently followed pathways of “cropping cycle” intensification and of “landesque capital” intensification (146, 147), both resulting in permanent restructuring of the physical as well as biotic landscape. These include a variety of irrigation, drainage, and other water control systems for agricultural production, terracing, field boundaries, and field systems (57, 60), landscape features that persist long after cultivation is abandoned, and that in some cases may be brought in and out of production as social and economic systems are transformed. Classic archaeological examples of such landesque capital agrarian landscapes include the vast canal networks of the Diyala Plain and elsewhere in Mesopotamia (148, 149), clearly visible through aerial photos millennia after they were abandoned; the canals, reservoirs, aqueducts, and similar agricultural facilities extending out over the landscape surrounding the Medieval city of Vijayanagara in southern India (150); and the dryland field system of Kohala, Hawaii Island (46, 147), a continuous landscape of thousands of field walls, boundaries, trails and other agricultural features covering more than 52 km².

The most artificial or anthropomorphized of environments is—without doubt—the true city, and the rise of urbanism is another facet of the built environment to which archaeology has made enormous contributions over the past century. Urban centers arose in Sumeria between the late fourth and early third millennia B.C. (91, 148, 149), with such famous cities as Nippur, Susa, Uruk, and ‘Ur. As noted earlier, the cumulative pressure on the resources of southern Mesopotamia deriving from the dense populations of these cities, including their surrounding villages and agricultural hinterlands, precipitated an environmental crisis by the third millennium B.C. Between 2500–2000 B.C., the Indus Valley civilization flourished with major urban centers such as Harappa and Mohenjo-Daro. In Mesoamerica, urban centers arose in several areas including the Maya lowlands (sites such as Tikal, El Mirador), Oaxaca (Monte Alban), and central Mexico (Teotihuacán) during the Classic Period of the first millennium A.D. (151). A city such as Teotihuacán is estimated to have had a population of at least 85,000 persons. In China, the Shang civilization of the second millennium B.C. also saw the rise of urbanism, with sites such as Anyang, which covered an estimated 24 km². All of these early cities, as with those which would follow them, constituted vast sinks into which energy and materials flowed from extensive catchments extending out from such centers many hundreds of kilometers.
ISSUES OF SCALE: SOCIAL AND DEMOGRAPHIC

One aspect of varying scale in the archaeological record of environmental change has already been noted: the sizes of the landscape catchments drawn upon by the former populations of particular sites, representing the larger area from which materials deposited in the site were collected. For smaller sites such as individual household dwelling units, these catchments may be relatively small (e.g., a few hectares up to perhaps 10 km² in extent), whereas in the case of ancient cities just described such catchments extended out over large distances.

Scale is also critical when one considers the hierarchical relationships between levels of sociopolitical organization and their population sizes, spatial extent, and temporal duration. Although discredited as a unilinear model of cultural evolution, a basic classification of human societies into four major categories (91, 152) remains useful as a heuristic device for understanding how the scale and relative impact of human social groups have expanded over the course of the Holocene (Figure 3). Throughout the Pleistocene and into the early Holocene, human groups were organized as family units, or bands, at times coming together into short-term assemblies for economic or ritual purposes. Such groups might range over fairly large territories and have considerable persistence over time, but their group numbers were small and their densities low. The first experiments with village life and the origins of a tribal level of social organization can be traced to the Pleistocene-Holocene transition period in the Near East (91). Although catchment size per se did not necessarily increase (mobile hunter-gatherers were, in fact, likely to cover more territory than sedentary farmers), both group size and density per land area increased significantly. A major transition in sociopolitical organization occurs with what anthropologists call the chiefdom, marked among other criteria by hereditary power and true “durable inequality” expressed as social stratification. Again, population size, catchment area, and density ratchet up significantly, with a corresponding increase in the potential impacts to the landscape exploited by a chiefdom society. Chiefdoms arose at different times in different regions of the world, but they were a dominant mode of sociopolitical organization after ca. 3000 B.C. in the Old World and after ca. 1000 B.C. in the New World, until—in many cases—these were supplanted by, or became tributary to, states. Early forms of the state, referred to as “archaic states,” are characterized by the rise of divine kingship, incipient forms of bureaucracy and taxation, and the use of force to maintain durable inequality. States display enormous variability in their attributes (not all are urbanized, for example), but for our purposes, we need only note that they once again ratchet up the scale of population size, spatial extent, and impact on the environment by at least an order of magnitude.

Of course, these four major classes of sociopolitical organization do not represent a unilinear evolutionary sequence, and over the past several thousand years, all stages coexisted and interacted in complex ways. Nonetheless, taking a very broad view of human history, it is notable that family groups and bands were the exclusive mode of organization from the emergence of *Homo sapiens* as a distinct species
Figure 3  Scale factors in sociopolitical formations. (A) Temporal persistence versus population sizes of four major kinds of sociopolitical formations. (B) Population sizes versus catchment areas of four major kinds of sociopolitical formations. Redrawn with modifications from Reference 7.
until the end of the Pleistocene. In the past 10,000 years that we call the Holocene, we have successively witnessed the development of tribal societies, chiefdoms, archaic states, nation states, and empires. The temporal pace of social change—and the corresponding changes in population size, spatial extent, and population density—are essentially exponential over the course of the Holocene. Needless to say, the relative impact that human groups have had on their environments has followed the same general exponential trend.

When looked at in terms of regional and local scales, of course, such general trends decompose into historical sequences that display considerable temporal variation, for example in demographic trajectories. Paleodemography, or demographic archaeology (100), requires large, statistically valid data sets, such as well-dated house counts, in order to derive estimates of population growth and decline over time. As archaeologists and paleoecologists work toward understanding the ways in which human and natural systems were tightly interlinked, however, having accurate paleodemographic data becomes increasingly important. The linkages between cycles of population growth and decline, and human-induced landscape transformation and degradation, are often complex and sometimes inverse. This is shown, for example, by the case of the Lake Pátzcuaro Basin, Mexico, where initial land degradation caused by human settlement later becomes ameliorated as a large, burgeoning population was able to invest large labor inputs into land management resulting in a decline in erosion (154). Following demographic collapse resulting from the Spanish conquest, however, the inability to maintain labor-intensive landscapes and their subsequent abandonment led to another cycle of land degradation. This example, one of many that could be cited, points up the necessity of deriving independent, accurate estimates of human population numbers and densities as an integral part of the investigation of human ecodynamics.

CAUSALITY, RESILIENCE, MODEL SYSTEMS

Anyone who has followed—even in a cursory manner—the advances that archaeology has made over the past half century in tracing the myriad ways in which human populations have irreversibly shaped the physical and biotic world we inhabit will recognize that global change has been underway since the early Holocene. The record of cumulative resource depression, translocations, extinctions, deforestation, erosion and sedimentation, expansion of agrarian landscapes, and increasing urbanization dispel any lingering views that pristine ecosystems persisted until the expansion of the industrialized West. Understanding how socio-natural systems have coevolved over time, however, requires more than merely cataloging the ultimate outcomes of long-term processes of change. It is essential to try to understand the processes of change themselves, which, as we have noted, are highly dynamic and nonlinear.

Mayr (155, p. 67) wisely observed that “it is nearly always possible to give both a proximate and an ultimate causation as the explanation for a given biological
phenomenon.” This dictum applies equally well to the study of long-term global change, the focus of considerable argument over whether particular sequences of ecosystem and landscape change have been caused by inevitable natural forces, especially climate, or by collective human actions. The debate has been intense with respect to the wave of megafaunal extinctions occurring in the terminal Pleistocene, with various proponents staking out positions on one side or other of the causal divide (66–69, 72). Similar debate, again invoking either climate or unsustainable land use practices, attends the question of the collapse of various sociopolitical systems in the southwestern Asia during the third millennium B.C. (33, 101, 102). In both cases, causality is likely to have involved complex interactions between both climate and human actions, so a simple deterministic explanation is unconvincing.

The study of human ecodynamics also needs to confront head on the issue of how past human societies perceived (or failed to perceive) environmental impacts, how social systems themselves adapted or responded to change, and the degree to which such systems could be resilient over long time cycles (29, 34). Because changing environmental conditions were themselves frequently, at least in part, the outcomes of prior human land use decisions (hence "contingent" landscapes), this is not simply a matter of attempting to track cultural response to climate change, although the matter is sometimes presented in such unidirectional terms of a nature → culture stimulus response (e.g., 156). Moreover, the degree to which a society is able to respond to environmental challenges, whether self-induced or not, depends greatly on its ability to perceive and analyze change and to act upon its assessments. As Van der Leeuw notes, “a society cannot communicate with its environment, it can only communicate about its environment within itself” (157, p. 139). A number of investigators have recently found the concept of resilience, “the ability of a system to maintain its structure in the face of disturbance, and to absorb and utilize change,” to be more theoretically informative than a simple concept of adaptation (157, p. 135). As Van der Leeuw observes for the Rhône Valley case, however, resiliency may over time lead to more dependencies and less ability to respond dramatically in the face of a sudden crisis, such as one brought on by drought or other environmental disasters. Delcourt & Delcourt (7) have drawn upon “panarchy theory” (36), which hypothesizes cycles of exploitation (r dominated) to conservation (K dominated), followed by collapse/release and reorganization to understand long-term ecosystem-scale human-natural systems in North America. Whether such metatheory will provide a successful means of integrating and understanding disparate historical sequences of human-natural systems coevolution remains to be seen.

Another valuable approach to understanding human-natural system dynamics over the long-term is that of identifying and analyzing model systems, an approach which has proved successful in a number of fields of science, including ecology (158). This is the perspective taken by our own multidisciplinary group attempting to understand the nonlinear dynamics driving linked cultural and natural system changes in the Hawaiian Islands (45, 46). Owing to its isolation, highly orthogonal
biogeochemical gradients, late colonization by humans introducing an agricultural economy, and rapid sequences of population growth, agricultural intensification, and political transformation, Hawai‘i is seen as offering one such model system. Equally important and complementary to the model systems concept is the use of agent-based simulation and similar computational models to test hypotheses of human-natural system interaction, response, and resilience (143).

CONCLUDING REMARKS

In just five decades, the state of our knowledge has advanced tremendously from where we were when the classic symposium *Man’s Role in Changing the Face of the Earth* attempted to synthesize the long-term impact that human populations have made upon the Earth and its resources; much of what we have learned has been gained from archaeology, often working in consort with paleoecology. This review has touched upon some highlights of what we now know concerning the extent to which humans transformed global ecosystems over the course of the Holocene. One thing is clear: *Homo sapiens* has been an environment transforming species virtually since we gained control over fire and launched our relentless trajectory of technological development, deep in the Pleistocene and early in our own biological history. In the Holocene, with the domestication of plants and animals, development of agrarian and pastoralist economies, evolution of increasingly stratified and complex sociopolitical systems, and rise of urbanism, virtually no parts of the planet remained pristine, even prior to the expansion of Europe and industrialization (the sole exception would be Antarctica). Understanding this history of global change is certainly valuable in its own right, and if nothing else puts the nail to the coffin of the pristine myth, a legacy of the Enlightenment period. Yet dare we hope that such retrospective understanding of how humans have transformed the Earth—and in the process suffered through a panoply of crises, social collapses, and restructurings—could possibly be of use in guiding our collective future? Some at least think that the archaeological record provides lessons that could guide our future (159). Whether we heed them is up to us.

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